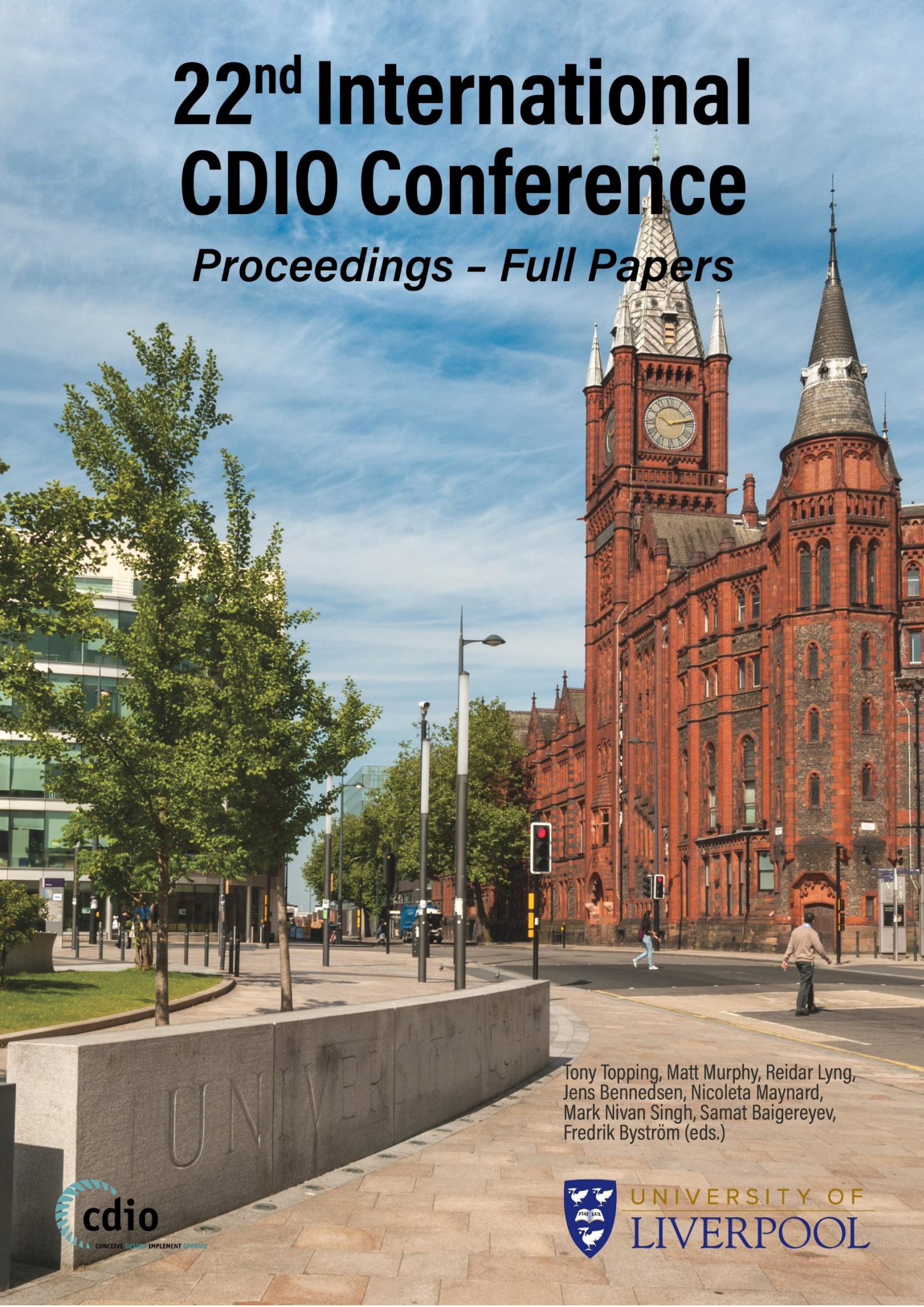
22nd International CDIO Conference

Proceedings – Full Papers



Tony Topping, Matt Murphy, Reidar Lyng,
Jens Bennedsen, Nicoleta Maynard,
Mark Nivan Singh, Samat Baigereyev,
Fredrik Byström (eds.)

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UNIVERSITY OF LIVERPOOL

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CDIO Initiative

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EDITORIAL

The CDIO initiative aims to reform how engineering education is developed and delivered by encouraging the adoption of modern curricula better suited to produce graduates ready for the challenges of the 21st Century. It encourages students to develop relevant professional skills and attitudes through a wide range of learning experiences alongside the traditional acquisition of disciplinary knowledge. The annual International Conference is the key event for the CDIO community where CDIO practitioners from all over the world come together, share knowledge and promote the advancement of the practice of the CDIO Initiative. It includes presentations of papers as well as specialised seminars, workshops, roundtables, events, and activities.

The 22nd International CDIO Conference was hosted by the School of Engineering at the University of Liverpool, UK and took place from 22nd to 25th June 2026. This year's conference drew participants from 63 educational institutes across 27 countries, spanning 6 continents, with 150 registered participants.

Under the main theme "Enhancing Student Professional Development: Innovation in Assessment and Feedback" this year's conference aimed to explore innovative assessment approaches that focus on the development of professional engineering competencies, skills and attitudes. In line with this, the opening keynote from Dr Pluen Hermsen highlighted the importance of reflection within engineering education, asking such questions as: How can we make students reflect authentically and meaningfully? How can we make sure that reflection supports development of socially responsible engineers? What is the role of educators? Should we stop asking students to reflect and instead create the conditions where reflection can emerge? In the second keynote, Dr Rhys Morgan and Emeritus Professor Peter Goodhew explored the work the Royal Academy of Engineering has been doing to rethink professional and technical skills to transform the engineering education landscape in preparation for future challenges. This included challenges form Peter to the CDIO community to evaluate their own practice and to consider whether a 'skills first' approach to engineering education should be adopted. The final keynote of the conference was presented by the CDIO Academy students, detailing a special project tasked to them by Professor Matt Murphy in which they identified the most common issues that impact student learning and wellbeing. The output of the project was '10 golden rules for happy and successful students', a set of easy to manage interventions for educators that aim to improve student satisfaction.

Once again the CDIO Academy ran parallel to the main conference. This year saw 19 students from 7 universities compete in a design-build-test competition to create an aerobatic aircraft to compete in a digital 'Red Bull Air Race' around the city of Liverpool. This took advantage of the School of Engineering's expertise in flight simulation, allowing students to use integrated simulation tools to build their virtual aircraft, before testing them in Liverpool's state-of-the-art HELIFLIGHT-R flight simulator with a professional test pilot. The winning team presented their work to the gathered international delegates. This activity exemplifies the CDIO framework, fostering a collaborative learning environment which gives students hands-on experience. This was not the only student input to the conference; Our undergraduate students, employed as helpers, managed to find time to attend number of sessions and contribute to the discourse. This contribution was welcomed by the sessions leads as it is often difficult to get a candid student perspective on the work we do. Hopefully, student involvement in sessions can continue at future conferences.

The peer review process maintained high scholarly standards, with 96 members of the international CDIO community filing around 250 review reports. These proceedings contain 67

Full Papers: 13 in the Advances in CDIO track, 32 in CDIO Implementation, and 22 in Engineering Education Research. Additionally, 4 CDIO Project in Progress contributions were presented (not part of these Proceedings), alongside 31 collaborative sessions across 17 Workshops, 12 Roundtable Discussions, and 2 Working Groups. These proceedings are indexed in SCOPUS and represent rigorous scholarship on engineering education practice. They contain both successes and candid accounts of challenges, established findings and preliminary investigations, answers and unresolved questions.

I'd like to thank: Matt Murphy, Steve Bode, Lesia Swain, Annie Watson, Tasha Whitehall, Sue Kelly and Nicola Gilmore whose significant contributions made the conference possible. I'd like to give special thanks to Chris Dadswell, Dani York and their team of PhD students who worked tirelessly to make the CDIO Academy a success. Finaly, I'd like to thank Professor Eann Patterson, Dean of the School of Engineering for his support in bringing the CDIO conference to Liverpool.

To everyone who contributed to CDIO 2026 - through papers, reviews, presentations, keynote speeches, facilitation, or thoughtful participation - thank you. Your engagement made this conference valuable.

Given the many difficulties presented by international travel and the concerns of the community about the environmental impact of such travel, the 23rd CDIO International Conference in 2027 will be an online conference hosted by the East Kazakhstan Technical University. Other than the necessary move to online formats forced by the COVID pandemic, this will be the first planned online CDIO conference. This is a great opportunity for the initiative to explore and develop more equitable and sustainable ways to connect and collaborate; I'm excited to see how the community continues to evolve.

I hope these proceedings support your research, curriculum development, and teaching practice as you work towards excellence in engineering education. I also hope that you benefit through the truly unique community of practice that exists within the CDIO Initiative.

Tony Topping
Conference Chair, CDIO 2026
Senior Learning Technologist
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2nd of July, 2026

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TABLE OF CONTENTS

Advances in CDIO 1

103: CDIO Framework and Cognitive Science: Human-In-The-Loop for Gen AI Use by Sin-Moh Cheah 2

104: Appraising CDIO Standards for Guiding Responsible Gen AI Use in Curriculum Design by Sin-Moh Cheah 16

105: Standard for Continual Faculty Development: Innovating Teaching and Learning With Gen AI by Sin-Moh Cheah 33

106: Safeguarding Human Creativity: Using Gen AI to Protect Against Gen AI by Sin-Moh Cheah 47

107: Review of CDIO Syllabus Version 3.0 to Include Development of AI-Human Competencies by Sin-Moh Cheah 60

108: CDIO Program Evaluation: Improving Self-Evaluation Process With Guidelines and Guiding Questions by Sin-Moh Cheah 84

109: CDIO and Gen AI for Sustainable Development: Design Principles and Enhanced Self-Evaluation by Sin-Moh Cheah 97

116: Spark Framework for Human-Centred Generative Artificial Intelligence Integration in CDIO Education by Katerina Yang, Mark Nivan Singh & Xin Hui Ng 110

134: Model Pathway in Chemical Engineering to Develop Students' Sustainability Mindset Using CDIO by Sin-Moh Cheah 118

219: AI Assisted Qualitative Analysis of CDIO Implementation by Kirsten From 136

222: Integrating Research-based Learning into the CDIO Framework by Fadi Alkhatib, Isam Zabalawi & Vladimir Simociv 145

CDIO Implementation 156

100: Strengthening Engineering Education Through Industrial Collaborations Within the CDIO Framework by Mortadha Alsaba, Mohamad Iyad Al-Khiami, Jean El Achkar & Mohammed Abdul-Niby 157

101: Incorporating an Integrated Development Environment to Teach Numerical Methods by Desmond Adair, Kairat IsmAllov & Martin Jaeger 168

110: Redesigning Assessment for AI-Supported Project-Based Learning: Evidence from Engineering Education by Mohamad Farhat, Mohammed Abdul-Niby & Hamzeh Aljarajreh 179

114: A Practice of a Creativity-Centered Pedagogical Model for Chinese Design Education by Yufan Zheng, Anne Nortcliffe, Hany Hassanin & Stuart Lambert 189

117: Ensuring Individual Accountability in Authentic Team-Based Assessments by Edward Causton 201

118: Designing Authentic Industry-Engaged Assessment for Professional Competence in Business Intelligence by Helga Ingimundardóttir 211

119: Identifying the Four Core Beneficiaries of Industry-Driven CDIO Projects by Soumya Kanti Manna, Nabila Naz, Salman Saeidlou & Anne Nortcliffe 221

120: Integrating CDIO and Team-Based Learning in a Management Course: Action Research Study by Cheng Mei Tung 234

122: Sustainability Considerations in Engineering Curriculum by Kristiina Brusila-Meltovaara, Susanna Vanhamäki & Sariselia Sore 245

125: Singapore Polytechnic and Polibatam Transnational Collaborative Student Project: Initial Exploration by Kim-FAI Soh, Hendawan Soebhakti, Muhammad Arifin, Nanta Fakih Prebianto & Abdurahman Dwijotomo 255

129: Problem-Based Learning Into the Income Tax Theory and System Course by Sheng Tung Chen..... 268

137: 25 Years With CDIO – a Linköping Perspective by Svante Gunnarsson, Helena Herbertsson & Annalena Kindgren..... 285

139: Using Pull Requests to Make Collaboration Visible in CDIO Project-Based Courses by Helga Ingimundardóttir 296

154: Nordic Institutional Rules and Regulations in the Light of Generative AI by Jens Bennedsen, Juha Kontio, Janne Roslöf, Elizabeth Keller, Fredrik Georgsson & Marisol Rico Cortez..... 306

157: Assessing Students or Their AI Teammate? Case Studies in the GAI Era by Jens Bennedsen, Joo Ghee Lim, Mark Nivan Singh, Mika Suutari, Reidar Lyng & Siegfried Rouvrais 323

160: A Two-Module Approach to Achieving CDIO Standard 4 in Introductory Engineering Education by Samat Baigereyev, Alfiya Zakimova, Zhadyra Konurbayeva & Darya Surova 336

163: Co-Location Labs for Authentic Learning: Experiences from Singapore Polytechnic's Engineering Cluster by Boon Seng Chew, James Yee, Joo Ghee Lim, Sharon Gan, Yihong Kok & Chow Leong Chia 346

171: Putting the 'Tech' Back Into Teaching Technical Fundamentals – Utilising the CDIO Approach by Katie Harte, Adam Richmond, Stephen Darragh, William Larmour, Scott Millen, Jonathan Preshaw, Conor Doherty, Mervyn Barr, Issac Forsythe, Karl Nash, Thomas Moon, Jose Rico Mourenza, Troy Patterson, John Carberry, Robert Vaughan, Louise Pick & Charles McCartan 361

180: Cultivating Sustainability Mindsets in Mechanical Engineering Education Through Design-Implement Experiences by Kim-FAI Soh & Sin-Moh Cheah..... 374

181: Empowering Ict Students as Life-Long Learners Through Authentic Projects by Nico Kranni..... 389

182: Bridging Knowing and Doing Through Habit Formation in CDIO Education by Yslam Orazov, Nurjemal Bayramova, Dayanch Nazarov & Gurbanmyrat Mezilov 396

183: Embedding Transversal and Societal Skills in Aerospace Engineering Programme: Bachelor Curriculum Revision by Mariana Cruz, Daniël Peeters, Angelo Cervone, Rene van Passen, Éva Kalmár & Joris Melkert..... 407

190: Peer Learning and Feedback Through the CDIO Framework in Engineering Education by Marika Säisä, Annukka Kinnari & Mika Luimula 421

193: Implementing the CDIO Framework in Data-Driven Engineering Context: a Course-Level Case Study by Ebru Turanoglu Bekar, Ida Gremyr, Kristina Henricson Briggs, Anders Skoogh & Jon Bokrantz 431

201: Impacts of CDIO Framework Implementation on Output Productivity and Interpersonal Skills Development by Muhammad Arifin, Iman Fahruzi, Siti Noor Chayati & Hendawan Soebhakti 445

202: Evaluating a Digital Signal Processing Course in AI Era by Aldo André Díaz-Salazar, Jalusa Andréia Storch Díaz, Emerson Nobuyuki Itikawa & Svante Gunnarsson 455

203: If AI Writes, Who Thinks? Student Perceptions in CDIO Education by Ahal Akgayev, Chynar Garlyyeva, Chynar Seytekova, Aygul Charyyeva & Yslam Orazov 465

204: A Teaching Model Applied to Functional Assessment Classes in Physiotherapy by Jalusa Andréia Storch Díaz, Aldo André Díaz-Salazar, Emerson Nobuyuki Itikawa, & Svante Gunnarsson..... 474

205: Project-Based Learning Approach for Low Cost ECG Construction and Cardiovascular Health Outreach by Emerson Nobuyuki Itikawa, Aldo André Díaz-Salazar, Jalusa Andréia Storch Díaz & Svante Gunnarsson 484

206: Orchestrating CDIO-Aligned Learning Tasks Through a Course-Type–Driven Assignment Framework by Vairavel Gurusamy, Deiva Sundari P & Siva Kumar M 494

207: Faculty Professional Development in CDIO during Curriculum Reform at a Cambodian University by Sokha Heng, Siteng Tieng, Sin-Moh Cheah & Mark Nivan Singh 507

212: Engineering Empathy: Using Person Centred Simulation to Foster Inclusivity in Engineering Design by Kathryn Fee, AIslinn McAleenan, Matthew Cairns & Gerard Gormley 524

216: Tampering, a Major Challenge for CDIO Boosting by Peter Hammersberg 532

217: Simulation-Driven Resilience: from CDIO to CDI'S' Assessments to Outsmart AI Shortcuts by Alix Vargas, Aland Escudero, Ankith Kamalakshi-Ramesh & Thomas Baker 547

Engineering Education Research 559

102: Chemical Product Design: a Case Study on ‘Learning from Failure’ by Katerina Yang, Sin-Moh Cheah, Yunyi Wong, Al Ye Oh, Thijs Willems & Qian Huang 560

113: Beyond Demonstrations: Student Led Learning Laboratories Through a CDIO Lens by Louise Pick, Charles McCartan, Angena Panaser & Geoff Cunningham..... 574

124: Beyond Linear CDIO: Process Patterns in Renovation-Oriented Architectural Engineering Education by Géza Fischl 584

126: Using Large Language Models as Tools in Introductory Programming Courses by Eli Roslöf & Janne Roslöf 594

127: Privacy-Adaptive Generative AI: from Unstructured Reports to Competency-Based Learning Analytics by Saul Garcia Huertes & Ramon Bragós 606

135: Reframing Professional Learning Assessment in the AI Era by Toh Yen Pang, Alex Kootsookos & Chi Tsun Cheng 616

140: AI-Supported Learning: Self-Assessment of Engineering Students by Bayarmaa Tsogtbaatar, Khulan Ojgoosh & Uranchimeg Davaasuren 628

141: Discovering Assessment Categories for Learning Diaries: AI-Assisted Formative Feedback in Engineering Education by Salu Ylirisku & Tua Björklund 637

143: AI-Supported Socratic Tutoring Chatbot in Manufacturing Education: a Theory-Informed CDIO Implementation by Abboy Verkuilen 653

148: Integrity by Design for Ethical AI Use Through a Reflective Assessment Model by Sean Cunningham & David Tanner 674

152: Mathematics Learning Beliefs of First-Year Engineering Students by Jonathan Cole 684

164: Self-Paced Assessment Approach Combining Robustness Against and Learning With Generative AI by Guttorm Sindre & Gabrielle Hansen 695

170: Steering Together: Student and Staff Perspectives on Autonomy in Final Year Projects by Matthew Cairns, Louise Pick, Charles McCartan & Eoin Cunningham 705

177: Integrating Artificial Intelligence Into Engineering Education: a CDIO-Aligned Instructional Design Approach by Bayarmaa Tsogtbaatar, Khulan Ojgoosh, Uranchimeg Tungalag & Luvsandorj Tsogdov 715

179: From Restricting to Integrating AI: a University Strategy for Engineering Education by Mikael Enelund, Niklas Broberg, Jim Brouzoulis, Fia Börjesson, Victoria Granström, AIdin Fanni, Knut Åkesson & Amanda Öberg 725

187: Linking Student Attendance to Course Results by Anna-Jonna Juth, Johanna Söderberg, Fredrik Byström, Peter Hammersberg & Erik Hulthén 739

188: Learning Outcomes of Digital Twins in Engineering Education: A Systematised Review by Isabella Coombs, Danielle Soban & Charles McCartan 749

192: Supporting Student Teams Tackling Wicked Problems: Introducing Cards of Ambiguity by Eva Kalmar, Wenyi Chu & Yiwei Tao 764

194: Redesigning Feedback to Enhance Student Development by Greg Watts 774

211: Beyond the Classroom: Longitudinal Evidence from a Decade of Challenge Based Learning by Mireia Sierra Andrés, Matteo Di Stasi & Ramon Bragos Bradia 785

Advances in CDIO

CDIO FRAMEWORK AND COGNITIVE SCIENCE: HUMAN-IN-THE-LOOP FOR GEN AI USE

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ABSTRACT

This paper present a mental model to help address on on-going discourse on the careless use of generative artificial intelligence (GenAI) technologies without understanding its potential pitfalls. While acknowledging the benefits of GenAI use, this paper focused on addressing the potential harm of GenAI misuse. It is especially meant for educators as they embraced GenAI and increasingly use it for various aspects of curriculum design or revamp, and in a case of academic expediency, leading to uncritical acceptance of GenAI outputs. They may also inadvertently slip in personal bias into the learning tasks designed to engage students in learning. This model was constructed based on an analogy with real-world applications in biological and engineering disciplines. The model combines extant AI ethical framework, constructive alignment and CDIO Standards to provide guidance to educators to use GenAI in a responsible manner – it does not advocate a complete ban of GenAI use in teaching and learning but a thoughtful, ethical and principled use that harness the power of GenAI to benefit students learning through the use of CDIO Framework. The paper first put forward an argument from cognitive science on the malleability of human brain that makes is susceptible to negative impact due to over-reliance of GenAI use. It posited that deliberate use of pedagogy or combination of pedagogies supported by CDIO Standards that stimulate cognitive engagement is a means to counter the deleterious effect of misguided GenAI use. Selected examples of human capacities from both cognitive and affective domains that are at risk of being compromised by GenAI misuse are identified. The model is then presented and key features explained, followed by a simplified example of how the model can be used. The paper then shares some limitations of the work done, and outlines areas of potential research where use of the proposed model; and concludes will a call for the development of greater trust between faculty and students over GenAI use; where transparency in the teaching and learning is of paramount importance – a factor that the proposed model strive to provide.

KEYWORDS

Generative AI, Cognitive Science, Human-in-the-Loop, Constructive Alignment, CDIO Standards: 1-12

INTRODUCTION: BRIEF DESCRIPTION & SCOPE OF THIS PAPER

Generative Artificial Intelligence (GenAI, or Gen AI in short) undoubtedly had created a storm in the education community (Qian, 2025; Tillmann et al, 2025; Wall et al, 2025; Cardona et al, 2023). Gonsalves (2025) highlighted the need for a nuanced strategy to integrate AI effectively into educational practices and charged that many current efforts "remain piecemeal and reactive rather than strategic and forward-thinking, risking a cycle of short-term fixes rather than sustainable transformation". She further noted that uncertainty persists about the best path forward despite widespread concern and numerous pilot initiatives and urged that "inaction is not an option: the evolution of pedagogy and assessment design is necessary to adapt to GenAI realities".

From his own study, this author noted that most of the current discussions on GenAI tended to focus on policies and ethical frameworks regarding its ethical challenges, governance, advantages and pitfalls, faculty and student perception on its use. With respect to students, many studies focused on increasing student engagement, for example, via the use of chatbots based on GenAI, adaptive system or personalized learning. For faculty, the main emphasis is on improving productivity through streamlining of previously manual processes related mostly to academic administration such as setting of assessment questions, automation of marking processes. The use of GenAI at program and course level tend to be very generic and filled with possibilities or claims of what GenAI can do in many aspects of teaching and learning without much deep analysis. Within disciplinary domains, use of GenAI is most extensively studied in areas of languages, information and communication technologies, writing and general education (Belkina *et al*, 2025; Wang *et al*, 2025). Comparatively there were not many publications in the domain of engineering. Within the CDIO community, use of GenAI first came into prominence at the 2024 International CDIO Conference in Tunisia.

This paper aims to contribute to the discourse from the perspective of curriculum redesign using the CDIO Framework. The purpose is to assist faculty in integrating GenAI into one's curriculum, guided by CDIO principles. This paper takes a different approach from extant literature. It extends the discussion on the responsible use of GenAI, starting with questioning what constitute "foundational core" that we seek to protect against proliferation of GenAI use (or misuse) among both faculty and students. The current discourse on "foundational core" included critical thinking, creativity and creative thinking, empathy, metacognition, self-regulated learning – skills and attitudes that are innate to human, something that machines are not able to replicate, or at least not yet. This paper goes even deeper, looking into the "foundations of foundational core" so to speak. The work in this paper leveraged on developments in neuroscience and cognitive science and argued that the ability of human to think and feel in ways that machine cannot, constitute the "the core" that needs protection. This paper proposes a model of GenAI for use in teaching and learning that incorporates CDIO principles as part of "human-in-the-loop" safeguards along with AI ethical framework to protect "the core" from being negatively affected by GenAI misuse.

NEUROSCIENCE & COGNITIVE SCIENCE: CONNECTION TO PEDAGOGY, TEACHING & LEARNING (INCLUDING ASSESSMENT)

Neuroscience and cognitive science are closely related but distinct fields that together aim to understand how the brain and mind work. Cognitive science focuses on mental processes that humans engage in such as memory, thought and decision-making; while neuroscience seeks to make sense of the biological mechanisms of the nervous system. Neuroscience provides the biological underpinning and mechanisms as basis for cognitive science's theories of mind.

Pedagogy in modern usage is most commonly defined in dictionaries as "the art, science, or profession of teaching". However, such a broad definition informed nothing about the word. In application, pedagogy encompasses the methods, strategies, and approaches used to facilitate learning and achieve educational goals, involving complex relationships between the educator, the learner, and the subject matter. Pedagogy is also shaped by different cultural, social, and political contexts under which it is used. This certainly did not make it any easier for a definitive definition, and as such the meaning of pedagogy is still hotly contested.

Recent developments in neuroscience had confirmed the scientific basis on the role played by human brains in teaching and learning (Holmes, 2019). Pedagogy based on cognitive science focuses on how the human brain works during the learning process, drawing on the memory of previously learnt materials, retention and recall; to inform teaching strategies that creates new learning by connecting to prior knowledge. Key principles include cognitive load management which take into consideration the limitation of human working memory, spaced learning with retrieval practices to strengthen long-term memory, etc. The discourse on cognitive science is sparse, where to the best knowledge of the author, there are only 2 publications to-date, with the work of Niewoehner *et al* (2011) being the first to emphasize the importance of incorporating learning from cognitive science into teaching and learning. Another work by Cheah *et al* (2016) reported on how to use the core principles of learning derived from cognitive science in the design of flipped classrooms.

There are now calls for faculty to be trained or at least exposed to the role of neuroscience in their professional development (Van Bergen, 2024; Chang *et al*, 2021). More specifically Waas *et al* (2023) advocated for pedagogical approaches that enhances faculty's ability to foster metacognition skills in students; and integrate cognitive and psychological findings into faculty professional development.

Pedagogy as a Learning Strategy

Based on the "traditional" interpretation above, the pedagogy based on principles of cognitive science can be considered as intentional design towards teaching and learning requiring human effort to scaffold learning through the deliberate and thoughtful use of specific instructional methods, mediated by social and cultural context, which seek to progressively develop desired competencies aligned to learners' stages of cognitive development.

Pedagogy as a Cognitive Manifestation

Expanding the notion of pedagogy in the advent of GenAI, this paper proposes to frame pedagogy as a manifestation of the human attempt to learn better, grounded in how our brains process information and use that information to make sense of our external world – in short: how we think and feel. In this sense, pedagogy is both a product of cognitive science and a tool to shape cognition. Pedagogy therefore is a structured response to the cognitive architecture of the human brain, as it relates to:

- How we perceive, process, and retain information, e.g. through sensory input, working memory, and encoding for storage in long-term memory
- How we construct meaning, e.g. via schemas, analogical reasoning and development of conceptual frameworks
- How we develop metacognition, e.g. self-awareness of factors affecting thinking such as emotion, use of learning strategies and reflection' and hence how we interact with our external world

Cognitive principles provide useful considerations in the design of learning tasks, for example chunking, deliberate practice, retrieval practice, structured reflection, Socratic questioning, metacognitive prompts, etc. Pedagogy in turn promotes cognitive activity through methods like problem-based learning, case studies, flipped classroom, etc.

Pedagogy doesn't just develop cognition, but also actively shaping it. This highlights a unique reciprocal relationship between pedagogy and cognition, in that it can be viewed as both a mirror and a mold of human cognition, reflecting the dual nature of teaching. How we teach is based on how we think, and the teaching process in turn actively reshapes how we think.

Risk to Cognitive Functions from Over-reliant on GenAI

One of the concerns raised in the increased use of GenAI by students and faculty alike is that they can become increasingly reliant on GenAI in their learning process (i.e. cognitive outsourcing), to the extent that deep learning is compromised. From the perspective of neuroscience, this concern is certainly a valid one. This is due to the malleable nature of the human brain (also known as neuroplasticity of the brain) – it changes and adapts based on the dynamic interaction between our biology and our experiences, as our external environment changes (Bear, Connors & Paradiso, 2015; Doidge, 2008)

While this is a good thing for humans to continue learning new things, it is bad news for over-reliant on GenAI use. Over-reliance on GenAI can subtly erode the very cognitive functions that pedagogy is meant to cultivate. Overuse of GenAI can shortcut the cognitive effort required for deep learning, for example not expending the required mental efforts to read, interpret and understand the materials presented, or to empathize with the needy; and thus not making as many neural connections as desired. Without the durable neural rewiring needed for transfer, abstraction, or innovation; students and faculty can become passive consumption of information, developing only surface-level familiarity on a given topic.

More significantly, over-reliance of GenAI to summarize findings, generate insights, prepare visualization, can be detrimental to another key human capability – that of executive functions such as planning and organization, self-monitoring, managing emotion, etc. Generations of performance evaluation matrix with its own criteria, summaries of articles, and conduct of sentiment analysis producing key themes and the like by GenAI can weaken students and faculty's ability to structure ideas independently. This can arise as neural pathways got rewritten – due the malleability of the brain – in a way that no longer make use of the core.

Cognitive Science Basis of CDIO Framework

The CDIO Framework, although not explicit in its formulation that it derived from cognitive science, can be seen as a curriculum redesign approach (in terms of the CDIO Standards) that was informed by and aligned with the principles of cognitive science. Examples include the following:

- The outcome-based learning of CDIO, which emphasizes "learning by doing", with clearly defined learning outcomes for knowledge, skills and attitudes
- The progressive development approach in the design of Integrated Curriculum to prepare graduate with the desired proficiency level
- The learning process that stresses the simultaneous learning of knowledge, skills and attitude within the same learning context, closely mimicking that of real-world workplace requirements in active and preferably also in an experiential manner, e.g. Design-Implement Experiences and Integrated Learning Experiences
- The assessment process that prioritized learning via a series of timely feedback

- The continual improvement orientation that uses self-evaluation using the core standards as the approach to Program Evaluation

MODEL FOR GEN AI USAGE GUIDED BY CDIO AND AI ETHICAL FRAMEWORKS

This endeavor was inspired by the work of Liu & Bridgeman (2023) who proposed a "two-lane" approach to address challenges of GenAI in assessing students learning. They opined that Lane 1 is where the assessment *of* learning is situated, whereas Lane 2 is for assessment *for* and *as* learning. Lane 1 is secured in the sense that students undertaking assessments in this lane are not permitted to use GenAI in their work; whereas in Lane 2 students have complete freedom to use GenAI in whichever way they preferred, or not to use it. For these authors, the separation between the 2 lane is absolute, as they noted: "We do not foresee a viable middle ground between the two lanes. It needs to be assumed that any assessment outside Lane 1 (i.e. that is un-secured) may (and likely will) involve the use of AI". Later, the role of GenAI appeared to have been "relaxed" for Lane 1 where the use is now at the discretion of the examiner (Liu, 2024). The "two-lane" approach has been both praised and criticized for its simplicity (Curtis, 2025; Reynoldson, 2025).

For our model, we have decided from the onset that it should be a holistic one, to bring together various disconnected topics as mentioned in the INTRODUCTION. The key feature is the use of CDIO Standards that can systematically guide faculty in the use of GenAI in teaching and learning, including assessment. The model will incorporate as is, application of relevant AI Framework the institution subscribed to. We deliberately leave out any specific reference to what is not permitted in GenAI use, and what is allowable and by how much. Instead the model will stress the importance of faculty oversight (human-in-the-loop) based on the AI Framework adopted, the use of appropriate pedagogies consistent with the learning context and desired learning outcomes. Effectively we layered on the familiar CDIO approach with additional considerations of responsible and ethical use of GenAI.

The model is shown in Figure 1 as comprising of a series of concentric tubes. This idea is heavily influenced by the author's training background in chemical engineering, specifically in membrane-based processes used in desalination (production of freshwater from seawater), dialysis (filtering of blood) and gas separation (e.g. production of oxygen from air). The semi-permeable membrane selectively permits only one-directional flow of specific materials (such as desired product, or undesired waste, contaminant) that migrates from the inner tube to the annular area. The driving force that affects the transfer can be differences in pressure, concentration, etc.

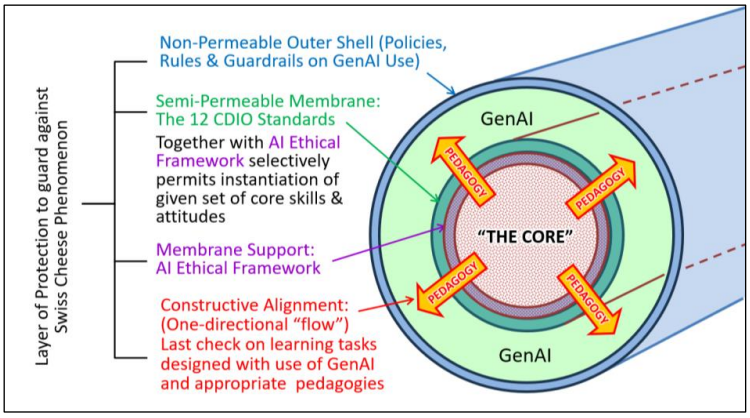


Figure 1. Model of GenAI use in T&L guided by CDIO and AI ethical frameworks

The innermost tube encompasses “the core” representing the ways humans think and feel, that we should develop in students, which needs to be shielded from being replaced by machines. Table 1 shows some elements in “the core” – human capacities from both cognitive and affective domains that at-risk human capacities at-risk of being eroded by over-reliance of GenAI use, as identified from the extant literature. The listing here is not exhaustive and is only to provide examples to justify why “the core” needs to be preserved as studies had reported on the potential downsides. This paper acknowledged that there are benefits of GenAI use. The absence of discussion in this paper did not imply that it is against GenAI use.

Table 1. CDIO syllabus describing “The Core”: Human capacities to be protected

Author(s)	Human Capacity	Key Insights from Paper
Chen *et al* (2025)	Emotional Regulation & Resilience	GenAI may lower cognitive effort, risking “cognitive atrophy” and reduced perseverance/resilience.
Fan *et al* (2024)	Emotional Regulation & Resilience	Reduced self-monitoring correlates with weakened motivation and resilience.
Gonsalves (2024)	Creative Thinking & Creativity	Stifled creativity when defaulting to AI-generated ideas; require AI-aware creative outcomes.
Lee *et al* (2025)	Critical Thinking & Judgment	High confidence in GenAI was linked to less critical thinking; and nature of critical thinking had *shifted* from *generating* and *analyzing* ideas to primarily *verifying* and *integrating* outputs from AI.
Moongela *et al* (2024)	Critical Thinking & Judgment	GenAI risks diminishing independent reasoning without scaffolded critique.
	Creative Thinking & Creativity	Heavy GenAI reliance reduces originality and divergent thinking.
Tomisu *et al* (2025)	Metacognition & Self-Directed Learning	Treating AI as “oracle” undermines metacognitive monitoring Outsourcing reflection to AI weakens SDL
Zhai *et al* (2022)	Critical Thinking & Judgment	Dependence on AI dialogue systems weakens decision-making and analytical reasoning.
	Metacognition	Overuse of AI reduces metacognitive engagement and verification.

The protection of “the core” is achieved by borrowing another concept in chemical engineering, that of layer of protection analysis or LOPA in short (see for example Willey, 2014). The concept of “defense-in-depth” in cybersecurity uses the same approach. Each layer of protection works independently of one another: If one layer of defense fails or is bypassed, subsequent layers are still in place to stop the attack or minimize its impact. Such layered security is designed to protect against the Swiss Cheese phenomena (Reason, 1990). This is a visual metaphor for accident causation in complex systems, where each slice of Swiss cheese represents a defense barrier with its own holes (weaknesses). Accidents occur when these holes align across multiple layers of defense, creating a clear path for a hazard to cause harm. The Swiss cheese model helps explain how failures arise from the combination of multiple, often minor, flaws, rather than a single catastrophic error.

The first protective layer (LOPA) surrounding “the core” is the AI Ethical Framework. In this paper, we made no specific recommendations on which framework to adopt. We noted that there are various authors and institutions that had already promulgated one’s own version of the AI Ethical framework. One notable framework is the Educational Integrity Enforcement Pyramid (Ellis & Murdoch, 2024). We will leave it to the program owner to decide on which AI Ethical Framework to use, to address the much-needed AI Literacy for faculty and students.

The second LOPA protective layer is the CDIO Framework, which together with the calibrated use of pedagogy or combination of pedagogies should guide the use of GenAI in various aspects of curriculum design. Different CDIO Standards will have their own constraints imposed on the acceptable use of GenAI. Due to page constraints, detailed discussions of the different CDIO Standards and how each of them guides GenAI usage is deferred to a separate paper by the author (Cheah, 2026a). Suffice to say that there are checkpoints in the CDIO Standards that ensure presence of “human-in-the-loop” to cross-check outputs produced by GenAI.

The use of GenAI in Figure 1 refers to the process of “Learning with AI” (Mattalo, 2024), which investigates the use of AI directly in pedagogical practices to assist students with learning or to assist educators with their teaching methods. To further protect “the core”, we borrowed a key understanding from object-oriented programming where we introduced the notion of “instantiation”, which is the process where one creates an instance of an object from the original blueprint. When you instantiate an object, you're bringing it to life for use in your program, and you then work with the instance of the object, leaving the original unaffected. This analogy implies that during humans interaction with GenAI when elements from the “the core” are needed, a “copy” of elements of “the core” is created and made available for use.

The arrows labelled “pedagogy” represents an intervention that seeks to leverage on GenAI to drive change in a program curriculum, for example, a series of learning tasks spread over the program duration to develop various CDIO skills and attitudes. The instantiation in this context means that the skills and attitudes embodied in “the core” had been “copied” for use alongside GenAI, to aid in desired aspect of the curriculum design effort, guided by relevant CDIO Standards; but leaving “the core” untouched by GenAI.

Next, we introduced the principles of constructive alignment into our model. The use of constructive alignment had been suggested by several authors (Schofield & Zhou, 2025; Stokkink, 2025) to systematically integrate AI literacy into curriculum design at the module level. Our model takes it one step further: constructive alignment as the ”last line of defense” in our LOPA concept mandating a check by “human-in-the-loop” after an intervention had been designed. We posited that CDIO Standards fit well with constructive alignment, as shown in Figure 2. The responsibility for ensuring alignment between learning outcomes, learning tasks and learning assessments will strictly be a human endeavor.

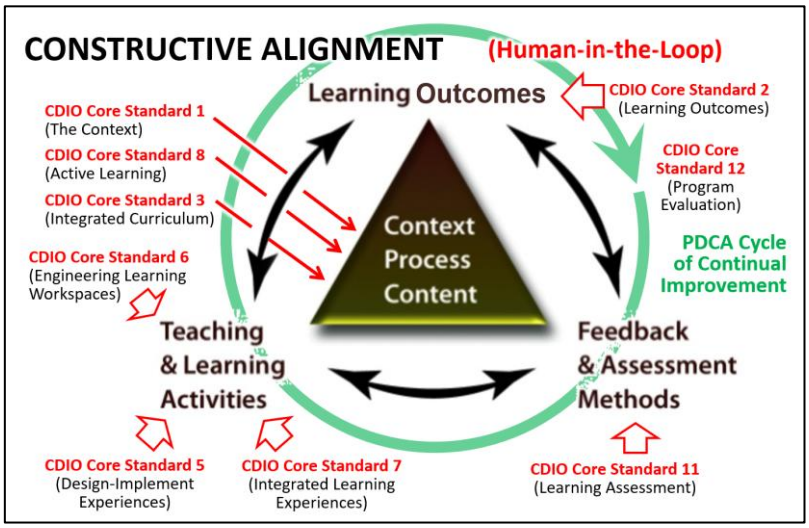


Figure 2. Constructive alignment and CDIO: Human-in-the-loop for GenAI use

In summary, our model emphasized a process approach to using GenAI in curriculum design, hence mandating faculty (human-in-the-loop) to consider the impact of using GenAI not only from perspective of its ethical use, but also in terms of protecting the core. As shown in Figure 1, pedagogy is not just a delivery system, it is also a neurological intervention. It specifically targets how humans think, being mindful of the influence of emotion in affecting the quality of thinking. It specifically requires faculty to make use of our long-term memory, drawing from the core ("instantiate") when using GenAI on the design task on hand; and in the process, strengthen existing neural connections and create new ones.

The outcome of such protection against GenAI is therefore towards "cognitive independence", which is explained as the ability to think critically, form personal judgements and make decisions based on one's owned reasoned outcomes based on one's own internal processing of information rather than by external prevailing opinions, which in this case, is the output from GenAI. By preparing learning tasks based on this model, faculty develop good practice of always checking on the appropriateness of using GenAI in every curriculum design situation; maintaining academic integrity and taking responsibility for GenAI use in education.

Example on How to Use the Model

As an example of how this model can be used, we consider processes in the design of a CDIO Integrated Learning Experience to integrate systems thinking in a hypothetical program in chemical engineering. The key steps are briefly listed in Table 2, showing where GenAI can be used and where human-in-the-loop is necessary:

Table 2. Using GenAI with human-in-the-loop for design of integrated learning experience

Task to be performed	Can be done by GenAI	To be overseen by human
Identify real-world workplace scenario where systems thinking is required	Suggest 2-3 scenarios, along with domain knowledge needed	Confirm the contextual factors and identify suitable course(s) with domain knowledge that match the scenario(s) identified
Write desired learning outcomes using Bloom Taxonomy	Suggest learning outcomes at different proficiency levels depending on task complexity	Check that the learning outcomes match that of the course and year of study, and aligned to institution's graduate attributes
Design learning tasks using CDIO principles: including any scaffolding that are needed	Prepare a draft step-by-step learning task, suggest needed resources, suggest questions for pre-experiment (formative assessment) or in-experiment or post-experiment debrief (can be summative) Draft a scenario that require application of desired competency	Verify how realistic tasks can be carried out in school environment, e.g. through visualization, or actual prototyping in the laboratory Ascertaining prior knowledge had been covered elsewhere and of the right depth and breadth Ascertain relevance of scenario, e.g. mimic real-world environment
Define and design the learning assessment, and identify evidence needed	Produce performance rubrics for assessment – generic or task-specific to a scenario Suggest questions to be posed Performing sentiment analysis in the case where students are required to submit reflection journal	Review if performance criteria are appropriate, descriptors are clear and understandable by students and meet intended learning outcomes Confirm relevance of questions and level of difficulty commensurate with tasks performed
Review and improve on the designed learning task	Check for grammatical errors, fluency of language used, and professionalism in format used	Check for constructive alignment, and that the original intent had not been unintentionally modified

As mentioned earlier, Cheah (2026a) provides in a separate paper, presenting a standard-by-standard discussion on areas where faculty can use GenAI, and other aspects where human oversight (presence of human-in-the-loop) is recommended. Faculty should use that paper as a "design companion" when using CDIO Standards together with GenAI in their work.

LIMITATIONS AND IDEAS FOR MOVING FORWARD

Our model as depicted in Figure 1 was formulated from the perspective of guiding faculty in using GenAI in curriculum design in mind. It can be further envisioned that the learning tasks designed in this manner will also engage students in learning with AI in a responsible manner. Our students will graduate into a world where AI is already prevalent, no longer a distant concept. The mantra of being "work-ready" should now include competency to effectively navigate and thrive in a new world of AI.

However, the model is still a theoretical consideration and needs to be validated in practice. Along with our current efforts to develop sustainability mindset among students (Cheah et al, 2025), we can kickstart the testing of this model by using it to design some integrated learning experiences to develop various key competencies for sustainability. With the rapid advances in technologies, it is reasonable to expect more advanced and powerful GenAI engines will soon appear in the very near future. These developments may render parts of the protective layers ineffective. For example, the next iteration of wearable technologies will include detection of variations of biometrics of faculty using the GenAI engine. It may misinterpret increased heartbeat as potential negative impact of the activity being designed. The GenAI can potentially trying to "compromise" on the level of difficulty of the learning task; thus defeating the intended learning.

It may also appear trivial, the use of "instantiation" to protect "the core" suggested in the model. Unless faculty is familiar with object-oriented programming, doing so may appear strange. The model relied on an abstract notion "duplication" of skills and attitudes which did not actually took place in any design effort, hence it may be hard to appreciate how doing so can shield "the core" from negative impact of learning task produced by GenAI. We argued that it is the discipline of the thought process that matters. We want to make explicit to faculty to think of the pros and cons of each curriculum change scenario that the process becomes habitual. The reason behind this is again cognitive science and the malleability of human brain – the rewiring of our neural networks, so that the practice becomes second nature.

Another point worth highlighting is that our literature review specifically focused on negative impacts of GenAI use. The are of course, many papers that reported on the benefits of GenAI use, but for the purpose of this paper, these were deliberately omitted. This is by no means intended to discount the advantages of using GenAI in teaching and learning.

Moving ahead, we noted from Mattalo (2024) that research into the use of AI in pedagogy in general remains underdeveloped. Indeed, Mattalo (2024) charged that although GenAI is often lauded as a solution to many of educations problems, it is rarely used in any meaningful way to improve learning outcomes. Given the potential of GenAI, and the dearth of high-quality research into its intersection with pedagogical practices, he noted that there is a significant opportunity for academics to advance this field of research and suggested a framework of Learning with AI that comprises 3 focus areas, listed below and shown in Figure 3.

- *Pedagogical Enhancement Research*
- *Pedagogical Breakthrough Research*
- *Administrative Research*

This paper focuses on the 2 pedagogical research areas only, as *Administrative Research* is concerned with using AI to automate and alleviate the administrative load on faculty so that they can spend more of their time in teaching and learning as well as research practices on the capabilities of AI. *Pedagogical Enhancement Research* is concerned with studying the effectiveness of using AI to implement already well-recognized best practices in pedagogy with AI tools. *Pedagogical Breakthrough Research* is concerned with discovering new pedagogical practices that are unlocked by AI and were not possible in traditional learning environments. This latter area of research requires a deep understanding of how AI technologies work, may require training AI models on specific tasks, and will certainly require creativity and experimentation to uncover new methods of teaching that were not previously possible (Mattalo, 2024).

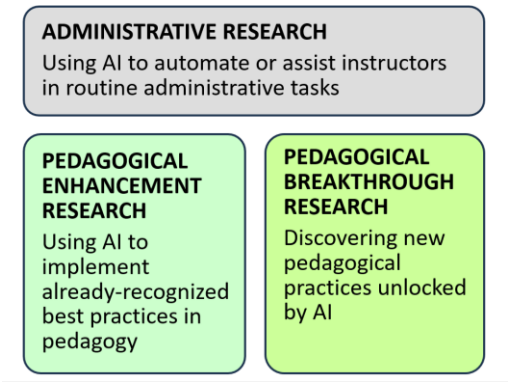


Figure 3. Modern learning with AI framework (adapted from Mattalo, 2024)

We can expect over the short-term that *Pedagogical Enhancement Research* will be the focus area, as more educators experimented with selected existing teaching and learning practices. Examples include AI-assisted previewing, AI-assisted questioning and feedback, AI-assisted group studying and AI-assisted personalized learning (Mattalo, 2024). Some examples of *Pedagogical Breakthrough Research* already being explored include prompt engineering, augmented reading and AI-based assessments. Over the longer run, it can be expected that new, innovative use of AI in teaching and learning will be introduced.

We believe that the model presented in Figure 1 will be able to support both *Pedagogical Enhancement Research* and *Pedagogical Breakthrough Research*. This is because the model was formulated to place greater focus on the learning processes rather than the outputs of GenAI. Notwithstanding that, it is worthwhile acknowledging the importance of balancing human expertise and integrity with GenAI capabilities when attempting curriculum innovation using GenAI (Francis et al, 2025). The author would speculate that *Pedagogical Enhancement Research* can be one area for investigating how “the core” can be strengthened using GenAI while being protected, for example, human creativity and creative thinking. And *Pedagogical Breakthrough Research* can drive innovations in teaching and learning, using enhanced human creativity and creative thinking, coupled with ethical and responsible use of GenAI.

Preliminary conceptualization of using GenAI for innovating teaching and learning practices was shared by Cheah (2026b) in his adaptation of the Rumsfeld Matrix to GenAI vs Human Intelligence. *Pedagogical Breakthrough Research* appears to be a promising way to explore the “unknown unknowns”, where both humans and machines do not know what they don’t know. Future work in this area will be shared at future conferences.

CONCLUSIONS

This paper presented an approach for faculty to use GenAI in an ethical and responsible manner, guided by a model backed by CDIO Standards, AI Ethical Framework and constructive alignment. It is hoped that greater transparency in GenAI usage can come to light using the suggested approach. This can be beneficial to foster greater trust between faculty and students, or students' perceived faculty distrust in them using GenAI to cheat (Reynoldson, 2025). It can be said that initial response among educational institutions when GenAI first came into the scene is one of suspicion: that academic integrity may be compromised. Although the focus area had gradually shifted to students' learning outcomes, the "damage is done" as both sides grapples with incidences of alleged students cheating while perceived loopholes in assessment procedures got plugged with various measures – such as policy guidelines – detailing what are permitted and what are not, regarding GenAI use.

AI technologies will continue to evolve and what seemed like novelty of what it can do today will fast become key elements for work and life. Already appearing over the horizon is Agentic AI, which is an AI system that combines multiple types of artificial intelligence that, together, make it capable of planning, acting, learning, and improving. Agentic AI don't just react or follow preset rules; they can act with autonomy, initiative, and adaptability to pursue goals. This form of AI is capable of independently making decisions and taking actions to fulfill objectives in dynamic environments (UiPath, n.d.)

The model shared in this paper presents an approach that equips faculty with a pedagogical basis to explain to students why they did what they did, how students can better transit to the working world rife with AI usage; as they had retained the "core" of human trait that sets us apart from machines, however smart the machines were designed to be. How it will fare when pitted against Agentic AI is not known. As it stands, we hope our model will provide us with a process-oriented compass to navigate the complexity of AI in education, which will no doubt gets even more complex in the near future; while attempting to preserve the human cognitive core. "The truth is out there" as the famous tagline from the TV-series The X-Files goes. That makes it all the more important to build trust with our own students in our journey in education using AI.

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APPRAISING CDIO STANDARDS FOR GUIDING RESPONSIBLE GEN AI USE IN CURRICULUM DESIGN

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ABSTRACT

This paper explores how the 12 CDIO Core Standards can continue to be used to guide curriculum design or redesign in the advent of generative artificial intelligence (GenAI) which use had been impacting the educational sector flaming expectations and raising concerns. The paper first gives a brief outline of the use of GenAI in teaching and learning, in particular the concern over their use in assessment. Concerns over excessive dependence of GenAI use in teaching and learning are also discussed. The paper then goes into detailed discussions of the plausible use of GenAI in each CDIO Standard. The analysis is based on the premise that all required input for machine learning are available and curated in the format appropriate for creation of customized GenAI. While this is likely not reflective of status of most institutions, the purpose is to expose faculty to the possibility of GenAI in addressing the needs of a given standard. Taking each standard in turn, areas where GenAI can be used to improve faculty efficiency and effectiveness when applying the standard are discussed, and published work is referenced if available. This is followed by highlights of areas where faculty review of GenAI responses are deemed necessary to maintain human-in-the-loop oversight. Use of GenAI in learning assessment in particular, in given a “light touch” given the on-going debate over the legitimate use of the technologies in providing genuine representation of student learning. This paper identify 4 key areas where use of GenAI, in its current state of technologies advanced as they may be – can still pose significant challenges if used for curriculum design or redesign Key takeaways from this paper is that the author does not recommend the use of GenAI in designing CDIO-type integrated curriculum and in performing self-evaluation for CDIO program evaluation. These 2 aspects should decidedly remain a human endeavor.

KEYWORDS

Responsible GenAI, Human-in-the-Loop, Collective Intelligence, CDIO Standards 1-12

INTRODUCTION: SCOPE OF THIS PAPER

Back in 2023, updating on the World Economic Forum Annual Meeting in Davos on January 16-20, Narayan & Larsen (2023) reported that Generative Artificial Intelligence (GenAI or Gen AI) is a game-changer that society and industry need to be ready for. Today, GenAI has emerged as a revolutionary technology with a wide array of applications, notably within the educational sector (e.g. Krause *et al*, 2025). It posed unprecedented challenges to education and faculty must critically examine the integration of these technologies into academic teaching and learning processes (Kurtz *et al* 2024; Bobula, 2024) over a range of concerns including biases, discrimination, data privacy, cheating and plagiarism, copyright issues etc.

This paper is not meant to be a critical appraisal of GenAI in teaching and learning, especially in areas of assessment, which probably received the most attention. Readers interested in this topic can refer to other works such as Belkina *et al* (2025), Bobula (2024), Giannakos *et al* (2024), Gonsalves (2025) and Mehdipour (2025).

The main emphasis here is to review how the current iteration (i.e. version 3) of the CDIO Standards can be used to guide their use in curriculum design in the advent of GenAI, where many processes can be performed using GenAI. The work is to support a model introduced by the author (see Cheah, 2026a) that uses CDIO Standards as a "layer of protection" to engage faculty in deep thinking when relying on GenAI to assist in design/redesign one's curriculum using CDIO Framework. The aim is to provide an approach that can assist faculty in navigating the responsible use of GenAI in higher education. Kurtz *et al* (2024) defined responsible AI as referring to the practice of designing, developing and deploying AI systems in a way that is ethical, fair, transparent and accountable.

The handling of GenAI also warrants that humans develop new sets of skills and attitudes and the term AI Literacy immediately came to mind. Markauskaite *et al* (2022) went beyond knowing AI Literacy to focus on human cognitive capacities, values and joint knowledge practices needed for success in a world with AI. There is also a need to strengthen existing skills and attitudes – especially foundational ones such as creativity and critical thinking, sense-making and decision-making from being eroded to guard against over-reliant of GenAI use – skills and attitudes deemed the "core" elements that differentiate humans from machines.

After a brief introduction of how GenAI is used in general in teaching and learning and in CDIO community, we continue with the review of each standard in turn and discuss how GenAI can be used along with the key principles espoused in the standard. This paper concludes with suggestions on how best to implement "human-in-the-loop" strategies for designing and reviewing CDIO-type curriculum given the current state of GenAI technologies.

BRIEF OVERVIEW ON USE OF GEN AI IN TEACHING & LEARNING

GenAI poses unprecedented challenge to academic learning and teaching methods (Tillmanns *et al*, 2025; Wall *et al*, 2025; Kurtz *et al*, 2024). The content for this section largely derived from the work of Bozkurt *et al* (2024) who prepared an excellent study of the positives and negatives of GenAI use in teaching and learning with the aim of establishing a balanced perspective by critically analyzing both its challenges and affordances. It is crucial that we as humans be mindful that any activities of GenAI are not self-driven but depend on programed and pre-trained inputs supplied by GenAI providers. There is always a risk that GenAI become a technology that reduces students' critical thinking and independent problem-solving skills.

Instead of fostering deep engagement with the learning material. Over-reliance on GenAI could lead to surface understanding and a reduction in effort, where students bypassing challenging cognitive tasks that are essential for developing expertise and long-term retention. The reduction of cognitive load may inadvertently suppress students' ability to handle complexity on their own. The shielding of students from such cognitive struggle by GenAI risk producing students who are adept in using tools but lack the cognitive depth to navigate novel challenges independently. Over-reliance on GenAI could also diminish the value of peer-to-peer exchanges, where emotional intelligence, empathy, and social cues are crucial in learning.

The area of learning assessment is the one that perhaps garnered the most discussions in academic circles and publications. Based on the results of a systematic review of assessment for learning using technology, Memarian & Doleck (2024) argued that such studies still lacked a technological perspective such as AI. There had been concerns over the impact of over-reliant on GenAI that compromised students' cognitive abilities and its impact on learning. A study from Zhai *et al* (2024) suggested that students are increasingly favoring fast (and perceived optimal) solution over slow ones constraint by practicality, accounting for the reason why "cognitive shortcuts" offered by GenAI are preferred even amidst the ethical issues. Pallant *et al* (2025) conducted a study on students learning using GenAI and compared 2 approaches to learning: mastery vs procedural. Results showed that students with a mastery approach achieved a higher level of learning where GenAI is used to construct and augment knowledge. In contrast, using GenAI procedurally without augmenting knowledge (i.e. procedural approach) resulted in lower-level learning outcomes. Students on the other hand, often contested allegations of them cheating using GenAI, for example on grounds of vicissitudes of trust in students vs. technology, and raising questions of constituted cheating (Gorichanaz, 2023). Rundle *et al* (2019) reported in their studies that only a small percentage (about 3%) of students engaged in contract cheating. The main reason for not doing so is morality and motivation for learning. Indeed, Reynoldson (2025) argued that more focus should be placed on fostering greater trust between faculty and students, than agonizing over prevention of student cheating.

The broad consensus from the academic community in addressing the use of GenAI in education is one that called for more AI-resilient curriculum (Nagelhout, 2023). AI-resilient is defined by FeedbackFruits (2025) as "…building learning experiences that are resilient by design – experiences that foster the kinds of thinking, creating, and connecting that GenAI alone cannot do". An AI-resilient curriculum would feature authentic real-world applications that requires high level of critical thinking, creativity, decision-making and problem-solving skills. This makes the CDIO Framework very well suited to serve as a powerful tool to provide guidance to programs seeking to integrate use of GenAI in the curriculum.

GEN AI & THE CDIO FRAMEWORK

The current version of the CDIO Framework (i.e. version 3) was the result of a review and updates back in 2020 to cater for developments in 4 areas: sustainable development, digitalization, services and faculty competences (Malmqvist *et al*, 2020). Although digitalization was addressed, the main change is limited to Standard 6 to highlight the role of digital technologies in the learning workspaces that support and enhance the quality of teaching and student learning. The advent of GenAI, however, is more far-reaching in that it can impact all the 12 core standards.

Currently, the exploration of GenAI and CDIO Standards is only emerging in the 2024 International CDIO Conferences where several papers discussed specific instantiations of GenAI use to enhance teaching and learning based on specific CDIO standards. For example, Kimpton *et al* (2024) reported on how generative AI can support active learning environments (CDIO Standard 8) and integrate diverse learning preferences into the engineering curriculum (CDIO Standard 7). Ajailia *et al* (2024) shared a course that provided ethical education to AI to graduating students. Zerai & Mosbeh (2024) shared the use of challenge-based learning within an AI project for an AI engineering curriculum. Kamoun *et al* (2024) suggested using GenAI to help faculty in designing effective assessments (Standards 10 & 11). Saeidlou *et al* (2024) reported on the use of GenAI to support the conceive, design, implement and operate stages of a module on Engineering Product Lifecycle. What is interesting in the last paper is the authors' deliberate effort to use learning tasks that make it challenging for students to look for answers using GenAI. There was o specific discussions on how GenAI affected the CDIO Standard per se.

Likewise in the 2025 International CDIO Conference, several papers covered use of GenAI in enhancing teaching and learning. Toh *et al* (2025) presented the development of an AI-powered feedforward tool designed to support students in designing effective prompts in using and engaging critically with GenAI, consistent with the requirements of CDIO Standards 1, 2, 3, 7, 8, and 11. Likewise, Hidila & Tabaa (2025) described using development of an AI coding assistant that addressed requirements of CDIO Standards 2, 3, 5, 7, 8 and 11. Guettat *et al* (2025) shared work done in creating a personalized life learning environment using GenAI, which introduce active learning (CDIO Standard 8) to support lifelong learning.

APPLICABILITY OF CDIO STANDARDS VIS-À-VIS GEN AI

This paper aims to provide comprehensive coverage of the CDIO Standards and address how GenAI can be used alongside each Standard. It expands on the use of each Standard, elaborates on how some of the principles embodied in each standard can potentially be performed by GenAI. In the following sections, each standard is discussed with reference to how use of GenAI can support the application of the standard. Areas where GenAI use is applicable will be presented, and where appropriate, extant literatures where it had been used will be shared. Areas where the outputs from GenAI appear questionable will be highlighted. It is important to note that the discussions here *presuppose that the necessary knowledge base are available as inputs for the GenAI engine used*. In other words, it is assumed that retrieval augmented generation (RAG) technique had been applied to enhance the large language model (LLM) used with institution-specific requirements, and program-specific information. Each section will conclude with our recommendations for faculty involvement in the use of the respective standard, stressing the importance of "human-in-the-loop".

Use of GenAI in CDIO Standard 1 The Context

CDIO Standard 1 emphasizes real-world context in engineering education. Today, this must include the pervasive role of GenAI across the engineering lifecycle of conceiving, designing, implementing, and operating sustainable products, processes, systems, and services; as briefly explained below:

- *Conceiving*: GenAI can help students summarize findings from external scans, identify trends and key issues, generate solution ideas, and draft proposals or business plans.
- *Designing*: GenAI can accelerate design by identifying regulations and standards, generating options and drawings, and supporting rapid prototyping and material selection.

- *Implementation*: GenAI can aid in manufacturing planning, software code generation, testing automation, and process optimization through data analysis.
- *Operating*: GenAI can compile manuals, prepare maintenance protocols, and draft troubleshooting guides, enhancing system reliability.

Given GenAI's reach, students must be introduced at an early stage to their capabilities, limitations, and ethical use. CDIO Standard 4 *Introduction to Engineering* is a suitable entry point for developing AI literacy, data fluency, and responsible attitudes.

Human-in-the-Loop Oversight for CDIO Standard 1

Faculty must critically review GenAI outputs, especially during problem identification, to ensure relevance to local contexts and stakeholder needs. This is vital when addressing "wicked problems" with conflicting viewpoints. Oversight helps guard against bias, cultural insensitivity, and over-reliance on dominant paradigms.

Use of GenAI in CDIO Standard 2 Learning Outcomes

CDIO Standard 2 emphasizes the formulation of learning outcomes that reflect the competencies needed by graduates (Pinski & Benlian, 2024). In the age of AI, two key facets must be addressed:

- *Integration of New AI-Driven Competencies:* Industry 4.0 and the rise of GenAI have introduced roles such as prompt engineer, data scientist, and AI ethicist. With Industry 5.0 on the horizon (Doven *et al*, 2025), demands for AI literacy and ethical awareness are intensifying (e.g. Allen & Kendeou, 2023; Laupichler *et al*, 2022). The United Nations Educational, Scientific and Cultural Organization publication *AI Competency Framework for Students* (UNESCO, 2024) outlines four domains – human-centered mindset, AI ethics, AI technologies and applications, and AI system design – across three proficiency levels: Understand, Apply and Create. GenAI can support STEEP (Social, Technological, Environmental, Economic, Political) analysis to identify emerging domain-specific skills and attitudes and help structure their progression using models like Dreyfus' five-stage skill acquisition framework (Dreyfus, 2004).
- *Strengthening Foundational Cognitive Capacities:* To support AI-related competencies, foundational skills such as critical and creative thinking, metacognition, decision-making, and resilience must be reinforced. These hybrid capacities underpin effective engagement with GenAI and are essential for adaptive problem-solving (Krause *et al*, 2025; Nguyen *et al*, 2025; Zhai *et al*, 2024).

Human-in-the-Loop Oversight for CDIO Standard 2

Faculty must ensure that learning outcomes drafted by GenAI must match the proficiency levels specified for the local industry job roles and responsibilities. Learning outcomes must also be validated with key stakeholders to ensure alignment with industry needs. Although GenAI can assist in analyzing survey data, faculty must review the insights and ensure outcomes are properly aligned with course-level goals, graduate attributes, and professional norms. Further discussion on learning outcomes will be expanded under Standard 11 *Learning Assessment*.

Use of GenAI in CDIO Standard 3 Integrated Curriculum

CDIO Standard 3 requires that AI Literacy and GenAI competencies be integrated into program curriculum and planned for progressive development across the program duration of

study. Students should be made aware of the limitations of GenAI, its ethical use and risks to their cognitive development associated with over-reliance on GenAI. The UNESCO *AI Competency Framework for Students* mentioned earlier offers a useful reference. However, it is worth noting that AI Literacy needs to be tailored for different user groups (Pinski & Benlian, 2024). Beyond AI Literacy, other emerging competencies can be embedded using the usual CDIO approach. GenAI can assist by mapping integration points across the curriculum and suggesting learning activities to support competency development. These strategies will be elaborated in Standard 7 *Integrated Learning Experiences*.

GenAI instruction should address both general and domain-specific knowledge. Students should understand GenAI's contributions to productivity and innovation, while also critically examining its impact on privacy, equity, and social norms. Domain-specific integration should align with disciplinary contexts, consistent with CDIO principles.

Human-in-the-Loop Oversight for CDIO Standard 3

Curriculum integration demands careful faculty oversight. GenAI may struggle with contextual reasoning due to limitations in relevant training data and lack of program-specific granularity. Local documents may not succinctly capture all nuances, limitations and constraints of a program are not available for coding as inputs for the RAG/LLM. Faculty must iterate prompts, review outputs critically, and apply tacit local knowledge of program structure. Even well-crafted prompts cannot compensate for incomplete or flawed input data. This challenge will be further explored by later standards. Challenges in using GenAI for designing program structure will be addressed in greater detail later.

Use of GenAI in CDIO Standard 4 Introduction to Engineering

CDIO Standard 4, which calls for an introductory course that prepares students for engineering practice, must include early exposure to GenAI. This foundation course should inform students of GenAI's benefits, limitations, and ethical implications. It should emphasize responsible use of GenAI in knowledge creation and professional conduct. Environmental and societal impacts can also be introduced, such as the energy demands of data centers powering the LLMs, as well as risks of bias, discrimination, and inequity in GenAI systems developed by commercial entities. These cross-cutting issues offer students a critical lens on the broader consequences of technological advancement.

Human-in-the-Loop Oversight for CDIO Standard 4

Faculty should lead the design and delivery of this course to ensure contextual relevance. GenAI may lack awareness of local industry structures, regulations, and governance. Faculty oversight is essential to embed local perspectives and ensure that students develop a grounded understanding of engineering responsibilities in their specific context.

Use of GenAI in CDIO Standard 5 Design-Implement Experiences

CDIO Standard 5 emphasizes authentic design-implement experiences. GenAI can propose projects of increasing level of difficulty across the program duration, support student engagement in several ways:

- *Extending Domain Knowledge*: GenAI can aid students in acquiring project-relevant knowledge through self-directed learning. However, faculty must guide responsible use, as the volume and speed of GenAI-generated information may overwhelm students or lead to superficial understanding if they are not critically engaged.

- *Supporting the CDIO Lifecycle*: GenAI can assist learning across the four stages — conceive, design, implement, operate — as outlined in Standard 1 *The Context*. Nikolic *et al* (2025) demonstrated how AI can comprehensively support project activities throughout this lifecycle.
- *Simulating Interdisciplinary Perspectives*: GenAI can emulate input from other disciplines, enriching project work with diverse viewpoints. This is especially valuable when interdisciplinary collaboration is impractical. Jones (2023) highlights how GenAI can help students tackle complex, transdisciplinary challenges.

Human-in-the-Loop Oversight for CDIO Standard 5

Faculty must ensure that projects proposed by GenAI are aligned to local contexts. Faculty must emphasize human creativity, especially during the "conceive" stage. While GenAI may outperform humans in idea quantity, its outputs often lack diversity and depth. Poon *et al* (2024) found that human-generated ideas tend to be more varied and higher in quality. Faculty should encourage students to exercise their own creativity and critically evaluate GenAI suggestions. Faculty must also ensure GenAI-generated ideas do not infringe copyrights or patents. In addition, for projects with industry sponsors, it is recommended that faculty consult his/her industry counterparts on the acceptability of proposal(s) or suggestion(s) from GenAI.

Use of GenAI in CDIO Standard 6 Engineering Learning Workspaces

CDIO Standard 6 emphasizes the importance of engineering learning workspaces. With the rise of digital technologies, these spaces are increasingly hybrid – blending physical and digital environments. While digital spaces are gaining prominence, full replacement of physical workspaces is neither feasible nor desirable. Faculty can leverage GenAI across both modalities to deepen student engagement (Parsons *et al*, 2019).

On campus, flipped learning has reduced reliance on large lecture halls, while Smart TVs in seminar rooms foster collaborative learning where GenAI supports students' personalized learning through data analytics. Laboratory automation can also leverage GenAI to analyze operational data to optimize equipment utilization and resource conservation. Increasing use of digital twins can be coupled with GenAI to further enhance learning (Boareto *et al*, 2025). The DTALE (Designing Teaching and Learning Environments) Model developed by Tondeur *et al* (2024) offers guidance for integrating physical and digital spaces effectively.

GenAI can streamline equipment procurement by comparing vendor proposals against program requirements, especially for off-the-shelf items. For customized equipment, GenAI can suggest configurations based on performance specifications and intended learning outcomes. It can also assist in facility layout planning, ensuring compliance with safety regulations (e.g. spacing, evacuation routes, fire protection). For existing facilities, GenAI can optimize utilization by identifying opportunities for cross-program equipment sharing and scheduling.

Human-in-the-Loop Oversight for CDIO Standard 6

Facility management, which can be led by a faculty, must collaborate with course owners to identify local requirements that GenAI may overlook. These include utility tie-ins, drainage routing, cable routing, and "wet areas" or designated waste collection point. Human insight remains essential to ensure safe, functional, and contextually appropriate learning spaces.

Use of GenAI in CDIO Standard 7 Integrated Learning Experiences

CDIO Standard 7 emphasizes learning tasks that mirror professional engineering practice in the workplace. GenAI can support this by generating realistic workplace scenarios and preparing instructional materials, from experimental protocols to task-specific guides, thus enhancing the richness of student experiences. GenAI is also very useful in assisting faculty in generating task-specific performance rubrics. However, faculty must review GenAI-generated content to avoid reinforcing biases or overly prescriptive tasks that limit student growth (Bozkurt *et al*, 2024).

GenAI is particularly effective in competency-based learning, such as Direct Observations of Practice (DOP) (Chan, 2008). Whether in physical labs or virtual simulations, GenAI can analyze performance data and provide targeted feedback. Video analytics, for example, can help faculty assess student actions in pilot-scale chemical plants and highlight areas for improvement in real time.

Human-in-the-Loop Oversight for CDIO Standard 7

Faculty must ensure GenAI-generated scenarios are contextually appropriate, free from bias, and aligned with the students' level of study. Sequencing integrated tasks across a course or program requires nuanced understanding that GenAI alone cannot provide. Faculty must design tasks that preserve the pedagogical intent of integrated learning experiences, using GenAI to support a mastery-oriented approach where students prioritize competence development over grades (Pallant *et al*, 2025). The tasks should not be overly prescriptive, restricting students to the content they already find manageable (Bozkurt *et al*, 2024). Faculty should encourage students not to overuse GenAI to assist with task responses, by explaining that doing so risks bypassing critical steps that foster metacognition and learning agency.

Use of GenAI in CDIO Standard 8 Active Learning

CDIO Standard 8 promotes using active learning strategies to foster deep engagement. GenAI can enrich these strategies across face-to-face and online settings, from simple Think-Pair-Share to complex Role Play and Debate. When GenAI acts as a "critical friend" or mentor, it facilitates dialogic learning by engaging students in meaningful conversations. Faculty can exercise creativity in using GenAI, for example by adapting GenAI as a virtual peer in traditional Think-Pair-Share, responding to student input and prompting deeper reflection. As a teaching assistant, GenAI can pose follow-up questions to stimulate critical thinking. In debates, GenAI can provide counterpoints that simulate diverse perspectives, broadening students' understanding. Other methods, such as one-minute papers critiquing GenAI-generated content or analyzing hallucinated outputs, can strengthen cognitive skills and metacognition. For faculty teaching in a "smart" classroom, GenAI enables near real-time instructional adjustments by automating feedback analysis. It can support teaching improvement through sentiment analysis of student reflections (e.g. "clear-as-mud" topics), helping refine active learning approaches.

Human-in-the-Loop Oversight for CDIO Standard 8

While GenAI's immediate feedback can correct misconceptions, it may also introduce new ones or encourage superficial understanding (Bozkurt *et al*, 2024). To mitigate this, students should be taught reflective practice and self-regulation. Faculty can assign tasks that require critical evaluation of GenAI-generated response to deepen learning (Abdelghani et al., 2023; Bozkurt et al., 2024).

Use of GenAI in CDIO Standard 11 Learning Assessment

CDIO Standard 11 focuses on assessing students' skills and attitudes in authentic contexts. In the extant literature, many discussions had centered on issues of integrity and security of an assessment system, and on how much GenAI use is permitted during examinations. This is due to the concern that with increasing sophistication of GenAI tools, it is increasingly difficult to distinguish students' original work from that completed using GenAI. This is especially for reflective tasks that was once thought immune to GenAI.

For the perspective of CDIO, assessment now faces two challenges: (1) evaluating new competencies like AI Literacy, and (2) safeguarding core skills such as critical thinking from erosion due to over-reliance on GenAI. A related challenge is the choice of assessment methods and the needed evidence of learning. The first is manageable through constructive alignment, as with other CDIO-based competencies. The second requires more deliberate design. "AI-resilient assessment" refers to tasks that retain educational integrity despite GenAI's capabilities. These assessments are not meant to be "AI-proof" but rather robust against inappropriate GenAI use by prioritizing process over product, requiring deeper cognitive engagement, and incorporating elements beyond text, such as reflection, interaction, and real-world application. However, as pointed out by Fawns (2024) assessment that focus on processes can also be problematic, on what actually got assessed.

Alternative approaches include allowing use of GenAI in parts of a task, followed by critical evaluation of its output. Moorhouse *et al* (2023) propose five themes for redesigning assessments: testing GenAI tools, rethinking task design, staging assessments, integrating GenAI, and using in-class formats. Examples include:

- Rewarding ethical and responsible GenAI use in complex problem-solving
- Reviewing student-submitted prompts in formative tasks
- Summative reflections critiquing GenAI-generated responses

Corbin *et al* (2025) advocate structural changes to assessment design that constrain how students interact with GenAI, moving beyond mere policy enforcement which is a "discursive" approach as currently practiced. Structural changes to assessments are modifications that reshape the underlying mechanics of the assessment tasks themselves, thereby directly influencing or constraining how students can interact with GenAI. Gonslaves (2025) recommends "contextual assessment," which is a framework that incorporate multiple layers of contextual complexity, that moves beyond professional realisms alone.

Human-in-the-Loop Oversight for CDIO Standard 11

As noted in the overview section of this paper, assessment with or without GenAI is a hotly debated area. The discussion here is deliberately broad to stay focused on the principles of assessment of diving into on-going debate on GenAI use in assessment. Faculty must design AI-resilient assessments constructively aligned with integrated learning experiences (Cheah, 2026a). A balanced approach that values GenAI as a learning companion while preserving student agency is key. Krause *et al* (2024) highlights differing priorities: academics focus on ethics and policy, while students prefer practical AI applications. Assessments should reflect both, reinforcing AI Literacy and contextual learning in line with CDIO principles.

Use of GenAI in CDIO Standard 12 Program Evaluation

CDIO Standard 12 promotes program-level evidence-based continual improvement via a self-evaluation process. GenAI offers promising capabilities in many aspects, such as automating

data collection, performing sentiment analysis, identifying gaps, generating scoring rubrics, and executing evaluations (Patel, 2023). While these benefits are well recognized, significant challenges remain. Unlike conventional evaluation, GenAI often generates data algorithmically, while humans interpret outcomes manually, creating a disconnect in validity and context.

The adage of GIGO (garbage in, garbage out) remains relevant. With machine learning and LLMs, flawed or incomplete input data can yield unpredictable outputs. This is especially problematic when GenAI is used to evaluate curriculum outcomes, where delivery over time can and often introduce variables that GenAI may not capture, such as shifts in student engagement or instructional nuance.

Current CDIO rubrics are broad and not easily parsed by GenAI for precise analysis. Building a robust, structured knowledge base for machine learning would require significant investment in academic management systems. Without this foundation, GenAI-generated evaluations risk lacking validity and contextual relevance.

Human-in-the-Loop Oversight for CDIO Standard 12

Faculty must critically assess GenAI's role in program evaluation. While automation can streamline processes, human oversight is essential to interpret results meaningfully, account for delivery nuances, and ensure alignment with intended learning trajectories to guide meaningful and impactful action plans for curriculum improvement. At present, cautious adoption is advised until data infrastructure and rubric precision are sufficiently developed. These points will be further elaborated in the later discussions.

Use of GenAI in (revised) CDIO Standard 9 Enhancement of Faculty CDIO Competencies and (new) CDIO Standard 10 Faculty Continuing Professional Development

Cheah (2026b) proposed revisions to CDIO Standards 9 and 10: absorbing Standard 10 into Standard 9 and rename the new Standard 9 as *Enhancement of Faculty CDIO Competencies* and refocusing Standard 10 on sustained professional growth and titled *Faculty Continuing Professional Development*. Under Standard 9, faculty must be equipped with AI Literacy to effectively integrate GenAI tools into CDIO-aligned teaching. They also serve as human-in-the-loop, ensuring ethical and responsible GenAI use. Standard 10 calls for continuous renewal of AI competencies to stay relevant in a rapidly evolving technological landscape.

GenAI can support both standards by automating training needs analysis, curating relevant programs, and serving as a virtual coach to guide faculty through personalized learning pathways. It can track progress, recommend additional training, and adapt to evolving professional demands. These capabilities help faculty stay current with AI advancements and integrate GenAI tools responsibly into CDIO-aligned teaching.

Human-in-the-Loop Oversight for CDIO Standards 9 & 10

To fulfill their role as human-in-the-loop, faculty must maintain ethical oversight of GenAI use in education. This requires continuous renewal of AI Literacy and critical engagement with emerging technologies. GenAI should scaffold faculty thinking – not replace it. As Bozkurt *et al* (2024) cautioned, the line between augmentation with GenAI and its dependency is thin, therefore professional development must guard against passive dependency and instead promote active cognitive engagement.

OVERALL DISCUSSIONS

The brief summary of what GenAI can and cannot support, and the required human responsibilities when using each of the 12 CDIO Core Standards is shown in Table 1.

Table 1. Summary of what GenAI can or cannot support and human-in-the-loop

CDIO Standard	What GenAI Can Support	What GenAI Cannot Support	Required Human Responsibilities
1 – The Context	Summarize issues, generate ideas, prepare proposals, automate design drawings, assist prototyping, and compile manuals.	Handle "wicked problems," balance conflicting viewpoints, ensure cultural/local relevance.	Validate outputs, review for bias, ensure stakeholder fit.
2 – Learning Outcomes	Suggest AI-related competencies, organize findings, draft outcomes using Bloom's Taxonomy.	Specify proficiency levels accurately, capture local industry context.	Align outcomes with graduate attributes, validate with stakeholders.
3 – Integrated Curriculum	Map AI literacy integration suggest learning activities, support progressive skill development.	Capture tacit knowledge, nuanced program structures, contextual constraints.	Refine prompts, validate curriculum design, ensure ethical integration.
4 – Introduction to Engineering	Introduce GenAI concepts early, highlight benefits/pitfalls, raise awareness of social/environmental impacts.	Provide local industry context, legislation, governance details.	Design and deliver course content relevant to local context.
5 – Design-Implement Experiences	Support project stages (conceive, design, implement, operate), simulate interdisciplinary perspectives.	Generate diverse, high-quality creative ideas; avoid copyright/patent issues.	Reinforce human creativity, validate originality, ensure responsible use.
6 – Engineering Workspaces	Suggest layouts, optimize utilization, streamline procurement, support digital twins and analytics.	Capture local facility requirements (utilities, drainage, safety specifics).	Validate layouts, ensure compliance with safety rules, adapt to local constraints.
7 – Integrated Learning Experiences	Suggest workplace scenarios, prepare manuals, design competency-based tasks, provide feedback via analytics.	Avoid reinforcing biases, stereotyping, or overly prescriptive tasks.	Validate scenarios, sequence tasks, promote mastery learning.
8 – Active Learning	Act as virtual peer/mentor, provide counterpoints in debates, automate feedback analysis, suggest case studies.	Prevent superficial understanding, avoid introducing misconceptions.	Teach reflective practice, self-regulation, critically assess GenAI content.
9 – Enhancement of Faculty CDIO Competencies	Assist in designing CDIO-type tasks, provide assessment tools, update disciplinary knowledge.	Replace reflective practice, tacit judgment, or authentic role modeling.	Engage in reflective practice, update knowledge, ensure ethical GenAI use.
10 – Faculty Continuing Professional Development	Provide training resources (prompt engineering, rubrics, analytics), suggest insights for teaching/research.	Replace institutional frameworks, evaluate long-term impact, substitute live training.	Conduct training needs analysis, participating in CPD, evaluation and updating competence.
11 – Learning Assessment	Draft rubrics, analyze reflections, automate sentiment analysis, suggest formative/summative questions.	Ensure fairness, set difficulty levels, align assessments with outcomes.	Validate rubrics, calibrate difficulty, ensure constructive alignment.
12 – Program Evaluation	Compile survey data, analyze trends, generate reports, identify improvement areas.	Interpret nuanced stakeholder feedback, contextualize cultural/industry needs.	Review evaluation results, align with institutional goals, act on findings.

To fully leverage GenAI's potential, a robust academic knowledge base must be developed: one that captures a wide spectrum of structured, contextualized data for training large language models (LLMs). This requires significant investment in academic management systems capable of curating curriculum metadata, assessment artifacts, and instructional nuances. However, deploying GenAI at the program level presents several persistent challenges:

Ambiguity in curriculum content and context: GenAI may lack access to the full curriculum structure, needed prior knowledge (especially if these are to be acquired outside stipulated curriculum hours), pedagogical intent in each course, etc. In addition, course syllabus and other documents may contain mistakes, e.g. wrong proficiency level implied due to choice of Bloom taxonomy used, some learning outcomes not captured although implemented in a course, etc. As a result, GenAI may resort to inferring progression logic, over-simplification, and misplacing advanced tasks too early.

Interdependency of competencies: Higher-order competencies are not standalone – they are built from foundational skills and attitudes (i.e. "skill to build skills) and deeply interwoven with other the technical domain and context under which they are practiced. Particularly hard to teach, and even harder to assess are attitudes, as they can be very context sensitive and affect by other factors, e.g. cultural. It will be challenging for GenAI to map such dependencies across courses and between integrated learning experiences if not provided with explicit relational data and may result in false alerts on possible gaps in the curriculum.

Student profiles: For obvious reasons of data privacy, plus potential for misuse, information on students' academic data will not be easily available for GenAI processing. GenAI will then design learning tasks without the full knowledge of students' prior knowledge, and other learning challenges, e.g. dyslexia or hearing impairment, etc. Supporting disadvantaged students cannot be met with one-size-fits-all learning interventions generated by GenAI without human review. Likewise, evaluating students' engagement with learning such materials can also be particularly challenging, especially for online learning such as asynchronous lessons.

Transparency of assessments: GenAI doesn't inherently know how skills and attitudes are developed, reinforced or assessed in actual implementation of the CDIO Integrated Curriculum. It may not have the granularity of different assessment methods used for any one course. The scaffolding or feedback mechanisms used may lie outside of the formal curriculum that are not captured by the RAG used. Consequently, GenAI may propose development stages that appear pedagogically sound but not practically possible, or it may unintentionally overload certain semesters with too many assessments.

Recommendations: Do Not Use GenAI for Standards 3 and 12

Given these limitations, this author recommends that design of integrated curriculum (Standard 3) and Program Evaluation (Standard 12) be led by a core faculty team, ideally under the stewardship of the program manager. GenAI should not be used for such endeavor. This preserves human oversight and leverages the distributed wisdom of educators; drawing on the tacit knowledge, contextual insight, and spontaneous idea generation. As French philosopher Pierre Lévy described, "collective intelligence" emerges when individual contributions resonate and build upon one another (Peters, 2015).

Program evaluation should likewise be team-based. GenAI's black-box nature, where the logic behind its analysis and recommendations remains opaque, poses risks in self-evaluation

contexts. CDIO rubrics are broad and subject to varied interpretation; and such subjective inputs are not easily parsed by GenAI. Without consistent, high-quality data, GenAI's outputs may lack validity and defensibility.

At the time of this writing, the field of "curriculum analytics" is just emerging, and a review by De Silva *et al* (2025) concluded that the technology is still developing and its maturity level is still not satisfactory. A collaborative approach enables faculty to cross-calibrate evidence, reduce subjectivity, and produce explainable, consensus-driven evaluation outcomes. Moving forward, this process can also support the development of shared templates and data standards needed for the design of a comprehensive academic knowledge base, and paving the way for future GenAI integration in a more structured and palatable manner.

CONCLUSIONS

The emergence of GenAI marks a transformative inflection point in education – reshaping not only how teaching and learning are practiced, but also how curricula are conceived, designed, and delivered. Continuing with business as usual is no longer tenable. GenAI must be understood not merely as a tool, but as an active agent capable of communicating, interacting, and generating content on demand – thereby influencing the neurocognitive processes through which humans learn and think.

This paper extends the model introduced by Cheah (2026a), urging faculty to explicitly consider GenAI when applying the CDIO Standards. In doing so, educators can cultivate a deeper understanding of GenAI's limitations and reinforce the critical role of human-in-the-loop oversight to ensure that AI-generated outputs serve their intended pedagogical functions.

As faculty advocate for responsible GenAI use among students, they must also embody those principles in their own practice. Responsible integration requires discernment—especially when using GenAI to design learning tasks. This paper highlights potential pitfalls across teaching and learning domains, equipping faculty to navigate GenAI use with greater fluency and ethical awareness.

AI technologies, and GenAI in particular, will continue to evolve rapidly. Today's limitations may be resolved by tomorrow's innovations. The CDIO framework, when thoughtfully enhanced with GenAI, offers a structured and adaptable pathway for curriculum design that can keep pace with technological change.

Although this commentary is primarily theoretical, its implications merit empirical validation. Future research should explore how contextual learning and contextual assessment influence student engagement, critical thinking, and academic integrity across disciplines. Such inquiry will inform ongoing refinement of the framework, ensuring that teaching and learning remain rigorous, responsive, and resilient in an accelerating educational landscape.

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STANDARD FOR CONTINUAL FACULTY DEVELOPMENT: INNOVATING TEACHING AND LEARNING WITH GEN AI

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ABSTRACT

This paper calls for a review of CDIO's 2 standards on faculty competency to firstly make them more relevant to today's AI-rich educational environment, and secondly to better reflect the dynamic nature of professional development in educational setting. This is predicated on the need to equip faculty with capability to maintain oversight over generative artificial intelligence (GenAI) use as human-in-the-loop. To this end, the paper argued for a need to prepare faculty for one's teaching role using a continuous improvement approach guided by the use of key AI Frameworks, namely the European Union's Digital Competency Framework for Educators and the United Nations Education Science and Culture Organization AI Competency Framework for Teachers. To accommodate this aspiration, while cognizant of the desired not to have a laundry list of CDIO standards, this paper suggests that existing Standards 9 and 10 be merged to better reflect how they had been implemented in practice. The need for continual professional development can then make up the new Standard 10. The advantage of doing so preserves the use of standards 9 and 10 as addressing faulty teaching and learning competency but emphasized the importance of professional development. This is demonstrated through the plan-do-check-act cycle of continual improvement which perfectly complements the CDIO approach's focus on the self-evaluation for program evaluation. By aligning continual faculty professional development, the paper further make the case that the approach can better support innovations in teaching and learning focusing on the Rumsfeld Matrix adapted for educational research. The key focus here is on the "unknown unknowns" where neither human intelligence nor artificial intelligence know what they don't know. This is an area where faculty leverage on the strength of GenAI to identify potential areas for innovation and uses one's own creativity to drive the change process consistent with curriculum redesign needs. The last concludes with suggested revisions Standard 9 and new Standard 10 for considerations.

KEYWORDS

Continuing Processional Development, GenAI Competency, Teaching & Learning Innovation, CDIO Standards: 9 & 10.

INTRODUCTION: USE OF STANDARDS IN CDIO

The main role of the 12 CDIO Standards is to serve as guidelines for educational program reform and evaluation, create benchmarks and goals with worldwide application, and provide a framework for continuous improvement. Over the years, there had been no lack of calls for additional standards for CDIO (Cheah & Leong, 2018; Maneeratana & Wangsaturaka, 2017; Campbell & Beck, 2010). As recent as the 2025 International CDIO Conference hosted by Monash University in Melbourne, Australia; there continued to be calls for the review of the CDIO Standards and Syllabus. The matter was again discussed at the 2025 CDIO International Working Meeting (IWM) hosted by Linkoping University in Linkoping, Sweden. For the CDIO Standards, possibility of new standards in areas of leadership, curriculum agility and student support had been floated.

The notion of having optional standards for CDIO can be traced back to the proposal by Malmqvist, Edstrom & Hugo (2017). The most recent changes made to the CDIO Standards is perhaps also the most significant to-date, that in moving from version 2 to version 3, the notion of optional standards was introduced (Malmqvist *et al*, 2020; Malmqvist, Edstrom & Rosen, 2020). A total of 4 topics, namely Sustainable Development, Simulation-Based Mathematics, Engineering Entrepreneurship, Internationalization & Mobility were introduced. All 12 existing standards were to become core standards, with improvements made in them, most notably the topic of sustainability and sustainable development were emphasized.

Among the 4 optional standards, sustainable development had proven to be problematic, resulting in many members questioning its “optional” status; pointing to the need to consider sustainability issues already mandated in the core standards. The confusion over the “optional” standard on sustainable development was again raised in Melbourne in June 2025. At the 2025 CDIO IWM, it has been decided that the “optional” standards will be re-categorized as “additional” standards. The question of faculty development was also discussed, and a team of CDIO members including this author will be taking a deep dive into the topic. Notwithstanding this development, this paper presents this author’s current thinking on existing standards for faculty competencies – namely Standards 9 and 10 – and a way to move forward in light of the advent of Generative Artificial Intelligence (GenAI).

GEN AI AND FACULTY COMPETENCE: SCOPE OF THE PAPER

Faculty needs to be equipped with the necessary competencies to leverage GenAI to enhance one’s teaching and students’ learning. Faculty GenAI Competency in the context of this paper refers to the knowledge, skills and attitudes that faculty possessed to enable him/her to undertake curriculum design efforts in an ethical and responsible manner when using GenAI, and to be able to exercise human judgment in analyzing outputs produced by GenAI, the be the “human-in-the-loop”. It elaborated on the importance of faculty professional development so that humans remain in control in key aspects of curriculum design, to protect mankind against being made irrelevant due to overuse of GenAI such that fundamental human traits (e.g. critical and creative thinking) are eroded (Cheah, 2026a).

This paper is built on the author’s view that GenAI – when handled responsibly – afforded educators with the opportunity to innovate teaching and learning practices in ways never before imagined. To take advantage of this opportunity faculty needs to be well equipped with the still-evolving AI Literacy and continue to pursue excellence in this area via professional development programs. The paper suggests using the CDIO approach in conjunction with 2 key AI frameworks, namely from the European Union (EU) and United Nations Education

Science and Culture Organization (UNESCO), to form the basis of generic faculty professional development program towards developing AI Competency. The paper then introduces the author's view on how to handle the balance of knowledge between human intelligence and GenAI adapted from Rumsfeld's Matrix. The author argued that faculty should make use of GenAI to venture to the "Unknown Unknowns" in a systematic way to identify opportunities for teaching and learning innovations.

This is followed by a call to revise the 2 CDIO Standards on faculty competency which currently stood at version 3, to better prepare faculty for the challenges ahead in a world dominated by AI that is evolving ever-rapidly. More specifically, this paper made the following 2 related proposals:

1. Merge existing Standard 10 *Enhancement of Faculty Teaching Competence* into existing Standard 9 *Enhancement of Faculty Competence*, to form a single Standard 9 renamed *Enhancement of Faculty CDIO Competencies*; and to introduce a new standard to replace Standard 10 which is now named *Faculty Continuing Professional Development*.
2. Include faculty competency in using AI in general and GenAI in particular, into both the expanded Standard 9 and new Standard 10; and adopt a more forward-looking approach in faculty professional development to address challenges in today's AI-dominated world.

DRIVER 1: GEN AI FRAMEWORKS FROM DIGCOMPEDU AND UNESCO

In this section, we will first briefly look at 2 prominent frameworks that aim to prepare human beings for work and life in a world with AI: (1) The EU's Digital Competence Framework for Educators (DigCompEdu) and (2) UNESCO AI Competency Framework for Teachers.

The DigCompEdu is a direct outcome from earlier EU initiative called the Digital Competence Framework for Citizens (DigComp) to define and support the development of digital skills. The DigCompEdu Framework aimed at identifying and delineating the digital competences educators require to foster effective teaching and learning in the digital age (Bekiaridis & Attwell, 2024). The comprehensive framework is structured around 22 elementary competences, organized into six distinct areas: (1) Professional Development, (2) Digital Resources, (3) Teaching and Learning, (4) Assessment, (5) Empowering Learners, and (6) Facilitating Learners' Digital Competence. It outlines six stages of development: Newcomer (A1), Explorer (A2), Integrator (B1), Expert (B2), Leader (C1), and Pioneer (C2). Each stage represents a phase in the development of digital competencies, from assimilating new information and developing basic digital practices to critiquing existing practice and developing new ones. It is designed to be universally applicable, serves not only as a guide for educators seeking to enhance their digital skills but also as a benchmark for curriculum development and professional training programs in educational institutions across Europe and beyond.

A supplement to The DigCompEdu Framework (henceforth referred to in this paper as DigCompEu-AI) was later published to enhance and extend the framework to include AI-specific competencies and serves as a critical addition, recognizing the growing influence and importance of AI in education (Attwell & Bekiaridis, 2024). This supplement focuses on integrating AI literacy and competencies into the existing framework, ensuring that educators are not only digitally competent but also proficient in understanding and applying AI technologies in their teaching practices. It includes competencies such as understanding AI concepts, ethical implications, data literacy, and the ability to leverage AI tools for personalized learning, assessment, and enhancing student engagement. Effectively this means that educators must now fulfil 2 roles: (1) They must be adept at leveraging GenAI tools to enhance

teaching and learning, and (2) They must prepare students for a future unlike the one they were trained – a world where AI is part of daily life and work.

Another organization, UNSECO, recently also introduced AI Competency Framework for Teachers along with another framework for students (UNESCO, 2024). The document defines the knowledge, skills, and attitudes teachers must master in the age of AI and outlines 15 competencies across five dimensions: (1) Human-centered mindset, (2) Ethics of AI, (3) AI foundations and applications, (4) AI pedagogy, and (5) AI for professional learning. These competencies are categorized into three progression levels: Acquire, Deepen, and Create. The framework is meant to guide the development of national AI competency frameworks, informs teacher training program, and helps in designing assessment parameters. It also provides strategies for teachers to build AI knowledge, apply ethical principles, and support their professional growth. This framework is henceforth referred to as “UNESCO Framework”.

The DigCompEdu-AI and the UNESCO Framework both aim to develop educators' AI skills, but they differ in their primary focus. DigCompEdu-AI offers a more granular, practice-oriented approach, integrating AI skills directly into educators' existing digital teaching activities. In contrast, UNESCO framework provides a broader, policy-oriented perspective, focusing on how AI can transform education systems as a whole, from curriculum to ethics. The primary difference is in their structure and focus. Table 1 below highlight some key differences.

Table 1. Comparison between frameworks: DigCompEdu-AI and UNESCO

Aspect	DigCompEdu-AI	UNESCO
Origin & Scope	European Commission initiative, extended via AI Pioneers project for VET and adult education	Global UNESCO initiative aligned with SDGs, applicable across all education levels
Philosophy	Builds on existing digital competence framework; AI is treated as an extension of digital fluency	Treats AI as a transformative force requiring ethical, human-centric rethinking of education
Focus areas	6 areas, provide guidance on operational integration of AI into teaching practices and digital pedagogy	5 dimensions, provide normative guidance on ethical, human-rights-based AI use and teacher empowerment
Progression Model	6-level proficiency scale (Newcomer to Pioneer)	3-level progression (Basic, Proficient, Advanced)
Ethical Emphasis	Embedded within areas like professional engagement and digital resources	Explicit dimension: Ethics of AI, with strong emphasis on human agency, fairness, and sustainability
AI as Subject vs Tool	Balanced view: AI as both pedagogical tool and curricular content	Stronger emphasis on AI as a subject requiring critical literacy and ethical reflection

One way to understand the difference is to consider DigCompEdu-AI as a practical framework organized around an educator's professional activities, i.e. "What you do". On the other hand, UNESCO's aspects are organized around higher-level overarching principles and themes: "How you should think and what you should know". In short, the 2 frameworks are highly complementary: an educator might use 5 dimensions from UNESCO to build their foundational understanding and ethical compass and then use DigCompEdu-AI to put those principles into practice in their daily teaching activities. DigCompEdu-AI is a practice-oriented scaffold for embedding AI into teaching workflows, and UNESCO as a normative compass for ensuring ethical, inclusive, and sustainable AI adoption. Together, they form a powerful combination for educators: one for doing AI well, the other for doing AI right.

DRIVER 2: RESOLVING CONFUSION OVER STANDARDS 9 AND 10

From the onset, the CDIO Framework had been introduced as a viable approach to address curriculum design or redesign by offering a systematic way to review one's program with focus on the "what" and the "how" of teaching and learning, and faculty capability to use the framework is encapsulated in the 2 standards 9 and 10. Hence it stands to reason that there would be 2 standards, one each to address the needs of "what" and "how". The initial version 1.0 of CDIO Standards 9 and 10 were named *Enhancement of Faculty CDIO Skills* and *Enhancement of Faulty Teaching Skills* respectively to reflect this distinction.

With the revision of the CDIO Framework to version 2.0, the 2 standards were renamed as *Enhancement of Faculty Competence*, and *Enhancement of Faculty Teaching Competence*, respectively, and the key differences between the 2 are shown in Table 1.

Table 1. Comparison between focus areas of Standards 9 vs 10

Standard 9 *Enhancement of Faculty Competence*	Standard 10 *Enhancement of Faculty Teaching Competence*
Developing faculty's **disciplinary fundamentals**: this is a given! Not further elaborated in CDIO…	Developing faculty ability to design learning tasks that help students to acquire the necessary skills and attitudes alongside disciplinary knowledge, i.e. **"how to teach"** → Namely Integrated Learning Experiences **(Standard 7)** & Active Learning **(Standard 8)**; as well as in assessing such learning had indeed taken place **(Standard 11)**
Developing faculty skills and attitudes as espoused in **CDIO Syllabus Parts 2, 3 and 4**, i.e. **"what to teach"** → This is faculty understand what skills and attitudes to impart to students so that they acquire them	
Develop faculty in expanded topics of CDIO Syllabus: Leadership, Entrepreneurship and Research	

The renaming of the 2 standards, however, did not illuminate the key difference in focus areas between them if one just made a cursory read of the name of the standard, as they only differ by one word – the extra word of "teaching" that was found in Standard 10.

More importantly, in most actual applications, both the 2 standards are used at the same time – for example, during self-evaluation. This is especially the case for a faculty who is responsible for both course development and course delivery. Furthermore, taking a literal interpretation of the words "teaching competence" also means that faculty are teaching students the skills and attitudes alongside the domain knowledge; meaning that students learn from activities designed using CDIO Standards (for example Standard 7 Integrated Learning Experiences) to understand the competencies expected of them when they enter the workforce upon graduation. All these happen within the same learning setting: "Dual-Impact Learning" (Crawley *et al*, 2007).

The 2 standards complements one another: faculty need to develop both competencies – first to be well-versed with the domain knowledge, personal, professional, interpersonal skills and attitudes, as well as product, process, system and service building skills plus their assessment (Standard 11); and second to develop expertise to design various learning tasks to engage students in developing these competencies, namely via design-implement experiences (Standard 5), integrated learning experiences (Standard 7), and active learning teaching methods (Standard 8).

As such, the author opined that there is no need for such "separation" of faculty capability into 2 different standards. This paper advocated the use of the terminology "Faculty CDIO Competencies" to mean capability to use BOTH the CDIO Syllabus as building blocks for skills

and attitudes, learning assessment as well as the ability to design CDIO-type learning using CDIO Standards. Merging the 2 standards into one focus the attention of faculty capability: one will work on both “what” to teach and “how” to teach within the same course review setting. This will “free up” one standard, enabling a new standard to be added without extending the list of core standards. As mentioned earlier, a discussion thread on faculty development had been initiated at IWM 2025, and the idea presented in this paper can serve as input for deliberation as we move ahead with the review of the CDIO Framework.

PROPOSAL: REVISED & EXPANDED STANDARD 9, NEW FOCUS FOR STANDARD 10

It is proposed that the 2 standards 9 and 10 be retained, with both still address faculty competency needs, but to be different in focus: One is on *current, immediate needs* to get faculty off-the-ground into one’s teaching duty, and the other is on *emerging future needs* so that faculty can be equipped with new capabilities in response to changing educational demands.

This preference is first and foremost, based on the author’s belief that it will provide a sense of familiarity among members as new version of the CDIO Standard (presumably to be called version 4.0) is introduced. This will avoid potential confusion if the new Standard 10 is named to reference other areas of interest such as student support system, or curriculum agility.

To address faculty’s *current immediate needs*, it is proposed that Standard 9 be retained and its scope expanded to absorb the requirements of current Standard 10. The new Standard 9 should be renamed as *Enhancement of Faculty CDIO Competencies*. Hence there is only one standard that focus attention on equipping faculty with competencies needed to design and deliver existing curriculum as needed. It also serves as a basis for preparing incoming faculty new to CDIO to quickly assume one’s role as an educator and start teaching using the CDIO approach; and also includes the use of GenAI in designing learning tasks for students.

For *emerging future needs*, a new standard on faculty continuing professional development can be introduced to take the place of Standard 10, retaining the standard number but carry a new name, entitled *Faculty Continuing Professional Development* to focus on faculty’s on-going continual improvement. It highlights the need to maintain the faculty’s CDIO competencies to be on par with changing educational requirements, that upgrading of one’s capability is needed as soon as new demands on curricular outcomes are identified.

This new Standard 10 is thus differentiated from the revised Standard 9 by its forward-looking nature, taking into considerations new developments impacting education in general and teaching in particular; that require faculty to continually renew one’s capability in all aspects – technical domain, pedagogy or pedagogies, use of technology in teaching and learning, etc. This is also consistent with the call for a more forward-looking CDIO program by Cheah (2023). The need to be forward-looking is especially important in today’s world of AI, where technological advancement is progressing at a very rapid pace. As education is inherently lagging behind any change in its external operating environment, the need to be able to predict with great accuracy the needs of future workplace requirements before students graduated are more pressing than ever. We need a CDIO Standard that mandates program owner and faculty alike to look ahead at what competencies are needed on an on-going continual basis.

Along with the use of DigCompEdu-AI and UNESCO frameworks, these suggested revisions can better serve the needs to prepare faculty for using AI in one’s teaching responsibilities, as explained in the next section.

How to Use Standard 9 and Standard 10

Figure 1 below shows how the expanded Standard 9 and new Standard 10 work together in accordance with the PDCA (plan, do, check, act) quality improvement cycle adapted for faculty professional development (Samuel & Farrer, 2025). This makes the 2 standards well-aligned with the continual improvement nature espoused in CDIO Standard 12 Program Evaluation. This demonstrates the forward-looking nature in faculty professional development that the author had been alluding to. Making faculty continuing professional development explicit in the new Standard 12 clearly communicates this to all key stakeholders of the importance of human capital in teaching and learning in today's world dominated by AI.

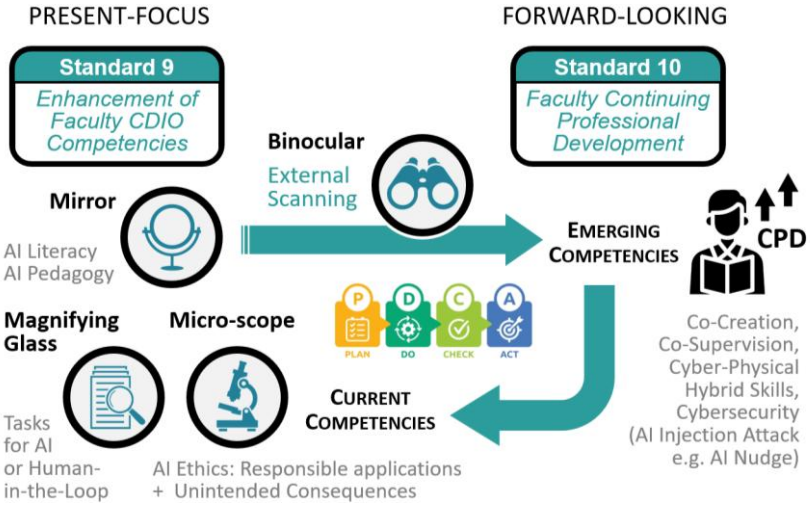


Figure 1. Using Standards 9 and 10 to develop faculty GenAI competency

It can be seen from Figure 1 there are 4 circles labelled mirror, magnifying glass, microscope and binocular. The mirror, microscope and binocular are metaphors the author first used in his earlier paper on improving faculty reflective practice (Cheah, 2022). The author had earlier argued that there is a need to strengthen reflective practice as a key element towards faculty self-improvement and the program's continual improvement; and it be made explicit in CDIO standards. In this paper another item – the magnifying glass is now added, and together the 4 metaphors can guide faculty development in GenAI competency as follows:

- *Mirror*: Guides self-evaluation to ascertain one GenAI Competency, using DigCompEdu-AI's 6 proficiency levels (Standard 9)
- *Magnifying Glass*: Identify areas where GenAI can be used in one's program and/or courses, to achieve the desired outcomes (Standard 2) via meaningful student learning activities (Standards 5, 7, 8)
- *Microscope*: Scrutinize the use of GenAI (human-in-the-loop) to ensure it is responsible and ethical, and plan the assessment accordingly (Standard 11)
- *Binocular*: Look ahead for emerging trends of AI technologies and plan one's own professional development program (Standard 10)

Standards 9 and 10 contributed to continual improvement for curriculum quality assurance by ensuring that faculty AI competency always remained current and up-to-date, via the PDCA cycle, adding to the pool of generic competencies new requirements delivered by faculty professional development program. For example as shown in Figure 1, AI Literacy is now an essential requirement for all faculty, especially on the ethical and responsible use of GenAI in education. Such requirements would fall under Standard 9. As noted by Cheah (2026b) an area where GenAI use that is hotly contested is learning assessment. As each iteration of the

GenAI will result in its greater sophistication, it will continue to render existing practices questionable. An example is the long-held superiority of authentic assessment the validity of which is now challenged (e.g. Gonsalves, 2025; Arnold & Croxford, 2024). Emerging areas for research include the contextual assessment model based on expanding Gilberts Model of Contest (Gonsalves, 2025), GenAI Assessment Literacy (Moorhouse *et al*, 2023), Product vs Process Assessments (Fawns, 2024), just to name a few. These can form the basis of faculty professional development under Standard 10. When new competencies got recognized and adopted essential competencies, they will "move" from Standard 10 to become essential feature of teaching and learning under Standard 9 as shown in Figure 1, reflecting the dynamic nature of faculty competency that need constant monitoring to keep abreast of technological developments.

Figure 1 can go one step further. The cyclical nature of PDCA will mandate continual improvement of faculty capability not just to keep up with the development in AI technologies, but it can also drive faculty to innovate one's teaching and learning practices using AI.

OPPORTUNITY FOR INNOVATIONS IN TEACHING & LEARNING USING CDIO & GEN AI

The distribution of intelligence possessed by humans and GenAI can be represented by an adaptation of the Rumsfeld Matrix as shown in Figure 2.

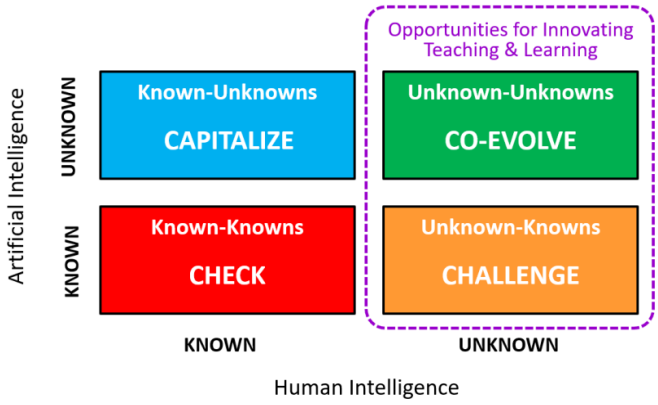


Figure 2. Engaging with GenAI under different scenarios and opportunity for innovation

The 4 quadrants of the matrix represent different balance of knowledge between human intelligence and AI, in the form of the famous "Known Knowns", "Known Unknowns", "Unknown Knowns" and "Unknown Unknowns". The 4 C's in the quadrants represent different actions that faculty can take when engaging with GenAI. Of most interest is the 2 top quadrants where educators can make use of GenAI to innovate teaching and learning practices. This matrix is briefly explained below:

- *Check (Known Knowns)*: This is a case where both knowledge types are well-informed among humans and machines. In this case, faculty will play a key role of human-in-the-loop, to stay on top of any GenAI-produced outputs to guard against GenAI misuse of the information. See Cheah (2026b) for more details.
- *Capitalize (Known Unknowns)*: This is a 'fortunate' case whereby humans still possess superior knowledge and know-how than GenAI, at least before Ganai catches up. Hence this may not be a tenable position in the long run as GenAI advances. Faculty should take advantage of this situation to innovate one's teaching approaches where possible.
- *Challenge* (Unknown Knowns): In this case, educators need to know what GenAI knows. This can form the basis for faculty development programs to keep one apprised on the

latest developments with regards to AI usage in education. This will then provide the springboard from which faculty can check on GenAI (Known Knowns), rethink how one's current teaching was carried out, and attempt at innovating teaching and learning.

- *Co-evolve (Unknown Unknowns)*: This is the most intriguing aspect where both humans and machines don't know what they don't know. This is also the quadrant that appears most promising for innovating teaching and learning. Hence the word 'co-evolve' is suggested to mean both educators and GenAI join forces to explore the education terrain, leveraging on the best of both: humans in one's curiosity and creative potential, critical thinking, sense-making, etc to complement what GenAI did best.

The last quadrant, to co-evolve to discover unknown unknowns to obtain insights and identify opportunities for innovating teaching and learning, is an area worthy of further research. The way faculty approach teaching and learning research can take on a new spin in this age of GenAI. An area for faculty professional development is how to write intelligent prompts (Cain, 2023; Korzynski *et al*, 2023) for educational research. The aim is to harness the power of GenAI to uncover knowledge unknown to both humans and machines and then uses human intelligence to identify opportunities and potentials for innovation in teaching and learning, while providing oversight via human-in-the-loop. Doing so will demand that faculty continue to nurture human traits – "foundational core" (Cheah, 2026a) from being replaced by GenAI. The research here can further support this endeavor.

With the author's recommended revisions to Standard 9 to become *Enhancement of Faculty CDIO Competence*, and a new on *Faculty Continuing Professional Development* to replace the old Standard 10, there is a need to review the write-ups for these 2 standards. The suggested amendments are shown in Appendix 1. This author suggested removing examples of how enhancement of faculty can be achieved, to allow program owners to explore new opportunities afforded by use of GenAI. Also removed are suggestions on hiring practices which the author opine can be left to the institution's policies. The initial text that were removed are shown using strikeouts. These suggested changes can be considered when Council decided to embark on revising entire CDIO Standards to bring it to version 4.0, to include among other things, the use of GenAI.

LIMITATION OF WORK DONE AND MOVING AHEAD

At the time of this writing, the proposed changes to the 2 standards had not been reviewed and debated within the CDIO Community. It is the author's contribution to the ongoing discourse on evolution of CDIO standards as part of continual improvement. The rationale for changes mentioned in this paper are based on the author's perspective and it is probable that other points of view are not included. As an academic paper, this work serves to stimulate the required discussions. Likewise, the approach presented in Figure 2 remained at this stage still a theoretical exploration and not yet validated with any programs within SP or other institutions. This approach is also somewhat contingent of the acceptance of the changes proposed to the 2 standards.

To advance innovation in teaching and learning, it is essential to study the underlying mechanics of how the PDCA cycle operates, particularly in navigating domains of "unknown unknowns" of Figure 2. Research shows that PDCA provides a systematic framework for continuous improvement and curriculum adaptation in higher education (Samuel & Farrer, 2025). However, traditional applications often struggle with unpredictable challenges that require novel solutions. The iterative nature of PDCA, when combined with the use of GenAI, offers a structured yet adaptive pathway for discovery. Recent studies highlight that GenAI

can surface hidden patterns, simulate alternative pedagogical strategies, and generate novel insights that feed into each stage of the cycle (Creely & Carabott, 2025; Ogunleye *et al*, 2024). This integration enables educators to move beyond incremental improvement toward transformative curriculum innovation, particularly in contexts where future challenges are uncertain and knowledge gaps remain undefined.

Moving ahead, we would like to invite fellow CDIO members to adopt the model and test it out within their respective programs; and make the necessary adaptation and suggest further refinements to the model to drive innovation in teaching and learning. Faculty professional development should be driven by the PDCA cycle, using Figure 2 to target the "unknown unknowns" for innovation where neither humans nor GenAI know what they don't know. Research in this space must explore co-evolution: designing intelligent prompts, experimenting with GenAI in novel teaching contexts, and systematically reflecting on outcomes to surface new competencies and learning pathways. The priority is to uncover insights beyond current knowledge, combining GenAI's pattern discovery with human creativity and judgment to generate fresh directions for curriculum redesign and educational research.

CONCLUSIONS

This paper presented a compelling reason to revise both Standards 9 and 10; to highlight the strategic importance of faculty professional development so that faculty continue to keep abreast with technological progress in particular the use of GenAI in teaching and learning. It is suggested to use both the EU DigCompEdu-AI Framework and the UNESCO AI Framework for Teachers to complement one another as the basis to guide the development of AI competency. A dynamic relationship between the revised Standard 9 and new Standard 10 is envisioned, where faculty continue to enhance one's AI competency in line with technological advancements. Special emphasis is placed on faculty leveraging on GenAI tools to explore knowledge unknown to both humans and machines, to innovate one's teaching and learning practices to better prepare students to thrive in today's ever-evolving digital world.

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Full Declaration: Comparison between DigCompEdu-AI and UNESCO had been carried out with the aid of GenAI, namely Gemini. The prompts used and responses obtained are available for review via the link below. Copilot was used to help the author refine the understanding and selection of the 'C' words for each of the quadrant in Figure 2 – in what Copilot called analyzing the 'semantic terrain' to match the context of use suggested by the matrix. A copy of the activity can be found in same below. (Note: Select PDF marked 105 for this paper) https://drive.google.com/drive/folders/1h5gPaRxba899Yjk2GbR5JqJ4jeeqMqLo?usp=sharing

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APPENDIX 1. Proposed CDIO Core Standards 9 and 10 incorporating use of GenAI

Standard 9 Enhancement of Faculty CDIO Competencies (REVISED)

Actions that enhance faculty CDIO competence, defined as knowledge, skills and attitudes pertaining to the CDIO Syllabus and skills in designing and delivering various CDIO-type learning tasks (design-implement experiences, integrated learning experiences, active learning lessons) and in assessing student learning. Also include actions that develop faculty competence in using GenAI tools.

Description

CDIO programs provide support for improving the collective competence of the engineering faculty with regards to *what to teach*, according to the full set of intended learning outcomes of the program as described in Standard 2. Faculty CDIO competence refers to personal, professional and interpersonal skills, product, process, system, and service building skills, including concepts and competences related to sustainable development. Faculty CDIO competence also refers to the ability to support students (*how to teach*) to achieve a deeper working understanding of the relevant disciplinary fundamentals by designing appropriate CDIO-type learning tasks such as design-implement experiences (Standard 5), integrated learning experiences (Standard 7), active learning lessons (Standard 8) and the assessment of student learning (Standard 11). Reflective practice is a key element of faculty undertaking to identify one's own training needs; and taking part in community of practice or formal training programs are ways to enhance faculty's CDIO competencies. Proficiency in using GenAI tools in ethical and responsible manner form the basis of faculty CDIO competency. ~~One way to strengthen the collective competence of faculty is to take these needs into account in faculty recruitment and promotion processes. Another way is to systematically support the competence development of the existing faculty members. The nature and scope of faculty development vary with the resources and intentions of different programs and institutions~~.

Rationale

If engineering faculty are expected to teach a curriculum of personal, professional and interpersonal skills, and product, process, system, and service building skills integrated with disciplinary knowledge, as described for instance in Standards 3, 4, 5, and 7, they as a group need to be competent in those skills. Engineering professors tend to be experts in the research and knowledge base of their respective disciplines, with only limited experience in the practice of engineering in business and industrial settings, and its role in sustainable development. A key aspect of expertise is technological pedagogical content knowledge, which refers to the ability to effectively support students in learning the subject, with aid of technology enhanced with use of GenAI. The rapid pace of technological innovation also requires continuous updating of engineering skills. The collective faculty needs to enhance its engineering knowledge and skills so that they can provide relevant examples to students and also serve as individual role models of contemporary engineers.

Rubric for self-assessment

5	Faculty competence in disciplinary knowledge and personal, professional, interpersonal, product, process, system, and service building skills as well as in designing CDIO-type learning tasks (with or without using GenAI) are regularly evaluated and enhanced where appropriate.
4	There is evidence that the collective faculty is competent in disciplinary knowledge and personal, professional, interpersonal, product, process, system, and service building skills; as well as in designing CDIO-type learning tasks (with or without using GenAI).
3	The faculty participates in competence development activities, and faculty recruitment considers the need for faculty competence, with regards to disciplinary knowledge and personal, interpersonal, product, process, system, and service building skills, as well as in designing CDIO-type learning tasks (with or without using GenAI).
2	There is a systematic plan for faculty enhancement in disciplinary knowledge and personal, professional, interpersonal, product, process, system, and service building skills; as well as in designing CDIO-type learning tasks (with or without using GenAI).
1	The need of a faculty competence development plan in disciplinary knowledge and personal, professional, interpersonal, product, process, system, and service building skills as well as in designing CDIO-type learning tasks (with or without using GenAI) is recognized.
0	There are no programs or practices to enhance faculty competence in disciplinary knowledge and personal, professional, interpersonal, product, process, system, and service building skills, as well as in designing CDIO-type learning tasks (with or without using GenAI).

APPENDIX 1. (cont'd)

Standard 10 Faculty Continuing Professional Development (NEW)

Actions that ensure faculty's CDIO competencies is up-to-date in response to changing teaching and learning environment brought about by rapid changes in today's fast-changing world to provide students with required new skills in the workplace, or emerging industry.

Description

CDIO programs take actions to enhance faculty teaching competence required for effectively creating, delivering and improving courses in the curriculum via continuing professional development is necessary in today's fast-changing world. ~~The need for faculty teaching competence include for instance the ability to provide integrated learning experiences (Standard 7), including design-implement experiences (Standard 5) and other active and experiential learning (Standard 8), as well as assessing student learning (Standard 11) and evaluating and improving courses and programs (Standard 12). One way to strengthen the collective faculty teaching competence is to take these needs into account in faculty recruitment and promotion processes. Another way to address the need is to systematically support the development of the existing faculty members' teaching competence. The nature and scope of faculty development practices will vary with programs and institutions.~~ This is particularly so, with regards to advancement in technology, faculty need to learn new skills such as prompt engineering for GenAI in research or in designing new CDIO-type learning tasks, in using GenAI for various research applications (e.g. identifying insights, performing sentiment analysis, designing performance rubrics to guide assessment of new skills, etc).

Rationale

If faculty members are expected to integrate new skills and/or attitudes (e.g. arising from new developments in the workplace, technological advances, etc), and hence to teach and assess in new ways, ~~as described in the CDIO Standards~~, they need opportunities to develop and improve these competencies. ~~Many universities have faculty development programs and services that might be eager to collaborate with faculty in CDIO programs. In addition, if CDIO programs want to emphasize the importance of teaching, learning, and assessment, they must recruit and promote faculty with these needs in mind, and they must commit adequate resources for faculty development in these areas.~~ Programs should have a systematic way to assess faculty training requirements and work with the institution's faculty professional development department to provide the required training. The impact of professional development program on teaching and learning should be evaluated.

Rubric for self-assessment

5	Faculty teaching and learning competency framework, AI competency framework and continuing professional development program is regularly evaluated with key stakeholders and updated where appropriate.
4	There is evidence that the collective faculty continuing professional development had been translated to ~~has the teaching competence needed for~~ effectively creating, delivering and improving courses in the curriculum, as well as ethical and responsible of GenAI.
3	Faculty members participate in continuing professional development activities to develop their CDIO competence and AI competence based on the institution's faculty teaching and learning competency framework and AI framework. ~~and faculty recruitment takes into account the need for faculty teaching competence.~~
2	A systematic plan for ensuring and enhancing faculty continuing professional development is developed (for example, training needs analysis, faculty teaching and learning competency framework, AI framework) and budgeted.
1	A need for ensuring and enhancing faculty continuing professional development is recognized and accepted within the team.
0	There are no programs or practices for faculty continuing professional development.

SAFEGUARDING HUMAN CREATIVITY: USING GEN AI TO PROTECT AGAINST GEN AI

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ABSTRACT

This paper puts forward an argument that while exploring and pushing the boundaries of what generative artificial intelligence (GenAI) can achieve, we should not lose sight of its erosion on core human capacities. This paper provides explanations from a cognitive perspective, how human creativity is at risk of being compromised by GenAI, as we continue to outsource such cognitive tasks to GenAI. The use of GenAI is disruptive because it does not lend itself easily to scrutiny, and much of its decision-making is a black box and as such is in constant need for human oversight. The paper suggests that we can leverage on GenAI's strengths to address its potential harm and illustrate this using creativity as the discussion point. The choice of creativity is rather straightforward: it was not long ago hailed as something that is uniquely human, but recent advances in GenAI technologies had threatened this claim. For example, artefacts produced by GenAI in the creative industries are now indistinguishable from those of human creation. This paper focuses on GenAI use in promoting creativity engineering education, an area where past attempts were not met with much success. In addition, impact of GenAI on creativity is already extensively studied in non-engineering disciplines where we have much to learn from. One important aspect is the greater emphasis on importance of creation process in addition to creative product. The approach made use of a mental model developed by the author that showed how use of GenAI can be scrutinized at several levels to ensure that it can be responsibly used in teaching and learning. A key feature of the model is the use of CDIO Core Standards to provide human-in-the-loop oversight on GenAI responses. This has the dual benefits of ensuring that the processes enhance core human capacity while the engineering products demonstrate strict adherence to professional standards in meeting ethical and safety obligations. The paper shares an idea of moving forward to use the approach outlined in this paper to enhance faculty contribution to innovative teaching and learning by addressing challenges that are "unknown unknowns" via working collaboratively with GenAI.

KEYWORDS

Generative Artificial Intelligence, Human Intelligence, Creativity, Unknown Unknowns, CDIO Standards 3, 5, 7, 12

INTRODUCTION

The importance of creativity in engineering education had long been recognized, yet progress to-date had not been satisfactory (Corrêa & Mourão, 2025; Egan *et al*, 2017). This paper posits that integrating creativity can be facilitated by the use of generative artificial intelligence (GenAI). This paper argues that now it is more imperative than ever to address this challenge, because creativity, being an important human capacity, needs to be protected against over-reliance on GenAI use. Creativity was once hailed as one of the several human traits that is difficult to duplicate in machines. However, in today's fast-changing world, GenAI-based creativity has surpassed human creativity, where artefacts produced by GenAI (arts, music, poetry, etc) are virtually indistinguishable from that produced by humans.

This paper suggests that through the use of a mental model developed by the author, the judicious use of GenAI can help not only to counter the potential negative effects but can potentially lead to innovative teaching and learning practices. The model shown in Figure 1 (Cheah, 2026a) provides guidance on how faculty can be cognizant of potential pitfalls when using GenAI in curriculum redesign where CDIO Core Standards are among other approaches forming multiple layers of protection and serving as guardrails (Cheah, 2026b) to check against GenAI outputs. Collectively these various layers of protection will a robust safeguard against an event termed Swiss Cheese Phenomenon, where a hazard (in this case, wrong GenAI output) managed to slip through due to failure of all layers of protection.

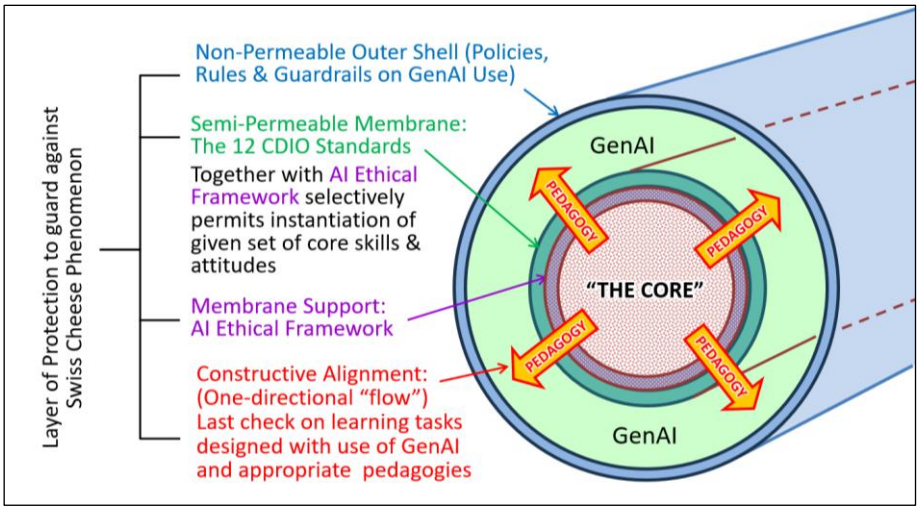


Figure 1. Model of GenAI use in T&L Guided by CDIO and AI Ethical Frameworks

While there is no single, universally agreed-upon formal definition of the human cognitive and affective aspects to be protected from GenAI, a consensus is emerging in research and commentary around several key capabilities that are considered fundamental and most susceptible to erosion from overuse or over-reliance on AI. For his work, Cheah (2026a) considers creativity, along with critical thinking, emotional regulation, metacognition and resilience, etc as the important human capacities, labelled as "The Core" in Figure 1.

Scope of This Paper

Whereas CDIO Standards and AI Ethical Framework provide the outer protection against GenAI misuse, this paper focuses on strengthening "The Core" itself, notably by enhancing human creativity and creative thinking. It firstly informs of the cognitive basis of creativity and hence argued that creative thinking can be trained. Not discounting the positive contributions

of GenAI to teaching and learning, this paper focuses more on the negative impacts of GenAI overuse and over-reliance to illuminate GenAI's impact on creativity with particular emphasis on engineering education. The paper moves on to discuss and unpack the underlying mechanisms of how GenAI works and the way it handles various aspects related to creativity, such as intuition and serendipity; and argues that the best safeguards against the erosion of the traits by GenAI is the use of GenAI itself.

The suggestion is based on the premise that in engineering education, the process of engineering design is more important than the product of engineering design, and this had remained the case even with the use of GenAI. Lastly this paper concludes with a call for the revamp of engineering education that leverages on GenAI to address the "Unknown Unknowns" domain of knowledge, arguing that with assistance of GenAI, faculty can more effectively innovate teaching and learning.

LITERATURE REVIEW

The Neurocognitive Basis of Creativity

Creativity is a multifaceted human ability that depends heavily on the confluence of personal attributes and environmental conditions (Weir, 2024). Various studies have confirmed the neurological basis of creativity (Chan *et al*, 2025; Kutsche *et al*, 2025; Malach, 2024; Beaty *et al*, 2019). Dietrich (2024) showed from studies in neuroscience that creativity does not exist as its own specialized entity in the brain. It is "everywhere" in that its neurocognitive mechanisms are distributed, embedded, and varied. Fundamentally, it requires dispositions such as curiosity (which drives the exploration of new ideas and the questioning of established norms) and open-mindedness (which allows one to suspend judgment, consider unconventional perspectives and integrate disparate concepts). Intuition – a neurological process (Volz & von Cramon, 2006) is another human trait that is linked to creativity (Styhre & Sundgren, 2005). Intuition can be described from a psychological perspective as anticipatory ability to understand or know something without knowing how you know or understand (Hardman, 2021). Another crucial factor is intrinsic motivation, for which research has shown connections to creativity (Cromwell *et al* 2023; de Jesus *et al*, 2013).

Creativity in Engineering Education: Opportunities & Challenges

Creative thinking in engineering education is essential for preparing students to develop novel and effective technological solutions to complex, evolving problems. It moves the focus beyond routine problem-solving, which relies on known procedures, toward innovation in design by encouraging students to challenge assumptions, generate diverse ideas, and synthesize disparate concepts. This ability is crucial for driving global economic competitiveness, meeting societal challenges (e.g. climate change, infrastructure), and transforming new ideas into tangible, useful products and systems.

Studies from neuroscience show that creativity can be learned through divergent training (Sun *et al*, 2016). A recent study Sio & Lortie-Forgues (2024) showed a meta-analysis of 169 creativity training studies across five decades and found a positive effect size of creativity training. Peng *et al* (2025) suggest that integrating neuroscience principles into educational practice appears to foster creativity. However, the integration of creativity and critical thinking in engineering programs remains poor (Sola *et al*, 2017). A more recent study by Beaulieu (2022) showed that engineering students do appreciate the importance of creativity but more needs to be done to integrate it into engineering education. A key challenge in embedding

creativity is the traditional heavy emphasis on narrow, deep technical specifications and rigorous, structured scientific paradigms in engineering curricula, leaving little room for flexible, ambiguous, or open-ended creative exploration.

Creativity and GenAI in Engineering Education Context: Benefits and Pitfalls

The use of GenAI is a rapidly evolving area that can significantly enhance creativity education by fundamentally altering the ideation, prototyping, and feedback stages of the creative process. Instead of acting as a replacement, GenAI functions as a cognitive co-pilot that expands human capabilities, especially in overcoming initial barriers to creation – the so-called "blank page syndrome", a modern spin on the common experience of 'writer's block,' coined by Austrian psychiatrist Edmund Bergler in 1947.

The "dual-edge sword" nature of GenAI use in education is often described as the "cognitive paradox of AI" (Jose *et al*, 2025). From a cognitive science perspective, GenAI raises significant concerns about "cognitive offloading", a term introduced by Risko & Gilbert (2016) to mean "the use of physical action to alter the information processing requirements of a task so as to reduce cognitive demand". In the context of today's advances in AI, it refers to the reliance on AI tools to perform mental tasks like information retrieval, data analysis, and problem-solving to reduce the mental effort required of humans. While this can increase efficiency by freeing up cognitive resources, it also raises concerns about potentially eroding critical thinking and deeper understanding by bypassing active, independent thought (Gerlich, 2025). One such risk is "cognitive atrophy", the term borrowed directly from the medical concept of "atrophy" which means the wasting away of a body part due to underuse, e.g. muscle atrophy. It is the "use it or lose it" principle applied to the mind. "Cognitive atrophy" therefore, describes the hypothesized degradation of cognitive skills (e.g. critical thinking, creativity) because they are no longer being exercised, having been "offloaded" with technology. Examples on impact of GenAI on creativity include the reduction of originality and divergent thinking for heavy GenAI (Moongela *et al*, 2024) and stifled creativity when defaulting to AI-generated ideas (Gonsalves, 2024), just to name a few.

Some findings from the impact of GenAI on creativity from non-engineering studies can be generalized to engineering, as both fields involve creative processes, problem-solving, and innovation. Here are the key transferable insights from Heigl (2025):

1. GenAI Literacy: Developing technical skills and understanding the limitations of GenAI is crucial. Engineers need to learn prompt engineering and understand the trade-offs of using GenAI compared to traditional methods.
2. Human-AI Collaboration: The importance of human agency in guiding GenAI creativity is important in engineering design. Engineers, like artists, act as curators and supervisors of AI-generated solutions and steer GenAI systems to ensure outputs align with technical requirements and creative vision.
3. Redefining Workflows: Design workflow can be improved by using GenAI as a companion. A cited example is the "triple-loop approach" of Seidel *et al* (2019) where engineers can use GenAI to generate design alternatives and refine inputs based on feedback. It is an active, iterative process of mutual learning with GenAI that influence the design process (i.e. reshaping the workflow) to attain the design goal.
4. Bias and Ethical Considerations: In engineering, similar concerns about inclusivity, fairness, transparency and ethical implications of AI-generated designs exist and should be addressed, especially in fields like product design and architecture.
5. Human Perception and Acceptance: Skepticism toward GenAI-generated content can arise during the conceiving state and distrusts during the designing stage. Moreover,

cultural background, expertise, and individual differences in evaluating GenAI outputs are also factors to consider. Understanding how these factors influence the adoption and perception of GenAI tools are important. Strategies are required to emphasize human oversight and promote collaboration to help improve integration of GenAI tools into engineering practices and drive acceptance of GenAI-generated solutions.

6. Evaluation Metrics: The use of subjective and objective measures to evaluate GenAI-generated content in creative contexts can be adapted to engineering. Metrics such as novelty, quality, and functionality can be used to assess the impact of GenAI on engineering designs.

DISCUSSIONS

Despite fundamental differences in human intelligence and GenAI, and more specifically in human creativity compared to artificial creativity (Runco, 2023) the rapid advances in technology in general and changes in GenAI capabilities in particular are cause for concern. This is because unlike other technologies before this, AI is fundamentally different in its relationship with humans. In the past, human creations have amplified our capabilities while remaining fundamentally under control. Today's AI systems are agents, not tools – they are capable of learning from data and possess a form of autonomy that no previous technology has exhibited before. Unlike previous technologies that process information using prescribed rules, an AI system is capable of developing its own rules from patterns it extracted from the information. We are faced with decisions from AI-based algorithms that affect our lives that are opaque to us (Whitaker, 2025).

The pace of change today offers little time for gradual societal adaptation (Whitaker, 2025). GenAI is fast catching up in replicating traits that once considered uniquely human. As mentioned in the scope of this paper, GenAI has already mimicked and exceeded humans in producing creative artefacts. Next, we briefly looked into how GenAI tackle the 2 aspects closely related to creativity namely serendipity and intuition:

- Serendipity arises from curiosity, intuition, and noticing something unexpected – a happy accident of finding something valuable or delightful when you are not looking for it, and is deeply tied to context, values and lived experience. GenAI on the other hand, uses its technology to facilitate unexpected discoveries and connections that surfaces surprising but relevant patterns. It is *engineered serendipity* relying on probabilistic exploration, randomness, or cross-domain data recombination.
- Human intuition is a fast, unconscious process derived from a lifetime of diverse learning and experiences. It often acts as a "gut feeling" that produce sudden insights and connections that helps the creative process by generating ideas and evaluating them. GenAI does not possess human-like intuition as it lacks consciousness, emotions, and lived experience. But its ability to identify complex statistical patterns and correlations in its training data that would be imperceptible to humans enables it to provide quick, seemingly insightful answers that mimic intuitive-like responses.

Here we see a common pattern that leads to GenAI's perceived superiority: it is the GenAI's foundation models that can process massive amounts of data to understand context, generate novel content, and solve complex problems across diverse domains with human-like proficiency. From a creativity perspective, this also means that GenAI is prone to the challenge of fixation bias as humans. A study by Desdevises (2025) showed that GenAI exhibited a comparable fixation bias, even as it demonstrated impressive fluency by producing a large number of creative ideas; most fall within conventional categories. The inability of GenAI to overcome the fixation bias highlights the necessity of human involvement, particularly for

properly evaluating and filtering the ideas generated. The fundamental differences between human creativity and machine creativity can be succinctly summarized in Table 1.

Table 1. Fundamental differences between human creativity and machine creativity

Human Creativity	Machine Creativity
Type: Generative, conceptual – can invent truly novel concepts or artefacts based on subjective insights, metaphor and intuition	Type: Combinatorial, pattern-based – generates output by remixing and statistically combining elements from its training data
Learning mechanism: Experience-based, can learn from sparse data; learn through direct sensory, social and emotional experiences often requiring only a few examples	Learning mechanism: Data-driven, feeds on bog data and learn through statistical correlation and pattern recognition across massive, pre-existing data sets

AI's ability to make consequential decisions without deep understanding we would expect from human decision makers is causing a fair bit of anxiety. Dennett (2018) had warned against the human tendency to attribute an excessive or inappropriate number of human characteristics, emotions, or intentions to such non-human entities. Despite this, advances in AI systems continue to demonstrate remarkable competence across domains without the comprehension we associate with human expertise: "competence without comprehension" (Dennett, 2018). While work had been on-going to make GenAI more transparent for example in "Explainable AI" (Ali *et al*, 2023) we need more immediate measures to help us address this challenge. Since we cannot look inside the black box, the next best thing is to scrutinize the outputs and identify needed improvements to be fed back as inputs to the models.

SAFEGUARDING HUMAN CREATIVITY: USE GEN AI TO PROTECT FROM GEN AI

We can now look into how the mental model introduced in Figure 1 can be used to protect core human capacities from being compromised by overuse of GenAI. Recall that one of the guardrails ("layers of protection") is the semi-permeable membrane, which permits movement of materials in one direction only. Using this analogy, elements of creativity such as intuition, open-mindedness are "retained" inside the inner tube. This means that one is required to use the innate human capacity, to benefit from serendipity and intuition; and not relying on GenAI use. In the mental model, this is referred to as "instantiations" of the human capacities permitting their use (Cheah, 2026a). Pedagogically (the arrows in Figure 1), faculty can design learning tasks (CDIO integrated learning experiences, design-implement experiences) supported by GenAI use; that facilitate the use of the "instantiations" of these human capacities to build up students creativity, guided by the CDIO Core Standards providing human oversight: human-in-the-loop (Cheah, 2026b) to evaluate appropriateness of GenAI outputs.

From these descriptions, one can see that Figure 1 emphasizes using the learning process to strengthen the core human creativity. There have been many debates, especially in the creative industries, on the importance of the process of creation if the products are virtually indistinguishable whether they were produced resulting from human intelligence or GenAI – the Process vs Product debate. Having said that, it has also been shown that GenAI exhibited a comparable fixation bias, with most ideas falling within conventional categories. Hence it can be argued that focusing on processes is important to protect the core human creativity.

The author argued that in engineering education, the engineering design process is even more important than the designed product. Engineering is a professional discipline where a heavy

emphasis is placed on macro ethics which directs the engineer's ethical and professional duty in doing what is needed for the long-term improvement of society (Vallero, 2008). An engineer is to hold paramount the safety, health, and welfare of the public. This duty of care is primarily discharged through the rigor and ethical standards applied *during* the design process, not merely judged by the final outcome. This applies to today's AI world as well, where engineers must balance the potential benefits to society of advances in AI technologies, while also avoiding their negative societal consequences. There is also a good alignment with the CDIO Core Standards, with their process-driven nature towards curriculum revamp and redesign; where human-in-the-loop oversight can be implemented (Cheah, 2026b). Collectively this can enhance the accountability needed in design decisions and demonstrate duty of care, therefore fostering greater trust in the use of GenAI in engineering design.

GenAI can be used to strengthen human creativity by tapping into its advantage to generate many ideas quickly, albeit the challenge of "fixation bias". An example of this can be illustrated using by aligning GenAI use with the *triple-loop approach* by Seidel et al. (2019) where autonomous tools and humans iteratively reshape tasks, processes, and even design logic through mutual learning. Building on this, the present paper situates GenAI within the CDIO Standards and ethical guardrails, not as a replacement for human ingenuity but as a structured mechanism for iterative co-creation. In this framing, GenAI's outputs are continuously scrutinized and refined through human oversight, ensuring that the process strengthens core capacities such as creativity and intuition. This conceptual alignment provides the foundation for moving from theoretical models to pedagogical practice, where faculty can design learning activities that cultivate reflective engagement, critical thinking, and creative confidence in students.

From the teaching perspective, faculty can harness the benefits of GenAI to cultivate critical and creative thinking, ethical awareness, and problem-solving skills in students. Stranges & MacNutt (2025) suggests that skilful use of reflective writing encourage students to engage deeply with course content and with their experiences, thoughts, and emotions to gain insights, make meaning, and develop as learner in the age of GenAI. Through timely feedback on the reflections, faculty can further strengthen the core human capacities by facilitating students in consolidating the learning outcomes.

With reference to Figure 1 although not explicitly shown, this is akin to the reverse osmosis process used in seawater desalination; where water under applied pressure, is pushed through a membrane to travel from the seawater side (with high salt content) to the purified water side (with lower salt content). In a pedagogical sense, this is analogous to the learnings gained outside the membrane is being "pushed back" into the inner tube containing the core human capacities. Students can now assimilate these learnings into their prior knowledge, forming new knowledge, hence enhancing the core capacities.

MOVING AHEAD: REVAMP OF ENGINEERING EDUCATION IN THE AGE OF AI

We propose that the opportunity is ripe to simultaneously achieve multiple objectives for the benefits of both students and faculty: rekindle the redesign effort to integrate creativity in engineering curriculum, imparting AI literacy to students, and building faculty resilience to GenAI by strengthening their creative capacity which is one of key elements of the human core. Doing so will enable faculty to better prepare in tackling the challenges in today's world, using GenAI as partners to address "wicked problems" typical of sustainable development issues, and in doing so, also help students reinforce their own creative capacity.

This paper proposes that the revamp of undergraduate engineering curriculum should be carried out using the CDIO approach in 2-part manner beyond what is covered in an introductory AI Literacy course which typically include the following areas as shown in Table 2. Details of the work done is covered separately by Cheah (2026d).

Table 2. Typical contents in an introductory AI Literacy course

Content Area	Key Topics
Fundamentals of AI	Key concepts like Machine Learning, Generative AI (e.g. Large Language Models), and the AI Lifecycle. Understanding the difference between AI, algorithms, and data.
Practical Application	Best Practices for Prompting/Interacting with AI tools (e.g. structuring prompts for clarity and precision). Identifying common AI tools and how they enhance learning and professional tasks.
Critical Evaluation	Learning to Evaluate AI Output for accuracy, bias, and credibility. Fact-checking and validating AI-generated content.
Ethics and Integrity	Responsible AI use, understanding algorithmic bias, data privacy, and security. Establishing best practices for academic integrity and avoiding over-reliance on AI.
Societal Impact	Reflecting on how AI is shaping the future of the workforce and its broader role in society, including issues of inclusion and equity.

- Part 1 is to equip students with knowledge beyond those covered in Table 2; to include elements of cognitive science on how the brain works, creativity and the supporting elements of curiosity, intuition, serendipity, etc; and how humans can work collaboratively with AI-powered machines. This should start with Standard 4 Introduction to Engineering where use of AI can be added to the coverage of roles and responsibilities of engineers. The coverage can be progressively enhanced as part of Standard 3 Integrated Curriculum over the early semesters on a program and include learning tasks designed with suitable pedagogies that carefully integrate AI resources with traditional teaching methodologies to foster creative confidence, divergent, and convergent thinking skills in students (Habib *et al*, 2023).
- Part 2 is to review and update the existing CDIO Syllabus (version 3.0) to include competencies needed to work collaboratively with AI-powered machines, thus reflecting the new reality of today's work environment. Cheah (2026d) had proposed changes to version 3 of the CDIO Syllabus to include the human-AI hybrid competencies. Part 1 of the syllabus, which is a placeholder for disciplinary fundamentals may need to make explicit importance of understanding cognitive science as well. There is also a need to review if existing skills and/or attitudes need to be strengthened, for example those related to intuition, serendipity, resilience, etc.

The revamp should be supported by faculty professional development programs to prepare them for the new challenge ahead: develop in students the required competency to work collaboratively with machines while understanding the benefits and pitfalls of GenAI. Cheah (2026c) presented a framework shown in Figure 2 on how different strategies can be used for faculty professional development using GenAI in innovating teaching and learning practices, depending on the relative distribution of knowledge between human intelligence and AI.

The framework can be used to guide the integration of creativity and creative thinking in engineering education to build faculty confidence in teaching this subject and in designing learning touchpoints for students via CDIO Standard 5 Design-Implement Experiences and Standard 7 Integrated Learning Experiences that requires human-AI collaboration.

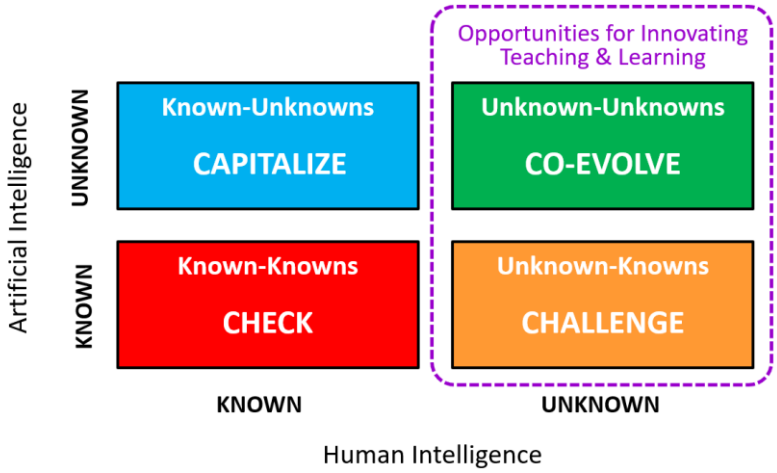


Figure 2. Engaging with GenAI under different scenarios and opportunity for innovation

The 4 strategies (CHECK, CAPITALIZE, CHALLENGE and CO-EVOLVE executed through Standards 5 and 7 provide a structured pathway for faculty and students to engage with GenAI while strengthening core human capacities. These are briefly explained below:

CHECK: Building Creative Confidence through Known Knowns

The CHECK strategy sets students off in comfortable footing. GenAI can be used to support ideation within familiar boundaries to build human confidence. For example, students can employ GenAI alongside established creativity tools such as SCAMPER or Six Thinking Hats to generate diverse design alternatives. A good application will be to address sustainability issues. Faculty can then prompt students to act as "Devil's Advocates," interrogating GenAI's suggestions, identifying assumptions, and refining ideas. In can also be GenAI that plays the role of "Devil's Advocate", helping students to uncover blind spots or identify confirmation bas. This process not only enhances creative and critical thinking but also reinforces the *process over product* ethos, ensuring that creativity is exercised rather than offloaded.

CAPITALIZE: Leveraging GenAI's Fluency to Expand Divergent Thinking

The CAPITALIZE strategy emphasizes harnessing GenAI's ability to rapidly produce multiple ideas. In practice, students might use GenAI to brainstorm dozens of potential solutions to a complex engineering challenge, such as low-cost renewable energy systems. Faculty guide students to sift through these outputs, identify unconventional possibilities, and recombine them with human intuition and contextual knowledge. By capitalizing on GenAI's fluency while retaining human judgment, students strengthen their capacity for divergent thinking and originality. Challenging GenAI in empathy, inequality and ethical nuances will further enhance students capacity to tackle wicked sustainability issues.

CHALLENGE: Strengthening Human Oversight and Ethical Awareness

The CHALLENGE strategy positions GenAI as a sparring partner. GenAI can inform faculty what it "knows" that faculty are not aware of yet. GenAI can easily process large amount of data and identify patterns, and faculty (or students) will study for plausible causations among key variables. Faculty can design tasks where students deliberately push GenAI to defend its outputs — for instance, asking the system to justify design trade-offs in terms of safety, sustainability, or inclusivity. Students then critique these responses, uncover biases, and propose counter-arguments. On the other hand, GenAI can be tasked to challenge students

with constraints on proposed solutions, requiring them to be creative in proposing alternatives. This iterative exchange sharpens metacognition, ethical reasoning, and resilience, ensuring that human creativity remains central in decision-making processes.

CO-EVOLVE: Advancing Human-AI Mutual Learning for Wicked Problems

The CO-EVOLVE strategy, as the most advanced form of human-AI collaboration, moves beyond oversight into genuine co-creation. It is most likely used for advanced-level design-implement experiences in the form of final-year capstone projects. This stage presupposes competence and experience with three earlier strategies of CHECK, CAPITALIZE and CHALLENGE. At this stage, students and faculty can iteratively co-create with GenAI, for example, using Seidel's "triple-loop approach" (Seidel *et al*, 2019) in tackling "wicked" sustainability problems where solutions are complex, uncertain, and constantly shifting due to changes in social, environmental, and economic contexts. GenAI contributes fluency and rapid prototyping, but human creativity, e.g. intuition, serendipity, and ethical judgment ensures that suggested solutions remain adaptive and inclusive. Wicked problems demand resilience and the ability to navigate uncertainty, capacities strengthened through earlier strategies: CHECK builds confidence in critical engagement, CAPITALIZE expands divergent thinking, and CHALLENGE reinforces ethical oversight. With these foundations, CO-EVOLVE amplifies human creativity, fostering responsible innovation for sustainability's "unknown unknowns."

CONCLUSION

If we continue to defer human judgements in favor of AI's recommendations, the asymmetrical relationship between human intelligence and AI will just widen, much to our detriment. There will be a profound shift in authority from human judgment with its capacity for empathy and contextual understanding and ethical reasoning, to algorithmic processes optimized for pattern recognition and statistical prediction (Whitaker, 2025).

This paper shares an approach to take advantage of GenAI's strengths and outlined strategies to develop and strengthen human creativity – a core capacity at risk of being eroded by overuse of GenAI, whose capabilities are increasing with every iteration of technological advancement. We suggest an approach using a mental model coupled with CDIO Standards to guide GenAI usage in teaching and learning. GenAI is like a coin with both a positive and a negative side. Using GenAI is like spinning the coin, but we want to "rig it so that it always lands with the positive side facing up".

Summing up, we note that John Culkin's reflection on Marshall McLuhan's insights "We shape our tools and thereafter they shape us" (Culkin, 1967), remains instructive for the adoption of GenAI in education. *"*We shape our tools*"* when educators and institutions determine whether AI is employed to enhance teaching and support student learning, or to automate instructional processes. Yet, *"*thereafter they shape us": If GenAI is used without regard to its limitations, the very meaning of learning risks being reduced to the replication of machine outputs rather than the cultivation of human judgment and understanding. The challenge, therefore, lies not simply in adopting GenAI, but in doing so with deliberate intention, ensuring that its integration sustains rather than undermines the human dimensions of education.

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REVIEW OF CDIO SYLLABUS VERSION 3.0 TO INCLUDE DEVELOPMENT OF AI-HUMAN COMPETENCIES

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ABSTRACT

This paper shares an approach in using generative artificial intelligence (GenAI) to assist in reviewing and updating of the CDIO Syllabus, reflecting the continual improvement nature of the CDIO Framework to keep abreast with changing educational landscape. The advent of GenAI and its rapid adoption across all spectrums of industries and educational institutions necessitates that faculty prepare graduates for the workplace of the future. Two main drivers for change are identified: first, to reaffirm the role of humans in an AI-dominated world; and second, to equip them with new competencies required for effective human–machine collaboration. The first concern arises from the rapid advancement of GenAI technologies which has fuelled fears that machines already surpassed humans in terms of intelligence and encroached upon traits that were once perceived as uniquely human, such as creativity, empathy, complex reasoning. This had important implications for the second concern, when humans and machines have to work together to derive maximum benefits leveraging on technological advancement supported by human oversight of work done by machines. The human-machine collaboration in particular holds great promises in addressing sustainability issues and sustainable development challenges. The CDIO Framework with its 12 Core Standards and an updated CDIO Syllabus lend itself readily to aid curricular redesign to address these challenges. The proposed revised CDIO Syllabus will incorporate skills and attitudes: (1) from AI Literacy Framework for Students from the United Nations Educational, Scientific and Cultural Organization; (2) from core human capacities that are distinct from GenAI no matter how sophisticated the algorithm driving GenAI behaviour develops, (3) needed for harnessing the “missing middle” – a collaborative space where human judgment, creativity, and empathy merge with the speed, pattern recognition, and scale of AI systems to achieve unprecedented productivity and performance gains, (4) required to support the development of a sustainability mindset. The rest of the paper discusses the relative merits of having a separate heading for human-AI collaboration compared to distributing them into relevant parts of existing heading, limitation of the approach used and plans for moving forward.

KEYWORDS

AI Literacy, Human-AI Collaboration, Missing Middle, Hybrid Competency, CDIO Syllabus

INTRODUCTION

In the advent of generative artificial intelligence (GenAI), many authors have called for our education system to be revamped to integrate practical, hands-on learning that emphasizes critical thinking, problem-solving, and creativity, while also building AI literacy and ethical AI use. Key strategies include embedding AI and digital tools into the curriculum, fostering strong soft skills like communication and teamwork, encouraging multi-disciplinary real-world projects through industry partnerships, etc; to prepare graduates for the workplace of the future.

Against this backdrop, the CDIO Framework can be investigated if it remains relevant to guide faculty in executing the required curriculum changes using GenAI. In his other work, the author has argued that the 12 Core CDIO Standards can be effectively used in conjunction with appropriate AI literacy framework to guide the process of curriculum redesign in general, and more specifically how each individual standard can also provide faculty with human-in-the-loop oversight during the redesign process (Cheah, 2026a; Cheah, 2026b). The author is motivated by the discussions at the 2025 CDIO International Working Meeting in Linkoping, Sweden where the need to review the CDIO Syllabus was mooted, to address the challenge of artificial intelligence (AI). This paper is the author's contribution to this on-going discourse.

Scope of This Paper

This paper reviews the existing CDIO Syllabus (currently at version 3.0) to ascertain its adequacy in covering the skill and attitudes students need in the AI-dominated workplace of the future. It shares the approach adopted by the author which consists of two major threads:

(1) Identify new skills and attitudes that need to develop, or existing ones that need to be enhanced, to enable individuals to function effectively in today's AI world. In the context of this paper, they will be referred to as "human competencies". "Human competencies" also include skills and attitudes required to reduce the erosion of innate human capacities due to over-reliance on AI technologies.
(2) Identification of emerging skills and attitudes individuals will need for workplace of the future, focusing on those needed for human-machine collaboration, using a framework suggested by Daugherty & Wilson (2024). In the context of this paper, they will be referred to as "hybrid competencies".

The existing CDIO Syllabus was then compared on how well it can cover the above 2 sets of competencies and improvements are suggested as appropriate. Subsequently the coverage was expanded to include competencies needed for sustainable development, as part of continual improvement of this author and coworkers' effort in using CDIO to design education for sustainable development (Cheah *et al*, 2025).

LITERATURE REVIEW: THE SHIFT IN THE FUTURE OF WORK

The CDIO Syllabus is the cornerstone of the CDIO Framework. It offers rational, complete, universal, and generalizable goals for undergraduate engineering education (CDIO, n.a.). It allows adoption for any field of program by allocating a placeholder for the disciplinary fundamentals (Part 1), focuses on personal and professional skills and attributes (Part 2), interpersonal skills (Part 3) and skills in conceiving, designing, implementing and operating systems in the enterprise, societal and environmental context (Part 4).

The current syllabus (version 3.0), published in 2022 (Malmqvist *et al*, 2022) was a significant "upgrade" from the version 2.0 published in 2011. It addressed challenges in sustainable

development, digitalization and demands of a rapidly changing world; as well as insights from the CDIO community. This version retained the previous version's format which is based on the UNESCO 4 Pillars of Learning aligned at a high level, national accreditation and evaluation standards of several nations (Crawley *et al*, 2011).

The quickening pace of technological advancements notably in AI in general and GenAI in particular necessitates another review. The advent of these technologies has resulted in significant changes in all aspects of work, emergence of new job roles that demand different competencies or enhancement of existing ones.

The World Economic Forum's *Future of Jobs Report 2025* makes clear that we are entering an era defined by human-AI collaboration: by 2030, technological and demographic shifts are expected to create 170 million new jobs while displacing 92 million, with the fastest growth in roles that combine AI literacy with human skills such as creativity, collaboration, and critical thinking (WEF, 2025a). The future of work is not about humans being replaced, but about humans and AI co-evolving. There will be significant increase in roles that combine domain-specific expertise with AI literacy – including AI system architects, ethics and governance specialists, human-AI collaboration designers, and physical AI specialists working in robotics and autonomous mobility (WEF, 2025b).

Some categories of work have shifted entirely from humans to machines because they involve high-volume, repetitive, rules-based tasks where machines excel at speed, accuracy, and scale. Examples include transaction processing, routine scheduling, or large-scale data iteration – activities that demand consistency but little judgment. Machines outperform humans here because they can process vast amounts of information without fatigue or error. By contrast, other types of work are best done through human-machine collaboration. These tasks combine the strengths of both sides: machines contribute pattern recognition, predictive analytics, and generative options, while humans provide creativity, ethical judgment, empathy, and contextual decision-making. The shift reflects a pragmatic division of labour: machines taking over what is routine and computationally intensive, while humans and machines together tackle complex, creative, and ethical challenges

Therefore, new industries built around AI-driven physical systems and AI-augmented decision-making are likely to emerge, creating new types of jobs and economic growth in untapped areas. A transdisciplinary systems mindset in education is essential to create a pipeline of graduates with these key skills to enable students to integrate across disciplines and work with AI systems.

A survey carried out by Portocarrero Ramos *et al* (2025) showed a widespread feeling among students of insufficient preparation for the challenges of the current labour market. AI skills are becoming a key differentiating factor in employability and formal incorporation into university curricula is urgently needed. Likewise, Bone *et al* (2025) reported from their study that a clear paradigm shift is occurring among employers, in that AI skills are increasingly more valuable than degrees in determining employability and wages. Employers are broadening their talent pools by dropping degree requirements and rewarding practical competencies.

The increasing use of AI technologies in the workplace also created a new kind of skills and attitudes required of human employees: the coexistence between human intelligence and AI; collaborating to leverage on the relative advantages of both for mutual enhancement that can benefit various sectors of society (Botha, n.a.). Not only that, AI-related jobs also have a higher skill intensity, which refers to the number and diversity of skills required in a job posting. It's essentially a measure of how "complex" or "multi-skilled" a job is compared to the average role

in the labour market. A study by Bone *et al* (2025) noted that the skill intensity for AI-related job roles in the U.K. stands at an average of 15 to 16 skills per position, compared to the average job posting in the broader labour market demands of around 5 skills.

METHODOLOGY

This paper investigates the skills and attitudes required in the age of GenAI from 3 different perspectives: (1) from the perspective UNESCO literacy which is to assist educators in preparing students to be responsible users and co-creators of AI; (2) from a wider philosophical humanistic perspective of what differentiates humans from machines focusing on traits that can be enhanced and notion of what it means to be human; and (3) from the workplace perspective so that humans can collaborate with machines powered by GenAI to accomplish tasks that humans alone cannot do and not being subordinated to GenAI. We use the term "human competencies" for skills and attitudes from (1) and (2); and the term "hybrid competencies" for (3).

Human competencies need to be strengthened against over-reliance on GenAI can be identified from the extant literature. Human competencies needed to co-exist in the world of GenAI can be from the AI Competency Framework for Students (AI CFS), published by the United Nations Educational, Scientific and Cultural Organization (UNESCO, 2024). Hybrid competencies for human-AI collaboration will largely be drawn from the work of Daugherty & Wilson (2024) who did extensive empirical research on 1,500 organizations examining how businesses are implementing AI to drive innovation and transformation, rather than just automation. The following sections explain how if the existing CDIO Syllabus adequate covers the skills and attitudes needed for human competencies and hybrid competencies.

AGE OF GEN AI: EXISTING HUMAN COMPETENCIES TO BE ENHANCED

This section addresses the skills and attitudes required for human competencies. With the advent of AI, there had been much discourse on what it means to be human; and calls for inclusion of AI Literacy in the curriculum. An AI Literacy curriculum can be based on the UNESCO AI CFS is shown in Table 1.

Table 1. UNESCO AI competency framework for students

Competency Aspects	PROGRESSION LEVELS		
	UNDERSTAND	APPLY	CREATE
Human-centered Mindset	Human Agency	Human Accountability	Citizenship in era of AI
Ethics of AI	Embodied Ethics	Safe & Responsible Use	Ethics by Design
AI Techniques & Applications	AI Foundations	Application Skills	Creating AI Tools
AI System Design	Problem Scoping	Architecture Design	Iteration & Feedback Loops

The UNESCO AI competency framework for students aims to help educators in this integration, outlining 12 competencies across four dimensions: Human-centred mindset, Ethics of AI, AI techniques and applications, and AI system design. These competencies span three progression levels: Understand, Apply, and Create. Detailed discussions on the competencies that students need to develop are beyond the scope of this paper. Suffice to note that one of emerging key skills to possess in interacting with AI is prompt engineering. Although not

explicitly mentioned in the UNESCO framework, this is captured under the competency of “AI Techniques & Applications”. Appendix 1 presents the mapping of UNESCO’s AI Competency Framework for Students to the CDIO Syllabus, highlighting where existing outcomes already align (e.g. AI foundations, ethics, system design) and where new competencies such as prompt engineering, explainability, and sustainability of AI models need to be added. Gaps identified will be covered in later section of this paper.

This paper suggests that in addition to the above, we need to strengthen skills and attitudes needed to support the key aspects of human capacities to guard against deterioration resulting from GenAI overuse. Botha (n.a.) provides a summary of 6 key human capacities as shown in Table 2.

Table 2. Key aspects of distinctive human capacities

Aspect	Description
Emotions and Empathy	Humans possess emotional intelligence, allowing us to understand, experience, and respond to emotions. This capability fosters empathy, compassion, and nuanced social interactions. Computers can simulate emotional responses but lack genuine emotional experiences.
Creativity and Innovation	Human creativity involves intuition, imagination, and novel problem-solving. Computers can generate new outputs based on data and patterns but lack the spontaneous creativity and intuitive leaps that define human innovation.
Consciousness and Self-awareness	Humans possess consciousness and self-awareness, enabling introspection and reflection on thoughts, emotions, and experiences. This self-awareness plays a role in personal growth and ethical decision-making. Computers, in contrast, lack consciousness and self-awareness.
Holistic Understanding	Humans can integrate diverse information sources, consider context, and draw on personal experiences for a holistic understanding. Computers process information more compartmentalised and data driven.
Adaptability and Flexibility	Humans can learn and adapt to new situations without predefined rules. Computers rely on algorithms and data, making them less flexible in novel situations.
Ethics and Morality	Humans can weigh multiple perspectives, values, and consequences in ethical decision-making. Computers can follow ethical guidelines but lack a nuanced understanding of conflicting values

The underpinning skills and attitudes were again investigated and mapped over to the CDIO Syllabus using GenAI, and results are shown in Appendix 2. This analysis shows that while many human capacities are partially addressed, explicit outcomes for emotional intelligence, creative metacognition, mindfulness, and pluralistic ethics are missing. Together, the two appendices provide a structured gap analysis that informs the proposed revisions to the syllabus, ensuring both AI literacy and the preservation of core human capacities are embedded in future curriculum design.

EMERGING COMPETENCIES DESIRED BY EMPLOYERS: HYBRID COMPETENCIES

Daugherty & Wilson (2024) suggested that work activities in the world of AI can be organized into three broad zones, as shown in Figure 1:

- Human-only activity: tasks that rely on uniquely human capabilities such as leadership, empathy, creativity, and ethical judgment. Machines cannot replicate them meaningfully.
- Machine-only activity: tasks best handled by machines, such as repetitive transactions, rapid iteration, large-scale prediction, and adaptive optimization.

- Human-machine hybrid activity: This is the fusion zone where humans and AI collaborate – they are hybrid activities that represent new roles and skills that emerge when humans complement machines and machines augment humans.

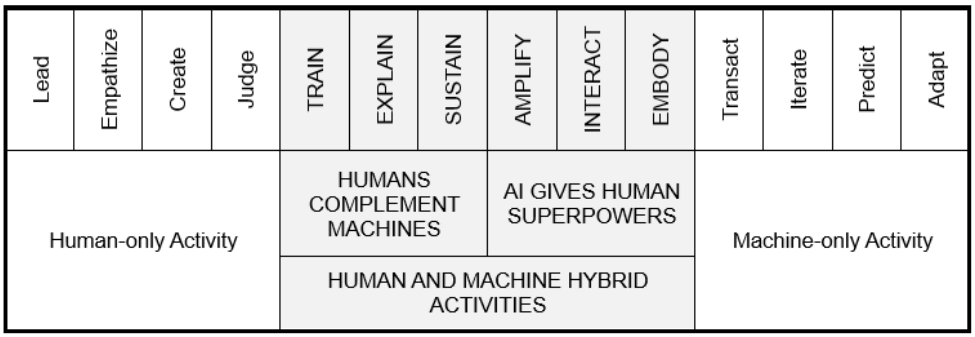


Figure 1. "Hybrid competencies" of the "missing middle" (Daugherty & Wilson, 2024)

Figure 1 shows the different strategies that can be used in each zone, the discussion of which is beyond the scope of this paper. The focus of this paper is the hybrid competencies needed for the hybrid zone, the area that redefine the future of work where humans and AI work together in a symbiotic, collaborative relationship. Daugherty & Wilson (2024) called it the "missing middle" because few companies are actively focused on this space, with most focusing on either full human labour or complete automation. But the real transformation lies in the hybrid zone. As noted in the WEF report from the previous section, this is now an emerging area, and the focus of this paper is on finding the skills and attitudes that humans will need to work collaboratively with machines in the hybrid zone. This is where curriculum design and assessment need to focus: developing hybrid skills such as trust calibration, ethical oversight, openness to machine creativity, and collaborative problem-solving with AI. The workflow of our approach is shown in Figure 2.

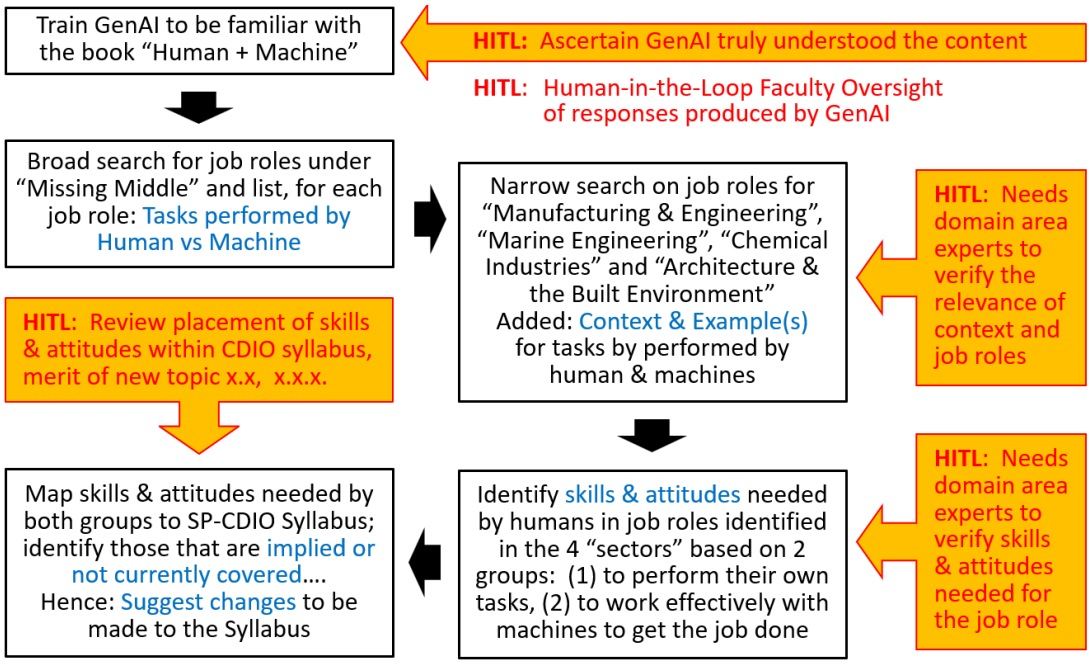


Figure 2. Approach used to determine hybrid competencies for the future of work

Skills and Attitudes Needed for the Future of Work

Figure 2 shows that skills and attitudes identified for the hybrid competencies were separated into 2 groups: (1) For humans to perform their own tasks, i.e. areas where humans complement machines, and (2) For human to work effectively with machines in completing the hybrid tasks. The rationale for doing so will be explained later, when we discuss the review and suggested revision of the CDIO Syllabus.

As the findings in this work is meant to be discipline agnostic and to be applicable to a wide range of programs, we relied heavily on the use of GenAI to help us. Therefore, it must be noted that outputs from GenAI need to be validated by experienced professionals with the domain knowledge for example on the job roles reported by GenAI which may be known differently in the workplace as GenAI is known to fabricate its own catchy terms. Likewise, the underpinning skills and attitudes also need to be validated. “HITL Markers” are shown in Figure 2 at various junctures in the process as requiring human-in-the-loop oversight.

The outcome from the process depicted in Figure 2 is a set of skills and attitudes needed for the hybrid competencies. For validating the GenAI’s outputs, we narrowed the work to focus on 1 generic area called “Manufacturing & Engineering” and 3 areas that are more targeted: “Marine Engineering”, “Chemical Industries” and “Architecture & the Built Environment”. The reason for this is simple: As we are exploring what GenAI can do, as a “proof-of-concept” so to speak, we strive to keep the task manageable, therefore limiting the number of subject matter experts to review the GenAI responses for this run. Appendix 3 provide the job roles identified for the “missing middle” for the 4 areas, and Appendix 4 shows the required skills and attitudes. These were then checked with the respective faculty within Singapore Polytechnic.

As in earlier work, we also investigated which skills and attitudes are already covered in the existing CDIO Syllabus and what are the gaps – for both groups of 2 groups: where humans are to perform their own tasks and where humans to work effectively with machines in completing the hybrid tasks. Perhaps not surprisingly, since the CDIO syllabus had been formulated to prepare graduates for the workplace, the skills and attitudes required by humans to perform their own tasks are very well covered, and hence not reported in this paper. This exercise reveals several gaps in skills and attitudes that humans need to work collaboratively with machines. These gaps together with those from earlier studies will be addressed next.

GAPS IN EXISTING CDIO SYLLABUS BASED ON STUDY IN THIS PAPER

For each of the 3 perspectives on skills and attitudes required in the age of GenAI, we supplied the GenAI tool with a copy of the SP-CDIO Syllabus and asked that it identify the gaps in the respective area. The results are shown in Tables 3, 4 and 5 respectively.

Next, we tasked the GenAI tool to combine the inputs from all 3 areas to produce a draft version of the revised SP-CDIO Syllabus. The process can be visualized as shown Figure 3(a). The figure also highlights areas where faculty oversights are needed against the outputs produced by GenAI, as marked by “HITL” for human-in-the-loop intervention. Indeed, it is the author’s experience that using GenAI to carry out the gap analysis and mapping exercises do not always yield satisfactory results after one pass. This brings to fore the lack of transparency in how GenAI went around executing its algorithm. In the case of Figure 3(a), satisfactory drafts of the mapping were obtained independently of one another for each of the 3 aspects of UNESCO, human capacities and “missing middle”, using 3 different sessions of GenAI

engagement. “HITL” is administered to each one of the sessions. There were relatively minor discrepancies between what it flagged as missing or inadequate in the existing syllabus and it proposed for the revised syllabus in each case. However, when it was asked to synthesis a draft syllabus by combining all 3 aspects (UNESCO, human capacities, and “missing middle”) while removing overlapping skills and attitudes and rationalizing the entries; it made more omissions in the combined proposed revision to the syllabus.

Table 3. Suggested skills and attitudes to be added to CDIO based on UNESCO AI CFS

Competency Area	Missing Specific Requirement	Explanation of Gap & Rationale for Addition	Suggested Location: CDIO (x.x.x)
B3: Create: Ethics of AI	Explicit requirement for designing for Transparency & Explainability (Xai).	The Syllabus addresses "supervision" (4.4.6) but lacks the specific modern ethical mandate to engineer for *explainable* outcomes in opaque AI models. Suggested outcome: Assess the trade-off between AI model complexity and the necessity for its decisions to be transparent, auditable, and explainable (Xai) based on the application's risk profile.	4.4.6 Design for Sustainability, Safety, Aesthetics, Operability and Other Objectives Add subtopic: : *Demonstrate design for explainability, transparency and auditability*
C2: Apply: AI Techniques & Applications	Explicit literacy in Generative AI (e.g. Prompt Engineering).	The Syllabus covers "data mining and analytics" (2.1.2), but this is insufficient for the unique skills required to effectively and critically use Large Language Models (LLMs) and other generative tools. Suggested outcome: Formulate precise, goal-oriented prompts for Generative AI tools and critically evaluate the fidelity, bias, and authenticity of AI-generated outputs.	2.1.2 Analytic Reasoning and Problem Solving Add subtopic:
D3: AI System Design (Create)	Explicit focus on environmental & computational cost of AI models.	The Syllabus mentions "sustainability" broadly (4.1.2) but lacks a direct requirement to quantify and mitigate the significant energy footprint of developing and deploying modern, large-scale AI systems. Suggested outcome: Analyse the resource consumption (data, energy, computational hardware) of a proposed AI solution and design for computational efficiency and environmental sustainability.	4.1.2 Address the Impact of Engineering on Society and the Environment

Expansion of Work Done

After several iterations where amendments were made and omissions included, we arrived at a working draft of the proposed revised SP-CDIO Syllabus. Next, we use GenAI to add 2 more aspects to the document to widen the coverage of the revised syllabus. The process is shown in Figure 3(b). First, we added an expanded skills and attitudes required for job roles performed by the “missing middle” beyond the initial 4 areas of “Manufacturing & Engineering”, “Marine Engineering”, “Chemical Industries” and “Architecture & the Built Environment”. The purpose is to ensure that other skills and attitudes that may be more relevant to non-engineering/technology fields are adequately captured.

Table 4. Suggested skills and attitudes to be added to CDIO based on human capacities

Aspect	Missing Elements in CDIO and Rationale for Addition	Suggested Location: CDIO (x.x.x)
Emotions & Empathy	• CDIO emphasizes communication and equity but lacks explicit training in *emotion regulation* and *restorative practices*. • Needed because students must navigate emotionally charged, diverse environments and build trust in human-AI collaboration	2.5.5 Demonstrate Respect for Equity, Justice, Diversity and Inclusiveness
Creativity & Innovation	• CDIO covers creative thinking but does not emphasize *creative metacognition* (awareness of one's creative process) or *incubation strategies*. • Needed because innovation requires not just generating ideas but managing the creative process and tolerating uncertainty.	2.4.4 Creative Thinking
Consciousness & Self-awareness	• CDIO includes reflection but misses *mindfulness* and *identity development*. • Needed because self-awareness is foundational for ethical decision-making and resilience in complex contexts.	2.4.6 Demonstrate Self-Awareness, Self-Reflection, Metacognition and Knowledge Integration
Holistic Understanding	• CDIO covers systems thinking but lacks explicit *integration of personal experience* and *well-being considerations*. • Needed because holistic understanding requires connecting disciplinary knowledge with lived experience and sustainability.	2.3.2 Understand Interactions in Systems and External to Systems
Adaptability & Flexibility	• CDIO mentions resourcefulness but does not explicitly cover *stress coping* and *cognitive reappraisal*. • Needed because adaptability is not just technical improvisation but emotional regulation under uncertainty.	2.4.3 Demonstrate Resourcefulness and Flexibility in Adapting to Change
Ethics & Morality	• CDIO emphasizes ethics but does not explicitly cover *civic reasoning* and *pluralistic ethics navigation*. • Needed because professionals must weigh conflicting values in diverse societies and act responsibly beyond compliance.	2.5.1 Apply Knowledge of Sound Values and Ethics, and Demonstrate Social Responsibilities

Second, we also added in skills and attitudes needed to support development of students' sustainability mindset, as a follow-up to our work in this area (Cheah *et al*, 2025), which we had noted that gaps existed in the existing SP-CDIO Syllabus. Recent developments had pointed to a convergence between GenAI and sustainability, with research showing its dual role as a driver of sustainable innovation and a subject of ecological concern. GenAI has been applied to forecast sustainability trends for policymaking, optimize smart energy systems and buildings, and advance circular economy practices, while scholars also highlight its significant carbon footprint and resource demands. This convergence underscores the need for a sustainability mindset so that professionals can harness GenAI responsibly while aligning practice with planetary well-being (see for examples Kim *et al* 2025; Hernandez *et al*, 2025; Sharma *et al*, 2025; Vamvakas *et al* 2025).

We asked GenAI to study the 12 sustainability mindset principles (Rimanoczy, 2021) and identify the underpinning skills and attitudes needed, how much of these are already covered in existing SP-CDIO Syllabus (i.e. gaps analysis) and suggestions to required skills and attitudes to close the gap.

Table 5. Suggested skills and attitudes to be added to CDIO based on workplace job requirement for human-machine collaboration

Gaps: Skill / Attitude	Comments on Rationale for Addition	Suggested Location: CDIO (x.x.x)
Tolerance for ambiguity	CDIO mentions uncertainty but not explicitly "comfort with ambiguity" as a mindset.	2.4.1 Demonstrate Positive Attitude and Willingness to Make Decisions in Face of Uncertainty
Trust calibration with machines	No explicit guidance on how to calibrate trust in AI outputs.	2.5.2 Demonstrate Professional Behaviour at Work and in Society
Openness to machine creativity	Creativity is covered, but openness to *AI-generated creativity* is not.	2.4.4 Creative Thinking
Collaborative mindset with AI systems	CDIO covers teamwork with humans, but not collaboration with AI agents.	3.1.3 Participate in Multi-perspective Collaboration
Skepticism balanced with trust	Critical thinking is covered, but balancing skepticism with trust in AI is absent.	2.4.5 Critical Thinking
Comfort with automation	CDIO covers technology use broadly but not attitudes toward automation.	2.4.3 Demonstrate Resourcefulness and Flexibility in Adapting to Change
Humility to cross-check machine outputs	Self-awareness is covered, but humility in relation to AI is not explicit.	2.4.6 Demonstrate Self-Awareness, Self-Reflection, Metacognition and Knowledge Integration
Vigilance for false positives/AI errors	CDIO covers error analysis in human problem-solving, but not vigilance for AI-specific errors.	2.1.3 Analyze Results
Stewardship mindset (environmental + AI governance)	Sustainability is covered, but stewardship in AI-human collaboration is not.	2.5.1 Apply Knowledge of Sound Values and Ethics
Collaborative design attitude with AI	CDIO covers multidisciplinary teamwork, but not human-AI design collaboration.	4.4.1 Formulate the Design Process
Attentiveness to AI alerts	CDIO covers monitoring systems, but not specifically AI-driven alerts.	2.4.2 Demonstrate Perseverance, Sense of Urgency and Will to Deliver
Ethical labour practices in AI optimization	CDIO covers ethics broadly, but not AI-driven labour allocation.	2.5.5 Demonstrate Respect for Equity, Justice, Diversity and Inclusiveness

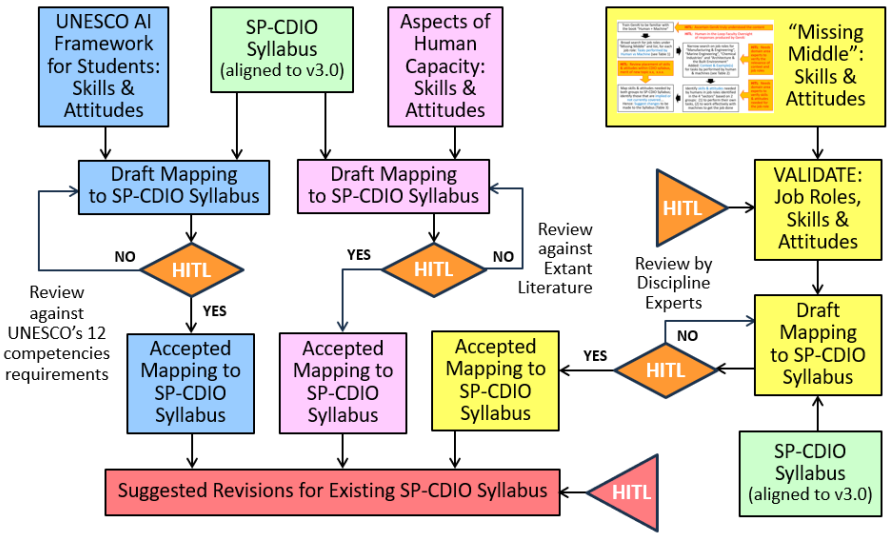


Figure 3(a). Original scope for revised SP-CDIO syllabus

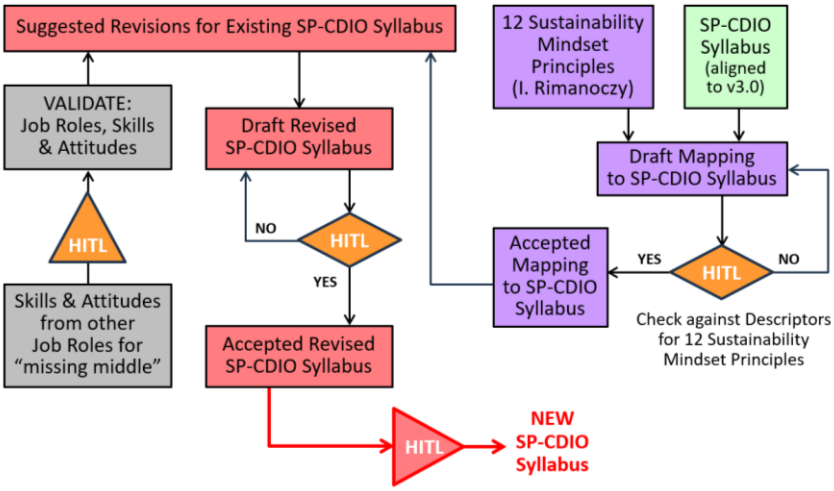


Figure 3(b). Widened scope of revised SP-CDIO syllabus

OVERALL CHANGES NEEDED FOR CDIO SYLLABUS VERSION 3.0

The integration of the drivers culminates in the proposed revisions for the CDIO Syllabus, as consolidated in Appendix 6. Note that the Syllabus still follows version 3.0's format. The additional skills and attitudes identified above are added to existing sections in the syllabus and shown in bold text.

It can be seen that much of the changes impacted Part 2 Personal and Professional Skills and Attributes of the CDIO Syllabus the most, notably Section 2.4 Attitudes, Thought and Learning, and Section 2.5 Ethics, Equity and Other Responsibilities. Next are selected topics in Part 4 Conceiving, Designing, Implementing and Operating Systems in the Enterprise, Societal and Environmental Context. This is hardly surprising, as it is expected that the shifts to human-AI collaboration would demand more adjustments on the side of humans to take advantage of the partnership with machines. Of particular importance is the need to retain core human abilities to guard against over-reliance of GenAI use.

Viewing the changes through the lens of the Conceive-Design-Implement-Operate lifecycle, Table 6 highlights a critical shift in engineering practice, summarised as "pros" and "cons" of impact of GenAI. While GenAI offers significant "pros" such as accelerated prototyping in the *Design* phase and proactive maintenance in the *Operate* phase, it also introduces "cons" like the potential loss of deep operational knowledge or the risk of "black box" outputs during *Implementation*. This table serves as a functional map for navigating these trade-offs, ensuring that human oversight remains the anchor for ethical and sustainable engineering. The implications of using GenAI in the context of CDIO Framework is discussed in detail elsewhere by the author (Cheah, 2026b).

DISCUSSIONS: USING THE SP-CDIO SYLLABUS

An important consideration when formulating the new SP-CDIO Syllabus is its utility. Past iteration of the syllabus have resulted in an increase in the number of pages. So, it is not entirely surprising that this is also the case with the current revision. Members within the CDIO community have already feedback that the syllabus in its current topical form is cumbersome to use. This is the dilemma confronting how best to present or structure the syllabus, as there are relative merits to having the new additions placed under new headings or add to existing

headings. The next section explores this challenge in greater detail, using human-AI collaboration as the topic of discourse.

Table 6. Impact of GenAI on engineering practice

Stage	Positive Impacts	Negative Impacts
Conceive	Faster, broader ideation with richer context: AI can rapidly analyze market data, user feedback, and technical constraints, helping teams identify opportunities and risks more comprehensively. Humans bring judgment, empathy, and ethical foresight to ensure conceived ideas align with societal needs.	Conceived solutions may reflect machine bias rather than human values: Over-reliance on AI-generated insights may narrow human creativity or embed hidden biases in problem framing.
Design	Expanded creative space, accelerated prototyping, better-informed design decisions: GenAI tools can propose thousands of design alternatives, simulate performance, and highlight trade-offs. Human designers evaluate feasibility, aesthetics, and compliance.	Loss of transparency and accountability in design choices: AI-generated designs may be technically optimal but socially or ethically inappropriate. Humans must guard against “black box” outputs.
Implement	Increased efficiency, reduced error rates, and more time for humans to focus on higher-level problem-solving: Machines automate repetitive coding, manufacturing, and testing tasks, while humans oversee integration, quality assurance, and safety.	Reduced resilience if systems fail and humans lack deep operational knowledge: Automation can deskill human workers if they are excluded from meaningful tasks. Humans may lose hands-on expertise.
Operate	Proactive maintenance, improved reliability, and enhanced sustainability.: AI systems monitor performance, predict failures, and optimize resource use. Humans interpret anomalies, make ethical decisions, and ensure sustainability.	Ethical lapses, safety hazards, or inequitable resource allocation: AI-driven optimization may prioritize efficiency over fairness or safety. Humans must remain vigilant to override harmful machine decisions.

New Separate Headings vs. Adding to Existing Headings

There are clear advantages to having a separate section for Human-AI Collaborations, summarized briefly as follows:

- Visibility & Emphasis: A dedicated section signals that human-AI collaboration is a core competency, not just a technical addition. It elevates these skills to the same level as analytic reasoning, system thinking, and ethics.
- Clarity for Faculty: Instructors can easily locate all AI-related outcomes in one place, rather than hunting across multiple headings.
- Curriculum Coherence: Students see the hybrid skillset as a distinct domain, reinforcing the idea that working with AI requires unique dispositions (trust calibration, humility, vigilance) beyond traditional problem-solving.
- Future-proofing: As AI evolves, new competencies can be slotted into the new heading without disrupting the rest of the syllabus.
- Assessment Alignment: Easier to design rubrics and evaluation protocols specifically for human-AI collaboration.

Potential drawbacks of having new, separate headings include the following:

- Some of the competency associated with human-AI collaboration are higher-order competencies. Their development needs to be scaffolded progressively from underpinning foundational skills and attitudes; which also form the building blocks of other high-order competencies. As such, these foundational skills and attitudes will necessarily remain in the current locations in the syllabus.

- Faculty need to be cognizant to be thorough in identifying the required foundational skills and attitudes to build up the higher-order competencies; and knowing where to link back to the existing sections for the required foundational skills and attitudes.
- Faculty may suffer from cognitive overload, running through lines and lines of outcome statements. It may be challenging for faculty to distinguish between what are new against what are existing ones.
- Focusing solely on the topics in the separate heading and missing out on some foundational skills and attitudes in existing sections may result in suboptimal development of the required higher-order competencies. It may also result in misguided treatment of AI as "separate" rather than embedded.

This is not a new dilemma though. When version 3.0 of the CDIO Syllabus was formulated, a similar conundrum arisen with regards to either retaining the subsection *Sustainability and the Need for Sustainable Development* from version 2.0 and expanded it to include additional skills and attitudes needed for sustainable development; or to do away with the subsection and redistribute the topics therein along with additional skills and attitudes into relevant sections in the new version 3.0. The decision taken then was to remove the subsection (Malmqvist *et al*, 2022). This was in line with the integration of other skills and attitudes introduced into version 2.0 to update the syllabus incorporating emergence of external change drivers (sustainability, digitalization, acceleration) and internal experiences within the CDIO community.

Limitation of This Work

The search for hybrid skills and attitudes required by humans to work alongside machines was carried out solely with the use of GenAI, due to the lack of extant literature at the time. We do not know how the GenAI tool that we used – Copilot and Gemini – went around conducting the search, and therefore the comprehensiveness of the search. The author did note that on more than one occasion, he found the GenAI outputs to be not satisfactory and he had to make more than one attempt with revised prompts. While this may be reflective of the author's poor grasp of the principles of prompt engineering, he did notice improvements in the GenAI outputs.

The job roles identified are likely not comprehensive. The current revision likely did not account for ongoing developments that identify skills and attitudes beyond the scope of this work. These unaccounted-for capabilities may stem from emerging tasks such as working with generative videos, proactive chatbots, privacy-focused GenAI, and utilizing synthetic data for analytics and simulation. Even GenAI will not be able to predict future job roles that are yet to be defined and not captured in the databases that it used.

In any case, the naming of "industry sectors" used by GenAI also did not conform to standard classifications such as the U.S. Standard Industrial Classification, Bloomberg Industry Classification Standard, just to name a few. Furthermore, due to limitation of time, not all the job roles, skills and attitudes needed for the "missing middle" were validated by experts.

Moving Ahead: Stakeholder Engagement and Validation

The skills and attitudes needed for the future of work, as espoused in this paper, needs to be validated by key stakeholders. As noted earlier, this work was prepared as contribution to the discourse of the future of CDIO Syllabus. There may be other inputs not covered in the paper from other stakeholders, hence the suggested additions as shown in Appendix 6 are likely not exhaustive. This will largely depend on how CDIO Council decides on the future version of the CDIO Syllabus – a new release as version 4.0, or as update for example version 3.1 to align

current syllabus reflecting inclusion of GenAI. Any stakeholder engagement (faculty, students, industries) will follow after the final draft of the revised CDIO Syllabus is worked out, to validate the suggested competencies. This author opines that a new version 4.0 is warranted given the number of changes identified in this paper alone.

Moving Ahead: Future Work

The advent of GenAI allows the automation of the tasks of scanning the CDIO syllabus to look for all the necessary skills and attitudes needed for any higher-order competencies, including those needed by humans to work collaboratively with machines. The unpacking of a given job role into the underpinning skills and attitudes required can be handled by GenAI. It can then prepare a cross-referencing index that provides clear guidance to faculty who needs to know which underpinning skills and attitudes are required and where in the CDIO syllabus they can be found.

The 5-step structured workflow is shown in Figure 4, which show how GenAI automates the creation of cross-reference indexes for job roles against the revised SP-CDIO syllabus, and supporting the entire process of designing a learning task for student learning.

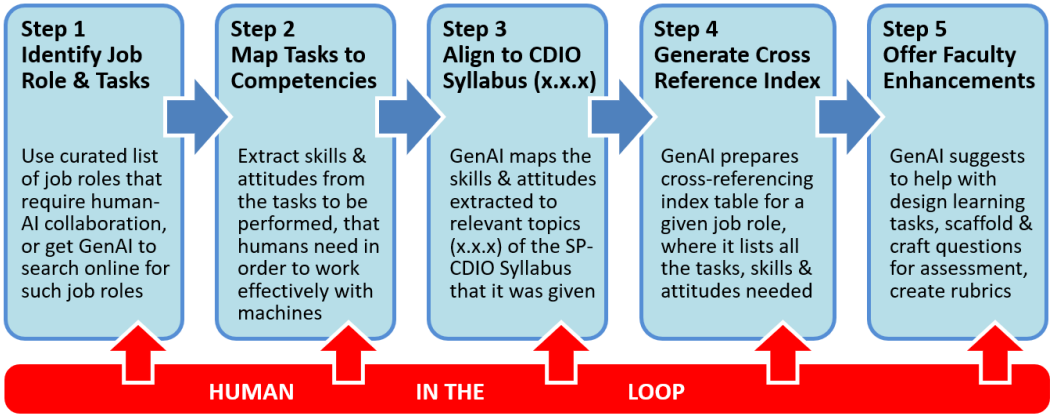


Figure 4. Workflow for using GenAI to prepare cross-reference index

We also emphasize in Figure 4 the needs for faculty oversight – Human-in-the-Loop – to review GenAI outputs for content accuracy and validity, diversity and biases, legal and ethical considerations, etc. In addition, where researching for emerging job roles for "missing middle" it is recommended that faculty adopted a more structured approach (e.g. PRISMA) within one's own professional field. Lastly, the CDIO Syllabus needs to be validated with key stakeholders.

CONCLUSIONS

This hefty paper proposes that the existing SP-CDIO Syllabus be updated to reflect new requirements of skills and attitudes brought about by the use of GenAI. Specifically, the updates included new skills and attitudes needed for humans to work effectively with machines powered by AI, for humans to retain key capacities over what GenAI can do, and for humans to contribute positively to sustainable development via development of sustainability mindset.

The proposed revised syllabus may not be comprehensive. The approach shared in this paper, however, serve less as an endpoint and more as a critical signpost highlighting the accelerating, uncontained evolution of the digital workspace. The gaps identified in this work did more than just point out missing competencies; it foreshadows the emergence of entirely

novel job roles and human capacities. As the exploration and application of GenAI continue to intensify, it is inevitable that this technological frontier will not just reshape existing positions, but will necessitate the continuous creation of new, currently unimagined professional categories and responsibilities.

ACKNOWLEDGEMENTS

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Full Declaration: Extensive use of GenAI tools – namely Copilot and Gemini – were used in the preparation of this paper. Their use is mainly to capitalize of their capability to search for vast quantities of data demanded by the scope of this paper. GenAI is used to scan the use of human-AI collaboration across a wide range of industries, to highlight the skills and attitudes required termed “hybrid competencies”. GenAI is also used to arrive at common denominator of what constituted core human traits termed “human competencies”. Prompts used will include listing of resources from which GenAI drew its output from, to enable the author to search for the articles to validate the work done by GenAI. GenAI is used to accelerate the comparisons of skills and attitudes required in this new age of GenAI, against current covered in existing SP-CDIO Syllabus. The flowcharts in Figure 3(a) and Figure 3(b) illustrate where GenAI is used and the HITL triangle pinpoint the area where faculty oversight is introduced to review the GenAI output. The prompts used and responses obtained can be found in the link below in the PDF file “107”. An important point to note the prompts and responses shown in the document did not necessarily follow the sequence of topics in this paper, because the way this author uses GenAI: as a consulting/reference tool as and when he revises the manuscript. GenAI is also used to create the first draft of the abstract from which the author revise it to his preference.
https://drive.google.com/drive/folders/1h5gPaRxba899Yjk2GbR5JqJ4jeeqMqLo?usp=sharing

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BIOGRAPHICAL INFORMATION

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APPENDIX 1. UNESCO'S AI COMPETENCIES FOR STUDENTS MAPPED TO EXISTING CDIO SYLLABUS

Dimension (Level)	Specific Competency	Corresponding SP CDIO Syllabus Entries (x.x.x) *Italic implies a level inside x.x.x*
A1: Human-Centred Mindset (Understand)	AI Literacy and Awareness *Understanding AI's potential, limits, and the need for human control.*	2.3.2 *Explain human-system integration and interaction*.
A2: Human-Centred Mindset (Apply)	Critical Evaluation of AI & Human Accountability *Assessing validity, proportionality, and ensuring human oversight.*	2.4.5 *Use a range of critical thinking skills (e.g. analysis, compare and contrast, inference and interpretation, evaluation).* 2.5.2 *Explain ethical issues in use of artificial intelligence (AI), e.g. discern validity, applicability and implications of recommendations from AI.* 4.4.6 *Demonstrate design for human factors, interaction and supervision*.
A3: Human-Centred Mindset (Create)	Citizenship in the Era of AI *Promoting human rights, inclusion, equity, and participation in AI governance.*	2.5.1 *Practice ethical reasoning on issues relating to personal and professional conduct.* 2.5.5 *Explain the need to treat others with equity and justice, including gender, race, ethnicity, religion, etc*
B1: Ethics of AI (Understand)	Embodied Ethics *Internalizing ethical principles and reflecting on personal values toward AI use.*	2.5.1 *Explain concepts of fairness, justice and responsibilities* 2.5.2 *Explain ethical issues in use of artificial intelligence (AI).* 4.1.4 *Explain the precautionary principle in the face of uncertainty over potential impact of one's work on society or environment*
B2: Ethics of AI (Apply)	Safe and Responsible AI Use *Identifying, assessing, and mitigating bias, privacy, and security risks in data/models.*	2.1.1 *Identify assumptions and sources of bias.* 2.1.2 *Identify uncertainty and ambiguity in information*. 2.2.3 *Manage experimental data* (this point may need to be enhanced, to be more explicit for managing for security/privacy). 2.5.5 *Explain the need to treat others with equity and justice, including gender, race, ethnicity, religion, etc*
B3: Ethics of AI (Create)	Designing for AI Ethics *Embedding ethical principles, accountability, and governance into system design.*	4.4.6 *Demonstrate design for human factors, interaction and supervision.* (Significant gaps exist)
C1: AI Techniques & Applications (Understand)	Foundational AI Concepts *Understanding data, algorithms, and different types of AI models.*	2.1.2 *Identify and select suitable conceptual, quantitative and/or qualitative models, where appropriate.* (Need context for AI)
C2: AI Techniques & Applications (Apply)	Effective Use of AI Tools *Utilizing AI tools and managing data for real-world problem-solving.*	2.1.2 *Identify limitations in digital tools.* 2.1.2 *Perform data mining and analytics.* 2.2.3 *Manage experimental data, e.g. organize, classify, categorize, especially big data.*
C3: AI Techniques & Applications (Create)	Developing AI Models *Building, training, and testing basic AI components and solutions.*	4.4.1 Formulate the Design Process (Significant gaps exist)
D1: AI System Design (Understand)	AI Problem Scoping *Defining the challenge, identifying constraints, and understanding the context for an AI system.*	2.1.1 *Select key issues to be resolved* *Write a problem statement.* 4.3.2 Understand Needs and Goal Setting
D2: AI System Design (Apply)	AI Architecture Design *Developing the conceptual and detailed structure of the AI system, including components and data flow.*	2.3.2 *Explain human-system integration and interaction*. 4.3.3 Evaluate Function, Concept and Architecture.(in context of AI) 4.4.6 Design for Sustainability, Safety, Aesthetics, Operability and Other Objectives (Need context for AI)
D3: AI System Design (Create)	Iteration & Feedback Loops *Developing systems using iterative processes and incorporating user/system feedback.*	4.6.4 Manage System Improvement and Evolution (Significant gaps exist)

APPENDIX 2. SKILLS & ATTITUDES NEEDED FOR HUMAN CAPACITIES MAPPED TO EXISTING CDIO SYLLABUS

Human Capacity	Skills Needed	Attitudes Needed	CDIO Section(s) Covered
Emotions & Empathy	• Identify and label own emotions • Listen actively to others' feelings • Express empathy verbally and non-verbally • Regulate emotional responses in group settings	• Willingness to consider others' perspectives • Patience in emotionally charged situations • Respect for differences	2.5.5 Demonstrate Respect for Equity, Justice, Diversity and Inclusiveness 3.2.7 Demonstrate Effective Interpersonal Communication, Inquiry, Listening, Dialog and Argumentation 4.3.2 *Demonstrate empathy for end users*
Creativity & Innovation	• Generate multiple solutions to a problem • Reframe problems from different angles • Combine ideas into new configurations • Use creative tools (e.g., brainstorming, mind-mapping)	• Curiosity to explore beyond the obvious • Openness to novelty • Playfulness in experimentation	2.4.4 Creative Thinking 4.4.1 Formulate the Design Process
Consciousness & Self-awareness	• Reflect on personal strengths and weaknesses • Monitor own thinking (metacognition) • Articulate personal values and beliefs • Adjust behaviour based on self-reflection	• Honesty with self • Willingness to accept feedback • Confidence balanced with humility	2.4.6 Demonstrate Self-Awareness, Self-Reflection, Metacognition and Knowledge Integration 2.4.7 *Explain how emotions and beliefs affect learning*
Holistic Understanding	• Gather information from diverse sources (technical, social, personal) • Compare and synthesize across contexts • Apply knowledge to real-world scenarios with multiple factors • Identify links between personal experience and disciplinary knowledge	• Openness to integrate different perspectives • Responsibility to consider wider impacts • Comfort with ambiguity and complexity	2.3.1 Understand the Basis and Methods of System Thinking 2.3.2 Understand Interactions in Systems and External to Systems 4.1 External, Societal and Environmental Context
Adaptability & Flexibility	• Adjust strategies when conditions change • Improvise solutions with available resources • Manage stress in uncertain situations • Learn new methods quickly	• Resilience in setbacks • Willingness to change course • Persistence in pursuing goals	2.4.2 Demonstrate Perseverance, Sense of Urgency and Will to Deliver 2.4.3 Demonstrate Resourcefulness and Flexibility in Adapting to Change
Ethics & Morality	• Identify ethical dilemmas • Weigh consequences of actions • Apply ethical reasoning frameworks • Resolve conflicts fairly	• Integrity in decision-making • Fairness toward others • Commitment to social responsibility	2.5.1 Apply Knowledge of Sound Values and Ethics, and Demonstrate Social Responsibilities 2.5.2 Demonstrate Professional Behaviour at Work and in Society

APPENDIX 3. SELECTED JOB ROLES WITH DIVISION OF TASKS WHERE HUMAN & MACHINE WORKING COLLABORATIVELY

MANUFACTURING & ENGINEERING		
Generative Design Engineer	**Human**	**Machine**
Context: Automotive and aerospace *Example:* Airbus engineers use AI-generated wing structures, then select viable designs	Define design constraints, evaluate manufacturability, approve final prototypes	Generate thousands of lightweight design options, simulate stress/fatigue
Digital Twin Orchestrator	**Human**	**Machine**
Context: Smart factories *Example:* Siemens turbines monitored by AI twins, engineers decide maintenance actions	Decide intervention strategies, set fidelity requirements	Run real-time simulations, detect anomalies, optimize throughput
CHEMICAL INDUSTRIES		
Process Optimization Specialist	**Human**	**Machine**
Context: Petrochemical plants *Example:* BASF uses AI to optimize catalyst performance; chemical engineers validate outputs	Define safety margins, interpret anomalies, approve process changes	Monitor sensors, run predictive models for yield/energy efficiency
Sustainability & Emissions Analyst	**Human**	**Machine**
Refining and chemical manufacturing *Example:* Dow Chemical integrates AI dashboards for emissions; humans decide corrective actions	Set compliance targets, interpret environmental trade-offs	Track emissions in real time, simulate reduction strategies
Lab Automation Supervisor	**Human**	**Machine**
Pharmaceutical R&D *Example*: Novartis labs use robotic AI systems for drug screening, scientists interpret findings	Design experiments, interpret results, decide next research steps	Automate repetitive assays, generate preliminary data
ARCHITECTURE & THE BUILT ENVIRONMENT		
Building Information Modelling (BIM) Coordinator	**Human**	**Machine**
Context: Construction firms *Example:* Arup architects use AI-driven BIM to optimize building layouts, humans finalize designs	Define design intent, resolve conflicts, ensure compliance	Generate 3D models, detect clashes, simulate energy efficiency
Smart Construction Planner	**Human**	**Machine**
Context: Prefabrication and modular construction *Example:* Singapore's Housing Development Board uses AI to plan modular housing assembly	Approve sequencing, manage safety and labour constraints	Optimize logistics, simulate assembly schedules
Green Building Strategist	**Human**	**Machine**
Context: Sustainable architecture *Example:* Architects in Singapore use AI to meet Green Mark standards	Set sustainability goals, balance aesthetics and regulations	Model energy flows, simulate daylight and HVAC efficiency
MARINE ENGINEERING		
Hull Design Engineer	**Human**	**Machine**
Context: Shipbuilding *Example:* Hyundai engineers use AI to propose fuel-efficient hulls, humans validate	Define hydrodynamic constraints, approve safety standards	Generate hull shapes, run CFD (computational fluid dynamics) simulations
Predictive Maintenance Specialist	**Human**	**Machine**
Context: Offshore oil rigs, shipping fleets *Example:* Maersk uses AI predictive systems for engine maintenance, engineers decide interventions	Interpret sensor anomalies, schedule repairs, ensure safety compliance	Monitor vibration, corrosion, and fatigue data; predict failures
Port Operations Optimizer	**Human**	**Machine**
Context: Maritime logistics hubs *Example:* Singapore's PSA International uses AI to optimize port operations, humans oversee exceptions	Manage labour, safety, and regulatory compliance	Optimize container routing, crane scheduling, berth allocation

APPENDIX 4. SELECTED JOB ROLES WHERE SKILLS & ATTITUDES NEEDED BY HUMANS TO PERFORM HUMAN PART OF TASKS AND TO WORK COLLABORATIVELY WITH MACHINES ON MACHINE PART OF TASKS

Job Role (Industry Context)	Skills & Attitudes (Human Job)	Skills & Attitudes (Human Working with Machines)
Generative Design Engineer (Automotive, Aerospace)	Systems thinking, engineering judgment, creativity, tolerance for ambiguity, safety-first mindset	Openness to machine creativity, critical evaluation of AI outputs, collaborative mindset, ethical responsibility
Digital Twin Orchestrator (Smart Factories, Energy)	Analytical rigor, decision-making under uncertainty, risk awareness, operational leadership	Trust calibration, ability to interpret simulation data, vigilance for false positives, adaptive problem-solving
Process Optimization Specialist (Chemical & Petrochemical)	Chemical engineering expertise, safety culture, resilience, detail orientation	Data literacy, openness to continuous improvement, skepticism balanced with trust, ethical oversight
Sustainability & Emissions Analyst (Chemical Manufacturing)	Environmental ethics, regulatory knowledge, systems thinking, long-term orientation	Attitude of stewardship, ability to interpret dashboards, collaborative sustainability mindset
Lab Automation Supervisor (Pharmaceutical R&D)	Scientific curiosity, hypothesis-driven thinking, precision, patience	Comfort with automation, ability to validate machine outputs, humility to cross-check
BIM Coordinator (Architecture & the Built Environment)	Spatial reasoning, design creativity, negotiation skills, regulatory awareness	Visualization literacy, openness to machine suggestions, collaborative design attitude
Smart Construction Planner (Modular Construction)	Project management, safety leadership, adaptability, communication	Trust in machine optimization, ability to interpret scheduling outputs, pragmatic flexibility
Green Building Strategist (Sustainable Architecture)	Ethical responsibility, creativity, systems thinking, stakeholder empathy	Environmental literacy, openness to machine insights, collaborative sustainability mindset
Hull Design Engineer (Marine Engineering)	Engineering rigor, safety-first mindset, creativity, resilience	Ability to interpret simulations, openness to machine creativity, vigilance for safety-critical outputs
Predictive Maintenance Specialist (Offshore Rigs, Shipyards)	Diagnostic reasoning, safety culture, resilience under pressure	Attentiveness to alerts, skepticism toward false positives, collaborative problem-solving
Port Operations Optimizer (Maritime Logistics Hubs)	Operational leadership, negotiation, fairness, adaptability	Systems thinking, openness to machine optimization, vigilance for ethical labour practices

APPENDIX 5. GAP ANALYSIS FOR SKILLS & ATTITUDES NEEDED FOR SUSTaiNABILITY MINDSET PRINCIPLES

Sustainability Mindset Principles	Ecoliteracy
Sections in CDIO Syllabus (1.4), (2.3), (4.1)	Ecoliteracy requires understanding of ecological systems and planetary boundaries. CDIO's system thinking and societal/environmental context explicitly embed ecological awareness.
	Gaps: Adequately covered
Sustainability Mindset Principles	My Contribution
Sections in CDIO Syllabus (2.5), (3.1), (4.1.1)	This principle emphasizes agency and responsibility. CDIO's ethics and professional responsibility sections operationalize this through social responsibility and professional conduct.
	Gaps: Adequately covered
Sustainability Mindset Principles	Long-Term Thinking
Sections in CDIO Syllabus (2.1), (4.1.6), (4.3.1)	Long-term thinking aligns with foresight, scenario planning, and sustainability visioning in CDIO. It also links to risk analysis and resilience.
	Gaps: Adequately covered
Sustainability Mindset Principles	Flow in Cycles
Sections in CDIO Syllabus (2.3), (4.4), 4.3.4)	CDIO explicitly references cradle-to-cradle and lifecycle design. Flow in cycles reinforces circular economic thinking in engineering design.
	Gaps: CDIO references cradle-to-cradle and lifecycle design but doesn't explicitly embed *circular economic thinking* or natural cycles beyond engineering context.
Sustainability Mindset Principles	Both-And Thinking
Sections in CDIO Syllabus (2.3.4), (3.2.8), (4.3.3)	Both-And thinking avoids false dichotomies. CDIO's trade-off analysis and conflict resolution sections operationalize this principle.
	Gaps: CDIO covers trade-offs and synergies but tends to emphasize resolution. Missing explicit cultivation of paradox tolerance (holding tensions without premature closure).
Sustainability Mindset Principles	Interconnectedness
Sections in CDIO Syllabus (2.3), (3.1.3), (4.1.2)	Interconnectedness is core to systems thinking and stakeholder collaboration. CDIO embeds this in multi-perspective teamwork and societal impact analysis.
	Gaps: Adequately covered
Sustainability Mindset Principles	Creative Innovation
Sections in CDIO Syllabus (2.4.4.), (4.2.3), (4.4)	Innovation is central to CDIO's design and entrepreneurship sections. Creative innovation principle strengthens the sustainability lens in these processes.
	Gaps: Adequately covered
Sustainability Mindset Principles	Reflection
Sections in CDIO Syllabus (2.4.6), (2.4.7), (3.2.7)	Reflection is embedded in metacognition, self-awareness, and dialog. CDIO already emphasizes reflective practice, which aligns with sustainability mindset.
	Gaps: CDIO emphasizes metacognition and critical thinking, but reflection is mostly cognitive. Missing paradigm-level reflection (questioning worldviews, assumptions about growth, progress, consumption).
Sustainability Mindset Principles	Self-Awareness
Sections in CDIO Syllabus (2.4.6), (2.5.3), (3.2.7)	Self-awareness in CDIO is explicit. Sustainability mindset deepens this by linking personal values to planetary responsibility.
	Gaps: CDIO includes self-awareness, but mostly in terms of skills and weaknesses. Missing explicit recognition of *biases, privilege, and positionality* in sustainability contexts.
Sustainability Mindset Principles	Purpose
Sections in CDIO Syllabus (2.5.3), (4.1.6), (4.2.2)	Purpose aligns with CDIO's emphasis on vision, career planning, and enterprise mission. Sustainability mindset ensures purpose is socially and environmentally aligned.
	Gaps: CDIO includes personal vision and career planning, but purpose is framed narrowly (professional development). Missing explicit alignment with *meaning, contribution, and sustainability*.
Sustainability Mindset Principles	Oneness with Nature
Sections in CDIO Syllabus (2.3.2), (4.1.2), (4.1.6)	CDIO references human-system integration and environmental impact. Oneness with nature extends this to experiential and ethical belonging.
	Gaps: CDIO mentions environmental impact and human-system integration, but it frames nature as an external system to be managed, not as a relational identity. Missing experiential and affective connections to nature.
Sustainability Mindset Principles	Mindfulness
Sections in CDIO Syllabus (2.3.2), (4.1.2), (4.1.6)	Mindfulness maps to CDIO's emphasis on self-regulation, reflection, and empathetic communication. It strengthens resilience and ethical decision-making.
	Gaps: CDIO covers reflection, metacognition, and emotional regulation, but mindfulness as *present-moment awareness* and *non-judgmental attention* is absent.

APPENDIX 6. PROPOSED SP-CDIO SYLLABUS VERSION 4.0

1 FUNDAMENTAL KNOWLEDGE AND REASONNING (UNESCO: Learning to Know)
1.5 KNOWLEDGE OF COGNITIVE SCIENCE

2 PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES (UNESCO: Learning to Be)
2.1 ANALYTIC REASONING AND PROBLEM SOLVING
2.1.2 Formulate a Strategy to Solve Problems
- **Formulate precise, goal-oriented prompts for Generative AI tools and critically evaluate AI outputs (Prompt Engineering).**
- **Show curiosity and tolerance when dealing with ambiguous information.**

2.1.3 Analyze Results
- **Detect AI-specific errors (false positives/negatives) and calibrate vigilance when interpreting machine outputs.**
- **Interpret calibration, confidence intervals, and uncertainty quantification in AI outputs.**

2.3 SYSTEM THINKING
2.3.2 Understand Interactions in Systems, and External to Systems
- **Integrate personal experience, well-being, and sustainability considerations into system perspectives (Holistic Understanding).**

2.3.4 Understand Trade-offs, Synergies, Judgment and Balance in Resolution
- **Exhibit courage and responsibility in taking calculated risks.**

2.4 ATTITUDES, THOUGHT AND LEARNING
2.4.1 Demonstrate Positive Attitude and Willingness to Make Decisions in Face of Uncertainty
- **Demonstrate comfort with ambiguity as a mindset.**

2.4.2 Demonstrate Perseverance, Sense of Urgency and Will to Deliver
- **Demonstrate optimism and ability to learn from setbacks.**

2.4.3 Demonstrate Resourcefulness and Flexibility in Adapting to Change
- **Apply stress coping and cognitive reappraisal strategies.**
- **Demonstrate comfort with automation as part of adaptation.**

2.4.4 Demonstrate Creative Thinking
- **Demonstrate openness to AI-generated creativity.**

2.4.5 Demonstrate Critical Thinking
- **Balance skepticism with trust when evaluating AI outputs.**

2.4.6 Demonstrate Self-Awareness, Self-Reflection, Metacognition and Knowledge Integration
- **Demonstrate humility by validating AI outputs against independent evidence and acknowledging model limits.**

2.4.7 Demonstrate Learning Agility, Engage in Lifelong Learning and Educating
- **Cultivate emergent learning and serendipity with AI; reflect and integrate insights into personal learning plans.**

2.4.8 Manage Time, Technology and Resources
- **Prioritize and respond appropriately to AI-driven alerts based on risk and urgency.**

2.4.9 Practice mindfulness and presence
- **Explain the role of mindfulness in attention regulation and decision-making under uncertainty.**
- **Demonstrate mindfulness techniques (e.g. breathing, grounding, mindful listening) in personal and team contexts.**
- **Apply mindfulness to enhance resilience, clarity, and ethical judgment in complex situations.**

2.4.10 Hold paradoxes and embrace both-and thinking
- **Explain the concept of paradox and its relevance to sustainability challenges.**
- **Demonstrate tolerance for ambiguity and explore integrative Both-And solutions.**
- **Resist premature closure by holding tensions and proposing balanced outcomes in problem-solving.**

2.4.11 Experiential connection with nature
- **Explain cultural and historical perspectives on human–nature relationships.**
- **Engage in practices that foster sensory awareness and immersion in natural systems.**
- **Articulate how personal well-being is linked to planetary well-being and integrate this awareness into decision-making.**

2.5 ETHICS, EQUITY AND OTHER RESPONSIBILITIES

2.5.1 Apply Knowledge of Sound Values and Ethics, and Demonstrate Social Responsibilities

- **Practice civic reasoning and pluralistic ethics navigation.**
- **Adopt stewardship mindset in AI-human collaboration (environmental + governance).**

2.5.2 Demonstrate Professional Behaviour at Work and in Society

- **Calibrate trust in AI outputs and override when necessary.**
- **Ensure privacy-by-design in AI-assisted decisions.**

2.5.5 Demonstrate Respect for Equity, Justice, Diversity and Inclusiveness

- **Demonstrate emotion regulation and restorative practices in diverse environments.**
- **Address ethical labour practices in AI optimization.**

2.5.7 Articulate Purpose and meaning in professional life

- **Explain the importance of purpose and meaning in professional and personal development.**
- **Define a personal sense of purpose that integrates values with contribution to sustainability.**
- **Demonstrate purpose-driven leadership in professional, enterprise, and community contexts.**

2.5.8 Reflect on Paradigms and Worldviews

- **Explain dominant paradigms (e.g. growth, consumption, progress) and their sustainability implications.**
- **Critically examine assumptions underlying professional and societal practices.**
- **Propose alternative paradigms that support regenerative and sustainable futures.**

2.5.9 Identify Biases, Privileges, Positionality

- **Explain the role of personal biases, privileges, and positionality in sustainability contexts.**
- **Recognize how positionality influences engagement with diverse stakeholders.**
- **Demonstrate awareness of biases and privileges to ensure equity and inclusiveness in sustainability practice.**

3 INTERPERSONAL SKILLS: COLLABORATION, TEAMWORK, AND COMMUNICATION (UNESCO: Learning to Live Together)

3.1 TEAMWORK AND COLLABORATION

3.1.3 Participate in Multi-perspective Collaboration

- **Collaborate with AI systems as partners in problem-solving and design.**
- **Orchestrate human and AI contributions to improve team decisions; document trade-offs.**

3.2 COMMUNICATIONS

3.2.1 Design Appropriate Communications Strategy

- **Communicate AI reasoning, uncertainty, and limitations to stakeholders.**

3.2.7 Demonstrate Effective Interpersonal Communication, Inquiry, Listening, Dialog and Argumentation

- **Apply restorative dialogue foundations (active listening, emotion labelling, neutral language, summarizing shared points).**

4 CONCEIVING, DESIGNING, IMPLEMENTING AND OPERATING SYSTEMS IN THE ENTERPRISE, SOCIETAL AND ENVIRONMENTAL CONTEXT – THE INNOVATION PROCESS (UNESCO: Learning to Do)

4.1 EXTERNAL, SOCIETAL AND ENVIRONMENTAL CONTEXT

4.1.2 Address the Impact of Engineering on Society and the Environment

- **Analyse environmental and computational cost of AI models; design for efficiency and sustainability.**

4.1.3 Recognise How One's Profession is Regulated in Society

- **Apply privacy-by-design (data minimization, consent, retention) to AI workflows.**

4.1.6 Describe a Vision for the Future

- **Construct AI-assisted scenarios; compare plausible outcomes and policy implications.**

4.2 ENTERPRISE AND BUSINESS CONTEXT

4.2.6 Understand New Technology Development and Assessment

- **Appraise AI governance controls (documentation, lineage, audits) and recommend safeguards.**

- **Evaluate synthetic data appropriateness and validate representativeness; document risks.**

4.3 CONCEIVING, SYSTEM ENGINEERING AND MANAGEMENT

4.3.3 Evaluate Function, Concept and Architecture

- **Specify appropriate levels of automation and human control points.**

4.3.6 Develop a Product Information and Knowledge Management System

- **Maintain artifact lineage, reproducibility, and auditability for AI-enabled assets.**

4.4 DESIGNING

4.4.1 Formulate the Design Process

- **Demonstrate collaborative design attitude with AI systems.**

4.4.6 Design for Sustainability, Safety, Aesthetics, Operability and Other Objectives

- **Demonstrate design for explainability, transparency and auditability (Xai).**

4.4.7 Integrate circular economy and regenerative design principles.

- **Explain the principles of circular economy and regenerative design.**
- **Apply lifecycle and circular economy analysis in product, process, and system design.**
- **Create designs that embed regenerative outcomes, ensuring sustainability beyond cradle-to-cradle.**

4.5 IMPLEMENTING

4.5.5 Conduct Test, Verification, Validation and Certification

- **Design red-team scenarios and AI safety tests; analyze outcomes and implement corrective actions for AI-in-the-loop systems.**

4.6 OPERATING

4.6.4 Manage System Improvement and Evolution

- **Establish telemetry and feedback loops for AI-in-operations; implement iterative refinements based on monitored performance and error modes.**

5 THE OPTIONAL CDIO SYLLABUS: LEADERSHIP, ENTREPRENEURSHIP AND RESEARCH

5.1 LEADING ENGINEERING ENDEAVORS

5.1.2 Thinking Creatively and Communicating Possibilities

- **Incorporate AI-augmented creativity while maintaining reflective evaluation of originality, feasibility, ethics, and societal impact.**

5.1.3 Defining the Solution

- **Define oversight checkpoints, levels of automation, and escalation pathways for AI-in-the-loop solutions.**

5.1.6 Planning and Managing a Project to Completion

- **Integrate AI safety tests, documentation, and governance checkpoints into project plans for AI-enabled solutions.**

5.1.7 Exercising Project/Solution Judgment and Critical Reasoning

- **Balance skepticism with trust in AI-generated evidence; justify overrides and escalation decisions transparently.**

5.2 ENGINEERING ENTREPRENEURSHIP

5.2.5 Conceiving Products and Services around New Technologies

- **Evaluate AI governance, privacy, and fairness implications in productization; define oversight and audit mechanisms.**

5.3 RESEARCH

5.3.1 Identification of needs, structuring and planning of research projects

- **Include plans for AI data governance, privacy protection, fairness assessments, and reproducibility audits where applicable.**

5.3.2 Execution of research

- **Detect and document AI-specific failure modes (e.g., hallucinations, miscalibration); justify overrides and escalation.**

5.3.3 Presentation and evaluation of research

- **Communicate AI reasoning, confidence, and limitations transparently; share governance and audit outcomes.**

5.3.4 Research ethics

- **Apply precautionary principle for AI-related risks; ensure equitable and privacy-preserving data practices.**

CDIO PROGRAM EVALUATION: IMPROVING SELF-EVALUATION PROCESS WITH GUIDELINES AND GUIDING QUESTIONS

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ABSTRACT

This paper presents the author's experience in his capacity as the Co-Leader for CDIO Asia Region in assisting new institutions interested in becoming a CDIO member. The first explains the submission requirements as part of the application process: notably the completion of an application form, and a self-evaluation report; and describe the challenges faced by these potential new members. One recurring theme is the lack of understanding on how to conduct the self-evaluation process; largely due to the lack of in-depth understanding of the CDIO Framework itself. This can be attributed to missed opportunities to get acquainted with CDIO. The author also noted the mismatch between outcomes of the self-evaluation report and the action plans reported in the submitted application form. Therefore a set of 2 documents had been prepared to assist applicants conduct the self-evaluation process to ascertain the current status of a program targeted for revamp. One document provided guidelines for using the CDIO Standards, as it is noted that different faculty can have different administrative responsibilities in the job role (Program Chair, Project Supervisor, etc) besides the academic accountabilities. A summary table highlighting for each standard the key focus areas at the program-level and course-level. Another document complements the first one, by providing guiding questions to aid the interpretation of the scoring rubric on every CDIO Standards. In this manner, this document expanded on the initial set of rubrics to provide greater clarity to all involved in the self-evaluation rating process with a common understanding based on the broad descriptors of scoring (Level 0 to 5) for each standard. Lastly, the paper shares the feedback from institutions that became CDIO members on their experience in using the 2 documents to aid the preparation of the application form and completing the self-evaluation exercise, with particular attention on the formulation of implementable action plans, prioritized based on the results of the self-evaluation exercise, aligned with the objectives of the curriculum revamp that led to the adoption of CDIO in the first place.

KEYWORDS

Self-Evaluation, Guiding Questions, Rubrics, CDIO Standards 1-12

INTRODUCTION

This paper is written as a contribution to the challenge faced by academic institutions in Asia Region who are interested in using CDIO to drive curriculum changes. As required by CDIO Council, to apply for "membership" into the CDIO community, an institution has to submit 2 documents: an application form and a self-evaluation report for the program chosen to adopt CDIO as the basis for its curriculum redesign. The application form is structured like a questionnaire, where applicant had to answer a range of questions ranging from the intent for joining, what curricular changes are to be made, how to contribute back to CDIO, etc. The self-evaluation report is to accompany the application form. Preparing the self-evaluation report is often the biggest challenge faced by the applying institutions because many only have limited understanding of CDIO. This author noted that there is a lack of explanatory notes on how to complete the self-evaluation report, as it was implied that referencing the performance rubrics alone would suffice. This challenge persisted, even after attending at least one CDIO event – be it the international conference or a regional meeting – as conducting self-evaluation workshop are not typically covered at these CDIO events. Another shortcoming noted by the author in the application submission is the apparent "disconnect" between the results of the self-evaluation and the action plans in the application form.

This paper shares the effort by the author, who in the capacity as CDIO Co-Leader for Asia Region, had prepared a set of documents to help institutions prepare the self-evaluation report. These documents should be of use to new members to CDIO too.

CDIO SELF-EVALUATION & USE OF RUBRICS

A review of past papers presented at the International CDIO Conferences showed that work reported on self-evaluation processes fall largely into the following categories: (1) On-going program continual improvement (e.g. Malmqvist *et al*, 2006; Kontio *et al*, 2012; Cheah *et al*, 2013; Cheah & Lee, 2016) to address a new initiative, including non-engineering program (e.g. Thollar & Rian, 2020); (2) "Validating" the application of the CDIO Framework to address changes in an educational institution's external operating environment (e.g. Cheah & Leong, 2018). It can be said that the outcome of the latter is to support program continual improvement as well, putting forward the argument that the CDIO Framework had remained useful to provide guidance to program owners in carrying out the necessary curriculum revamp to keep the program up-to-date and relevant.

Cheah *et al* (2013) had shown how the CDIO self-evaluation process can be aligned to the institution's own academic quality management system, as both are based on the same plan-do-check-act (PDCA) continual improvement cycle. Cheah & Lee (2015) went further by positing that since a program is made up of a collection of courses thoughtfully arranged in a meaningful sequence over the program duration to progressively develop students' competencies desired by key stakeholders, the self-evaluation process can be "cascaded" down for use at the course level. Bennedsen & Schrey-Niemenmaa (2016) reported on a process of cross-sparring collaborative model, whereby two institutions acting as critical friends use self-evaluation to find areas of improvement of both institutions' programs. This is the "precursor" of subsequent CDIO Peer-to-Peer Support Initiative.

Evolution of the CDIO Self-Evaluation Process

On using the self-evaluation process for continual improvement, Kontio (2008) is probably the first author to suggest improvements to the process itself using an "extended" evaluation

model, which serves to provide valuable information for focusing on the development actions. The extension proposed was based on a study of the innovation process in organizations-model from the diffusion of innovations theory. This study showed that the five ratings in the CDIO self-evaluation model and the five phases of the innovation process are very similar to each other. Hence, the author proposed that combining the innovation process to the analysis of the implementation process would support the interpretation of the evaluation results.

Bennedsen, Georgsson & Kontio (2014) then evaluated the self-evaluation process from the view of a program responsible, asking questions such as: “Are the descriptions understandable”, “Do the descriptions need extensions, clarifications, precisions”, etc. The authors also analyzed each of the rubrics associated to the standards, based on their own experience in doing self-evaluations; and provided proposals for clarifications, precisions and extensions of the rubrics.

Later, Georgsson, Kontio & Bennedsen (2015) sent out a questionnaire survey to all CDIO collaborators and recipients were asked to evaluate each of the 12 standards with respect to understandability and hierarchical consistency of the standards. The respondents were asked to evaluate their proposed changes of the rubrics. The respondents provided very useful comments and arguments for the development of the revised rubrics. Based on the feedback, changes in the rubrics for the 12 standards were proposed. The updated version of the self-evaluation rubric was approved by CDIO Council on 13 November 2015 (Bennedsen, Georgsson & Kontio, 2016)

Challenges in using the Self-Evaluation Process and its Rubrics

Doing a self-evaluation is a major effort towards continual improvement and the use of rubrics is meant to help a program owner reflect on the quality of one’s program. In general, the usefulness of the revised rubrics was reported to be more understandable (Georgsson, Kontio & Bennedsen, 2015). It is worth noting that the evaluation of the revised rubrics was done by key users; almost all of which had good knowledge and experience in conducting self-evaluations.

Newcomers to CDIO are unlikely to possess the same level of proficiency. Based on this author’s experience, using the self-evaluation process posed challenges to institutions new to CDIO who are interested in joining the community. This is despite them having gotten some exposure to CDIO, for example, by attending a regional meeting, online sharing on CDIO by the author, visitation to the author’s affiliation, etc.

More often than not, applicants tend to give high scores to their self-evaluation report. It can be said that since self-evaluation means that the same person carrying out the process will evaluate the findings from the process, there is much uncertainty that surrounded the validity of the findings reached. Carter & Dunning (2008) for example, noted that research increasingly showed that people were not very good at assessing their own competence and character accurately. The authors in fact opined that the extant literature had shown that people often have such erroneous view of their competence because self-evaluation is an intrinsically difficult task, if not an impossible one. Hence it is “unreasonable to expect more than a meager amount of accuracy in self-judgments”. Carter & Dunning (2008) further argued that the information environment in which people provide self-evaluations is too impoverished to allow them to report accurate findings. This means that the data people have available to them as they strive toward some sort of honest evaluation are incomplete to enable the determination of their true level of competence. This author opined indeed this is the case for new applicants. Lack of understanding of CDIO, the number of documents to be referenced in gathering the

evidence needed, underestimation of time needed, all contributed to the less-than-ideal self-evaluation outcome. Flawed self-assessments are therefore a function of an inadequate information environment, and not necessarily a sign of bias, wishful thinking, or foolishness on the part of the individual.

Bennedsen, Georgsson & Kontio (2016) cautioned that the use of rubric with the highest attainment being Level 5, can be misconstrued as having reached the final state, indicating that the work on program revamp is now completed if one scored at this level. These authors reminded that, quite the contrary, continual improvement implied that the self-assessment will never be finished and that one should still systematically use the process to identify any shortcomings in one's program. Furthermore, as reminded by Bennedsen, Georgsson & Kontio (2014), the main benefit of assigning a score for the self-evaluation resides not in the level itself but the insights one gets from doing the self-evaluation in the first place.

A related issue is that of sufficiency of coverage to constitute satisfactorily meeting the description of any given level of attainment in any rubric. Faculty carrying out self-evaluation often grapple with the challenge of how much evidence is needed to justify a score that is to be given. For example, how many courses in a given program must have active learning in the classroom, and how many lessons in a given course (e.g. 5 out of 10 weeks?) must make use of active learning? The current set of rubrics did not provide sufficient clarity on such matters. A score given based on current practices does not necessarily reflect the aggregate of efforted expended in meeting the requirement of a given level of performance for a given standard. From a cost-benefit perspective, it may be argued that the extra efforts to drill down to lesson levels may be too time-consuming and did not justify the resulting granularity. "Good enough is just good enough", so the saying goes. However, a different person looking at the overall results, one who did not have the understanding on how a score is derived, can walk away with the misinformed notion about the actual attainment for a given program.

Lastly, it can be said that the self-evaluation process is "not created equal", meaning that its application can cut across a whole spectrum of the endeavor depending on whether the area under evaluation is down to the task-level or stays at the program-level. The key faculty involved is also likely to be different at various scale of review – different levels of complexity. Self-evaluation thus requires participant by different individuals with different levels of job responsibilities, e.g. faculty self-evaluation of a certain learning intervention introduced in one's own classroom (e.g. as part of action research), course coordinator interested in checking the effectiveness (or otherwise) of an intervention to integrate at course-level certain competency (e.g. for addressing sustainable development issues), or a program owner carrying out a continual improvement review to ascertain the adequacy of existing curriculum in meeting new stakeholder requirement. A self-evaluation carried out by the program owner alone is likely not able to produce a well-informed outcome for program improvement.

IMPROVING THE CDIO SELF-EVALUATION PROCESS

We prepared the following 2 documents to help institutions interested in becoming CDIO members conduct the self-evaluation process:

1. Guidance for using CDIO Standards for Self-Evaluation
2. Guiding Questions for Rating during CDIO Self-Evaluation

The main objective is to help the applicant develop a better understanding of the current status of the program to be revamped, to ensure that the CDIO Framework is indeed the means to meet the institution's strategic plans leading to the needs for curriculum redesign. To this end,

the documents suggested a team approach, led by the program owner, to conduct the self-evaluation exercise to ensure everyone is on the same page. Most importantly, it is to ensure that action plans formulated are solidly grounded in the findings of the self-evaluation process, where the scoring using the prescribed set of rubrics is based on consistent interpretation of the criteria therein, resulting in agreeable action plans that are implementation, and prioritized based on the institution's curriculum's redesign objectives and available resources.

Guidance for using CDIO Standards for Self-Evaluation

This first document informs new applicants that the CDIO Standards are "not created equal" and alluded to the involvement of a team of faculty with different job roles and responsibilities to take part in the self-evaluation process. This process acknowledged that faculty did take on other work functions (some administrative in nature) related to teaching and learning. This is illustrated in Table 1, which is based on the practice in SP. Institution carrying out a self-evaluation should first understand how the CDIO Standards are to be used, and can create a similar matrix as shown in Table 1 for its own internal use.

In interpreting the tick (✓) marks, one has to note that the larger number simply means that the standard is of greater importance to the appointment holder and therefore warrants more attention. Other institutions adopting this table should adjust the relative importance based on own's local context and institutional policies etc. A set of guidelines to prepare the team to carry out the self-evaluation exercise is shown in Appendix 1.

Table 1. Application of CDIO core standards to program-level and course-level *

CDIO Core Standard	Program Owner	Course Coordinator	Course Member	Facility In-Charge	Project Supervisor
1. The Context	✓✓✓	✓✓	✓	✓✓	✓✓
2. Learning Outcomes	✓✓✓	✓✓	✓	✓✓	✓✓✓
3. Integrated Curriculum	✓✓✓	✓	✓	✓	✓
4. Introduction to Engineering	✓	✓✓	✓	✓✓	✓✓✓
5. Design-Implement Experiences	✓✓	✓✓	✓	✓✓	✓✓✓
6. Engineering Learning Workspaces	✓	✓	✓	✓✓✓	✓
7. Integrated Learning Experiences	✓	✓✓✓	✓	✓✓	✓
8. Active Learning	✓	✓✓✓	✓	✓✓	✓✓
9. Enhancement of Faculty Competence	✓✓✓	✓✓	✓	✓	✓
10. Enhancement of Faculty Teaching Competence	✓✓✓	✓✓	✓	✓	✓
11. Learning Assessment	✓✓	✓✓✓	✓	✓✓	✓✓✓
12. Program Evaluation	✓✓✓	✓	✓	✓	✓

* In SP's context, we use the word "Course" when referring to a "Program" and the word "Module" when referring to a "Course"). Also, we use "staff" to mean "faculty". A staff in SP often hold multiple job roles, for example the Program Owner is known as Course Chair and the Course Coordinator is known as a Module Coordinator. The Course Chair can also at the same time be a Module Coordinator for one course, and a Module Member in yet another course. Likewise a Module Coordinator can be a Module Member in one or more courses. Junior staff are often assigned as Module Member only for one or more modules, as part of a teaching team led by a Module Coordinator. A staff can also take on "special" role as project supervisor or in-charge of a facility, such as workshop and/or laboratory.

Table 2 further elaborates on how the CDIO standards can be used at either the program-level by the program owner or at the course-level by a course coordinator. When using Table 2 it is important to note the difference between “CDIO” skills and “C-D-I-O” skills as used in the table. Here “CDIO Skills” refers to skills and attitudes associated with Parts 2 and 3 of the CDIO Syllabus (i.e. the personal, interpersonal and professional dimensions) whereas “C-D-I-O Skills” refers specifically to skills and attitudes associated with the process of conceiving, designing, implementing and operating a product, system, process of service as covered in Part 4 of the CDIO Syllabus. Also note that the entries for Standards 9 and 10 are based on the proposals suggested in this paper. Human-in-the-loop checks are referenced in Standards 9 and 10 instead of repeating across the rest of the standards.

Table 2. Interpretation of CDIO core standards at program-level and course-level

Core Standard	Program-Level	Course-Level
1. The Context	Compulsory for Program Owner: Overall coverage or any change needed in the program to set the direction of development for affected courses	Course Coordinator: Look at possible specific changes to selected aspect of one’s own course where applicable , to support overall direction in the program
2. Learning Outcomes	Compulsory for Program Owner: Program-level Learning Outcomes is the focus, alignment to overall program aim(s) which also consider the institution’s mission and vision; and how they were cascaded into various Course-Level Learning Outcomes	Course Coordinator: Look at learning outcomes (CDIO and C-D-I-O Skills) in one’s own courses, and ensure alignment with overall program outcomes, in particular to peg them at the correct proficiency levels, written using suitable taxonomy (e.g. Bloom)
3. Integrated Curriculum	Compulsory for Program Owner: Sets the approach of how all the courses are to be arranged in meaningful sequence from Year 1 Semester 1 to Year 4 Semester 2 for a 4-year Degree Program; so as to progressively develop the desired CDIO and C-D-I-O skills to the appropriate level of proficiency	Course Coordinator: Be aware of how your course fits into the overall program structure, how it contributes to the development of desired skills and/or attitudes, in particular how to leverage on students’ prior learning from courses before your own course; and how your course provide basis of learning later topics in courses after your course
4. Introduction to Engineering	Program Owner: Be aware of coverage in this course (usually Semester 1 Year 1) and how it sets the contexts and contents for studying the chosen field of engineering (or other discipline)	Course Coordinator for this specific course: This is a unique course, so there is a need to ensure that it provides good rationale and motivation to students, often through a basic-level design-implement experience (see Standard 5)
5. Design-Implement Experiences	Program Owner: Ensure appropriate use of projects in selected courses to develop appropriate C-D-I-O Skills – hence there is often a range of such design-implement experiences from basic level to advanced level, often as part of a series of courses that uses project-based learning; and also ensure that CDIO Skills needed for project work are properly developed in other courses and properly sequenced	Course Coordinator for courses that specifically use projects to engage students in developing C-D-I-O Skills, who must also be aware how CDIO Skills are developed in other courses that can be leveraged on in projects (with different combinations of C, D, I and O), as part of the program’s integrated curriculum (Note: Often C-D-I-O Skills are used in conjunction with certain CDIO Skills – see Standard 7)
6. Engineering Learning Workspaces	Program Owner: Often work closely with Facility Development (or similarly named department) and selected Course Coordinators, to identify desired configurations of learning workspaces that support learning activities that lead to the development of C-D-I-O Skills and/or CDIO Skills	Course Coordinator for courses that has a laboratory or workshop component for student learning (see Standard 7); and Course Coordinators for courses with projects (see Standard 5): Identify types of learning workspaces and equipment or pilot plants needed to develop the desired C-D-I-O Skills and/or CDIO Skills
7. Integrated Learning Experiences	Program Owner: Ensure the proper “translation” of the integrated curriculum into a series of learning activities for students to develop desired CDIO Skills from laboratory work, workshops and assignments that mimic or reflect real-world workplace scenarios that students may encounter	Course Coordinator: Look at possible specific changes to selected aspect of one’s own course where applicable, to design or redesign learning activities that uses knowledge from one’s course, to support overall direction in the program to develop desired CDIO Skills at the proper proficiency levels

Table 2. (cont'd)

8. Active Learning	Program Owner: Ensure the proper "translation" of the integrated curriculum into a series of learning moments for students to develop desired CDIO Skills during lectures and tutorials using appropriate active (and preferably experiential) learning strategies	Course Coordinator: Look at possible specific changes to selected aspect of one's own course where applicable, using specific active (and preferably experiential) learning strategies to develop selected skills and attitudes to support overall direction of the program
9. Enhancement of Faculty CDIO Competence (as revised)	Program Owner: Working with course coordinators to ensure that GenAI tools are used in ethical and responsible manner aligning to other CDIO Standards; and working with Academic Resource Manager or Training Manager to ensure needed competencies are in place	Course Coordinator: Identify the CDIO skills and AI competency needed for one's own course, as well as the needs of the teaching team if applicable and liaise with Academic Resource Manager or Training Manager for the necessary training
10. Faculty Professional Development (as newly proposed)	Program Owner: Engage key stakeholders to identify new competencies needed for one's program (including GenAI) and work with Academic Resource or Training Manager to ensure needed competencies are in place	Course Coordinator: Liaise with Academic Resource or Training Manager for the necessary training for self, and teaching team members where applicable
11. Learning Assessment	Program Owner: Ensure meaningful and consistent assessment of development of required CDIO Skills and C-D-I-O Skills at the proper proficiency levels; with a good balance of formative and summative components in all courses	Course Coordinators: Select suitable assessment tools along with relevant evidence of learning and provide timely facilitation and support consistent with students learning needs; and to ensure constructive alignment
12. Program Evaluation	Program Owner: Ensure periodic review of a program using CDIO Self-Evaluation Rubrics by consolidating inputs from all Course Coordinators; and where the institution already has quality assurance framework, to use the CDIO Framework to complement it.	Course Coordinators: Review one's own course and how it contributes to the development of competency needed by key stakeholders; especially in terms of how one's course can support and be supported by other courses in one's program.

Guiding Questions for Rating during CDIO Self-Evaluation

The guiding questions are provided to help Program Owner and/or Course Coordinator review one's curriculum in terms of achievement as compared against the rubrics in each Standard. The guiding questions are formulated more or less in the sequence to start from a low rubric score, and progressively move towards a higher rubric score, although it must be acknowledged that such "transition" is not always clear-cut. In moving from the lower to higher score in the rubrics, it can be seen that the responsibility increasingly moved from that of a Course Coordinator to that for a Program Owner. The onus is on the Program Owner to make an informed decision on the rating given based on best information available.

Table 3 shows the standard format for the guiding questions to be used for all 12 core standards. The "Description" and "Rationale" of the standard were omitted to avoid clutter. An example for Standard 3 Integrated Curriculum is shown in Appendix 2.

DISCUSSIONS: EXPERIENCE FROM NEW CDIO COLLABORATORS

The author had shared the 2 documents with institutions who contacted him and expressed interest in becoming CDIO members. After initial contact (online) where he ascertained that an institution is genuinely interested in adopting the CDIO Framework, he will send them the application form, self-evaluation template, and the 2 documents shared above.

Table 3. Standard format for providing guiding questions for each CDIO standard

Standard Number and Standard Name	
One paragraph description of the standard	
Rubric (scale 0 to 5) for the standard	
5	
4	
3	
2	
1	
0	
Guiding Questions: • • • •	

Four institutions had recently been accepted as CDIO members following their presentations at the 2025 CDIO Asia Regional Meeting hosted by Politeknik Negeri Batam in Indonesia in August. A simple survey (see Appendix 4) had been conducted with the institutions to obtain their feedback on using the 2 documents in preparing the application. These are briefly discussed below.

For the document "*Guidance for using CDIO Standards for Self-Evaluation*", 2 institutions found it "Extremely Useful" (The instructions were comprehensive and very clear, allowing us to carry out the self-evaluation process with clarity and confidence) and 2 others found it "Very Useful" (The instructions were clear and well-structured, giving us a clear picture of how the carry out the self-evaluation process with minimal difficulty). Applicants found the guidelines to be helpful, especially in ascribing different responsibilities of different standards to various appointment holders. What can be done better is to make it clear that upfront that applicant can modify the table to suit their own institution's faculty job roles, as one applicant noted that it did not use this table. Areas of improvement include making some guidelines clearer and using a flowchart.

For the document "*Guiding Questions for CDIO Self-Evaluation Exercise*", 2 institutions reported it as "Extremely Useful (The guiding questions were insightful, comprehensive, and provide good clarity in scoring across all standards), one reported as "Very Useful" (The guiding questions were clear, well-structured, and helped us in scoring across most if not all of the standards) and 1 reported as "Moderately Useful" (The guiding questions were generally understandable, but we can benefit more if additional questions are provided). Applicants in general find the guiding questions useful, as they provide greater clarity of what is expected because the descriptors for the rubric can be rather broad. Some areas of improvement include reducing overlapping coverage in more than one standard which can lead to confusion; and providing some examples.

CONCLUSIONS

These documents had been used by the author acting in his capacity as the CDIO Co-Leader for Asia to provide advice to institutions applying to join the CDIO community for the last 3 years. One particular area that warrants special attention is the formulation of action plans by the applying institution. Here the author informed applicants that implementable action plans are one of the major considerations of the application; and suggests applicants prioritize the action plans based on the results of the self-evaluation to clearly articulate how CDIO will be used in driving curriculum change for the program(s) chosen. So far, applications received had been satisfactory as witnessed by the action plans prepared. Anecdotal "evidence" gathered via informal conversations with applicants informed that they found the guidelines and guidance questions useful.

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This paper did not make use of GenAI.

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BIOGRAPHICAL INFORMATION

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APPENDIX 1. Guidelines for Carrying Out CDIO Self-Evaluation

1. The CDIO 12 Core Standards are presented in numerical sequence from 1 to 12. For each standard a short description of the standard is given, followed by a rubric for use in the self-evaluation of that given standard, from a score of “0” to “5”. Note that the rubric is hierarchical, meaning that a higher score will require that the criteria for the scores below it had been met.

2. The purpose of self-evaluation is to ascertain to what extent the skills and attitudes desired by key stakeholders had been attained during the duration of the study program. Recall that the CDIO Syllabus provides guidance on the types of skills and attitudes that key stakeholders required. For the purpose of this document, we will use the term “CDIO Skills” to mean skills and attitudes associated with the personal, interpersonal and professional dimensions as covered in Parts 2 and 3 of the CDIO Syllabus. We will also use the term “C-D-I-O Skills” to specifically means skills and attitudes associated with the process of conceiving, designing, implementing and operating a product, system, process of service as covered in Part 4 of the CDIO Syllabus.

3. The person or persons involved in this process will go through the standards one-by-one, and review the items covered in each standard against what had been done in the chosen program, to ascertain the extent to which the current had implemented part or all of the CDIO recommendations as spelt out in the 12 Core Standards.

4. The self-evaluation process is best led by the Program Owner (or Program Manager, Program Chair, or other similar named position: this is a person who is tasked with managing or running a program) in conjunction with the program team involved in teaching the program. Other team members will include Course Coordinators (persons who is in-charge of a given course, or other similarly named position; who has overall responsibility for a course especially if taught by more than one faculty).

5. Note that the aim here is NOT to score “5” in any or all categories; as the aim of the self-evaluation is to provide the program owner with “as-accurate-as-it-can-get” the most current status of the program as far as adoption of the CDIO Framework is concerned. This then serve as the basis for actionable items to improve the concerned program.

6. The CDIO standards each had a specific focus area, some of which are more applicable at Program-level and hence needs the input from Program Owner; while others can be applicable to all teaching faculty, especially one who assumed a lead role as Course Coordinator. Table 1 provides a simple explanation of which standard(s) are most pertinent to which faculty role in the chosen program and hence should be involved in the self-evaluation process. The greater the number of tick marks (✓) indicated higher importance. Table 2 provides more explanation of how the standards apply to Program Owner and Course Coordinator respectively.

7. Where GenAI is to be used, self-evaluation takes on a different context: it is one that checks for ethical and responsible use of GenAI when it is used in conjunction with a given standard. Here the self-evaluation serves as an oversight function with human-in-the-loop review and sanction the GenAI use.

APPENDIX 2. Sample Guiding Questions for CDIO Self-Evaluation - Standard 3

Standard 3 Integrated Curriculum	
A curriculum designed with mutually supporting disciplinary courses, with an explicit plan to integrate personal and interpersonal skills, and product, process, system, and service building skills.	
Rubrics	
5	Internal and external stakeholders regularly review the integrated curriculum and make recommendations and adjustments as needed.
4	There is evidence that the students have achieved the intended learning outcomes concerning personal, interpersonal, product, process, system, and service building skills.
3	The approved integrated curriculum concerning personal, interpersonal, product, process, system, and service building skills is in use.
2	The curriculum that integrates learning outcomes of personal, interpersonal, product, process, system, and service building skills is approved, and a process has been initiated to implement the curriculum.
1	The need to analyze the curriculum is recognized and initial mapping of disciplinary and skills learning outcomes is underway.
0	There is no integration of skills or mutually supporting disciplines in the program.

Guiding Questions:

A common misconception here is that the program had adequately focused on getting students to integrate technical knowledge covered in different courses. In CDIO, the notion of integrated curriculum extend beyond technical knowledge to include integration of skills and attitudes needed to support problem-solving using the domain technical knowledge.

Also: there are many skills and attitudes that needs to be integrated. It is not expected that a given program will have addressed ALL of them, as new skills and attitudes will emerge later at one point or another when the external operating environment changes. While there is no number of skills/attitudes specified here, that needs to be addressed, it is reasonable to expect that – regardless of which program one is studying – students are required to possess some skills in teamwork and collaboration, communication, thinking and problem-solving; and positive attitudes such as growth mindset and resourcefulness. See also Standard 5 for C-D-I-O skills – skills developed via project work. Are all these skills and attitudes taught explicitly to students?

- Are these skills and attitudes taught explicitly to students? If yes, which are the courses? Are they used – or assessed – even though they were not taught? If so, in which courses are they used? Again, there is no explicit requirement on the number of courses to have a number of skills and attitudes integrated. The position here is that it is reasonable to expect the above-mentioned fundamental skills of teamwork and collaboration, communication, thinking and problem-solving should be covered.
- What about other skills and attitudes that had been identified as needed but not yet integrated? Have you ascertained the desired level of proficiency?
- Is there a systematic way to develop these skills and attitudes over the duration of the program? Have you identified suitable courses to include these skills?
- Is there a plan in place to design an integrated curriculum for a chosen program?
- Are the courses logically sequenced to allow progressive development of desired CDIO Skills and C-D-I-O Skills? Is there a need to reconsider the program structure (i.e. the arrangement of the courses that promote the development of these skills)?
- As a Course Coordinator, what about your own course(s)? Where is your course located in your program structure? Can you build on outcomes (knowledge, skills, attitudes) from other courses (in earlier stage or same stage of study) to enhance the learning outcomes of your own course? Likewise, what other courses in later stage of study can leverage of what you had covered in your own course?
- How would you know that your students had benefited from the integrated curriculum? Do you have activities in your own course such as assignments that require students to make use of skills and attitudes covered in different courses to complete your course assignment?
- What are the evidence that demonstrates that students had attained the desired competency in integrating knowledge, skills and attitudes in problem identification and problem solving?
- How often do you review the program structure to ensure it remains relevant to develop the desired competency (KSA)? Did you involve your key stakeholders in the review process?
- Has GenAI been used in an ethical and responsible manner in the application of this standard?

APPENDIX 3. Survey Questionnaire for New Members to CDIO Asia Community

For the document "*Guidance for using CDIO Standards for Self-Evaluation*"

Q.1 On a scale of **1** to **5** based on the descriptions below, how do you feel the document "*Guidance for using CDIO Standards for Self-Evaluation*" had helped you in carrying out the self-evaluation process to support your application?

Scale	Meaning	Explanation	Answer (X)
5	Extremely Useful	The instructions were comprehensive and very clear, allowing us to carry out the self-evaluation process with clarity and confidence.	
4	Very Useful	The instructions were clear and well-structured, giving us a clear picture of how the carry out the self-evaluation process with minimal difficulty.	
3	Moderately useful	The instructions were for the most part easy to understand but several areas still require some clarification before carrying out the self-evaluation process.	
2	Slightly Useful	The instructions were somewhat unclear in some areas or lacked detail, so it is quite challenging for us to carry out the self-evaluation process.	
1	Not useful at all	We had difficulty understanding the most parts of the instructions and had much difficulty carrying out the self-evaluation process	

Q.2 Please elaborate on your decision above, and be as specific as possible, e.g. which paragraph(s) is/are unclear or confusing for you.

Q.3 Notwithstanding the above shortcomings elaborated in Q.2 earlier, please share your ideas – if any – to further improve the document.

For the document "*Guiding Questions for CDIO Self-Evaluation Exercise*"

Q.4 On a scale of **1** to **5** based on the descriptions below, how do you feel the document "*Guiding Questions for CDIO Self-Evaluation Exercise*" had helped you in giving a score for each standard during the self-evaluation process?

Scale	Meaning	Explanation	Answer (X)
5	Extremely Useful	The guiding questions were insightful, comprehensive, and provide good clarity in scoring across all standards	
4	Very Useful	The guiding questions were clear, well-structured, and helped us in scoring most if not all of the standards.	
3	Moderately useful	The guiding questions were generally understandable, but we can benefit more if additional questions are provided	
2	Slightly Useful	The guiding questions were somewhat helpful but lacked clarity or alignment with some rubric levels.	
1	Not useful at all	The guiding questions are confusing or irrelevant, and we still had difficulty doing the scoring during self-evaluation.	

Q.5 Please elaborate on your decision above, and be as specific as possible, e.g. which question(s) in which standard(s) is/are unclear or confusing for you.

Q.6 Notwithstanding the above shortcomings elaborated in Q.5 earlier, please share your ideas – if any – to further improve the document.

CDIO AND GEN AI FOR SUSTAINABLE DEVELOPMENT: DESIGN PRINCIPLES AND ENHANCED SELF-EVALUATION

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ABSTRACT

This paper addresses the integration of sustainable development into a program building on earlier effort to integrate key competencies for sustainability to develop students sustainability mindset. The paper provides a high-level coverage of the endeavor looking at both “front end” and “back end” of the process – namely that of designing and delivery of a curriculum integrated with sustainable development; and the evaluation of the effectiveness of implementation via program evaluation. For curriculum design to integrate sustainable development, the paper build on the model that the author and his team developed and shared the 2025 International CDIO Conference, taking into consideration the potential use of generative artificial intelligence (GenAI) assisting the process. The outcome is a set of design principles that guides integration of sustainable development with special focus on areas where application of GenAI is encouraged, as well as other areas where faculty oversight (human-in-the-loop) is recommended. The paper then suggests an enhancement to the CDIO program evaluation when using it to ascertain the level of integration of sustainable development in a given program. It posits that as most programs are still rooted in the “education for sustainable development” paradigm or in the process of transitioning to the preferred “education as sustainable development” paradigm. This paper suggests the use of the current 12 core standards with specific focus on sustainable development guided by the requirements of the additional standard on sustainable development. This is because most programs are still implementing “education for sustainable development” and program owner can use the current approach to program evaluation. This paper suggests the use of guiding questioning targeting integration of sustainable development within the focus area of each core standard. The paper rounds off the program evaluation process with a checklist to aid faculty exercising oversight responsibility to ensure that the design guidelines on GenAI use is followed.

KEYWORDS

Sustainable Development, Design Principles, GenAI, Program Evaluation, Standards: 1-12

INTRODUCTION

This paper presents a comprehensive approach towards integration of sustainable development into a curriculum using the CDIO Framework aided by Generative Artificial Intelligence (GenAI). It builds on the approach towards development of students' sustainability mindset proposed by Cheah *et al* (2025) whereby key competencies for sustainability were systematically integrated, contextualized to the program needs in addressing selected United Nations Sustainable Development Goals (UNSDGs). This is shown in Figure 1 below.

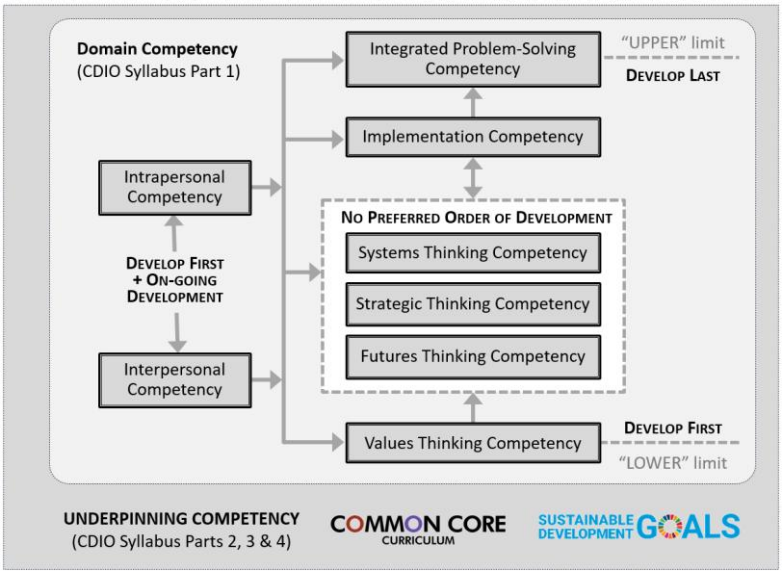


Figure 1. Model for integrating key competencies for sustainability (Cheah *et al*, 2025)

Scope for This Paper

There are 3 main parts to this paper. Part 1 covers the "front end" work by proposing a methodology to design a series of learning tasks in a given program to integrate key competencies for sustainability needed to develop the required sustainability mindset in students. Part 2 closes the loop by providing a methodology at the "back end" to evaluate the curriculum redesign effort after its implementation and identify areas of improvement.

Part 1 of the paper introduces a systematic approach to integrate the key competencies for sustainability within one's program, to aid implementation of the model shown in Figure 1, with additional considerations on impact of GenAI not covered in previous work. It first shares a brief literature review of recent developments in sustainable development vis-à-vis adoption and use of artificial intelligence (AI). This is done by first formulating a set of design principles (Herrington & Reeves, 2011) specifically for sustainability-themed learning tasks. These are then updated for the use of GenAI within the educational sector, informing areas where use of GenAI is advantageous and areas where faculty oversight (human-in-the-loop) is required.

Part 2 of the paper suggests a "special edition" of the self-evaluation process dedicated to sustainable development. This is done by first drawing faculty attention to the Additional Standard for Sustainable Development to understand how each Core Standard is to address sustainability issues. This part first provides a brief historical account of the inclusion of sustainability topics in the CDIO Standards and its evolution to current position; followed by discussions on the challenges faced in carrying out self-evaluation to review integration of sustainable development .

Part 3 of the paper shares an approach to conduct self-evaluation specifically focusing on integration of sustainable development in a program. This provides an alternative to using the Additional Standard for Sustainable Development for program evaluation. This is because many programs in are still very much rooted in the paradigm of "education for sustainable development", with few programs only beginning to transition to the "education as sustainability" paradigm (Gajparia *et al*, 2022). As such, this author opined that a self-evaluation process grounded in the current process of program evaluation sits more comfortably with these programs as opposed to using self-evaluation process for Additional Standard for Sustainable Development. Also, these programs are at varying degrees of integrating other skills needed to support transformative learning where key competencies for sustainability are still being developed. Using the current approach of program evaluation for sustainable development conveyed a sense of familiarity to program owners who are reviewing integration of sustainable development at the same time when they are reviewing integration of other skills and competencies. This section therefore presented a self-evaluation process based on the existing 12 Core Standards, with extra assistance in the form of guiding questions that connects the performance rubrics of each standard to the standard's relation to sustainable development. An added bonus is that we had also included questions on GenAI use to assist faculty in maintaining human oversight on GenAI response should one use them in the application of the core standards vis-à-vis sustainable development.

PART 1: DESIGN PRINCIPLES FOR INTEGRATION OF SUSTAINABLE DEVELOPMENT USING CDIO WITH ASSISTANCE FROM GEN AI

With the advent of AI in general, efforts towards sustainable development had shifted towards leveraging on the power of AI – notably data science – to address the extant challenges. One of the most critical contributions of data science to sustainable development is the handling of big data. Advances in these areas offer unprecedented opportunities to provide actionable insights, drive innovative solutions, and create long-term strategies for sustainable development (Shaddick *et al*, 2025). The descriptive, predictive, and prescriptive analytics from data science can support policy design, optimize resource allocation, and assess environmental impact. Key data science tools like geospatial analysis, machine learning, and big data analytics enable stakeholders to make informed, transparent, and evidence-based decisions (Adepoju *et al*, 2024). Examples of areas where AI-backed data science can be used in addressing sustainability issues include the followings as suggested by Shaddick *et al* (2025):

- Quantification and tracking progress towards the UNSDGs
- Embedding AI technologies to reduce emissions at source, e.g. research into new chemical catalysis, improve agriculture and food production
- Developing systems to increase our resilience to natural hazards, e.g. earthquakes, tsunamis, flooding
- Net Zero and the built environment, e.g. through building retrofitting, digital twins for energy management

Toderas (2025) cautioned that although AI holds transformative potential for achieving sustainability, its widespread implementation is not without inherent challenges and risks. Besides the familiar limitations of AI (inherent bias, infringement of copyright, privacy concerns, etc), AI has its own significant ecological footprint that must be proactively managed. Furthermore, as highlighted by Ren & Wierman (2024), AI's environmental impacts are not evenly distributed – often disadvantaging regions or communities that are already vulnerable to the resulting environmental harms, e.g. water consumption rate for data center heat

rejection. Toderas (2025) suggested 3 categories of risks that need to the addressed as shown in Figure 2.

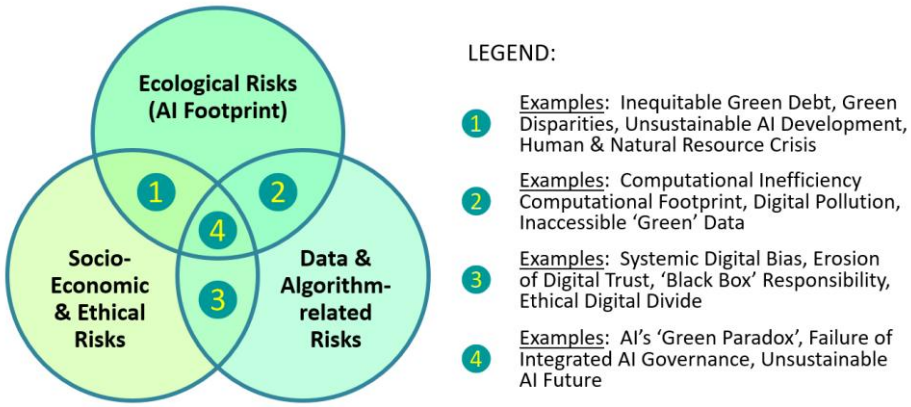


Figure 2. Categories of AI risks in the context of sustainability (Toderas, 2025)

Design Principles to Support Design of Sustainability-themed Learning Tasks

As we moved forward in using CDIO to design curriculum that integrates sustainable development, we need to be cognizant of the rapid development of AI technologies, especially when GenAI and the upcoming Agentic AI are being used in all aspects of teaching and learning. Our CDIO-based approach to curriculum redesign needs to incorporate measures to guard against the unintended consequences arising from these technologies. For the "front end" part of curriculum redesign, we look at the use of design principles to guide our effort.

Design principles had been defined by Herrington & Reeves (2011) as "…considerations that can be used to guide the design and development of learning environments in higher education that are based on sound practical and theoretical principles, and that can promote student engagement through innovative learning tasks". Design principles are not "set in stone". They exist in a range of different contexts, and they enable faculty and instructional designers to use well-researched ideas as guidelines for their own efforts to enhance student engagement and learning outcomes. Herrington & Reeves (2011) suggested that they are best regarded as informed reusable guidelines for others wishing to create their own solutions to educational problems across sectors. With the widespread use of GenAI, this author updated the considerations to include use of GenAI, specifically in the context of education for sustainable development (ESD). This is shown in Table 1. This paper henceforth complement efforts by Cheah (2026a) where he showed that the 12 CDIO Core Standards can be used by faculty acting as human-in-the-loop to provide human oversight when GenAI is used to assist in designing learning tasks that integrates sustainable development.

A set of templates in the form of worksheets had been designed by this author to help program owners integrate key competencies for sustainability as shown in Table 2. There are 6 worksheets that collectively guide faculty in designing CDIO Integrated Learning Experiences to integrate selected key competencies for sustainability into one's courses.

The upper half of the Appendix shows a sample of Template 1 of 6 (Worksheet 1) that sets the context for learning. Note the use of guiding questions (including the use of GenAI) for the worksheet to guide faculty in the design process.

Table 1 . Design principles for integrating sustainable development

Design Principle	Principle	GenAI Role	Human Oversight
Contextual Anchoring	Ground learning tasks in authentic, local sustainability challenges relevant to industry and national strategies.	Generate contextualized sustainability scenarios based on national SDG priorities and industry trends.	Validate GenAI's interpretations of policy and accreditation frameworks to avoid misalignment or misrepresentation.
Constructive Alignment Across Curriculum Layers	Align Program Learning Outcomes (PLOs), Course Learning Outcomes (CLOs), and task-level objectives using Bloom's Taxonomy and key competencies for sustainability.	Draft CLOs and PLOs using progressive cognitive, affective, and psychomotor verbs; suggest mappings to systems thinking and values thinking competencies.	Ensure disciplinary fidelity and progression logic; refine GenAI outputs to reflect institutional mission and learner diversity.
Progressive Scaffolding of Sustainability Competencies	Sequence learning tasks to build proficiency in systems thinking, intrapersonal, interpersonal, and values thinking competencies.	Visualize curriculum progression; suggest activation strategies (e.g., pre-class quizzes, literature prompts); simulate competency development pathways.	Confirm that scaffolding matches actual student readiness and avoids over-generalization or cognitive overload.
Authentic, Real-World Scenario Design	Use plausible workplace scenarios to situate learning within complex sustainability contexts.	Script multi-dimensional scenarios with ecological, economic, and societal tensions; simulate stakeholder perspectives and unintended consequences.	Vet scenarios for realism, ethical sensitivity, local applicability, and disciplinary relevance; avoid bias or oversimplification.
Integrated Learning Across Courses and Years	Design tasks that connect across semesters and disciplines, reinforcing sustainability competencies over time.	Map course interdependencies; suggest cross-course scenario extensions; generate prompts for interdisciplinary synthesis.	Ensure GenAI-generated linkages reflect actual curriculum structure and workload feasibility.
Ethical and Reflective Assessment Design	Assess both product and process, with emphasis on attitudes, values, and systems thinking.	Draft performance rubrics; simulate feedback loops; generate formative assessment variants.	Review rubric criteria for fairness and transparency; ensure feedback is pedagogically sound and context-sensitive.
Student Agency and Meta-cognition	Empower students to co-create, critique, and reflect on their learning journey with GenAI as a cognitive partner.	Prompt reflective journaling; support self-assessment; simulate peer review dialogues.	Guide students in evaluating GenAI outputs critically; scaffold ethical use and authorship boundaries.

PART 2: EVALUATION OF INTEGRATION OF SUSTAINABLE DEVELOPMENT – ENHANCEMENT USING GUIDING QUESTIONS

The CDIO Framework addressed the challenges of sustainable development via revisions to its Syllabus and Standards. In version 3.0 of the CDIO Standards sustainability and sustainable development were referenced in selected core standards (Malmqvist, Edstrom & Rosen, 2020). Additionally, a set of 4 other standards – one of which is sustainable development – was also introduced as "optional" (Malmqvist, et at, 2020). Applying an "optional" standard to a program first requires that the program satisfy all 12 core standards.

The "optional" feature the following criteria (Malmqvist *et al*, 2020):

- Not be sufficiently addressed by interpretation of a core standard
- Reflect ongoing development in several CDIO programs

- Reflect a program-level approach, and not be obtainable by implementation in a single course
- Be assessable by the CDIO standards rubrics

At the 2025 CDIO International Working Meeting in Linkoping, Sweden, it is decided that the word “optional” will be replaced with “additional”.

Table 2. Set of 6 worksheets for integrating sustainable development into curriculum

Worksheet	Focus Areas of Integration	Reference
1	• Select relevant UNSDGs • Identify suitable courses	1 – The Context
2	• Desired outcomes for key competency for sustainability • Increasing proficiency levels	CDIO Syllabus 2 – Learning Outcomes
3	• Progressive development of competency • Other supporting competencies needed	3 – Integrated Curriculum
4	• Real-world workplace scenarios re: sustainability issues • Relationship with other UNSDGs not selected	7 – Integrated Learning Experiences
5	• Increase complexity: Different perspectives on 3 pillars of sustainability	7 – Integrated Learning Experiences (cont’d)
6	• Assessment method, scaffolding & evidence of learning • Constructive alignment	11 – Learning Assessment

The CDIO Syllabus version 3 which featured modifications to existing coverage of sustainable development, along with other updates was introduced 2 years later (Malmqvist *et al*, 2022). A seemingly ironic part of version 3 of the syllabus is the intentional removal of a section dedicated to sustainable development. This is in recognition that the skills and attitudes needed for sustainable development had much in common with other skills and attitudes covered in other areas. As well, skills presented under sustainable development also have utilities for other competencies; so it is better to distribute them in suitable parts in the syllabus. Doing so also requires that faculty using the CDIO syllabus to look through different parts of the syllabus as necessary (e.g. based on the job role or nature of tasks), instead of locking into a limited number of skills and attitudes contained within a specific section of the syllabus.

Challenges in Carrying Out Self-Evaluation for Sustainable Development

Rosen *et al* (2017) had used the optional standard on sustainable development on a wide scale. With some proposed indicators and rubric modifications, the authors concluded that the optional standard is “a useful tool for evaluating, promoting, and guiding, integration of sustainable development, not only in programs with particularly high ambitions regarding sustainable development, but in basically any engineering program. It is recommended that the new standard, with the proposed modifications, is used for setting university-wide goals and for providing teachers and program directors with a framework for enhancing the future relevance of engineering education programs.”

However, the “optional” standard was not commonly used by institutions in the Asia Region. By and large; majority of the programs in CDIO members in Asia are still rooted at the “education for sustainability” stage, whereby transformation towards sustainability had been made by integrating sustainable development into existing curriculum in selected courses;

rather than having programs designed upfront with sustainability as the main focus ("education as sustainability"). They are more likely to be using the current 12 core standards to perform any evaluative work on effectiveness of integration of sustainable development.

As it currently stands, version 3 of the CDIO standards already explicitly mentioned the need to address sustainable development issues in Standards 1, 2, 3, 4, 5, 7, 9 and 11. Clearly, the descriptions for Standard 6, Standard 8, Standard 10 and Standard 12 can easily be amended to mandate considerations of sustainable development issues as well.

This author opined that the challenge for most institutions extend beyond this, based on his experience reviewing applications for CDIO membership from Asian institutions. One of the requirements in the application is the completion of the self-evaluation report. Discussions with applicants indicated that it is the use of the rubrics that is problematic, as the rubrics is meant to be generic for any skills and attitudes integrated and developed within a program. Therefore more guidance will be required for the explicit evaluation of how key competencies for sustainability and sustainability mindset are to be investigated.

PART 3: PROPOSAL FOR CONDUCTING SELF-EVALUATION ON INTEGRATION OF SUSTAINABLE DEVELOPMENT

This author had earlier introduced the use of guiding questions to aid the self-evaluation process for using 12 core standards (Cheah, 2026b) . This can be seen as enhancement for the self-evaluation for integration of any generic skill and/or attitude. The self-evaluation of integration of sustainable development introduced in this paper, can be seen as a "special edition" of the self-evaluation process, with specific guiding questions to aid evaluation of sustainable development vis-à-vis each core standard. To do so, we will tap into the description of the Additional Standard for Sustainable Development.

Understanding the Additional Standard for Sustainable Development

The one-sentence description of Additional Standard for Sustainable Development reads:

"*A program that identifies the ability to contribute to a sustainable development as a key competence of its graduates. The program is rich with sustainability learning experiences, developing the knowledge, skills and attitudes required to address sustainability challenges*."

This is followed by further elaboration on the focus area on sustainable development for each of the 12 Core Standards. Table 3 reproduces such focus area into tabular format as shown.

A set of 12 templates were developed: one for each standard with specific focus on how the standard addresses integration of sustainable development. The format of the template is shown in Table 4 and a sample for CDIO Core Standard 1 The Context is shown in the lower half of the Appendix. It can be seen that the one-sentence description for the standard is shown immediately below the name of the standard. This is followed by "Key Focus on Sustainable Development" which is the text extracted from the description for Additional Standard for Sustainable Development. On the bottom part of the template, one can find on the left side, a list of guiding questions related to sustainable development to be considered under Core Standard 1. Next to the guiding questions, on the right of the template is the same performance rubrics for self-assessment using Core Standard 1. It can also be seen that the guiding questions mirror the performance rubrics but customized for sustainable development.

Table 3. Coverage of sustainable development in 12 core CDIO standards

Standard	Description (as extracted from the write-up for then “Optional” Standard
1	The program emphasizes environmental, social and economic sustainability in the adoption of the CDIO principles as the context for engineering education.
2	Sustainability related knowledge, skills and attitudes, are explicitly addressed in program goals and learning outcomes
3	Aspects of sustainable development are integrated in several mutually supporting disciplinary courses and projects, possibly in combination with specific sustainability courses
4	Concepts of sustainability, potentials and limitations of science and technology and related roles and responsibilities of engineers, are established at an early stage of the education
5	Design-implement experiences provide students with opportunities to apply and contextualize sustainability knowledge, skills and attitudes, both in the development of new technology and in the reuse, redesign, recycling, retirement, etc, of existing technology
6	Physical and digital learning environments enable interdisciplinary and transdisciplinary collaborative learning and interaction with various external stakeholders
7	Sustainability learning experiences are integrated with the learning of disciplinary knowledge, personal and interpersonal skills, and product, process, system and service building skills
8	Active experiential and transformative learning activities develop students’ key competences for sustainability
9, 10	Enhancement of faculty competences for sustainability and related teaching competences is actively promoted
11	Approaches appropriate for assessing sustainability related learning outcomes are implemented
12	The integration of sustainable development is evaluated by students, faculty, industry and societal stakeholders, and in relation to relevant UN and other frameworks

DISCUSSIONS: USE OF GEN AI FOR INTEGRATING SUSTaiNABLE DEVELOPMENT

Part 1 shared that GenAI had been used to formulate a set of design principles that guides the integration of sustainable development into a curriculum. Also as mentioned in Part 1, such design principles complements the author’s work that provide guidance of how CDIO Standards can support faculty acting as human-in-the loop, provide oversight on responses produced GenAI (Cheah, 2026a). In a similar intent, human-in-the-loop is required for faculty oversight if GenAI is used for carrying out self-evaluation on integration of sustainable development. This requirement had been added to the list of guiding questions based on the template in Table 4. As an example, it can be seen in the lower part of the Appendix that the use of GenAI had been included as a guiding question for Core Standard 1 The Context.

Parts 2 and 3 shared an approach for conducting self-evaluation specifically on integration of sustainable development in a program. The process is built on a generic approach to elf-evaluation using guiding questions suggested by Cheah (2026b). The self-evaluation for integration of sustainable development made use of focus areas highlighted in the Additional Standard for Sustainable Development, to produce a specific set of guidance questions for each of the 12 Core Standards. The performance rubrics of each core standard is viewed through the lens of sustainable development, and the guiding questions were formulated accordingly.

Table 4. Standard template for evaluating integration of sustainable development

<table>
<tr><th colspan="3">CDIO Core Standard X Name of Standard X</th></tr>
<tr><td colspan="3">One paragraph description of Standard X</td></tr>
<tr><td colspan="3">Key focus on Sustainable Development
Extracted from description for “Additional Standard for Sustainable Development” (see Table 3) that is relevant for Core Standard X</td></tr>
<tr><td rowspan="7">Guidance Questions:
(consider these alongside the rubrics on the right)
• Question 1
• Question 2
• • •
• Which aspects of the work was carried out by GenAI?
• Has the output been validated by faculty?
(Consult checklist for GenAI usage)</td><td colspan="2">Rubrics for Self-Assessment
(Shown here is the generic format applicable to each standard)</td></tr>
<tr><td>5</td><td>Evidence related to the standard is regularly reviewed and used to make improvements.</td></tr>
<tr><td>4</td><td>There is documented evidence of the full implementation and impact of the standard across program components and constituents.</td></tr>
<tr><td>3</td><td>Implementation of the plan to address the standard is underway across the program components and constituents.</td></tr>
<tr><td>2</td><td>There is a plan in place to address the standard.</td></tr>
<tr><td>1</td><td>There is an awareness of need to adopt the standard and a process in place to address it.</td></tr>
<tr><td>0</td><td>There is no documented plan or activity related to the standard.</td></tr>
<tr><td colspan="3">Evidence of Coverage:
(please be detailed)
• Evidence 1
• Evidence 2</td></tr>
</table>

Call for CDIO Members to Adopt/Adapt/Modify the Suggested Approach

The 2 set of templates introduced in this paper were enhancements of the training materials the author used in his past workshops on integrating sustainable development into a program. These 3-hour workshop was delivered as part of faculty professional development within Singapore Polytechnic during the vacation; or to overseas institutions where the author was one on the invited speaker for the institution’s event to talk about ESD. Due to its duration, there was only sufficient time to introduce participants to the templates for using it at their own pace later. Overall responses for the workshops were positive with participants acknowledging the usefulness of the approach, but there was no systematic collection of participant experiences in using the tool.

On reflection, this author decides to leverage on the possible contributions from the CDIO community to obtain feedback and ideas to further improve the templates used. With the advent of GenAI, 2 broad guiding questions were added, to serve as human-in-the-loop check on GenAI use. These questions requires that faculty refer to the checklist in Table 5. This checklist complements the “front end” design principles by ensuring that GenAI contributions in the “back end” self-evaluation process remain pedagogically intentional, ethically sound, and contextually relevant. A notably item in Table 5 is that for “environmental justification”, to critically evaluate solutions proposed by GenAI so that they deliver the desired positive environmental impacts, sustainability benefits, or efficiency gains produced do outweigh the carbon footprint, energy consumption, and water usage required to run it.

However, it is also to be noted that the “broad stroke” of “environmental justification” will not be sufficient given the myriads of risks from AI in the context of sustainability as shown in Figure 2. Again, the collaboration among CDIO community members can be a plausible way moving forward in addressing the ever-changing sustainability and AI landscape.

Together, the guiding questions and checklist provide a dual-layer safeguard: they help faculty critically validate GenAI outputs while reinforcing the integrity of sustainable development integration across curriculum design and evaluation.

Table 5. Checklist for faculty oversight on GenAI use

Pedagogical Alignment
• Confirm GenAI use supports explicit learning outcomes and disciplinary goals.
• Avoid novelty-driven use; embed only where it enhances cognitive or metacognitive engagement.
Authenticity & Complexity
• Validate that GenAI-generated scenarios reflect real-world sustainability challenges.
• Check for ethical sensitivity, local relevance, and multi-stakeholder perspectives.
AI Literacy & Student Agency
• Scaffold students use GenAI progressively, with clear guidance on capabilities and limits.
• Encourage critical evaluation, authorship boundaries, and ethical reflection.
Environmental Justification
• Check that GenAI-suggested solution produces “net positive” gains.
• Ensure that there is alignment to the stated sustainability goal(s).
Transparency of Use
• Require documentation of GenAI’s contributions in student work.
• Make AI involvement visible in rubrics, feedback loops, and evaluation reports.
Assessment Integrity
• Design assessments that demand contextual judgment, process explanation, or personal interpretation.
• Validate GenAI-generated formative materials against learning objectives to prevent plagiarism or misalignment.

CONCLUSIONS

A self-evaluation approach to review the integration of sustainable development in a selected program is shared in this paper. It is meant to assist program owners whose programs are under the paradigm “education for sustainable development” stage of transitioning to “education as sustainability”. This approach maintains a sense of familiarity for program owners as it is the same as what they had been doing for program evaluation using the 12 Core Standards; given the thoroughness and robustness of the approach. The provision of guiding questions – which draw attention to consider responses of GenAI if one is used – can provide greater clarity during the self-evaluation process as a program owner reviews his/her program going through each core standard in turn. It is this author’s opinion that this will be less confusing to newcomers to CDIO who intend to use the framework to address integration of sustainable development into one’s *existing* programs. The author welcomes all CDIO members to try out the approach suggested in this paper, to use the 2 templates within their

own programs, modify as needed; and to share them with other institutions interested in joining CDIO and in using CDIO to address sustainability issues.

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Full Declaration: Table 1, Table 5 and the preceding paragraph had been prepared with the aid of Copilot. The responses were reviewed and edited as appropriate. The prompts used and responses obtained are available for review via the link below and selecting PDF file “109”. https://drive.google.com/drive/folders/1h5gPaRxba899Yjk2GbR5JqJ4jeeqMqLo?usp=sharing

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APPENDIX. SAMPLE WORKSHEETS

For Part 1: Design of Sustainability-themed Learning Tasks – Sample

Worksheet 1 of 6	Designing an Integrated Learning Experiences with Sustainable Development
Context of Learning (CDIO Core Standard 1): Focus area of your Program and related UN SDGs	
Ascertain the context for learning by referring to requirements of key stakeholders for your program with respect to sustainable development and identify several key UN SDGs. Identify suitable courses (across several years of study) in the program with contents that can be related to sustainability issues, so that students can see the relevance of what they can do to address one or more of the selected UN SDGs using knowledge gained from the courses? NOTE: The sustainability issues would preferably be situated in your own country's context.	
Guiding Questions: 1. Identify the industry or industries your program is serving 2. Identify area(s) of Sustainable Development (UN SDGs) that is the focus on the industry 3. How about professional accreditation – any requirements? 4. Narrow the focus down to your country's context, are there some existing strategies, that you can make references to? 5. Did you use GenAI? Did you validate the outputs produced with professional review?	
Your Answers:	

For Part 2: Evaluation of Program's Integration of Sustainable Development – Sample

CDIO Core Standard 1	**The Context**	
Adoption of the principle that sustainable product, process, system and service lifecycle development and deployment - Conceiving, Designing, Implementing and Operating - are the context for engineering education		
Key Focus on Sustainable Development The program emphasizes environmental, social and economic sustainability in the adoption of the CDIO principles as the context for engineering education.		
Guidance Questions: (consider these alongside the rubrics on the right) • To what extent did your program already included coverage of SD, e.g. has it been included in one or more years of the program? • Did program review for continual improvement regularly look for efforts to improve coverage of SD? Had this been documented anywhere in the program? • Which aspects of the work was carried out by GenAI? Has the output been validated by faculty? (Consult checklist for GenAI usage)	Rubrics for Self-Assessment	
	5	Evaluation groups recognize that CDIO is the context of the engineering program and use this principle as a guide for continuous improvement.
	4	There is documented evidence that the CDIO principle is the context of the engineering program and is fully implemented.
	3	CDIO is implemented in one or more years of the program.
	2	There is an explicit plan to transition to a CDIO context for the engineering program.
	1	There is a willingness to adopt to a CDIO context for the engineering program.
	0	There is no plan to adopt the principle that CDIO is the context of engineering education for the program.
Evidence of Coverage: (please be detailed) • •		

SPARK FRAMEWORK FOR HUMAN-CENTRED GENERATIVE ARTIFICIAL INTELLIGENCE INTEGRATION IN CDIO EDUCATION

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ABSTRACT

The rapid emergence of Generative Artificial Intelligence (Gen-AI) is transforming how students in engineering courses learn, design and create. In higher education, this shift raises a fundamental tension on how institutions can preserve mastery of disciplinary fundamentals while preparing graduates to collaborate effectively with intelligent systems. This paper aims to provide a conceptual pedagogical framework named SPARK within the CDIO Innovation Process that guides educators in redesigning teaching and assessment in which Gen-AI acts as a trusted partner in thinking, creating and learning for students. SPARK represents **S**cope the Problem, **P**ropose Solutions, **A**ssess Critically, **R**efine and Integrate, and **K**nowledge Artefact and Presentation. Each phase corresponds to a CDIO stage where students conceive by scoping authentic problems, design by ideating and proposing solutions, implement through testing and refinement, and operate by communicating artefacts and reflections. The model is grounded in constructivism, self-regulated learning, reflection-in-action and authentic assessment, ensuring that pedagogy rather than technology anchors Gen-AI integration. SPARK also advances several CDIO Standards. It strengthens Standard 2 (Learning Outcome) by embedding Gen-AI literacy and ethical reasoning. It can enhance Standards 7 and 8 through active learning and integrated learning experiences and it supports Standards 9 and 10 by providing a vehicle for faculty competence and pedagogical innovation. As a design-based reasoning framework, SPARK moves fluidly across contexts and remains resilient to technological change. Its focus on inquiry, reflection and ethics renders it relatively immune to rapid disruption. Future implementation at Singapore Polytechnic will test SPARK in authentic modules, examining its impact on student agency, self-directed learning and cognitive engagement. Findings will inform its effectiveness and lessons learnt. In doing so, this work contributes to CDIO's global mission of preparing engineers who can conceive, design, implement and operate responsibly in a Gen-AI enabled world.

KEYWORDS

Generative Artificial Intelligence, Critical Thinking, Creative Thinking, Systems Thinking, SPARK Framework, CDIO Innovation Process, CDIO Standard 8

INTRODUCTION

The rapid advancement of Generative Artificial Intelligence (Gen-AI) has prompted educators to rethink how engineering education shall be transformed. Gen-AI tools such as ChatGPT, Copilot and DALL·E influence how students conceive problems, design solutions and communicate outcomes. While these technologies offer unprecedented opportunities for creativity and productivity, they also raise fundamental questions about the nature of learning itself, particularly whether reliance on Gen-AI may erode students' conceptual reasoning and problem-solving abilities (Williamson & Eynon, 2024; Zawacki-Richter et al, 2019).

Educators face a dual challenge, that is to leverage Gen-AI as a learning partner while safeguarding the disciplinary fundamentals that underpin engineering thinking. As Holmes et al (2023) observed, the potential of Gen-AI in education lies not in automating cognition but in amplifying it through guided pedagogy and ethical design. Yet most institutional responses to Gen-AI adoption have centered on assessment integrity or tool policies rather than rethinking the pedagogical processes that shape students' engagement with knowledge. The threats and opportunities introduced by Gen-AI are discussed in later sections of this paper and this discussion serves to identify the existing gap that this paper aims to address by recommending a pedagogical framework that embed Gen-AI meaningfully within the teaching and learning cycle, preserving human agency, metacognition and ethical judgement. The recommended pedagogical framework, named SPARK Framework, could be used to guide educators in designing learning experiences for students that integrate the use of Gen-AI meaningfully and ethically while strengthening the CDIO thinking skills.

A HUMAN-CENTERED PEDAGOGICAL PHILOSOPHY

Gen-AI has evolved from a novel tool into a foundational component of professional and academic life. Students should be empowered to harness Gen-AI tools to explore ideas, identify and solve complex problems, and develop habits of self-directed learning and learning to learn while upholding ethical and responsible use. Gen-AI can act as a trusted partner in thinking, creating and learning. Through this approach, every student is supported by a personalised learning assistant that enhances adaptive engagement while maintaining mastery of disciplinary fundamentals. This philosophical stance aligns with Luckin's (2018) concept of "intelligence augmentation" which positions Gen-AI as an amplifier of human potential rather than its replacement. Similarly, Muller (2023) emphasises the importance of "AI resilience", ensuring that students retain deep disciplinary cognition and critical judgement even when assisted by intelligent systems.

Within this context, the Conceive, Design, Implement, Operate (CDIO) Framework (Crawley et al, 2014) offers an ideal foundation for integrating Gen-AI into engineering education. CDIO's experiential emphasis on authentic problem-solving, reflection and iterative design aligns naturally with Gen-AI's capacity to support inquiry, ideation and evaluation processes. However, as Gen-AI tools become increasingly embedded in learning, CDIO institutions must rethink how students conceive and evaluate solutions in an Gen-AI enabled landscape. Thus, there is a need for pedagogical models that bring CDIO's disciplinary rigour with the reflective, human-centered ethos of Gen-AI.

THREATS BROUGHT ABOUT BY GEN-AI

Gen-AI is already reshaping student behaviour, blurring the lines between academic and personal life. Students are relying on these tools for efficiency, from automating research to drafting assignment reports. This offers new avenues for personalised learning but also raises concerns about potential cognitive dependence. The ease of access to powerful Gen-AI tools also creates a knowledge asymmetry, making it imperative that educators train students to critically evaluate information and understand the ethical implications of Gen-AI use, including biases and misinformation. Gen-AI's disruptive effect evident in some industries. For example, the Finance sector uses Gen-AI for fraud detection and algorithmic trading (Forbes, 2024). Occupations with repetitive, knowledge-based tasks are at high risk of disruption particularly in administration roles (Brinkmann et al, 2023). Our graduates will not be entering a world where Gen-AI is a distant concept; they will be joining a workforce where it is a foundational, embedded component. In order to prepare students for a Gen-AI augmented job market, educators must adapt the engineering curriculum to emphasise a new hierarchy of skills. Traditional teaching methods and assessments are at risk of being circumvented by Gen-AI. To mitigate the risk of cognitive degeneration, we must innovate our teaching and assessment methods.

The ease with which students can generate self-reflections using Gen-AI poses a significant challenge to authentic assessment. Students can readily craft prompts that enable Gen-AI tools to produce reflections on their learning experiences. When these reflections pertain to a common activity undertaken by a large cohort, this practice can lead to a homogenisation effect where submissions lack individuality and originality. Such uniformity undermines the integrity of assessment, as lecturers struggle to differentiate genuine, thoughtful reflections from Gen-AI generated content. Consequently, appropriate grading becomes difficult, and more critically, the learning process is compromised where students bypass the essential cognitive exercise of reflection and critical thinking, which are central to deep learning.

OPPORTUNITIES WITH GEN-AI

Gen-AI has transformed the landscape of knowledge acquisition by providing immediate, accurate responses to prompts that require factual recall and conceptual understanding. This capability challenges the traditional role of mass lectures as a primary mode of knowledge transmission, rendering them increasingly obsolete. Lower-order learning outcomes in Bloom's taxonomy such as those require recalling definitions or explaining foundational engineering principles can now be efficiently addressed through Gen-AI tools. Consequently, engineering education must pivot toward fostering higher-order cognitive skills, even within introductory courses. Competencies within the CDIO syllabus such as Systems Thinking (2.3), Creative Thinking (2.4.4), and Critical Thinking (2.4.5) have become more essential for mitigating cognitive atrophy and ensuring that students engage deeply with the purpose and relevance of their learning.

According to Monat et al (2022), Systems Thinking (2.3) provides a holistic perspective that recognises the relationships among system components. The components and the environment that the system interacts with are as important as the components themselves. This is particularly applied in the CDIO Innovation Process where students are taught to understand the technical system, its function and behaviour as well as its elements, and Gen-AI can be used to aid them in understanding the psychological, cultural, economic and environmental implications of their engineering decisions.

Creative Thinking (2.4.4) is largely used in conceptualisation and ideation in the CDIO Innovation Process. Without Gen-AI, students carry out these tasks through brainstorming that relies heavily on their past experiences, prior knowledge and by searching and combing through the internet in search for inspiration and ideas. The conceptualisation and ideation process is divergent initially then students need to converge to a few practical ideas to move forward to the Implement phase of the CDIO Innovation Process. Students typically require a few weeks within the semester to complete the Conceiving and Designing phase. With Gen-AI, this process can be shortened with the both divergent and convergent tasks being done by Gen-AI, creating more time for students to use Critical Thinking to deliberate ideas.

When students deliberate ideas using Critical Thinking (2.4.5), they can challenge the assumptions made, have logical arguments to discuss fallacies and consider multiple perspectives so that they can make informed and concerted decisions that includes societal and multidisciplinary aspects.

As Gen-AI entered higher education with extraordinary speed, reshaping how students search, write, design and communicate, students must learn to adapt to changes (CDIO Syllabus 2.4.3) and learn to use it with integrity and ethically (CDIO Syllabus 2.5.1). It is important to discern validity, applicability and implications of recommendations from Gen-AI. This is another opportunity for students to compare and contrast the information provided by Gen-AI, thereby applying Critical Thinking.

SPARK Framework

In order to strengthen the development of Systems Thinking, Creative Thinking and Critical Thinking, a SPARK Framework is proposed to engage students in iterative process that preserve disciplinary rigour while leveraging Gen-AI for higher-order learning. Figure 1 illustrates the pedagogical reasoning cycle that enables educators to design learning experiences that integrate Gen-AI meaningfully and ethically thereby strengthening the CDIO thinking skills.

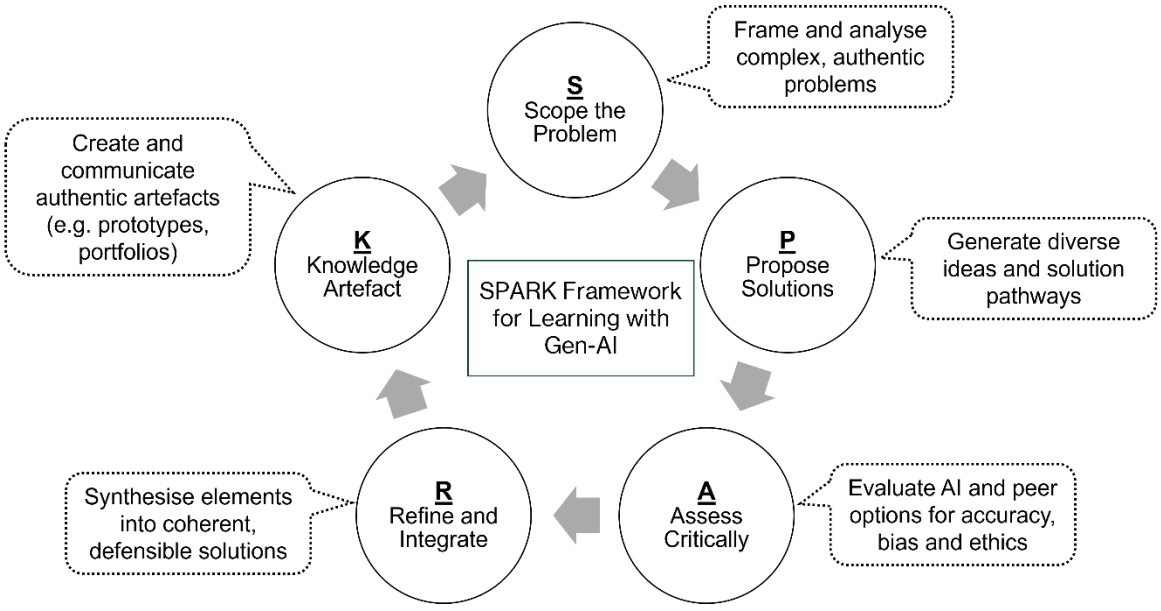


Figure 1. SPARK Framework for learning with Gen-AI

Educators can use the SPARK Framework to guide the redesigning of learning experiences for the era of Gen-AI. Developed within the context of engineering education, SPARK

Framework consists of five iterative phases to strengthen CDIO thinking skills: **S**cope the Problem, **P**ropose Solutions, **A**ssess Critically, **R**efine and Integrate, and **K**nowledge Artefact and Presentation. Each phase supports students in working with Gen-AI while maintaining cognitive ownership, critical evaluation and ethical reflection. This framework is pedagogically anchored in constructivism (Vygotsky, 1978), self-regulated learning (Zimmerman, 2002), and reflection-in-action (Schon, 1983), providing a structured yet flexible approach adaptable across disciplines.

Implementation of SPARK Framework is guided by Biggs' constructive alignment model (Biggs & Tang, 2011). Educators review learning outcomes, design active learning tasks aligned to SPARK's phases and redesign assessments to emphasise reflection and ethical use of Gen-AI. By situating SPARK within the constructive alignment, educators ensure that Gen-AI adoption remains sustainable and evidence-based, anchored in outcomes, not tools.

Table 1 illustrates the pedagogical intent of each phase of the SPARK Framework applied within the CDIO Innovation Process (CDIO Syllabus 4), role of Gen-AI and suggests what lecturers should focus on when re-designing learning activities and assessment for students.

Table 1. SPARK Framework for Learning with Gen-AI

SPARK Phase	Pedagogical Intent	CDIO Innovation Process	Role of Gen-AI	Suggestion on learning design
Scope the Problem	Frame and analyse complex, authentic problems	Conceiving, System Engineering and Management (CDIO Syllabus 4.3)	Use Gen-AI for sense-making	Curate open-ended contextual problems; guide students on ethical Gen-AI use
Propose Solutions	Generate diverse ideas and solution pathways	Designing (CDIO Syllabus 4.4)	Use Gen-AI as creative catalyst	Design tasks that require divergent thinking
Assess Critically	Evaluate Gen-AI outputs for accuracy, bias	Implementing (CDIO Syllabus 4.5)	Use Gen-AI as analytical collaborator	Scaffold reflection, critique and evaluation
Refine and Integrate	Synthesise elements into coherent and defensible solution	Implementing (CDIO Syllabus 4.5)	Use Gen-AI as a reflective partner	Document revisions, rationale and learning growth
Knowledge Artefact	Create and communicate authentic prototypes and portfolios	Operating (CDIO Syllabus 4.6)	Use Gen-AI as co-creator and feedback generator	Balance process and product; incorporate oral presentation or reflection

By positioning Gen-AI as a cognitive collaborator rather than a content generator, SPARK Framework encourages lecturers to design learning environments where students interrogate,

critique and extend Gen-AI generated ideas that strengthens the CDIO thinking skills. The framework thus contributes to the evolving discourse on Gen-AI pedagogy by reasserting the educator's role as designer of learning, not gatekeeper of tools.

SPARK Framework's strength lies in its pedagogical core. As a reasoning-based model, it transcends specific Gen-AI tools and can be applied across disciplines. It is focused on inquiry and reflection, ethics makes it resilient, if not immune, to immediate technology disruption (Luckin, 2018). The SPARK Framework also fosters self-direction, meta-cognition and ethical awareness, cultivating engineers who can work with Gen-AI responsibly (Zimmerman, 2002; Schon, 1983). This parallels CDIO's goal of producing reflective professionals who continually design, implement and operate within complex systems.

The SPARK Framework can also serve as a faculty development framework, equipping lecturers to align learning outcomes, learning activities and assessments with Gen-AI-enabled pedagogy. It advances CDIO Standards 9 and 10 by deepening competence in learning design and reflective practice. Over-reliance on Gen-AI, bias, ethics and faculty readiness can be potential challenges, so SPARK Framework can mitigate these through reflection checkpoints, structured evaluation and professional development.

Overall, SPARK Framework offers a pedagogically sustainable, cross-contextual and human-centered model for Gen-AI integration, reaffirming that while Gen-AI can generate information, only pedagogy transforms it into learning.

CONCLUSION AND FUTURE WORK

This paper proposed the SPARK Framework as a pedagogical approach for guiding educators in redesigning teaching and assessment in which Gen-AI acts as a trusted partner in thinking, creating and learning for students to support the CDIO thinking skills. By grounding Gen-AI integration in pedagogy rather than technology, SPARK repositions educators as architects of learning and Gen-AI as a cognitive collaborator. It ensures that engineering education remains human-centered, ethical and adaptive amid accelerating technological change.

Despite the potential benefits brought by the SPARK Framework, the use of Gen-AI within the framework presents notable risks. Technological advancement is rapid and it may out-pace lecturer's readiness in facilitating the use of Gen-AI with students. Uneven Gen-AI literacy and access among lecturers and students can lead to inconsistent and inequitable use. Specifically, differences in access for Gen-AI tools such as disparities between free and subscription-based versions may give rise to unequal learning experiences. Students with enhanced access to advanced features can engage in more frequent iterations and refined performance improvements thereby gaining potential advantages. Conversely, students with limited access may face constraints that hinder their ability to fully benefit from AI-supported learning activities. Such disparities risk unintentionally introducing inequities even where SPARK Framework is designed to promote inclusive and equitable learning outcomes.

So, the next phase will involve testing and implementing SPARK across multiple programs at Singapore Polytechnic. This will begin with a systematic review of learning outcomes in all modules, followed by the application of Constructive Alignment (Biggs & Tang, 2011) to redesign learning activities and assessments. Pilot studies will explore student learning experiences, including perceptions of agency, engagement and cognitive development in Gen-AI-supported environments, as well as lecturer adoption and teaching design practices

Focus group discussions with lecturers could yield in-depth insights into the aspects of SPARK Framework that were effective versus those that were less successful. In addition, evidence drawn from students' reflective journals could offer rich perspectives on their learning experiences in using Gen-AI as a learning collaborator. Future publications will share findings from SPARK's implementation, its impact on teaching and learning and insights for scaling across CDIO and other global contexts.

By anchoring Gen-AI in pedagogy, SPARK contributes to the sustainability of teaching and learning innovation, ensuring that as technology evolves, the essence of education remains human.

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MODEL PATHWAY IN CHEMICAL ENGINEERING TO DEVELOP STUDENTS' SUSTAINABILITY MINDSET USING CDIO

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ABSTRACT

This paper examines the evolving role of chemical engineering education in balancing process and product design to address sustainability challenges. Chemical engineering education has traditionally emphasized process design and operation, culminating in capstone plant design projects. In recent decades, however, chemical product design has emerged as an important complementary pathway, offering opportunities to address sustainability challenges more holistically. With the advent of the United Nations Sustainable Development Goals (UNSDGs), the discipline is increasingly being called upon to integrate sustainability principles into both process and product contexts. This paper builds on earlier work using the CDIO Framework to embed sustainability mindset development in chemical engineering curricula, extending the model to a "double helix" dual pathway of process and product design. The paper demonstrates how integrated learning experiences can be designed using GenAI and systematically structured to cultivate key competencies for sustainability. A revised set of eight competencies, aligned with the European GreenComp framework, is proposed to strengthen connections to sustainability mindset principles and address prior gaps such as problem framing. Systems thinking and values thinking are identified as the anchor competencies, one for each strand of the "double helix" pathway that intertwines analytical and ethical dimensions of sustainability learning. This pairing ensures that students not only grasp systemic complexity but also internalize fairness, responsibility, and personal agency. This paper shares a possible double helix for chemical engineering, with integrated learning experiences that progressively expose students to sustainability issues of increasing complexity, supported by faculty oversight. The approach is equally applicable to programs with only process pathways or beyond chemical engineering, offering a reproducible model for embedding sustainability mindset across disciplines. Lastly, the paper discusses the advantages and limitations of the double helix model, and the need to continue keeping abreast with technological development given the dynamic nature of sustainable development.

KEYWORDS

Sustainability Mindset, Chemical Engineering, Key Competencies for Sustainability, Double Helix, CDIO Standards 1, 2, 3 and 7

INTRODUCTION

The discipline of chemical engineering often focused on the teaching of chemical process design and operation, culminate in the final year plant design project where students working in teams using professional simulation software, produced a design "package" of a chemical processing plant to produce a given chemical product of desired specifications, complete with a blueprint of how the plant is to be constructed. This had been the dominant approach for all chemical engineering programs. On the other hand, starting in the late 1990s to early 2000s, the coverage of chemical product design and development started to appear in some chemical engineering programs, see for example Moggridge & Cussler (2000). This is followed by the publication of the textbook *Chemical Product Design* by these 2 authors, widely considered as the first dedicated contribution to the teaching of the subject (Cussler & Moggridge, 2001).

With the introduction of United Nations Sustainable Development Goals (UNSDGs), education had become a key approach to addressing sustainability issues. Chemical engineering programs are no exception, and the teaching of chemical engineering principles has been enhanced to include contribution of the discipline towards sustainable development. Traditional programs that focused on chemical process design and operation have begun introducing chemical product design and development into the curriculum. The chemical engineering program from Singapore Polytechnic (SP) is one such program that used the CDIO Framework to redesign its traditional curriculum to offer both process and product learning pathways to its students (Cheah, 2021). Further work on integration of sustainable development in SP centered on using the CDIO Framework to develop sustainability mindset for students and the effort is still on-going (Cheah *et al*, 2025; Yang & Cheah, 2025).

Scope of This Paper

This paper continues the previous effort, leveraging on new developments in the use of generative artificial intelligence (GenAI) in tandem with the CDIO Framework reported by Cheah (2026a). More specifically, this paper strives to demonstrate how the model of progressive learning pathway by Cheah *et al* (2025) can be designed for a chemical engineering program with both process design and product design learning pathways. The author further argues that such dual pathway chemical engineering programs are uniquely posed to offer a more integrated approach toward addressing sustainability challenges.

This paper also contributes to the ongoing discourse in the chemical engineering community on the teaching of chemical product design, which had been slow to permeate into the traditionally process-oriented nature of chemical engineering education. This paper will briefly discuss the challenges faced in driving chemical product design forward, despite the acknowledge benefits it delivers. It will also improve on the model by Cheah *et al* (2025) by incorporating new developments in key competencies for sustainability and strengthen the connection to sustainability mindset principles. The approach shared will add to the repertoire of tools progressive developed for chemical product design and development, focusing on active and experiential learning in implementing sustainability initiatives to develop students' sustainability mindset.

However, it must be stressed that the approach outlined in this paper is equally applicable to chemical engineering programs with only process design pathway, and for that matter any program beyond chemical engineering. However, the choice of the dual pathway is meant to illustrate the mutually supporting and complementary nature of the 2 pathways which augurs well with the intent of the integrated curriculum design of CDIO.

CHEMICAL PROCESS VS PRODUCT DESIGN: SUSTAINABILITY CHALLENGES

In chemical engineering education, both pathways share core principles unique to chemical engineering such as mass and energy balances, chemical thermodynamics, reaction kinetics and transport phenomena. Henceforth the same principles are used in both pathways, although the learning objectives are different for each pathway. Chemical process design focuses on *how* to make something efficiently (focusing on topics such as unit operations, thermodynamics, simulation, safety, scale-up), while chemical product design focuses on *what* to make (focusing on formulations, material properties, functionality for end-use, market needs). Process design optimizes existing or new production lines (distillation, reactors), whereas product design creates novel materials or formulations for specific applications (pharmaceuticals, specialty chemicals, personal care).

Chemical process design and operations differ significantly from chemical product design and development when it comes to sustainability issues, with divergence both in scope and impact. These can be summarized in Table 1 below.

Table 1. Key sustainability challenges for chemical process vs product design

Chemical Process Design & Operations	Chemical Product Design & Development
• Energy intensity & emissions: Chemical plants contribute significantly to global CO_2 emissions; decarbonizing energy use is critical • Feedstock variability: Transitioning from fossil-based to renewable feedstocks (biomass, waste streams) introduces variability in quality and supply • Waste minimization: Designing closed-loop systems to reduce hazardous by-products and effluents • Safety & resilience: Balancing sustainability with operational safety, especially under uncertain supply chains • Integration with circular economy: Processes must adapt to recycling and revalorization of materials	• Life-cycle impacts: Products must be designed with cradle-to-grave considerations - minimizing hazards, emissions, and waste across their entire lifespan • Material innovation: Developing safer, biodegradable, or recyclable chemicals and polymers • Consumer & regulatory pressures: Sustainability is now a market differentiator, but aligning innovation with evolving regulations is complex • Green chemistry principles: Embedding atom economy, safer solvents, and reduced toxicity into product design • Scalability & adoption: Sustainable products often face barriers in scaling economically while competing with entrenched conventional products

Despite their inherent differences, a compelling case exists for integrating these two pathways to cultivate a robust sustainability mindset in students. Regarding chemical process design and operation, students must look beyond mere efficiency to prioritize systemic resilience, adaptability, and long-term environmental health. This shift demands a high tolerance for ambiguity, the ability to navigate complex socio-economic trade-offs, and the courage to challenge conventional economic models. Regarding chemical product design and development, students must embrace a deeper sense of responsibility – anticipating unintended consequences and championing ethical innovation through life-cycle stewardship. Integrated, these pathways empower chemical engineers to safeguard ecological systems while driving meaningful economic and societal progress.

Coverage of Chemical Product Design in Chemical Engineering Curriculum

This author conducted a "quick-and-dirty" survey to ascertain the number of chemical engineering programs worldwide that offer chemical product design in the curriculum. This is just to obtain a sense of the extent of adoption of chemical product design to-date. Therefore, an exact percentage of undergraduate chemical engineering programs with elements of chemical product design is not necessary. The methodology is straight-forward. The author first obtained the name of universities offering chemical engineering programs from the Times Higher Education (THE) World University Ranking. The list is fed into Google Gemini with prompts requesting it to visit the website of each university and report on the chemical engineering program offered, and where chemical product design is present; and if present to indicate with short explanatory notes whether the coverage of chemical product design is explicitly mentioned or inferred. Due to the sheer number of universities, only the top 259 was analyzed. Results with inferred presence of chemical products were eliminated via manual check by the author, as the inference was made based on subjects offered, which may be related to product design. The final result showed that the distribution is almost equal: 47.5% of universities offer chemical product design, i.e. explicitly mentioned in its website.

Challenges in Integrating Chemical Product Design

In October 2023, Computer Aids for Chemical Engineering (CACHE), a non-profit organization dedicated to developing and distributing technology-based educational materials and software for the profession, commissioned a Design Task Force dedicated to conducting a year-long review of chemical product design education worldwide. It delivered a disappointing finding that the integration of chemical product design remained limited (Seider *et al*, 2025). Most programs are still dominated by chemical process design, with chemical product remaining at the peripheral.

The challenges hampering progress include the following (Seider *et al*, 2025; Fung & Ng, 2018; Rodrigues & Cussler, 2016; Seider & Widogdo, 2012; Skov & Kiil, 2011):

1. *Lack of standardization*: No consensus on what and how to teach chemical product design resulting in teaching approaches vary widely across institutions. There is also no "standard" software compared to chemical process design.
2. *"Beyond engineering"*: Teaching chemical product design requires interdisciplinary thinking, and competency in various "soft" skill such as creativity, customer needs, market demand.
3. *Lack of teaching resources*: There is no agreed model for teaching, resulting in varying approaches across institutions. Lack of understanding on how product formulation and/or processing conditions lead to final product performance is also another concern.
4. *Use of specialized technologies*: Chemical products often rely on equipment and unit operations not usually covered in core curriculum.
5. *Faculty discomfort*: More ambiguity and uncertainty over the outcomes, coupled with the higher workload perceived for handling product design which is more open-ended in nature.
6. *Industry support*: Collaborations between academia and industry exist but are not widespread; with many programs lack strong industry ties for experiential learning, e.g. due to faculty lacking relevant real-world experience to form partnership with industry.
7. *Sustainability*: This will add another dimension to the teaching of chemical product design, adding to the challenges identified above, e.g. dealing with empathy, values and beliefs, lifecycle analysis, carbon footprint, etc.

SP-CDIO MODEL FOR INTEGRATING KEY COMPETENCIES FOR SUSTaiNABILITY & COVERAGE OF SUSTaiNABLE DEVELOPMENT IN SP-CDIO SYLLABUS: AN UPDATE

Cheah *et al* (2025) had shared an approach to developing students' sustainability mindset using the CDIO Framework, which is useful for adoption by any programs. It is derived from an extensive review of extant literature on what constituted the key competencies for sustainability that are needed to carry out sustainability initiatives. The approach predicates on a set of 12 sustainability mindset principles (Rimanoczy & Llamazares, 2021) that can be developed alongside the application of key competencies for sustainability, leading to the development of sustainability mindset (Kassel, Rimanoczy & Mitchell, 2016).

One key omission from the works of Cheah *et al* (2025) is the inclusion of the European framework for sustainability competence called the GreenComp (Bianchi *et al*, 2022). GreenComp suggests 4 areas with 3 competences each: (1) *Embodying Sustainability Values*, (2) *Embracing Complexity in Sustainability*, (3) *Envisioning Sustainable Futures*, and (4) *Acting for Sustainability*. A quick analysis of the underpinning skills and attitudes for the 12 competences (not elaborated in this work) showed close matching to the 8 key competencies for sustainability from Cheah *et al* (2025) except for "Problem Framing". This is a key distinction from GreenComp and an important one – it explicitly brings out attributes such as fairness and adaptability; and directly address the drivers for "bias for action" in tackling sustainability issues via individual initiative, collective action and political agency. Hence, for this work, this author proposed that it be subsumed into Integrated Problem-Solving Competency, and the GreenComp "Problem Framing" added, to be termed Problem Framing Competency as enhancement of the earlier model by Cheah *et al* (2025).

Furthermore, the inclusion of Implementation Competency into the key competencies has been debatable (Cheah *et al*, 2025). This, plus the desire to avoid creating of a laundry list of key competencies for sustainability, this work proposes that Implementation Competency be subsumed under Integrated Problem-Solving Competency, thus maintaining the number of key competencies for sustainability at 8. The descriptors for the revised set of 8 key competencies for sustainability were reworded for better alignment for the 4 competences areas of GreenComp. The result is shown in Table 2.

The revised key competencies for sustainability along with another strand of work by the author to revise the existing SP-CDIO Syllabus, also lend themselves more readily to better alignment with the 12 sustainability mindset principles which was grouped into 4 areas: (1) *Ecological Worldview* with 2 principles of "Ecoliteracy" and "My Contribution"; (2) *Systems Perspective* with 4 principles of "Long-term Thinking", "Flow in Cycles", "Both+And Thinking" and "Interconnectedness"; (3) *Spiritual Intelligence* with 3 principles of "Purpose", "Oneness with Nature" and "Mindfulness"; and (4) *Emotional Intelligence* with 3 principles of "Creative Innovation", "Reflection" and "Self-awareness".

Detailed discussions of the suggested revisions to the CDIO Syllabus version 3.0 have been detailed elsewhere (Cheah, 2026c). Suffice to note here that earlier work by Cheah *et al* (2025) had noted the "not-too-ideal" mapping between the CDIO Syllabus with the 12 sustainability mindset principles. One key aspect of the suggested revisions is to include more "inner dimensions" of skills and attitudes desired in students. This would improve the mapping between the revised and updated CDIO Syllabus and the 12 sustainability mindset principles. Table 3 shows the updated mapping with the addition of Problem Framing Competency and the absorption of Implementation Competency into Integrated Problem-Solving Competency.

Table 2. Alignment of 8 key competencies for sustainability to GreenComp competence

#	Key Competency	Descriptor (updated with GreenComp input)	Alignment to GreenComp
1	Values Thinking	Ability to anchor decisions in ethical principles, fairness, and responsibility, ensuring sustainability choices reflect human and ecological integrity.	*Embodying sustainability values:* 1.1 Valuing Sustainability 1.2 Supporting Fairness
2	Intrapersonal Competency	Ability to cultivate self-awareness, resilience, and mindfulness to manage ambiguity, align personal values, and sustain motivation in complex contexts.	*Envisioning sustainable futures:* 3.2 Adaptability 1.3 Promoting Nature
3	Interpersonal Competency	Ability to collaborate across diverse stakeholders, communicate effectively, and build trust for collective sustainability action.	*Acting for sustainability*: 4.1 Political Agency 4.2 Collective Action
4	Systems Thinking	Ability to analyze interconnections within natural, social, and technical systems, recognizing feedback loops, trade-offs, and unintended consequences.	*Embracing complexity in sustainability:* 2.1 Systems Thinking
5	Futures Thinking	Ability to anticipate long-term scenarios, envision alternative futures, and design resilient strategies under uncertainty.	*Envisioning sustainable futures:* 3.1 Futures Literacy 3.3 Exploratory Thinking
6	Problem Framing Competency (new)	Ability to define and structure sustainability challenges, clarify boundaries, and reframe issues to reveal opportunities for innovative and responsible solutions.	*Embracing complexity in sustainability:* 2.3 Problem Framing
7	Strategic Thinking	Ability to identify leverage points, prioritize interventions, and design phased pathways for systemic change.	*Embracing complexity in sustainability:* 2.2 Critical Thinking 2.3 Problem Framing
8	Integrated Problem-Solving Competency (merged with Implementation)	Ability to synthesize diverse knowledge and perspectives into coherent solutions, and to design actionable pathways for adoption, piloting, and scaling.	*Acting for sustainability:* 4.3 Individual Initiative

DEVELOPING SUSTaiNABILITY MINDSET FOR CHEMICAL ENGINEERING STUDENTS

Systems thinking is the most important consideration in traditional chemical engineering program – which as we had seen earlier, is solidly grounded in chemical process design and operation. It provides a holistic perspective that considers the complex interactions and interdependencies among all process components in a chemical plant, ensuring greater safety, efficiency, and sustainability. It helps engineers anticipate unintended consequences that arise when optimizing only isolated parts of the plant. A particular type of systems thinking is lifecycle thinking which underpins the concept of circular economy, an important framework in promoting net zero emission practices throughout the lifecycle of a product (Heard & Vaccari, 2024). Hence using systems thinking competency to serve as the “spine” to progressively develop students’ sustainability mindset over the program duration is the most appropriate choice. This can be done via a series of CDIO integrated learning experiences (Standard 7) using suitable UNSDGs as the learning contexts, supported by other key competencies for sustainability (Cheah *et al*, 2025). When used in chemical product design and development, it can aid in identifying possible unintended consequences by surfacing interactions between elements that are not immediately obvious.

Table 3. Mapping between revised key competencies for sustainability with sustainability mindset principles

Sustainability Mindset Principles		Values Thinking	Intrapersonal	Interpersonal	Systems Thinking	Futures Thinking	Problem Framing	Strategic Thinking	Integrated Problem-Solving
Ecological Worldview	Ecoliteracy				X		X		
	My Contribution	X	X	X					
Systems Perspective	Long-term Thinking				X	X	X	X	
	Flow in Cycles				X		X		
	Both+And Thinking			X	X		X	X	X
	Interconnectedness	X		X	X	X	X	X	X
Spiritual Intelligence	Purpose	X	X	X		X		X	X
	Oneness with Nature	X							
	Mindfulness	X	X		X		X		X
Emotional Intelligence	Creative Innovation		X					X	X
	Reflection	X	X	X	X	X	X	X	X
	Self-awareness	X	X				X		X

Furthermore, sustainable development is inherently a value-laden topic. Sustainability challenges are inherently normative and contested, requiring students to navigate trade-offs, justice, and long-term ethics. This is because sustainability is not merely a technical or scientific issue but one fundamentally intertwined with ethics, morality, and subjective societal beliefs. Decisions regarding sustainability often involve balancing competing priorities and differing worldviews about what constitutes a desirable and just future. Given the cognitively heavy demand of systems thinking, it may over-emphasize analytical reasoning at the expense of emotional, spiritual, and values-based dimensions of sustainability mindset. Students may grasp systems logic but not internalizing personal agency or values that are essential for transformative impact towards sustainable development: “Head without heart”. There is a risk of “intellectualization of sustainability” where students understand complexity of the challenges but remain emotionally detached. This will undermine the much-needed mindset change. Transformative learning requires emotional engagement, introspection, and ethical reflection – dimensions not inherently activated by systems logic. These aspects of transformation are best developed using values thinking competency. In the absence of value-based considerations, systems models may focus solely on efficiency, potentially overlooking important factors such as equity and ecological integrity.

Hence, it would be logical to “pair” systems thinking competency with values thinking competency, creating what the author call a “double helix” (a term borrowed from the life sciences describing the structure of a DNA molecule where the 2 strands wound around each other, carrying the genetic instructions for all living organisms) development pathway for sustainable mindset development of students from for chemical engineering programs focusing on both chemical processes and products. Such an approach offers greater opportunities for tackling different aspects of sustainability issues. One “strand of the DNA” would be the systems thinking competency, and the “other DNA strand” would be the values thinking competency.

A hypothetical example is shown in Figure 1, where a series of CDIO integrated learning experiences is designed using systems thinking competency and values thinking competency as "key anchors" onto which students working in teams address sustainability issues of increasing complexity from simple to complicated to complex.

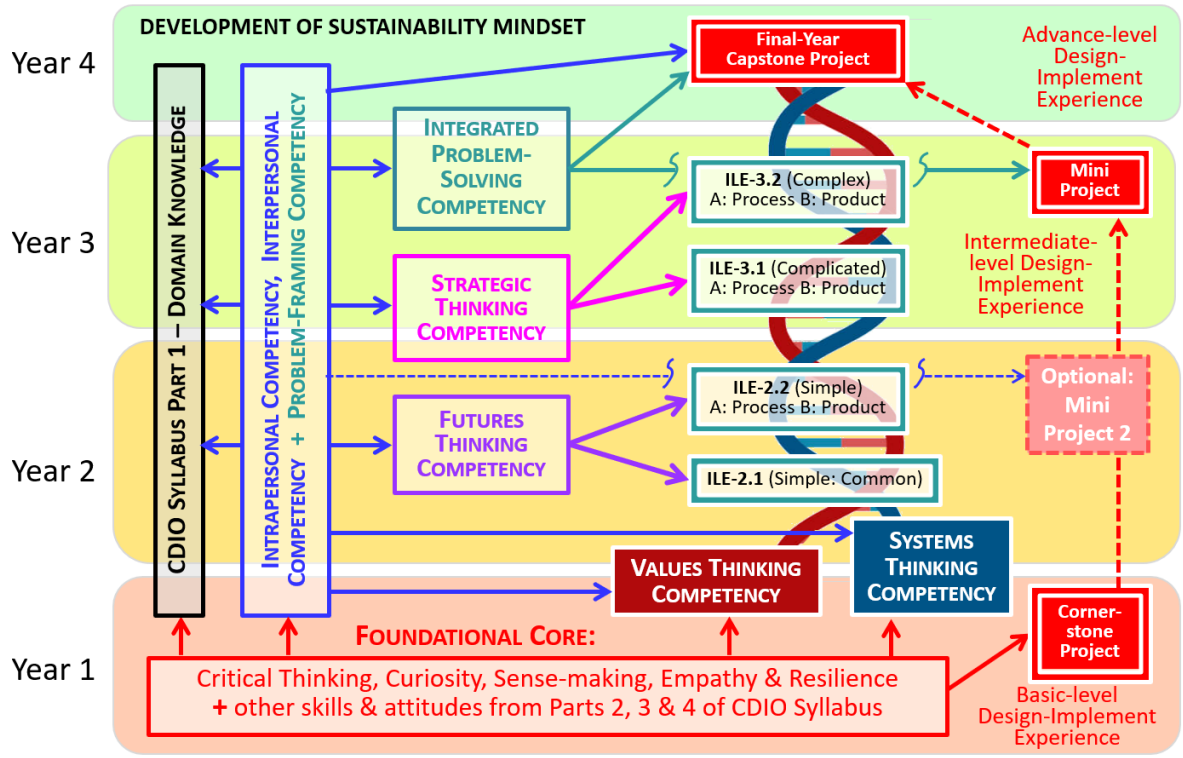


Figure 1. Proposed double helix development pathway for developing sustainability mindset

Integrated learning experiences are preferred over design-implement experiences for the systematic development of sustainability mindset. This is because integrated learning experiences offer a most systematic and "controlled" way to structure the learning experiences such that all students are exposed to the challenges in the same manner, to the desired level of proficiency. This contrasts with the use of projects in design-implement experiences where there are more variations from project to project, such that it is more challenging to mandate the same affective-type learning outcomes from different projects.

As can be seen in Figure 1, there are altogether 7 integrated learning experiences denoted by the acronym ILE-X.X. As an example, ILE-2.1 denotes integrated learning experience for Year 2 Semester 1, which is the very first learning task for students, with simple sustainability issues to be addressed.

This model shows that Year 1 is used to introduce students to the fundamental skills and attitudes needed to develop key competencies for sustainability. We suggest that the learning context for ILE-2.1 to be based on sustainability issues that are familiar to students to illustrate how the systems thinking competency and values thinking competency mutually support one another. Subsequent ILEs beginning with Year 2 Semester 2 (i.e. ILE-2.2) will feature learning contexts aligned to the 2 learning pathways: "A" for chemical process design and operation, and "B" for chemical product design and development.

Futures thinking competency is introduced in Year 2 to "prime" students to envision a more sustainable future, while strategic thinking competency is introduced in Year 3 to start exposing students to the need to plan for engaging key stakeholders in launching their proposed sustainability initiative. Students will be required to demonstrate the various key competencies for sustainability in their respective final year capstone projects.

The pedagogical logic for the 3 integrated learning experiences for increasing challenge in addressing sustainability issues can be summarized as follows:

- ILE-2.1: Familiar, everyday sustainability issue to build awareness and invoke a sense of personal responsibility
- ILE-2.2: Discipline-specific but simple sustainability issues to introduce technical grounding in process and product contexts
- ILE-3.1: Complicated industrial issues, with the need to address various trade-offs and resolve contested values while maintaining the required technical rigor
- ILE-3.2: Complex systemic redesign to tackle wicked problems requiring integration of systems thinking and values thinking

Design of Integrated Learning Experiences for Sustainable Development

Among the many aspects that GenAI can assist faculty in matters related to teaching and learning, of interest in this paper is the design of integrated learning experiences to develop the key competencies for sustainability as envisioned in Figure 1. Cheah (2025b) had shared how faculty can use GenAI guided by CDIO Standards to carry out curriculum design, highlighting aspect of the effort that required human oversight (human-in-the-loop) to guard against limitations of GenAI. Table 4 summarizes key considerations of relevant CDIO standards related to using GenAI to aid the design of the development pathways.

Table 4. Use of GenAI and faculty oversight for related CDIO standards

CDIO Standard	Use of GenAI	Faculty Oversight (Human-in-the-Loop)
1 – The Context	Identify appropriate UNSDGs relevant to the program and scenarios used (see Standard 7)	Each scenario is of appropriate level of difficulty, progression is acceptable Context is appropriate for year of study
2 – Learning Outcomes	Suggest skills and attitudes needed Suggest possible learning outcomes	Ensure underpinning skills and attitudes, e.g. teamwork, communication, critical thinking, etc are already adequately developed in earlier courses, although the contexts may be different
3 – Integrated Curriculum	NOT USED	Decide on which courses are most appropriate for each scenario Identify available supporting courses with needed prior knowledge
6 – Engineering Learning Workspaces	NOT USED	Identify adequacy of existing facilities and environment to support learning context and desired learning outcomes
7 – Integrated Learning Experiences	Generate task scenarios for different levels of difficulty: Simple Complicated and Complex; suggest plausible unintended consequences for each scenario	Ensure suitable scaffolding are provided at each level and matched to the level of difficulty
11 – Learning Assessment	Suggest questions for in-class assessment, debrief, and report writing Prepare performance rubric	Review questions posed for relevance and validity Check reasonableness of rubrics Ensure that skills and attitudes are assessed in context and constructive alignment is maintained
12 – Program Evaluation	Suggest potential areas that require faculty oversight	Look into one's own experience to ascertain any other aspects that GenAI may have missed

As argued in earlier section of this paper, adding the considerations from GreenComp to the key competencies for sustainability had strengthened the connections with sustainability mindset principles. With the design of the 7 ILEs using GenAI we can have an implementable approach that build on the theoretical considerations of Cheah *et al* (2025) towards developing students' sustainability mindset. Effectively they serve 2 purposes: first is to develop the necessary sustainable mindset principles in students, appropriate to the context of the task-at-hand; and secondly to link the principles to key competencies for sustainability that are to be used in tackling the sustainability issue. Table 5 shows the different sustainability issues as suggested by GenAI for the integrated learning experiences, and the main sustainability mindset principles activated.

Table 5. Sustainability mindset principles activated in each integrated learning experience

Year & Level	Sustainability Issue	Main Sustainability Mindset Principles Activated
Year 2.1 Simple: Common	Reducing single-use plastics in campus cafeterias	**Ecoliteracy** (understanding plastic impacts) **My Contribution** (personal agency, footprint reduction) **Interconnectedness** (linking campus choices to global pollution) **Flow in Cycles** (materials must circulate) **Reflection** (journaling on convenience vs. consequence)
Year 2.2 Simple: A. Process	Reducing energy waste in laboratory-scale distillation units	**Ecoliteracy** (energy flows, emissions) **Interconnectedness** (lab choices → campus energy budgets) **Both+And Thinking** (efficiency + safety) **Long-term Thinking** (sustaining improvements across cohorts) **Mindfulness** (attentiveness to operational discipline) **Reflection** (learning from iterative improvements)
Year 2.2 Simple: B. Product	Formulating eco-friendly cleaning products for campus use	**Ecoliteracy** (toxicity, biodegradability) **Interconnectedness** (users, wastewater systems) **Creative Innovation** (new formulations) **Both+And Thinking** (performance + ecological safety) **Purpose** (aligning with stewardship and health) **Reflection / Self-awareness** (challenging assumptions about "clean")
Year 3.1 Complicated: A. Process	Optimizing water & energy use in a mid-scale chemical plant	**Interconnectedness** (water–energy–emissions links) **Long-term Thinking** (resource stress scenarios) **Both+And Thinking (**quality + efficiency) **Flow in Cycles** (reuse/recovery loops) **Purpose** (aligning plant goals with community) **Reflection / Self-awareness** (bias checks in optimization)
Year 3.1 Complicated: B. Product	Developing safer solvents for industrial and consumer applications	**Ecoliteracy** (hazards, exposure routes) **Long-term Thinking** (regulatory foresight) **Interconnectedness** (supply chain mapping) **Creative Innovation** (ionic liquids, CO_2 solvents) **Both+And Thinking** (performance + safety + cost) **Self-awareness** (worker/consumer perceptions)
Year 3.2 Complex: A. Process	Designing a circular economy strategy for chemical processes	**Interconnectedness** (multi-party flows) **Flow in Cycles** (closed-loop systems) **Long-term Thinking** (multi-decade scenarios) **Both+And Thinking** (economic + ecological goals) **Purpose** (stewardship charter) **Mindfulness / Reflection** (deliberation under uncertainty)
Year 3.2 Complex: B. Product	Designing circular economy strategies for chemical products (e.g. polymers, pharmaceuticals	**Ecoliteracy** (polymer recyclability, toxicity) **Interconnectedness** (value chain mapping) **Flow in Cycles** (design for disassembly, passports) **Long-term Thinking** (future infrastructure, standards) **Creative Innovation** (safe-by-design prototypes) **Both+And Thinking** (durability + recyclability) **Purpose / Mindfulness / Reflection** (ethical navigation of trade-offs)

Each of the integrated learning experiences will require students to use systems thinking to identify the potential trade-off and plausible unintended consequences that may arise from each proposed solution. These activities will also provide students with ample opportunities to discuss the relative merits of each situation not only from the technical requirements and feasibility, but more importantly from socio-economic and cultural perspectives – i.e. applying values thinking – to develop a more holistic understanding of the sustainability issue on hand. Table 6 shows summarize the trade-offs and unintended consequences as suggested by GenAI for each integrated learning experience. Faculty interpretations of the suggestions using one's domain expertise are necessary to provide the required human-in-the-loop scrutiny of GenAI outputs to ensure relevance.

Table 6 also shows examples of how other key competencies, namely interpersonal, intrapersonal, futures thinking and strategic thinking can support the double helix competencies of systems thinking and values thinking. Table A1 in the Appendix provides examples of other skills and attitudes required to develop these required key competencies for sustainability. Note that the list shown is not exhaustive and that actual "sequence" of their integration must necessarily follow specific program's own approach in developing the key competencies for sustainability. Note also that specific courses where such skills and attitudes are to be included are also deliberately omitted. The flexible approach afforded by this model is meant for any program to leverage on its own curriculum structure to progressively build up students' sustainability mindset in using the appropriate UNSDGs as learning contexts.

Lastly, Table 7 shows the performance indicators for each of the integrated learning experiences produced by GenAI, based on the specific task scenarios. GenAI can help to further develop them into performance rubrics, for example using the Dreyfus Scale. Once again, human oversight is necessary to ensure the proper use of GenAI.

DISCUSSIONS: ADVANTAGES AND LIMITATIONS OF DOUBLE HELIX APPROACH

The double helix approach towards sustainability mindset development can potentially provide a more structured approach to tackling wicked sustainability issues, by emphasizing both "head and heart" to work in tandem: systems thinking ensuring that students can analyse complex interdependencies, optimize processes, and anticipate unintended consequences; while values thinking anchors those analyses in ethics, fairness, and ecological responsibility, preventing purely efficiency-driven solutions. Ethical reflection guides students in navigating the trade-offs and can potentially inspire more innovative system redesigns that might not emerge from technical analysis alone.

One aspect that flows naturally that needs to be addressed in the future is that of convergence between chemical process design and chemical product design, which further extend the development of sustainability mindset towards a holistic encapsulation. Much work needs to be done in this area. Fung & Ng (2018) for example presented a comprehensive approach that integrates product design with process design. It begins with a market study to gather market information, compare competing products, identify qualitative product attributes for satisfying consumer preferences which are then converted to quantitative technical parameters through heuristics, mathematical models, experiments, tools, and databases. A suitable manufacturing process is then synthesized to produce the product with the required product specifications, followed by a financial analysis to evaluate product profitability. Two case studies were shared. The author hope that the double helix approach presented in this paper can contribute positively to this endeavour.

Table 6. Summary of integrated learning experiences designed by Gemini

Year & Level	Sustainability Issue	Main SDGs	Key Trade-off	Unintended Consequences	"Double Helix" Competency	Other Supporting Competencies (not including Integrated Problem-Solving)
Year 2.1 Simple: Common	Reducing single-use plastics in campus cafeterias	12, 13, 14	Convenience & cost vs. ecological responsibility	1. Higher water/energy use for washing reusables 2. Hygiene risks if cleaning inadequate 3. Resistance due to inconvenience	Systems thinking (material flows, waste loops) Values thinking (responsibility, fairness)	Intrapersonal (personal responsibility, habit change) Interpersonal (peer influence, collective action)
Year 2.2 Simple: A. Process	Reducing energy waste in laboratory-scale distillation units	7, 12, 13	Efficiency gains vs. upfront modifications	1. Added complexity in lab operations 2. Potential safety risks if insulation poorly applied 3. Increased maintenance burden	Systems thinking (energy flows) Values thinking (resource stewardship)	Strategic Thinking (targeting low-hanging efficiency gains) Intrapersonal (attention to detail, stewardship mindset)
Year 2.2 Simple: B. Product	Formulating eco-friendly cleaning products for campus use	3, 6, 12	Performance & cost vs. ecological safety	1. Reduced cleaning effectiveness 2. Higher costs for biodegradable ingredients 3. Wastewater treatment challenges from new formulations	Systems thinking (life cycle of products) Values thinking (health, ecological safety)	Interpersonal (user safety, stakeholder empathy) Strategic Thinking (balancing performance vs. safety)
Year 3.1 Complicated: A. Process	Optimizing water and energy use in a mid-scale chemical plant	6, 7, 9, 12	Operational efficiency vs. capital investment	1. Water reuse concentrates contaminants 2. Reduced cooling may affect product quality 3. Increased emissions from added treatment chemicals	Systems thinking (resource interdependencies) Values thinking (equity in resource use)	Strategic Thinking (multi-variable trade-offs) Futures Thinking (long-term resource resilience) Intrapersonal (resilience under constraints)
Year 3.1 Complicated: B. Product	Developing safer solvents for industrial and consumer applications	3, 9, 12, 13	Safety & sustainability vs. performance & cost	1. Bio-based solvents compete with food crops 2. New infrastructure/disposal needs 3. Market resistance if performance drops or costs rise	Systems thinking (life cycle, substitution impacts) Values thinking (health, justice, responsibility)	Futures Thinking (anticipating regulatory shifts) Interpersonal (collaboration across supply chain) Strategic Thinking (designing for adoption)
Year 3.2 Complex: A. Process	Designing a circular economy strategy for chemical processes	7, 9, 12, 13, 17	System redesign vs. economic competitive-ness	1. Impurity accumulation in recycling loops 2. Increased operational complexity & safety risks 3. Higher global energy demand despite local waste reduction	Systems thinking (closed loops, cross-sector integration) Values thinking (long-term stewardship, fairness)	Futures Thinking (scenario planning, long-term loops) Strategic Thinking (leveraging systemic interventions) Interpersonal (cross-sector collaboration)
Year 3.2 Complex: B. Product	Designing circular economy strategies for chemical products (e.g. polymers, pharmaceuticals)	3, 9, 11, 12, 17	Innovation & sustainability vs. scalability & affordability	1. Lack of recycling infrastructure 2. Regulatory delays for safe-by-design products 3. Consumer scepticism/ greenwashing concerns	Systems thinking (cradle-to-grave product flows) Values thinking (safe-by-design, justice, transparency)	Futures Thinking (designing for future infrastructure) Interpersonal (engaging consumers, regulators) Intrapersonal (ambiguity tolerance, ethical creativity)

Table 7. Performance indicators for integrated learning experiences

Year & Level	Pathway	Sustainability Issue	Performance Indicators
Year 2.1 (Simple)	General	Reducing single-use plastics in campus cafeterias	Identifies material flows of plastics and alternatives (systems thinking) Articulates ethical trade-offs between convenience and ecological responsibility (values thinking) Demonstrates reflection through journaling or discussion Proposes feasible campus-level interventions with cost-benefit awareness.
Year 2.2 (Simple)	Process	Reducing energy waste in lab-scale distillation units	Calculates energy balances and quantifies efficiency improvements Applies safety checks when modifying lab setups Explains stewardship values in resource use Documents unintended consequences (e.g. maintenance burden) in lab reports.
Year 2.2 (Simple)	Product	Formulating eco-friendly cleaning products	Designs and tests formulations with measurable biodegradability/toxicity outcomes Balances performance vs. ecological safety in product evaluation Reflects on consumer perceptions of “clean” in written reports Demonstrates creative innovation in proposing alternatives
Year 3.1 (Complicated)	Process	Optimizing water & energy use in mid-scale plant	Builds simulation models showing water-energy-emission interdependencies Identifies trade-offs between operational efficiency and capital investment Justifies decisions using fairness in resource allocation Communicates optimization results with stakeholder-oriented clarity
Year 3.1 (Complicated)	Product	Developing safer solvents	Compares solvent properties (toxicity, performance, cost) using quantitative metrics Anticipates regulatory and market adoption challenges Applies substitution analysis (life-cycle impacts) Reflects on justice and responsibility in solvent design choices
Year 3.2 (Complex)	Process	Designing circular economy strategies for chemical processes	Maps closed-loop flow across multiple sectors Identifies impurity accumulation and safety risks in recycling loops Proposes phased redesign strategies balancing competitiveness and stewardship Demonstrates long-term thinking in scenario planning
Year 3.2 (Complex)	Product	Designing circular economy strategies for chemical products	Conducts cradle-to-grave analysis of product flows Designs safe-by-design prototypes with measurable recyclability Anticipates unintended consequences (e.g. infrastructure gaps, consumer skepticism) Demonstrates transparency and justice in trade-off communication.

At the time of this writing, the SP chemical engineering program is undergoing curriculum revamp to adopt the SP-CDIO model of integrating key competencies for sustainability to develop the sustainability mindset of its students. Given the complexity of the program, it may pilot with only systems thinking as a “single DNA strand” as a staged approach focusing first on the process design and operation pathway. Details of work done can be expected at future conference. Another program from SP, that for mechanical engineering, will be piloting using the double-helix model, but using Integrated Problem-Solving Competency and Systems Thinking Competency as the 2 drivers for sustainability mindset development. Details of this work is covered elsewhere (see Soh & Cheah, 2026).

Until then, there ideas and approaches presented in this paper is still grounded in theoretical considerations. Pilot running to operationalize the model has been initiated, and earlier programs in SP that uses the first version of the model (Chia & Cheah, 2025; Liow & Cheah, 2025) can provide valuable insights that can improve on the model and may adopt the double-helix enhancement in the respective program's later iteration.

However, there are potential downsides to the double helix approach, for example, when one over-emphasize either systems thinking or values thinking. If systems thinking dominates, students may end up focusing on models, efficiency, and optimization while neglecting values, empathy, and justice. On the other hand, if values thinking dominates, students may become idealistic without sufficient technical grounding, leading to solutions that are ethically sound but impractical or unscalable. The approach may make the teaching of sustainable development even more challenging for faculty, as they perceived the need to grapple with more topics that are beyond what they were comfortable with – especially those dealing with values, empathy, beliefs and fairness. Assessments can be particularly problematic. Traditionally systems thinking outcomes such as process simulations, efficiency metrics are easier to measure. On the other hand, values thinking outcomes are more subjective and harder to evaluate consistently. Faculty may struggle to design rubrics that capture learning outcomes for the affective domain without reducing them to superficial checklists.

DISCUSSIONS: USE OF GEN AI, AND MOVING AHEAD

With the advent of GenAI, the experience from this author in using it to design integrated experiences for this paper had demonstrated that the effort can be accomplished in much shorter time than doing them manually. The massive capability of GenAI can helped to assemble the whole suite of workplace scenarios, mapping to relevant UNSDGs, suggest student activities along with task-specific performance rubrics. With skilful crafting of the prompts and closely scrutinizing the outputs produced by GenAI, faculty can exercise responsible use of the tool required by human-in-the-loop to maintain oversight (see Table 4). Comprehensive faculty professional development in GenAI for example using the United Nations Educational, Scientific and Cultural Organization (UNESCO) AI Competency Framework for Teachers will be useful (Cheah, 2026d). More importantly, the outputs produced by GenAI, notably those related to the use of domain knowledge need to be reviewed by the subject matter expert(s) especially on the various scenarios, and the corresponding key trade-off and unintended consequences (Table 6) as well as the performance indicators (Table 7) to ascertain their suitability for in the real-world context for developing the required key competencies for sustainability (Table 5) and sustainability mindset principles (Table 6).

One area that warrants further research is the possible influence that values or beliefs has on problem framing competency that we added to the model. Values and beliefs can function as a filter and/or a lens through which individuals interpret information, giving meaning to situations and determining which aspects of a problem are considered important. This process significantly shapes how a problem is framed, influencing the definition of the issue, the potential solutions considered, and the willingness to cooperate with others.

Lastly, we need to remember that the challenge of sustainable development is a dynamic one because the nature, scope, and solutions related to sustainability are constantly evolving. Sustainability is not a single issue but a complex web of interconnected challenges. This dynamism is driven by several factors, for example new scientific understanding such as complex feedback loops of climate change, technological advancements, and shifting societal

values (Tibbs, 2011). Vatn *et al* (2024) noted that decision-making geared towards a more sustainable and just future requires us to acknowledge the diversity of values and to balance, as well as prioritize, among competing types of values held by different people. Martin (2015) advocated for decision-making methods that provide a transparent means to value outcomes and integrate disparate information, and perceptions are the most useful in settings with a variety of stakeholders that value different outcomes. Ng (2025) for example, suggested a value-based design framework (aligned with UNSDG Goal 12 Sustainable Consumption and Production) offers a new set of measures to redefine a more prosperous and sustainable chemical process design which considers tangible and intangible impact within the selection process. The approach shared in this paper is generic enough to allow these emerging developments to be "absorbed" into the development process and operationalize in suitable learning contexts.

CONCLUSIONS

This paper proposes a model pathway for developing sustainability mindset of chemical engineering students by coupling the chemical process design and chemical product design that were traditionally taught separately in an innovative CDIO integrated curriculum exemplified by the DNA double helix comprising the key competencies for sustainability of systems thinking and values thinking. This model provides an implementable approach that can help in developing students' sustainability mindset through a suite of CDIO integrated learning experiences in an increasing level of proficiency in a progressive manner. These activities are designed – at each level of difficulty – to simultaneously bring forward the principles of sustainability mindset, applications of key competencies for sustainability to engage students in tackling sustainability challenges. The use of GenAI can support such curriculum development but requires disciplined faculty oversight. The model addressed gaps in the chemical product design education, but the generic approach presented in the design and implementation of the double helix can accommodate future developments in this important area of discourse.

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Full Disclosure: The summaries shown in Tables 1 to 4 were derived from Gemini, based on the prompts provided by the author. The entries in Table 1 have been reviewed by the author and accepted as valid for the field of chemical engineering. For Table 2, the revised descriptor for all the key competencies for sustainability were derived from Table 1 of GreenComp (pp.14-15) and earlier work by the author and colleagues (Cheah *et al*, 2025). GenAI is used to provide consistent wordings that begins with "Ability to…". Results from Table 3 were given a cursory review and found to show improved matching compared to a first iteration made under the works reported in Cheah *et al* (2025). As noted in the text, the responses produced by GenAI in Table 5, Table 6 and Table 7 need to be further validated with subject matter experts to ensure their suitability for each integrated learning experience shown. The full document – prompts and responses – is available from the link below in file "134". A point to note is that the sequence of chats with GenAI captured in the file does not necessarily match the "flow" on this paper. This is because GenAI is only used as a consultative manner and prompts entered represents the author's multiple revisions of this paper; and to write the paper per se. As such, not all outputs from GenAI were used in the writing of this paper.

https://drive.google.com/drive/folders/1h5gPaRxba899Yjk2GbR5JqJ4jeeqMqLo?usp=sharing

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Appendix A.

Table A1. Key CDIO skills & attitudes developing key competencies for sustainability

Learning Task	Key Sustainability Competencies	Supporting CDIO Skills Needed (selected items only – not exhaustive) (Can be very context-dependent such as alignment to which UNSDGs)
Year 2.1 – Plastics Reduction (General)	Systems Thinking Values Thinking	2.1 Analytic Reasoning & Problem Solving (problem identification, framing, modelling) 2.3 System Thinking (lifecycle, interactions – external to systems) 2.4 Attitudes, Thought & Learning (critical thinking, sense of urgency) 3.1 Teamwork & Collaboration (multi-perspective) 3.2 Communication (dialog and argumentation, advocacy) 4.1 External, Societal & Environmental Context (issues & values, vision for the future)
Year 2.2 – Energy Waste in Distillation (Process)	Systems Thinking Values Thinking	2.1 Analytic Reasoning & Problem Solving (quantitative modelling) 2.2 Experimentation, Investigation & Knowledge Discovery (lab modifications, testing) 2.3 System Thinking (increased complexity) 2.5 Ethics, Equity & Other Responsibilities (resource stewardship) 3.1 Teamwork & Collaboration (e.g. during experimentation) 3.2 Communication (lab reporting, safety documentation)
Year 2.2 – Eco-friendly Cleaning Products (Product)	Systems Thinking Values Thinking	2.1 Analytic Reasoning & Problem Solving (formulation design) 2.2 Experimentation, Investigation & Knowledge Discovery (testing biodegradability, toxicity) 2.3 System Thinking (interaction external to systems, trade-off) 2.5 Ethics, Equity & Other Responsibilities (health, ecological safety) 3.2 Communication (negotiation, compromise)
Year 3.1 – Water & Energy Optimization (Process)	Systems Thinking Strategic Thinking	2.1 Analytic Reasoning & Problem Solving (simulation, optimization) 2.3 System Thinking (interaction in systems, balance in resolutions) 2.5 Ethics & Responsibility (equity in resource use) 3.1 Teamwork & Collaboration (multi-disciplinary collaboration) 3.2 Communication (technical reporting, stakeholder presentations) 4.2 Enterprise & Business Context (finance & economics)
Year 3.1 – Safer Solvents (Product)	Systems Thinking Values Thinking Futures Thinking	2.1 Analytic Reasoning & Problem Solving (comparative evaluation) 2.2 Experimentation, Investigation & Knowledge Discovery (testing solvent properties) 2.3 System Thinking (life-cycle substitution impacts) 2.4 Attitudes, Thought & Learning (holding paradoxes) 2.5 Ethics, Equity & Other Responsibilities (justice, health) 3.2 Communication (regulatory foresight, consumer education) 4.2 Enterprise & Business Context (Impact on society & environment)
Year 3.2 – Circular Economy Strategy (Process)	Systems Thinking Strategic Thinking Futures Thinking	2.1 Analytic Reasoning & Problem Solving (complex system redesign) 2.3 System Thinking (closed loops, cross-sector integration: unintended consequences) 2.4 Attitudes, Thought & Learning (long-term stewardship) 2.5 Ethics, Equity & Other Responsibilities (fairness, justice) 3.1 Teamwork & Collaboration (multi-sector collaboration, networking) 3.2 Communication (policy advocacy, stakeholder negotiation) 4.1 External Context (sustainability, regulatory frameworks) 4.2 Enterprise & Business Context (vision of the future, cost-benefit analysis)
Year 3.2 – Circular Economy Products (Product)	Systems Thinking Values Thinking Futures Thinking	2.1 Analytic Reasoning & Problem Solving (strategy to solve problems: cradle-to-grave analysis) 2.2 Experimentation, Investigation & Knowledge Discovery (prototype testing) 2.3 System Thinking (trade-off, product flows, recyclability) 2.4 Attitudes, Thought & Learning (resourcefulness & flexibility in adapting to change) 2.5 Ethics, Equity & Other Responsibilities (justice, transparency, trust) 3.1 Teamwork & Collaboration (multi-sector collaboration, networking) 3.2 Communication (consumer engagement, addressing skepticism) 4.2 Enterprise & Business Context (scalability, affordability)

CDIO ALIGNMENT IN B.ENG. MODULE SPECIFICATIONS: AN AI-ASSISTED QUALITATIVE ANALYSIS

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ABSTRACT

This paper examines documented CDIO alignment across the full portfolio of Bachelor of Engineering module specifications at DTU. Using AI-assisted qualitative document analysis, 284 publicly available module specifications were analysed with the CDIO Standards 3.0 and Syllabus 3.0 as the formal analytical point of departure. Microsoft Copilot was used to support semantic reading at scale, while interpretive judgement remained with the researcher. The analysis focused on overall documented alignment rather than isolated standards. Each module was categorised on an ordinal scale of documented CDIO alignment: Weak, Weak-Medium, Medium, Medium-Strong, and Strong. Across the portfolio, 8 modules (2.8%) were classified as Weak, 132 (46.5%) as Weak–Medium, 129 (45.4%) as Medium, 10 (3.5%) as Medium–Strong, and 5 (1.8%) as Strong. The findings suggest that strongly documented CDIO alignment is relatively rare in the module specifications, while a large proportion of the portfolio shows some visible alignment without documenting it strongly enough to count as clearly substantial. The overall picture is therefore one of a portfolio dominated by partial or limited alignment, alongside a smaller number of more clearly convincing cases. The study also suggests that stronger documented alignment tends to emerge where several pedagogical elements are articulated in mutually supportive ways within a module, so that the specification presents a coherent learning design rather than a set of separate signals. The paper contributes both a portfolio-level picture of documented CDIO alignment and a methodological discussion of AI-assisted qualitative document analysis in educational quality assurance.

KEYWORDS

CDIO alignment, AI-assisted qualitative document analysis, engineering education, module specifications, educational quality assurance, CDIO Standards: 1-8, 11

INTRODUCTION

Educating engineers for a VUCA world has become an increasingly urgent challenge in recent years. Volatility, uncertainty, complexity, and ambiguity now characterise not only geopolitical and economic systems but also the technological infrastructures that underpin contemporary societies. Accelerating developments in digitalisation and AI, combined with climate-related pressures, are reshaping expectations of what engineers should know and be able to do - and by extension, what engineering education should prepare them for.

These dynamics also formed part of the rationale behind the recent revision of the CDIO Initiative's Standards and Syllabus to version 3.0 (Malmqvist et al., 2022). Since its inception in 2001, CDIO has positioned itself as a framework for practice-oriented engineering education, aiming to support member institutions in continuously improving their programmes. Version 3.0 responded to emerging global and professional demands by introducing optional standards that reflect expanded conceptions of engineering practice (Malmqvist et al., 2022).

The Technical University of Denmark (DTU) adopted the CDIO framework from 2008 (DTU, 2013), particularly within its Bachelor of Engineering programmes. Since then, programme-level implementation has been assessed several times through internal self-evaluations. While such evaluations offer important insights, they also have recognised limitations - most notably their reliance on the perspectives and interpretations of those responsible for the programme (Rouvrais & Lassudrie, 2014). CDIO itself emphasises that the Standards are intended as guidelines for continuous improvement rather than as a formal accreditation regime.

Over time, organisational restructuring, staff turnover, and shifting priorities mean that institutional knowledge about CDIO at DTU may have become unevenly distributed. In the wake of the 3.0 revision - and in the context of intensifying VUCA pressures - it may therefore be a good time to revisit how CDIO is currently being expressed across the B.Eng. programmes at DTU.

This makes module specifications a relevant but complicated site for examining CDIO alignment. On the one hand, they can show whether elements associated with CDIO are documented across a programme portfolio. On the other hand, they do not provide direct access to enacted teaching practice, and they do not automatically reveal whether apparently CDIO-like language reflects a coherent pedagogy or only a partial articulation. This is especially important in a large portfolio, where the question is not only whether CDIO-related elements appear, but how convincingly they are documented across many different modules.

This leads to the following research question:

What insights into CDIO alignment and implementation status can AI-assisted qualitative document analysis at scale offer?

Terminology: To align with usage in the CDIO International conference host country (UK), the terms *modules* and *module specifications* are used instead of the Danish terms courses and course descriptions.

METHODOLOGY

Theory

Chapter 2 in Rethinking Engineering Education (Crawley, Malmqvist, Östlund, Brodeur, & Edström, 2014) is used here as the main foundational point of departure. The chapter explicitly refers to a pedagogical foundation for CDIO and points toward a set of educational traditions rather than one single unified theory. Among the references most relevant here are Biggs on constructive alignment, Marton and Säljö on deep and surface approaches to learning, Kolb on experiential learning, and Johnson on contextual teaching and learning. These theories were not used as a predefined coding frame from the outset, but as interpretive support for clarifying distinctions that became necessary during the analysis.

Biggs and Tang (2011) provide the clearest account of constructive alignment, and this is particularly relevant to CDIO because it foregrounds coherence between intended learning outcomes, teaching and learning activities, and assessment. The related idea of backwash is also important, since assessment strongly shapes what students actually attend to and learn. This fits closely with CDIO's concern for outcomes, integrated curriculum, active learning, and assessment.

Marton and Säljö (1976) represent the tradition of deep and surface approaches to learning, which is also explicitly part of the reference background of Chapter 2. This tradition is relevant because it distinguishes between richer forms of learning oriented toward meaning and relationships, and more superficial forms of engagement based on reproduction or box-ticking. That distinction is highly pertinent to CDIO, where apparently active or project-like forms of teaching may still remain educationally shallow.

Kolb (1984) is the main reference here for experiential learning. Kolb's account of learning through experience, reflection, conceptualisation, and experimentation resonates strongly with CDIO's emphasis on integrated learning experiences, design-implement work, and engineering education in the context of practice. Experiential learning therefore offers an important part of the pedagogical language through which CDIO can be understood.

Johnson (2002) provides the most direct reference for contextual teaching and learning. This is relevant because CDIO explicitly frames engineering education in relation to the context of conceiving, designing, implementing, and operating real products, processes, systems, and services. Contextual learning helps explain why such context matters pedagogically: not as background illustration alone, but as something that gives knowledge relevance, meaning, and direction.

Bloom et al. (1956) and Krathwohl (2002) remain important for the question of cognitive demand. Bloom's taxonomy, and its later revision, provide a widely used language for distinguishing between lower-order and higher-order forms of learning. In the present context, this matters because engineering tasks may appear innovative or project-based while still implying only routine understanding or application rather than analysis, evaluation, or creation.

Method

An AI-assisted document analysis of the module specifications was conducted, drawing on directed qualitative content analysis (Hsieh & Shannon, 2005). The CDIO Standards 3.0 (Malmqvist et al., 2020) and CDIO Syllabus 3.0 (Malmqvist et al., 2022) were used as a

combined analytical framework to examine module specifications for documented CDIO alignment.

Ontological and epistemological approach

In this study, module specifications are not treated as an objective mirror of enacted teaching practice. Rather, in line with document analysis traditions (Bowen, 2009), they are understood as institutional documents (Prior, 2008): texts produced and used in socially organised ways that may reflect institutional purposes, conventions, and the circumstances of their authors at the time of writing.

At the same time, module specifications do remain valid empirical material. Document analysis involves examining and interpreting texts to elicit meaning and develop understanding (Bowen, 2009). Accordingly, no claims are made about teaching practice. Instead, the analysis concerns documented intent and declared pedagogical commitments, inferred from what is explicitly articulated in the documents.

Data and units of analysis

For the academic year 2025 - 2026, all 301 module specifications of the complete portfolio of B.Eng. modules (across 21 specialisations) are made public in the DTU course base (www.kurser.dtu.dk). All module specifications were downloaded. Some modules have duplicates due to being offered in different locations, or more than once throughout the year, hence, it was decided to keep only one instance of each module reducing the dataset to 284 unique specifications. Each specification follows a fixed structure where the main elements are 8-12 learning objectives, overall objectives, content descriptions, assessment type. These were the focus of the analysis.

Use of AI in document analysis

Microsoft Copilot was used as a thinking tool to support exploratory, corpus-wide reading of the module specifications within the analytical lens described above. Its role was to assist in surfacing recurring formulations, candidate patterns, and possible tensions relevant to documented CDIO alignment across a dataset that would have been difficult to engage with holistically through close manual reading alone.

The analysis was iterative from the outset and involved repeated movement between the CDIO framework, the module specifications, and AI-supported reading. AI-supported outputs were not treated as final interpretations in themselves but were repeatedly checked and reconsidered in order to keep interpretive judgement with the researcher. Due to the size of the dataset, it was not feasible to verify every AI-supported reading individually. Instead, analytic quality was supported through iterative review of cases where interpretations appeared uncertain, inconsistent, or pedagogically unconvincing. Diagnostic instances were cases where AI-supported readings appeared overly generous, inconsistent with the analytical lens, or insufficiently attentive to tensions between learning outcomes, content, and assessment. These diagnostic instances informed the refinement and stabilisation of the analytical lens. A targeted validation sample of 30 unique module specifications was reviewed during the refinement process. Of these, 7 borderline cases were revisited in order to clarify and settle their final placement.

As the analysis progressed, it became clear that the CDIO Standards and Syllabus alone did not fully specify how stronger and weaker forms of documented alignment should be

distinguished in practice. In particular, some modules appeared CDIO-aligned in wording or format, yet seemed less persuasive when considered in pedagogical terms. The later refinement of the analysis therefore drew on a small number of educational theories, not because these had been imposed deductively from the outset, but because they made it possible to articulate more explicitly the pedagogical assumptions already informing the judgement of what counted as more genuine alignment and what appeared aligned in name only. Interpretive judgements remained the responsibility of the researcher.

The analytical lens – including the evidence hierarchy and the alignment considerations guiding interpretation – is described below.

Analytical lens

CDIO Standards 3.0 and CDIO Syllabus 3.0 documents were used as an analytical lens to interpret documented CDIO alignment. CDIO Standards 9, 10, and 12 were excluded from the analysis, as they concern faculty competence and programme-level evaluation, which are not documented at module level. Alignment for Standard 2 cannot be evaluated at programme level in this study and was therefore considered at module level instead. Standard 4 (Introduction to Engineering) was included only where explicitly relevant at module level.

Rather than being operationalised as discrete indicators, the standards and syllabus informed a holistic, semantic interpretation of intended pedagogy. Each module specification was read as a whole in order to assess the strength and coherence of documented CDIO alignment, examining how learning objectives, content and activities, assessment forms, and pedagogical language combined across the specification.

During the analysis, it became clear that the CDIO Standards and Syllabus alone did not fully explain why some module specifications appeared more convincingly aligned than others. In particular, some modules appeared CDIO-aligned in wording or format, yet seemed less persuasive when considered in pedagogical terms. The considerations below were therefore formulated to make these distinctions more explicit and to support more consistent judgement across the portfolio.

The considerations emerged from recurring distinctions that became important during the refinement of the analysis. In particular, borderline cases often differed only marginally in terms of openness, higher-order thinking, authenticity, integration, or assessment alignment, yet these differences became important when deciding whether a module should be placed in Weak–Medium, Medium, or Medium–Strong. The considerations were therefore formulated as a way of making these recurring distinctions explicit and supporting more consistent judgement across the portfolio. For example, repeated difficulty in distinguishing between design as independent judgement and design as bounded implementation contributed to the consideration of design-as-create versus design-as-assembly, while repeated tensions between ambitious learning language and traditional written examinations contributed to the consideration of assessment alignment.

These are not to be understood as criteria or a checklist, but as interpretive supports that orient holistic judgement by drawing attention to dimensions along which documented CDIO alignment may be strengthened or weakened.

CDIO alignment considerations

These considerations were formulated in response to recurring tensions in the material, where module specifications appeared CDIO-aligned in wording or format, yet seemed less convincing when considered in pedagogical terms.

Open-endedness and higher-order thinking, including whether tasks allowed for more than one plausible solution, non-trivial decision-making, or creative problem solving. *This consideration emerged from cases that appeared project- or design-oriented in wording, but where tasks seemed tightly structured, cognitively limited, or primarily oriented toward routine execution rather than analysis, evaluation, or creation.*

Design-as-create versus design-as-assembly, distinguishing between activities that required students to independently formulate and justify design decisions and those that primarily involved implementing predefined solutions. *This distinction emerged from modules that used the language of design, but where student work appeared mainly to involve carrying out given solutions rather than engaging in more genuinely generative design work.*

Assessment alignment, particularly whether assessment formats supported the evaluation of complex outcomes (e.g. design reasoning, integration, process) or whether traditional sit-down written examinations dominated. *This consideration emerged from cases in which ambitious or practice-oriented learning outcomes appeared poorly matched by assessment formats, raising concerns associated with constructive alignment and the backwash effect of assessment.*

Integration, understood as the application of a variety of disciplinary knowledge, process skills, and other competencies within the same learning activities rather than as add-on elements. *This consideration emerged from modules in which knowledge, skills, and activities appeared alongside one another in the specification, but without clear evidence that they were brought together within the same learning work.*

Authenticity, including the presence of realistic contexts, constraints, or problems that are not just abstract or purely illustrative examples. *This consideration emerged from cases in which real-world context was mentioned, but seemed to function mainly as illustrative background rather than as a meaningful condition shaping the pedagogical design of the module.*

Categorisation and scoring

Based on the analysis, each module was categorised on an ordinal scale of documented CDIO alignment: Weak, Weak–Medium, Medium, Medium–Strong, and Strong. Each category was assigned a corresponding score from 1 to 5 in order to support visualisation of the findings.

The intermediate categories Weak–Medium and Medium–Strong were used to distinguish cases that leaned clearly downward or upward from Medium without being fully convincing as Weak or Strong.

RESULTS

The results are reported at the level of overall documented CDIO alignment, since the more meaningful judgement in this study concerned the coherence of the module specification as a whole rather than isolated strengths on individual standards.

Across the 284 module specifications, 8 modules (2.8%) were classified as Weak, 132 (46.5%) as Weak–Medium, 129 (45.4%) as Medium, 10 (3.5%) as Medium–Strong, and 5 (1.8%) as Strong.

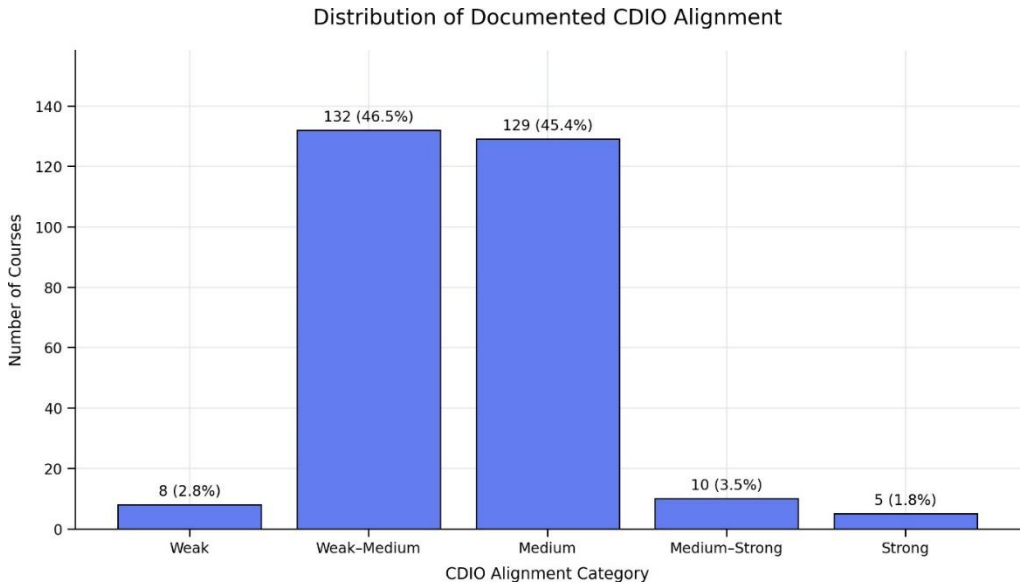


Figure 1: Final validated distribution of documented CDIO alignment across the 284 module specifications.

The distribution indicates that strongly documented CDIO alignment is relatively rare in the module specifications, while a large proportion of the portfolio shows some visible alignment without documenting it strongly enough to count as clearly substantial. In many cases, module specifications appear to include CDIO-relevant elements, but these are only partially articulated or weakly supported when the specification is read as a whole.

The overall picture is therefore one of a portfolio dominated by partial or fragile alignment, alongside a smaller number of more clearly convincing cases. The modules in the Medium–Strong and Strong categories are those where the specifications more clearly document a coherent pedagogical logic, typically through some combination of openness, higher-order thinking, authentic context, design or development work, and assessment formats that plausibly support such learning. By contrast, the large number of Weak–Medium specifications suggests that many modules contain some visible CDIO-related elements, but not enough to form a strongly convincing whole.

DISCUSSION

What stronger CDIO alignment looks like

A question that emerged in the study is what stronger CDIO alignment actually looks like at module level. This study suggests that stronger alignment does not require every CDIO standard to be represented in every module. Rather, it appears where several pedagogical

elements are articulated in mutually supportive ways within the same module, so that the specification presents a coherent learning design rather than a set of separate signals. In the stronger cases, higher-order thinking, openness, design or development work, authentic context, and assessment seem to reinforce one another.

Although integration is central to the CDIO framework, it was not among the most clearly articulated dimensions in many of the module specifications and was less often the decisive factor in distinguishing stronger from weaker cases.

Importantly, this study does not aim to assign responsibility or attribute shortcomings to individual actors. Moreover, the findings do not permit such inferences, as no claims about enacted teaching practice can be made. It is therefore possible that integrative and contextual elements are present in practice but not explicitly articulated in the module specifications. What can be concluded with confidence is that this is how CDIO alignment is currently documented in the analysed module specifications.

Reflections on the use of AI in document analysis

One clear methodological takeaway concerns the use of AI-assisted semantic analysis. While large language models are effective at identifying patterns in language across large datasets, semantic reading alone proved insufficient. Several modules initially identified by the AI as CDIO-aligned were, upon closer inspection, found to lack pivotal elements such as explicit higher-order thinking or integrative intent.

This underscored the necessity of human interpretive oversight, including the formulation of explicit alignment considerations and an evidence hierarchy to constrain interpretation. At the same time, this raises an open methodological question about how human caution and AI-supported pattern recognition should best be balanced in future document analyses.While speculative, this question points to the value of future methodological experimentation to calibrate human-AI collaboration prior to large-scale analysis.

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INTEGRATING RESEARCH-BASED LEARNING INTO THE CDIO FRAMEWORK: A MODERN APPROACH TO ENGINEERING EDUCATION REFORM

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ABSTRACT

This study advances a unique framework that integrates Research-Based Learning (RBL) with the twelve core CDIO standards and four supplementary standards to modernize engineering education. By introducing specific pedagogical adjustments, the framework details how essential research competencies—including critical thinking, methodological rigor, data analysis, and ethical inquiry—are embedded across the curriculum. This integration shifts the educational paradigm from traditional practitioner roles to "practitioner-scholars" capable of conducting scientific discovery alongside systems design. The paper outlines the conceptual rationale for the CDIO-RBL framework, presents updated standards that emphasize inquiry-driven pedagogy and faculty preparedness, and demonstrates how these enhancements strengthen the research–teaching nexus. This approach ensures graduates are technically proficient and research-literate, equipping them to address complex 21st-century challenges such as climate change, Industry 4.0, and digital transformation within a knowledge-based economy.

KEYWORDS

Research-based learning, Engineering education, Curriculum reform, Inquiry-driven pedagogy, Standards 1-12, Supplementary standards 1-4.

INTRODUCTION

Engineering education is currently evolving as global challenges, digital technologies, and knowledge-driven economies reshape the expectations placed on future engineers. The field is under immense pressure to overcome the complex problems of the 21st century, including climate transformation, sustainability, rapid digital transformation, Industry 4.0, and the need for innovation within growing knowledge economies (National Academy of Engineering (NAE), 2004; UNESCO, 2010; World Economic Forum (WEF), 2023). These challenges require graduates who are not just technically capable, but alert and nimble thinkers with the ability to solve engineering problems while actively participating in the creation of new knowledge and its ethical implications. Traditional, content-focused delivery models no longer provide the competencies required for navigating uncertainty, making evidence-based decisions, or innovating responsibly (Felder et al., 2016; UNESCO, 2010). Consequently, a vital shift toward innovation, profound inquiry, and noticeable societal impact is required.

These needs call for inquiry-driven approaches such as Research-Based Learning (RBL), which emphasizes question formulation, methodological rigor, and scholarly investigation (Healey & Jenkins, 2009; Japiashvili, 2021). RBL offers a prevailing pedagogical approach that provides more than just research outcomes; it engages students in the research process itself through articulating proper questions, applying various design practices, evaluating data, interpreting results, and reporting findings (Healey, 2005; Jenkins et al., 2010). Adopting RBL nurtures the very skills required by the modern age, including curiosity, critical thinking, creativity, intellectual rigor, and the capacity to contribute to knowledge creation (Brew, 2013; Prince et al., 2006).

The CDIO framework (Conceive-Design-Implement-Operate), created by E. F. Crawley et al. (2007), has become the worldwide answer to positioning engineering education closer to real-life professional practice. Built around the CDIO lifecycle, it provides an inclusive roadmap of twelve core standards and four supplementary ones needed to develop the skills required for dealing with complex systems in the work environment. While the CDIO approach has successfully enhanced graduate readiness for professional roles (Crawley et al., 2014; Crawley et al., 2007), an enhancement is required to accommodate rapid technological advancements that focus on evidence-based, research-informed decision-making across all engineering fields (European Society for Engineering Education (SEFI), 2022; M. Borrego and J. Bernhard, 2011).

The CDIO approach naturally combines the fundamentals of investigation and design. Embedding RBL within CDIO enriches curricula by integrating research competencies with design and implementation processes (Brew, 2003; Noguez & Neri, 2019), allowing students to conceive, design, implement, and operate in addition to investigating, innovating, and generating knowledge (Zhou, 2012). Successful implementation of this integrated framework depends on curriculum redesign including research pathways, inquiry-based projects, and analytical assignments (Mashwama & Dywili, 2023; Morris, 2025) and faculty development to support instructors in designing research-rich learning environments (Streveler et al., 2007). Student engagement is further strengthened through authentic research experiences that cultivate creativity, resilience, ethical reasoning, and responsible innovation (Lopatto, 2010). Undergraduate research is recognized as a high-impact practice (Kuh, 2008) that enhances persistence and professional identity while aligning engineering programs with societal needs through sustainability-oriented solutions (Graham, 2018).

Overall, this study addresses the critical need for educational modifications to the CDIO standards, framed through the lens of RBL. By revisiting the core standards and

supplementary standards, the improved CDIO-RBL framework prepares students for professional excellence, lifelong learning, and the exploration of accountable, sustainable engineering solutions.

FROM CDIO TO CDIO-RBL

Standard 1: CDIO-RBL Context

The context of engineering education is expanded to include the development of engineering researchers and innovators. The learning environment must simulate both engineering practice and the research process.

Table 1. Key Additions of Integrating RBL into CDIO Standard 1

Core Concept	Impact on Education
Embeds Research ("R") as a fundamental pillar.	Shifts focus on inquiry, problem identification, and methodological rigor alongside systems thinking.
Cultivate students as Practitioner-Scholars.	Develops a hybrid role: engineers capable of both system design and scientific discovery.
Anchors learning in authentic, complex problems.	Uses ill-defined challenges (SDGs, new tech) requiring research integrated with design for solutions.
Leverages institutional and external research infrastructure.	Utilizes research centers and industry collaborations to enable student participation in actual research.

Standard 2: Learning Outcomes

Graduating students must possess a robust set of research competencies alongside technical and interpersonal skills, scaffolded through a hierarchical development model.

Table 2. Hierarchical Development of Research Competencies (Bloom's/RBL)

Level of Taxonomy	RBL Competency and Skill Development
Remember	Identification of core research concepts, terminology, and foundational principles.
Understand	Comprehension of research structures, scientific ethics, and the purpose of inquiry.
Apply	Competence in data collection, application of analytical tools, and software usage.
Analyze	Critical critique of existing literature and systematic analysis of empirical data.
Evaluate	Assessment of validity, reliability, and the implications of research findings.
Create	Designing original research projects and generating new engineering knowledge.

Standard 3: Integrated Curriculum

The curriculum is designed to integrate research-based learning pathways vertically and horizontally, ensuring a scaffolded progression of inquiry skills across the four-year program.

Table 3. Key Additions of Integrating RBL into CDIO Standard 3

Component	Key Features and Implementation Examples
1. Vertical Integration	Scaffolded progression: Year 1 (Foundational) to Year 4 (Capstone).
2. Horizontal Integration	Embedded across Science, Engineering, Humanities, and Design.
3. Year 1 Progression	Basic information literacy and formulation of research questions.
4. Year 2 Progression	Research methods and small projects (e.g., vibration data analysis).
5. Year 3 Progression	Advanced methods and collaborative research (e.g., 10-article synthesis).
6. Year 4 Progression	Capstone thesis/project and dissemination via student conferences.
7. Mutually Supporting Subjects	Methodology in Math, ethics in Humanities, applied research in Engineering.
8. CUREs	Course-based Undergraduate Research Experiences (Mini-review articles).
9. Curricular Flexibility	Research electives, credited internships, and Innovation streams.

Standard 4: Introduction to Engineering and Research

This introductory course exposes students to engineering practice while grounding them in scientific inquiry and the ethics of knowledge production.

Table 4. Key Additions of Integrating RBL to CDIO Standard 4

Topic	Description
Dual Orientation: Practice and Inquiry	Blends engineering design with research methods and research question formulation.
Understanding the Research Cycle	Introduces problem identification, background search, and data analysis.
Mini-Research/Inquiry Project	Group projects focused on sustainable solutions or data from open databases.
Information and Data Literacy	Training in academic databases, citation tools, and critical source evaluation.
Communication of Findings	Deliverables like research briefs, posters, or technical blogs.
Ethics and Social Responsibility	Discussion of societal impact, experimental ethics, and responsible use of AI.

Standard 5: Design–Implement–Investigate (DII) Experiences

The traditional model is expanded to "Investigate," requiring students to validate design decisions through systematic research.

Table 5. Key Additions of Integrating RBL to CDIO Standard 5

Topic	Details
1. From Design to Design + Inquiry	Move beyond prototyping to testing assumptions and evidence-based conclusions.
2. Evidence-Driven Design Thinking	Justification of designs using theoretical models, empirical data, simulations, literature reviews and benchmarking studies
3. Framing Researchable Questions	Learning to define engineering questions and appropriate research methodologies.
4. Extended DII Capstone	Includes research proposals, experimental design, and formal publication.
5. Integration of Research Methods	Use of statistical analysis and technical writing within design-implement projects.

Standard 6: Engineering and Research Workspaces

Workspaces must support both hands-on building and scholarly inquiry, providing access to digital infrastructure and research tools.

Table 6. Key Additions of Integrating RBL into CDIO Standard 6

Topic	Details
1. Dual-Purpose Workspaces	Labs supporting both prototyping and hypothesis-driven research.
2. Dedicated Research Spaces	Areas for independent research with access to advanced computing tools.
3. Digital Infrastructure	Access to MATLAB, GitHub, Python, SPSS, and digital twins for modeling.
4. Equipment and Mentorship	Availability of tools outside of class with faculty/assistant guidance.
5. Dissemination Facilities	Resources for technical writing, poster design, and visualization.

Standard 7: Integrated Learning Experiences

Learning experiences blend disciplinary knowledge with research mindset development.

Table 7. Additions of RBL Integrating CDIO Standard 7

Topic	Description
Blended Learning Experiences	Modules combine technical content with literature reviews and experimentation.
Scaffolded Skill Development	Progressive growth from source evaluation to full-cycle research dissemination.

PBL with Inquiry Elements	Projects incorporate problem framing and validating designs through simulations.
Interdisciplinary Integration	Applying research methods across sustainability, business, and social sciences.
Communication Skills	Use of research papers, posters, and reflective essays to share findings.

Standard 8: Active Learning

Active learning is redefined as a constructivist process where inquiry and exploration are foundations of engagement.

Table 8. Additions of RBL Integrating CDIO Standard 8

Topic	Description
Inquiry as Foundation	Students ask questions, evaluate evidence, and reflect on their discovery process.
Research-Driven Strategies	Use of guided inquiry, case-based learning, and student-led seminars.
Learning by Doing Research	Production of research outputs like infographics, podcasts, or mini projects.
Metacognition	Use of research diaries to reflect on the design and inquiry process.
Collaborative Environments	Simulating academic or industry lab environments through teamwork.

Standard 9: Faculty Competence

Institutions must support faculty in becoming expert educators and research mentors.

Table 9. Additions of RBL Integrating CDIO Standard 9

Topic	Description
Faculty as Mentors	Guiding students in question formulation, data analysis, and dissemination.
Professional Development	Workshops on supervising undergraduate research and research-based pedagogy.
Capacity Building	Training in designing inquiry-based assessments and using digital research tools.
Research–Teaching Nexus	Integrating personal research into teaching and co-publishing with students.
Incentivization	Grants, awards, release time, and recognition for student research supervision.

Standard 10: Enhancing Faculty Teaching

Focuses on instructional strategies required for research-integrated learning.

Table 10. Additions of RBL Integrating CDIO Standard 10

Topic	Description
Research-Informed Practices	Designing courses around researchable questions and inquiry outcomes.
Instructional Strategies	Flipped classrooms for research tasks and reflective teaching methods.
Digital Tool Use	Support in using statistical software, survey platforms, and collaboration tools.
Assessment Competencies	Learning to use specialized rubrics for evaluating student research work.
Peer Observation	Engaging in peer reviews focused on the integration of research in the classroom.

Standard 11: Assessment of Learning

Assessment systems capture achievement in the research cycle, including problem formulation and ethical reasoning.

Table 11. Additions of RBL Integrating CDIO Standard 11

Topic	Description
Assessment of Competencies	Aligning outcomes with literature review, research design, and conclusions.
Multi-Modal Assessments	Annotated bibliographies, experimental designs, posters, and peer reviews.
Formative and Iterative	Rubric-based feedback environments for continuous skill development.
Research Skill Rubrics	Assessing clarity, rigor, and critical evaluation in student outputs.
Alignment with Attributes	Data used to evaluate graduate attributes like evidence-based reasoning.

Standard 12: Program Evaluation

Evaluation tracks RBL integration effectiveness through specific KPIs and stakeholder feedback.

Table 12. Additions of RBL Integrating CDIO Standard 12

Topic	Description
Expansion of Scope	Tracking student engagement, output quality, and faculty mentorship quality.

Multiple Data Sources	Using direct direct assessment, surveys, and reviews from industry and alumni.
Program-Level KPIs	Measuring number of research outputs and student participation rates.
Feedback Loops	Using evaluation data to guide curriculum revisions and support services.
Benchmarking	Benchmarking against global practices and accreditation standards (Elhakim, 2025).

Supplementary Standard S1: Sustainable Development

Table 13. Additions for Research-Based Sustainable Development

Topic	Details
Sustainability Research Projects	Inquiry into renewable energy, circular economy, and green infrastructure.
Impact Analysis Methods	Application of Life Cycle Assessment (LCA) and Sustainability Impact Assessment (SIA).
Research Methodologies	Mixed methods combining field data with simulation and carbon footprint modeling.

Supplementary Standard S2: Internationalization and Mobility

Table 14. Additions for Research-Based Internationalization

Topic	Details
Global Collaboration	Participation in international research exchange and cross-border capstone projects.
Virtual Research Mobility	Remote internships and co-authoring reports with international peers.
Intercultural Competence	Development of awareness regarding global contexts and research ethics.

Supplementary Standard S3: Research-Driven Innovation and Entrepreneurship

Table 15. Additions for Inquiry-Driven Entrepreneurship

Topic	Details
Inquiry-Driven Ideation	Identifying societal needs and validating market gaps through research.
Commercialization Training	Training in Intellectual Property (IP), technology transfer, and startup development.
Entrepreneurship Challenges	Research-backed pitches and data-driven innovation in hackathons.

Supplementary Standard S4: Research-Based Service Learning

Table 16. Additions for Community-Engaged Research (CER)

Topic	Details
Community Partnerships	Co-developing research questions and collecting data with community partners.
Ethical Inquiry	Training in participatory action research and responsible data handling.
Social Impact Reflection	Reflecting on bias, positionality, and the societal impacts of engineering research.

DISCUSSION

The CDIO-RBL framework represents a comprehensive integration of research-based learning into the traditional CDIO model, aiming to produce engineering graduates who are both technically proficient and research-capable. By integrating these two models, the framework meets the current demand for critical thinking, creativity, and the ability to apply academic knowledge to solve complex engineering problems. This synergy fosters the development of new scientific methodological frameworks for exploration, providing a systematic way for students to learn and develop their engineering knowledge. The expected benefits of this integration include enhanced technical competency, refined research skills, and a much broader perspective of the student's field of study.

This integration is operationalized through the enhanced standards which focus on research-oriented learning, active inquiry, and program evaluation. Furthermore, the framework extends to sustainable development, Internationalization and mobility, entrepreneurship and community engagement through two supplementary standards. This collaborative and research-heavy engagement exerts a powerful effect on the ability of students to address and solve real-world issues. Ultimately, the participation of engineering educators is vital to the successful delivery of these research-centered approaches, which will have an enormous impact on students' ability to participate in meaningful research and innovation.

CONCLUSION

The integration of Research-Based Learning (RBL) into the CDIO framework represents a fundamental shift in the educational paradigm for engineers, equipping academic programs to address the multifaceted challenges of 21st-century learning. By embedding research within traditional CDIO principles, students develop an inquisitive approach, refined analytical reasoning, and a deeper consideration for the ethical aspects of technical decision-making. This framework ensures that graduates remain capable of both conducting rigorous research and developing complex engineering systems, effectively bridging the gap between professional practice and scholarly inquiry.

The implementation of the CDIO-RBL framework relies on enhanced standards (1–12) that emphasize scaffolded research skill development, active inquiry, and research-informed communication. These standards are supported by institutional initiatives for faculty training and mentorship, alongside comprehensive assessments to ensure continuous program improvement. Furthermore, supplementary standards (S1–S4) extend this impact by

promoting entrepreneurial thinking and community engagement through research-driven innovation and service learning. Ultimately, this strategic response to the needs of a knowledge-based economy prepares socially responsible, research-capable professionals for lifelong learning and leadership in a rapidly evolving global marketplace.

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CDIO Implementation

STRENGTHENING ENGINEERING EDUCATION THROUGH INDUSTRIAL COLLABORATIONS WITHIN THE CDIO FRAMEWORK

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ABSTRACT

Industrial collaboration has become a cornerstone of modern engineering education, ensuring that students graduate with both technical competence and professional readiness. This study examines how structured industrial collaboration operationalizes the CDIO framework at the Australian University (AU) in Kuwait through a longitudinal institutional case study covering the period 2015–2025. It analyzes how industry engagement is integrated across multiple channels, including Industrial Advisory Boards (IABs), field trips, internships, industry-linked project-based learning (PBL), capstone projects, and research partnerships. These initiatives collectively support the Conceive–Design–Implement–Operate (CDIO) framework, providing students with authentic contexts in which to apply theoretical knowledge to real-world engineering challenges. Students conceive problems under the guidance of industry mentors and through structured field visits that expose them to operational and environmental constraints. In PBL and capstone courses, they design and implement feasible solutions to employer-defined briefs, often using real datasets and industry standards. At the same time, collaboration with practitioners enhances their design thinking, problem-solving, and communication skills. Through joint research and student–faculty co-authored publications, results are disseminated and evaluated to support continuous improvement. Evidence of impact includes data from 633 internship placements, 178 industrial judges evaluating graduation projects, and 205 students co-authoring 62 publications between 2015 and 2025. Early indicators reveal measurable improvements in employability, innovation, and teamwork, supported by structured feedback loops and accreditation-aligned evaluation. This study concludes that embedding industrial collaboration throughout the CDIO cycle strengthens learning, enhances professional competence, and offers a transferable model for universities seeking to modernize engineering curricula aligned with Industry 5.0 priorities.

KEYWORDS

Industrial Engagement, Industrial Collaboration, Project-Based Learning, Engineering Education, Standards: 1-3, 5, 7-11.

INTRODUCTION

Current engineering education pedagogies remain instructor-centered rather than student-centered, resulting in unmotivated and disengaged learners (Al-Khiami et al., 2024). As Gürdür Broo et al. (2022) note, "The World we live in has evolved tremendously while our education systems try to hold on to old patterns of teaching, learning, and consequently conferring qualifications." Many universities still measure educational success by classroom hours rather than competencies developed. Such approaches lead to weak knowledge retention, limited creativity, and poor problem-solving and critical thinking abilities, as well as higher dropout rates (Cantos et al., 2021; Christie & de Graaff, 2017). Consequently, many engineering graduates enter the workforce insufficiently prepared to meet the complex, interdisciplinary, and rapidly evolving demands of modern industry (Mathur et al., 2016).

This highlights the need for learner-centered approaches that actively engage students in problem-solving and decision-making within an authentic context. Engineering education is experiencing a paradigm shift driven by rapid technological change to accommodate a digital-native student body (Al-Khiami et al., 2024), sustainability imperatives, and evolving employer expectations. Industry leaders increasingly demand graduates who possess not only technical competence but also creativity, communication, teamwork, and adaptability (Gürdür Broo et al., 2022). To meet these demands, institutions are rethinking curricula to integrate industry-informed learning experiences that mirror professional practice. Collaboration between academia and industry has thus become essential for producing industry-ready engineers capable of navigating complex socio-technical challenges (Male et al., 2016).

The Conceive–Design–Implement–Operate (CDIO) framework offers a structured and widely adopted approach for bridging theory and practice, ensuring that graduates develop both disciplinary knowledge and professional skills within real engineering contexts (Edelbro et al., 2017; Mejtoft, 2015). CDIO provides a coherent model that embeds authenticity, interdisciplinarity, and reflection across the educational experience, thereby aligning learning outcomes with the complete engineering lifecycle. Across CDIO institutions, industrial engagement is embedded through multiple mechanisms, including Industrial Advisory Boards (IABs), internships and cooperative education, project-based learning (PBL), industry-outsourced capstone projects, and collaborative research. These elements collectively provide authentic opportunities for students to engage in the full engineering cycle, conceiving solutions to real problems, designing feasible systems, implementing prototypes, and operating within practical constraints.

Empirical studies demonstrate that such engagement enhances both learning outcomes and employability. For instance, project-based collaborations at Umeå University and Kristianstad University enabled students to deliver tangible prototypes to industry partners while strengthening problem-solving, teamwork, and communication skills (Mejtoft, 2015; Frisk et al., 2022). Similarly, the integration of outsourced CDIO projects has been shown to systematically embed employability competencies throughout the curriculum (Manna et al., 2023).

Internships and cooperative programs represent another critical avenue for authentic learning. Kamp and Verdegaal (2015) illustrated how the Delft University of Technology's structured internship model provided measurable learning outcomes and quality-assured assessment mechanisms that align with CDIO Standards 7, 8, and 11. Through intentional feedback loops between students, employers, and faculty, such programs enable continuous curriculum improvement and promote alignment with industry needs. Equally, industry-inspired experiential activities that use professional rubrics and self–peer assessments foster

professional behaviors consistent with workplace standards (Tio, 2016), while direct interactions with industry representatives through Lean and Six Sigma projects enhance student engagement and reflective learning (Berglund et al., 2022).

At the institutional level, IABs play an essential role in sustaining curriculum relevance and responsiveness. These boards validate program outcomes, inform strategic curriculum redesign and competency frameworks (Edelbro et al., 2017). The emerging concept of Curriculum Agility, recently proposed within the CDIO community, further expands this notion by advocating adaptive and iterative curriculum models that respond swiftly to evolving industrial and societal demands (Lyng & Nortcliffe, 2024). Collectively, these studies reinforce that structured, long-term collaboration between academia and industry leads to stronger employability outcomes, continuous curriculum enhancement, and deeper professional identity formation among engineering students.

While most CDIO literature focuses on large or established universities, little research examines how emerging institutions apply the framework within fast-evolving industrial contexts. This paper addresses that gap through the Australian University (AU) model, which adapts CDIO-based industrial collaboration to the Gulf region.

This study examines how structured industrial collaboration operationalizes the CDIO framework at AU and presents an evidence-based institutional model for embedding industrial collaboration within developing higher-education systems while aligning engineering curricula with emerging Industry 5.0 and sustainability priorities (El Achkar, 2025). Specifically, the study examines how industry collaboration channels are integrated across the CDIO lifecycle at AU, what measurable institutional outcomes emerge from sustained collaboration between academia and industry, and how these practices may inform transferable models for engineering education in developing higher education systems.

Research Design and Data Sources

This study adopts a longitudinal institutional case study examining the implementation of industry collaboration at AU between 2015 and 2025. Data were collected from institutional sources including internship records, Industrial Advisory Board reports, capstone evaluation data, student reflections, and undergraduate research publication records.

Quantitative data, including internship numbers, sector distribution, student publications, and participation of industrial judges, were compiled from College of Engineering databases. Qualitative insights were derived from student reflections and employer feedback. Text preprocessing techniques (stop-word removal and term-frequency analysis) were used to generate thematic summaries and the word-cloud visualization presented in this study.

FRAMEWORK OF INDUSTRIAL COLLABORATION AT AU

Institutional Context

The Australian University (AU), established in 2004 in Kuwait, is a multidisciplinary institution comprising four academic units: the College of Engineering (CoE), the College of Business, the School of Aviation, and the School of Maritime Studies. Each contributes to AU's mission of delivering practice-oriented education aligned with national and industry priorities. This manuscript focuses on the CoE, which offers undergraduate programs in Civil, Mechanical, Electrical, and Petroleum Engineering through a 2+2 articulation model. In 2016, AU partnered

with Aalborg University in Denmark to embed PBL across engineering curricula. This collaboration aligned the College with the CDIO framework after joining the initiative in 2018, fostering authentic, student-centered learning.

The College's programs are audited by Engineers Australia (EA), ensuring international standards and continuous improvement. Combined with IAB feedback, these audits reinforce CDIO Standards 9-11 on evaluation and improvement. Recent reforms have integrated digitalization, AI, and sustainability to prepare graduates for evolving challenges. Collectively, these initiatives provide the foundation for AU's evidence-based, industry-aligned implementation of the CDIO framework.

Channels and Mechanisms of Industry Collaboration

At AU, industry engagement operates through structured channels connecting engineering education with professional practice. These include IABs, internships, project-based and capstone courses, and joint research partnerships. Each mechanism targets specific phases of the student learning journey while reinforcing CDIO competencies across the curriculum.

The IABs serve as strategic platforms through which industry experts validate program learning outcomes, recommend curriculum updates, and advise on skill priorities emerging from the national and regional job market. Their guidance has directly influenced course revision cycles, particularly in sustainability and digitalization. This continuous dialogue ensures alignment with CDIO Standards 1 to 3 by linking program objectives to stakeholder needs.

Field trips represent another important channel for early industry exposure. Since Fall 2021, the College has coordinated 80 field trips, exposing students to engineering environments relevant to the "Conceive" stage of CDIO. These visits provide students with firsthand observation of industry practices and workplace requirements.

Internship placements serve as the primary vehicle for experiential learning. Students complete a minimum of 120 hours in industrial settings under joint supervision from academic mentors and field engineers, applying classroom knowledge to real-world engineering operations. Employers' feedback is formally incorporated into course reviews and accreditation reports, directly supporting CDIO Standards 7 and 8.

Within coursework, PBL and capstone projects act as structured interfaces between students and industry partners. Companies frequently outsource defined technical problems that students address through the CDIO process. These projects develop teamwork, communication, and system-thinking skills while reinforcing iterative CDIO design and implementation phases. Finally, research collaborations involving students and faculty provide opportunities for knowledge creation and dissemination through co-authored conference papers and journal publications. Such initiatives extend learning into the "Operate" stage of CDIO by emphasizing reflection, evaluation, and contribution to professional knowledge.

Alignment of Collaboration Channels with CDIO Stages

The CDIO framework provides the organizing structure that connects each collaboration channel to a defined phase of the engineering lifecycle. Figure 1 summarizes the alignment between AU's collaboration mechanisms and CDIO stages. This alignment ensures that industrial engagement is not fragmented but systematically integrated into every stage of student development, from problem conception to project operation.

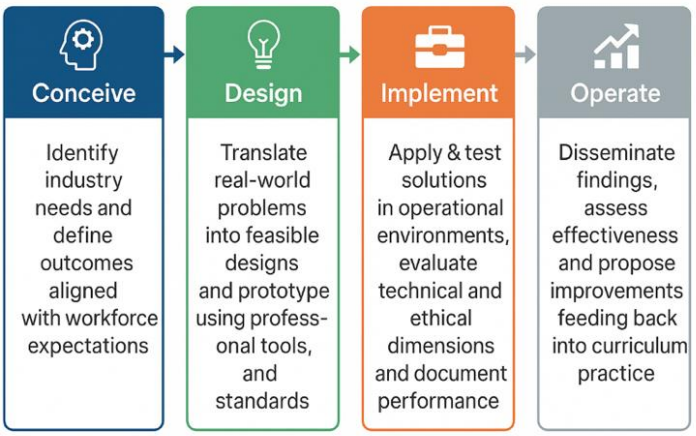


Figure 2. Alignment of Collaboration Channels with CDIO Stages at AU

Curriculum Integration

The CoE systematically embeds industrial collaboration within its curriculum architecture. Beginning in the diploma phase, students engage in introductory PBL modules emphasizing teamwork and technical communication. At the degree level, discipline-specific design courses incorporate authentic case studies provided by industry partners. Capstone projects constitute the culmination of this pathway, requiring students to synthesize technical, ethical, and sustainability considerations in employer-defined contexts. This progressive integration from diploma to bachelor level ensures continuous exposure to authentic engineering challenges and reinforces CDIO Standards 5 and 7 related to design-build experiences and integrated learning.

Industry feedback from IAB meetings and internship reports is analyzed annually to refine course learning outcomes. For example, the evaluation rubrics for capstone projects, often assessed by industry guest judges, now emphasize originality and innovation, technical quality, practical implementation, and societal impact, alongside explicit criteria for sustainability and safety awareness. These revisions ensure that student projects are judged not only on technical merit but also on their relevance to real-world challenges and communication effectiveness, as reflected in the structured evaluation framework used across the four engineering departments. This cyclical integration of external input demonstrates AU's sustained commitment to CDIO Standards 9–11, emphasizing evaluation, stakeholder feedback, and continuous improvement.

Representative Industry-Linked CDIO Projects

Several initiatives illustrate how AU operationalizes the CDIO framework through collaboration with external partners. The Life Energy Solar Laboratory and Solar Academy exemplify projects where students collaborated with industry engineers to design solar-PV container systems for remote oil-rig operations. These projects follow the CDIO cycle, where students conceive problems with industry partners, design solutions, implement simulations, and present operational outcomes to industry evaluators, demonstrating the practical feasibility of renewable energy solutions in remote industrial environments.

Interdisciplinary teams have also participated in national and international innovation competitions, where AU students achieved top rankings. Since Fall 2022, 178 industrial judges have evaluated senior projects during the Graduation Projects Exhibition, providing

professional feedback and validating student outcomes. These initiatives demonstrate the effective application of CDIO principles through authentic, industry-driven learning experiences that enhance engagement and professional competence while reinforcing AU's reputation for innovation and practice-oriented education.

Feedback and Continuous Improvement

Feedback mechanisms form the backbone of AU's quality-assurance loop for industrial collaboration. Data sources include employer evaluations, student reflection reports, IAB consultations, and accreditation reviews. Quantitative internship feedback is aggregated annually to identify competency gaps, while qualitative testimonials inform curriculum enrichment.

Moreover, the CoE conducts biannual program review meetings in which faculty present evidence of CDIO implementation and discuss feedback received from industry mentors. Recommendations are documented and tracked in subsequent cycles to ensure that curriculum and facility updates are evidence-based, thereby institutionalizing continuous improvement and reinforcing CDIO Standards 10 and 11.

LESSONS LEARNED AND INSTITUTIONAL IMPACT

Observed Benefits

Over nearly a decade of practice, several key lessons have emerged. Formalizing partnerships through structured frameworks such as IAB charters and Memoranda of Understanding has proven critical for sustainability and accountability. Student engagement has also increased when industrial collaboration is introduced early in the curriculum rather than being reserved for the final year, while faculty capacity-building, including training in PBL facilitation and industry liaison, has further enhanced the effectiveness of CDIO integration. Collectively, these practices have strengthened graduate employability and professional readiness, as reflected in employer satisfaction and internship performance data. They have also improved curriculum agility, enabling the inclusion of emerging technologies and sustainability topics, and elevated the institution's visibility through student participation in research and innovation competitions.

Furthermore, these efforts have reinforced alignment with accreditation standards, including those of Engineers Australia and CDIO Standards 1–11. Embedding industrial collaboration across CDIO stages has produced a sustainable, evidence-driven model of engineering education that remains responsive to evolving regional and global needs. These institutional results are consistent with prior research demonstrating the dynamic integration of sustainability and climate change perspectives in engineering curricula via CDIO at AU (El Achkar & Alsaba, 2024).

Challenges

Despite the positive outcomes associated with AU’s industry collaboration model, several challenges remain in sustaining and scaling such partnerships. These challenges can be grouped into institutional, operational, and partnership-related factors, as summarized in Table 1. These challenges may affect several CDIO Standards, particularly Standards 5, 7, and 8 related to design-build and integrated learning experiences, as well as Standards 9–11 associated with faculty development, program evaluation, and continuous improvement.

Table 2. Key Challenges in Sustaining Industry Collaboration within the CDIO Framework at AU and Corresponding Mitigation Strategies

Challenge	Description	Mitigation Strategy
Institutional Coordination	Misalignment between academic and industry timelines limits mentor availability and project engagement.	Early coordination and flexible scheduling with industry partners.
Faculty Workload and Resource Constraints	Supervising internships and industry-linked projects requires significant faculty coordination.	Shared supervision and institutional support mechanisms.
Variability in Industry Project Scope	Differences in project scope, supervision, and data access affect consistency of learning outcomes.	Standardized project guidelines and evaluation rubrics.
Sustaining Industry Engagement	Smaller companies may lack resources for long-term collaboration.	Formal partnerships and regular advisory board consultations.

INSTITUTIONAL IMPACT

Internship Placement Outcomes (2015–2025)

The internship dataset spans academic years 2015–2016 to 2024–2025 and includes 633 interns from AU's CoE. The analysis first examines the distribution of interns across the four engineering programs, followed by an assessment of placements by host-sector category (Figure 2).

Placements were led by Mechanical Engineering (ME) (34.3%), followed by Petroleum Engineering (PE) (30.3%) and Civil Engineering (CE) (28.1%). Electrical and Electronics Engineering (EE) (7.3%) formed the smallest share, which may reflect cohort size and sectoral demand patterns. Overall, participation is broad across programs, with particularly strong engagement from ME and PE.

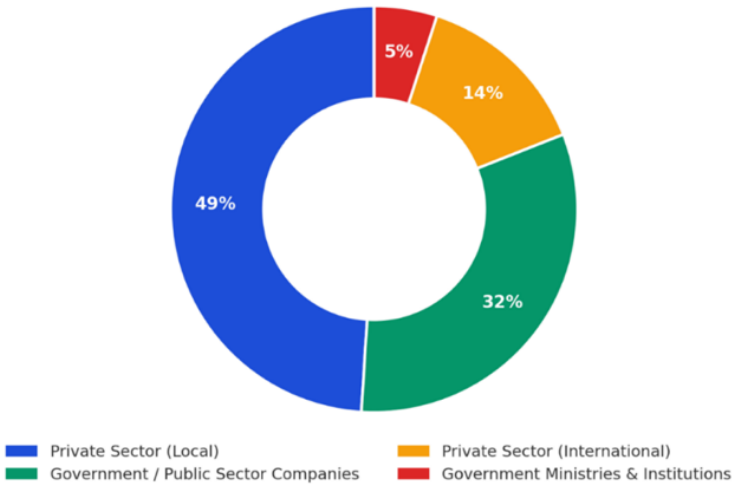


Figure 2. Distribution of Interns Across Organizational Categories

Nearly half of the interns (≈49%) were placed in the Private Sector (Local), indicating strong collaboration with national firms and consultancies. Government / Public Sector Companies accounted for ≈32%, reflecting the central role of state-owned enterprises, particularly in energy. Private Sector (International) represented ≈14%, providing exposure to global practices and standards, while Government Ministries & Institutions accounted for ≈5%. The distribution evidences a diversified placement ecosystem spanning both public and private stakeholders, ensuring broad exposure to industrial environments.

These results indicate that AU's internship model successfully connects students with both public and private engineering sectors. The strong representation of private-sector placements reflects effective collaboration with local industry partners, while international placements expose students to global engineering practices. This diversified placement ecosystem strengthens experiential learning and enhances graduate employability.

Beyond quantitative distributions, qualitative feedback from students was also examined to capture their perceptions of learning outcomes and internship experiences. Student evaluations collected over a five-year period were analyzed, and a word-cloud visualization was generated (Figure 3). The text body, containing 4,676 raw words, was processed using systematic text-cleaning methods that reduced it to 1,231 meaningful terms (a 73.7% reduction) by removing stop words and non-informative descriptors.



Figure 3. Word Cloud Derived from Qualitative Analysis of Student Internship Testimonials (Five-Year Dataset)

The most prominent themes emerging from student feedback centered on "field" (38.1% of comments), "skills" (36.5%), "real" (22.2%), and "project" (22.2%), highlighting students' emphasis on the practical relevance of their internship experiences. Thematic categorization revealed that students most frequently mentioned technical-skills development (76 mentions), professional development (51 mentions), academic learning connections (36 mentions), and real-world value (32 mentions). The word cloud effectively captures the dual-perspective nature of AU's internship program, where students recognized both the application of theoretical knowledge from university courses and the acquisition of workplace-relevant competencies such as teamwork, communication, and supervisory relationships.

Across 633 placements (2015–2025), the outcomes demonstrate that sustained multi-channel industry engagement within the CDIO framework yields broad opportunities across programs and sectors. These results reaffirm that AU's experiential learning model strengthens graduate readiness, aligns with regional workforce needs, and supports the university's commitment to industry-connected engineering education.

Student Involvement in Research Publications

An important institutional impact observed over the last ten years (2015–2025) is the significant engagement of undergraduate students in scholarly publications, both in journals and conference proceedings. Across the CoE, 62 publications have included undergraduate student participation, with 205 students listed as co-authors. This reflects how PBL and CDIO-oriented practices have successfully fostered student-led inquiry, collaboration with faculty, and early exposure to research dissemination.

The distribution of publications and student participation highlights notable trends. CE leads with 31 publications and 92 student co-authors, representing the largest share of undergraduate involvement. PE follows with 17 publications and 68 student co-authors, demonstrating strong integration of research within its curriculum. ME and EE also contributed with 9 publications (29 students) and 5 publications (16 students), respectively.

These patterns demonstrate that integrating research opportunities into undergraduate education strengthens not only student learning outcomes but also the institution's overall research culture. By embedding research participation in CDIO-based projects, students develop transferable skills in critical thinking, collaboration, and dissemination, thereby enhancing both institutional visibility and student preparedness for advanced studies or professional practice.

CONCLUSIONS AND RECOMMENDATIONS

This study demonstrates how the Australian University (AU) has successfully integrated the CDIO framework across multiple channels of industrial collaboration to enhance engineering education. By aligning IABs, internships, project-based learning, and research partnerships with CDIO stages, the CoE has established a coherent system that connects academic learning with real-world engineering practice. The outcomes, evident through internship data, student feedback, and research engagement, confirm that CDIO-based industrial collaboration strengthens graduate readiness, fosters professional competencies, and sustains continuous curriculum improvement.

Institutional experience over the past decade highlights that success in such initiatives depends on structured partnerships, faculty capacity-building, and systematic feedback loops. The AU model may provide a transferable framework for universities seeking to modernize engineering programs through authentic, practice-oriented learning.

Future directions should focus on expanding cross-sector collaborations, particularly in renewable energy, automation, and data-driven engineering, to reflect emerging industry demands. Establishing more formalized mechanisms for long-term industry engagement, joint project supervision, and faculty internships within companies will further strengthen integration between academia and practice. Moreover, embedding data analytics into feedback systems can improve evidence-based curriculum updates, ensuring alignment with CDIO Standards 9–12. Through these continuous efforts, AU will continue to consolidate its role as a regional leader in innovative, industry-connected engineering education and contribute to shaping sustainable, forward-looking engineering practices.

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INCORPORATING AN INTEGRATED DEVELOPMENT ENVIRONMENT TO TEACH NUMERICAL METHODS

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ABSTRACT

In this work the rationale, methodology and results of using the computer language Python within an integrated development environment, (IDE) as the method of implementing numerical algorithms derived from the theory of numerical methods is described. This work is part of a First-Year core Numerical Techniques for Mechanical & Aerospace Engineering module at master's level, and the integrated development environment provides an easy-to-use interface to develop, execute and provide results, including appropriate visualizations, so enhancing a student's interaction, and hence learning, with both numerical methods theory and practical skills. It is demonstrated here how Python can first be introduced to students through a short course with intensive exercises, followed by several mini projects of increasing complexity, leading to several major projects. Quick turn-around times and detailed assessment of these tasks are necessary for efficient student development. Student engagement and learning outcomes are evaluated through pre- and post-course surveys and focus group discussions. It was found that students broadly reported the course to be engaging, together with usefulness. As the course is at the introductory stage, care was taken in terms of set-up and design of the learning activities, together with thinking as to how to improve the course in future years.

KEYWORDS

Python, numerical methods, inquiry-based learning, computer-programming assessment, CDIO Standards: 8, 12

INTRODUCTION

The central reasoning for incorporating Python programming into teaching numerical methods is to bridge the gap between theoretical mathematical concepts and practical computational implementation**,** using a language that is both intuitive for beginners and powerful enough for professional scientific computing.

Python is an object-orientated language originating from around the late 1980s as a scripting language (Kiusalaas, 2005) and can be viewed as a fast-emerging language which is still being developed and refined. Programs written in Python are not compiled into machine code but are run using an interpreter. This helps with the speed of execution. Also, the use of an interpreted code means that computer programs can be tested and debugged more quickly so allowing the user more time to concentrate on the principles behind the program. However, a disadvantage of the use of an interpreter is that stand-alone applications are not possible. A further advantage of Python, compared to some well-established computer languages, is that it is open-source software. Now many Linux distributions include Python as standard. In fact, Python can be used on all the major operating systems, i.e., UNIX, Linux, Windows, Mac OS, and interestingly a program developed on one system can be exported to other operating systems without change. This paper reports on the use of Python as an integrated component in the teaching of numerical methods for engineers. Modern numerical methods courses must include a computer programming vehicle to perform calculations based on numerical algorithms derived from numerical methods theory. Numerical methods are techniques by which mathematical problems are formulated so that they can be solved with arithmetic operations (Chapra and Canale, 2002). Numerical methods provide a large and diverse choice for engineering solutions, but these methods all have one common characteristic: they invariably involve large tedious arithmetic calculations. This problem is solved with the use of fast, efficient and accurate computers. The normal process is to use or derive theoretical governing equations, sometimes originally continuous in nature in terms of discrete mathematics. These equations are then used to solve problems directly or are used as a basis for a numerical model (usually with assumptions). Numerical algorithms are then generated and solved using computer hardware and software to give output from given input, and, where it must be recognized and remembered that approximations are being used. Therefore, much effort is employed in numerical methods to ascertain the accuracy of given results.

It can be said that two quite different emphases have been, and to some extent still are, prominent when teaching numerical methods. The first, and one favoured by the European Society for Engineering Education (SEFI) (2002), has been called the ‘just-in-time’ approach. Here numerical methods are taught where the main purpose is to teach the mathematical theory involved. A second approach, and the one preferred here, is to teach numerical methods using specialized courses devoted to numerical analysis (Kaukič, 2005). The reasoning behind adopting this option is because of the current and growing trend of using numerical methods as a foundation for numerical simulations and the ubiquitous presence of computers in almost all engineering specialties.

Application of inquiry-based learning when teaching numerical methods is used in this course. The pedagogical and design decisions to implement inquiry-based learning (IBL) into a more “hands-on” course are driven by the need to shift from passive rote memorization to active, deep learning that mirrors real-world research practices. These decisions are justified to improve student engagement, development of critical thinking, and the acquisition of transferable research skills. Inquiry-based learning has received a great deal of attention (Lappas and Kritikos, 2018) with the focus being mostly on students’ engagement in active

discovery learning and learning in environments which include some active participation, self-action, observation, exploration and experimentation (Psycharis, 2011; Kyrizis *et al*., 2009; Gormally et al., 2009; Justice et al., 2007; Richardson and Liang, 2008). It can be argued that numerical methods, when the use of computers is employed, is ideally suited to incorporate some and indeed all of these inquiry-based attributes. The opportunity to learn numerical methods effectively does depend on a wide range of factors, but among the most important are those associated with activities and practices within the education process (Martin-Caraballo and Tenorio-Villalón, 2015; Olagide, 2014). Details of programming pedagogy and self-efficacy relevant to this work are also found in the literature (Pham *et al*., 2014; Reng and Kofoed, 2012; Lai *et al*.,2025).

For the current numerical methods course, a didactic framework based on the Process of Scientific Inquiry (PoSI) (Lappas and Kritikos, 2018), which has three main components each using a particular cognitive tool, was used. The framework has the three general aims of: helping with understanding basic aspects of numerical methods; providing space for practice of computer and critical-thinking skills; and, to give an understanding of scientific research (Lappas and Kritikos, 2018). Within these aims lie the more specific important goals of understanding important mathematical concepts like stability and convergence of solutions; selection of the best appropriate numerical method to suit the problem in question; developing and implementing a suitable algorithm followed by testing and debugging. The IDE is heavily integrated into achieving all of these aims when writing computer programs for developed algorithms.

Regarding assessment, theoretical aspects of the course were assessed in a traditional way using quizzes, assignments and a final examination. However, consideration was given in how to combine effective and efficient assessment of computer programming work, mainly in the form of assignments. It was decided to carefully incorporate a form of peer reviewing into the computer programming assessment scheme.

In line with the CDIO 2026 conference theme, this work contains development of professional engineering competencies, skills and attitudes. Integrating numerical methods with computer programming significantly enhances professional development by bridging the gap between theoretical knowledge and practical application across fields like engineering, finance, and data science. This synergy equips professionals with the ability to solve complex, real-world problems that lack exact analytical solution.

The integration of numerical methods and computer programming is also in line with CDIO competencies where technical knowledge and skills are greatly increased with problem - solving and critical thinking coming to the fore. Other competencies used in the design of the course include life-long learning, effective reporting and teamwork. The course offers hands-on learning, integrated learning and active learning techniques.

The sub-theme of simulation and modelling found in numerical methods combined with programming, particularly when integrated with innovative assessment and feedback, enables a "learn-before-doing" approach, allowing students to experiment in low-cost, risk-free environments before engaging with real-world physical systems. This approach acts as a bridge between theoretical knowledge and professional practice.

USING THE INTEGRATED DEVELOPMENT ENVIRONMENT

Python Environment

The Jet Brains PyCharm Community Edition 2021.1.2x64 integrated development environment (JetBrains, 2021) was used for all computer programming work in this course. The Windows installation of PyCharm was used here. The first part of this course was to familiarize the students with the IDE and to show its possibilities. This was achieved with a demonstration followed by very simple exercises. At this point such common, and useful, Python tools such as `numpy` (a library for the programming language which offers comprehensive mathematical functions, random number generators, linear algebra routines, Fourier transforms, and more), and `matplotlib` (a comprehensive library for creating static, animated, and interactive visualizations in Python) were introduced to the students.

Some Preliminary Remarks

The students taught in this course did not have much prior programming experience, and what they did have was usually using MATLAB. However, it was found that the students who had used MATLAB found it quite easy to adapt to the similar syntax of *numpy* with the help of Python tutorials geared towards engineering users. It was found that a 2-hour laboratory session was sufficient to acquaint the students with the basics although it was necessary to introduce further topics as the course progressed. During this time students were actively encouraged to cooperate and even collaborate with each other to help with their computer skills.

Generally, the students had been introduced to a given algorithm during a lecture period, and this was then reinforced with brief notes containing explanations and exercises during the computer laboratory sessions. During the early stages of the course most of the code needed to complete exercises was made available with students having to change fragments here and there or extending the provided code. However, the amount of code provided became progressively less as the student programming skills improved, and eventually students were asked to implement algorithms of subroutines from scratch. Occasionally quizzes were used to provide incentive and to get feed-back that students were approaching the work in a systematic way.

How much assistance to give to students was also considered. It was important to give students the freedom to fix their code when it failed, even struggle a little to try to find a solution. When assistance was given, it was of a type where the instructor asks questions to give guidance as to how to trace-back and diagnose their code. The main method of instruction during the laboratory periods was one-to-one, as the cohort was only 15 students and this proved very effective. During these periods students were also expected to give explanations of their coding strategy in brief 5-minute presentations to generate discussion and ideas.

The delivery strategy fell into three main areas: intensive exercises; mini projects and finally several major projects. Some details of these three components are now described.

Intensive Exercises

Preliminary intensive exercises were used to introduce common programming procedures necessary to solve numerical problems. Throughout these exercises comprehensive notes and almost complete programs were given to the students together with problems where students simply had to change the given code to affect a solution. The instruction staff were

fully engaged in helping students with well-placed questions and suggestions. The exercises fell neatly into three main areas with the first containing: how to use variables; the use of library functions; and vectorization and plotting.

When instructing how to use variables, a very simple mathematical model was first chosen for introduction, for example, the prediction of the vertical position z of a ball at time t using the equation

$$z = v_i t - \frac{1}{2} g t^2 \tag{1}$$

where v_i is the initial upwards velocity and g is the local acceleration of gravity. The students were given a Python program which solved this model and the program was dissected line-by-line. The students were encouraged to vary the variable to get different results. The use of library functions was introduced with an explanation that much functionality exists in Python libraries, but to activate this functionality the functions must be explicitly imported. An important component of this area was plotting. At this stage only *x-y* plots were introduced as well as necessary libraries to effect plotting. Next to be introduced was the formatting of text, numbers, and arrays, and the printing and input of data.

During the intensive exercise period the very important group of topics were introduced, i.e.: `If` tests, colon, indentation; Python `For` loops; Python `While` loops; and Python Lists.

Mini projects

Some eight mini projects, which were carefully graded regarding the level of difficulty, were used during this course. To give an idea of a typical mini project this sub-section gives a description of one.

Mini Project - “An Oscillating One-Dimension System”.

Many engineering scenarios use oscillating springs. To illustrate this a simple system modelled using the general second-order differential equation was used

$$u''(t) + \omega^2 u(t) = 0 \tag{2}$$

where $u(t)$ is the unknown variable at time t and ω is a physical parameter. No damping is imposed on this system, and to complete the model two initial conditions must be given. A numerical scheme to effect solution has now to be chosen. One way is to write the governing equation as a first-order system of two differential equations and introduce $u = x$ and $v = x' = u'$ as two unknown functions. This gives

$$u' = v, \quad v' = -\omega^2 u \tag{3}$$

The Forward Euler method can now be applied for the differential equation system which results in the solution scheme

$$u^{n+1} = u^n + \Delta t v^n, \quad v^{n+1} = v^n - \Delta t \omega^2 u^n \tag{4}$$

Using Python, the solution scheme was coded together with the exact solution. Calculations were conducted using 20 intervals per period resulting in solutions for the exact and numerical calculations as shown on Figure 1.

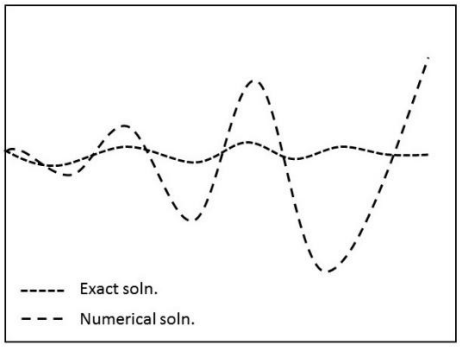


Figure 1. Simulation of an oscillating system.

It can be seen there is very little similarity in the solutions. This discrepancy gives the opportunity for a good learning experience in that, is it due to a programming error, or is there a problem with the numerical solution method. Even though everything was developed logically and seemingly correctly, the two solutions do not match. So how was this rectified by the students? First the computer program was tested against some hand-calculations, but everything appeared correct. The students were then asked what could be changed without altering the numerical solution method. It became clear that the choice of 20 intervals per period was arbitrary and could therefore be adjusted. Therefore, this number was steadily increased, and better correspondence of the two solutions resulted.

Major Projects

Part of the course assessment consisted of two major projects, each of which consisted of assembling the correct equations for solving, assigning boundary conditions, developing the algorithm, writing the solution code and finally writing code for the post-solver visualizations. As an example, the following outlines one of the projects used.

Major Project: “Calculate and Visualize the Characteristics of a Lid-Driven Cavity Steady-State Flow using the Streamfunction/Vorticity Approach”.

The project takes a student through several necessary stages in the development of a suitable numerical method. These are: writing the Navier-Stokes equations in the streamfunction and vorticity form; stating suitable boundary conditions at the walls of the cavity in terms of vorticity and streamfunction; discretization of the transport equations suitable for a Cartesian grid; derive a solver; and display the results.

The first task involves defining vorticity and streamfunction followed by the derivation of the Navier-Stokes equations for incompressible steady-state flow in the vorticity-streamfunction form where ω is the vorticity and ψ is the streamfunction.

The next major task for the students is to discretize the transport equations and write a solution algorithm. The method chosen was that due to Burggraf’s (1966). To include the boundary nodes of the cavity, central differencing is used to discretize the non-dimensional governing equations and the number of nodes in the *x* and *y* directions was set at *nx* and *ny*, respectively. The mesh used by the students was a regular Cartesian grid with the nodes equally spaced

at a distance *h*. Eventually the students are to arrive at the non-dimensional advection-diffusion and elliptic equations. The solution method uses residual functions; that is, if the values of ψ_{ij} and ω_{ij} are exact on the nodes spanned by the residual functions $\mathcal{R}_{ij}$ and $\mathcal{L}_{ij}$, then

$$\mathcal{R}_{ij}^{k+1} = \mathcal{L}_{ij}^{k+1} = 0 \tag{5}$$

where

$$\mathcal{R}_{ij}^{k+1} = \frac{1}{2(1+\gamma^2)}\left(\psi_{i+1,j}^{k} + \psi_{i-1,j}^{k+1} + \gamma^2\left(\psi_{i,j+1}^{k+1} + \psi_{i,j-1}^{k+1}\right)\right) + h^2\omega_{ij}^{k} - \psi_{ij}^{k} \tag{6}$$

and

$$\mathcal{L}_{ij}^{k+1} = \frac{1}{2(1+\gamma^2)}\left(\left(\omega_{i+1,j}^{k} + \omega_{i-1,j}^{k} + \gamma^2\left(\omega_{i,j+1}^{k} + \omega_{i,j-1}^{k}\right)\right)\right. \tag{7}$$

$$\left. -\frac{Re}{4}\gamma\left(\left(\psi_{i,j+1}^{k} - \psi_{i,j-1}^{k+1}\right)\left(\omega_{i+1,j}^{k} - \omega_{i-1,j}^{k+1}\right) - \left(\psi_{i+1,j}^{k} - \psi_{i-1,j}^{k+1}\right)\left(\omega_{i,j+1}^{k} - \omega_{i,j-1}^{k+1}\right)\right)\right) - \omega_{ij}^{k}$$

where γ is the ratio of width to height of the cavity and Re is the Reynolds number. These equations can be solved using a fixed-point iterative procedure, based on the Gauss-Seidel scheme and as the equations have been discretized using central differencing much work is also necessary to give the final boundary conditions.

COURSE FEEDBACK

Student Feedback and Experience

Two surveys, here referred to as the pre-course survey and the post-course survey, were conducted to assess any change in student self-efficacy and interest in the inclusion of Python as suitable for solving numerical methods. The sample size in each survey was $N = 15$. Included in the post-course survey questions were those needed to assess the design and deliver of the course. As well as the surveys, focus group discussions were held at the end of each session of the course to elicit further details concerning the content. The verbal data collected during the focus group discussions was documented and used in conjunction with the survey data to give a deeper understanding of student responses.

The survey instrument design was intended to get feed-back concerning pre-course instructions, high activation barriers, and confidence concerning using programming with numerical methods. The scales used were of a Likert type, with some expanded beyond the usual five-point scale, to try to lessen the effect of subjectivity. Each focus group consisted of five students. The first few moments of the discussion were critical. In a short time, the moderator created a thoughtful, permissive atmosphere, provided ground rules, and set the tone for the discussion. Much of the success of the group interviewing was attributed to the development of this open environment. The pattern for introducing the group discussion was: welcome, overview of the discussion and ground rules, followed by the discussion.

Informed consent was obtained from each student involved and from the university ethics committee. The participants confirmed they understood the process, why their participation was required and in what way the research findings would be used and reported.

In this section the analysis of student feedback both verbal and from the survey data is divided into three sub-sections: Introduction to Python and code familiarization; content and structure of the parts of the course involving Python; and lastly reaction to how the Python computing language was delivered and integrated into the course. Extensive notes with annotated screenshots as to how to set-up the programming environment were compiled and the student reaction to the comprehensiveness and ease of following these documents is summarized on Figure 2.

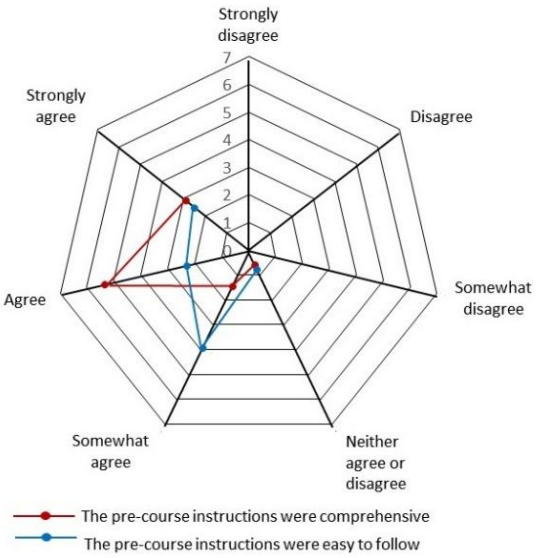


Figure 2. Student reaction to questions related to the pre-course instructions and set-by-set guide for setting up the PyCharm IDE.

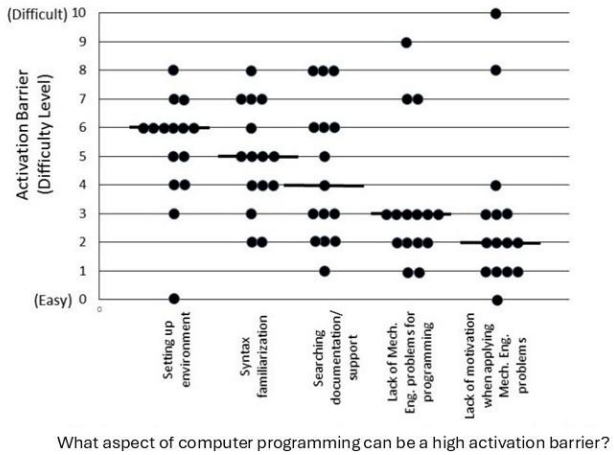


Figure 3. Student assessment of what they consider high activation barriers: 0 here means – no barrier, and 10 means - a high activation barrier. The horizontal solid lines represent the medians.

There is often a point reached in the early stages of programming where frustration encroaches for the programmer, even when writing the simplest of codes. Of course, such

experiences can be very instructive, but they can also be very de-motivating for beginners. It was important therefore to try to ascertain from a student's point of view as to what they saw as "activation barriers/difficulties" associated with beginning and applying Python programming. The results of the surveys are shown on Figure 3. As can be seen there was a fair spread of opinions on each of the proposed barriers with setting up the environment and syntax familiarization thought of as giving high barriers to programming. It is clear therefore that more care will be needed in future to reduce this problem and create a more enabling environment for experiential learning (Wood and Bhute, 2019; Shah *et al*., 2020).

On Figure 4 is shown results for how the students would regard incorporating Python into the numerical methods calculations. The results shown on Fig. 4 are encouraging as the students generally stated that their confidence in using Python computing language veered mostly in the positive direction.

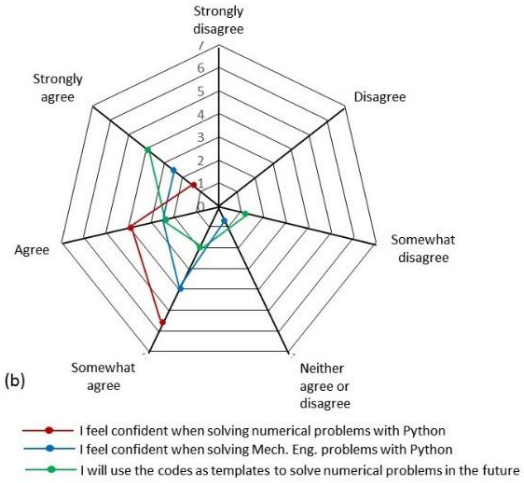


Figure 4. incorporating Python into the numerical methods calculations.

Regarding the delivery of the course, some students expressed a desire for more active and structured learning components which related to the actual code and running of simulations. The students did like formal and structured questions rather than being left to explore too much. However, every opportunity was still maintained to encourage the students to go deeper into a given problem.

CONCLUSIONS

The use of PyCharm as a suitable integrated development environment for the introduction of the Python programming language to students with very little coding experience has been demonstrated. The course was designed so that each exercise was built on previously taught material which help with delivery efficiency. The open-source nature of PyCharm meant that availability is not an issue, and it is recognized that Python itself is a rapidly developing language, and new libraries must be continually reviewed. Also, the students are developing skills in programming which are immediately transferable to later employment in industry and academia. Within this course there was a good variety of problems (projects) with different complexities which could, without much resistance, be given to the students to help with a variety of learning objectives. There was an improved student perception of Python post-course, and confidence and self-efficacy improved with much satisfaction. It is recognized that the student surveys were conducted with a small sample size, and further studies will be important to assess whether the findings here are transferable to a much larger cohort.

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REDESIGNING ASSESSMENT FOR AI-SUPPORTED PROJECT-BASED LEARNING: EVIDENCE FROM ENGINEERING EDUCATION

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ABSTRACT

The integration of Artificial Intelligence (AI) tools into engineering education is reshaping how students learn, collaborate, and complete project-based tasks. In Project-Based Learning (PBL) environments, where students design, build, and justify complete engineering solutions, AI offers powerful advantages, including enhanced productivity, improved conceptual understanding, and support for ideation and debugging. However, increasing reliance on AI also presents significant challenges for assessment fairness, authenticity, and the evaluation of individual student contribution. This study investigates how engineering students use AI within a PBL course, examines their perceptions of its benefits and risks, and analyzes the implications for traditional assessment structures. Survey results from 38 students reveal that AI is extensively used across all stages of the PBL workflow, yet students acknowledge that fair assessment requires mechanisms ensuring they can explain, justify, and validate AI-assisted work. Based on these exploratory findings, this paper proposes an AI-aware PBL assessment framework grounded in four principles: transparency of AI use, prioritization of understanding over output quality, incorporation of multiple evidence sources for individual contribution, and proportional weighting of tasks susceptible to automation. The framework introduces practical mechanisms such as AI-use declarations, micro-vivas, process-oriented artefacts, and rebalanced rubrics, all of which can be integrated into existing assessment structures. This work contributes a practical CDIO-aligned approach for incorporating AI into engineering education without compromising academic integrity or learning outcomes. By emphasizing accountability, understanding, and responsible AI use, the proposed framework supports the evolving needs of modern engineering programs while maintaining fairness and rigor in PBL assessment.

KEYWORDS

Artificial Intelligence (AI); Project-Based Learning (PBL); Engineering Education; Academic Integrity; Standards 5, 6, 7, 8, 11.

INTRODUCTION

Within the Conceive-Design-Implement-Operate (CDIO) framework, engineering education aims to develop graduates capable of conceiving, designing, implementing, and operating complex systems while demonstrating professional and ethical competence.

Project-Based Learning (PBL) is widely adopted in engineering education due to its effectiveness in integrating technical knowledge with transversal skills such as teamwork, communication, problem-solving, and self-directed learning (Boud & Feletti, 1997; Boud, 1985; Barrows & Tamblyn, 1980; Crespí et al., 2022; Chen et al., 2021). By engaging students in real-world engineering challenges, PBL supports deep learning and professional readiness, aligning closely with active and integrated learning principles.

In parallel, accreditation frameworks and policy documents, including the Accreditation Board for Engineering and Technology (ABET) criteria (ABET, 2025–2026) and the European Key Competences for Lifelong Learning (Council of the European Union, 2018), emphasize the importance of professional competencies such as communication, collaboration, critical thinking, and ethical responsibility alongside technical expertise.

Despite its strengths, assessment within PBL remains challenging, particularly when evaluating individual contributions in team-based projects (Farhat et al., 2021; Devlin et al., 2016). These challenges have intensified with the rapid emergence of Artificial Intelligence (AI) tools capable of generating code, designs, and technical documentation. While AI can enhance learning efficiency and student confidence, it complicates instructors' ability to verify authorship, understanding, and individual contribution.

Recent studies on generative AI in higher education similarly highlight both opportunities and risks for learning and assessment. AI tools can support idea generation, feedback, coding, writing, and self-directed learning; however, they also raise concerns related to academic integrity, authorship, over-reliance, accuracy of generated outputs, and the validity of traditional assessment methods (Kasneci et al., 2023; Cotton et al., 2024; Perkins, 2023; Farrelly & Baker, 2023; Xia et al., 2024). These concerns are particularly relevant in PBL environments, where students are assessed not only on final outputs but also on process, reasoning, teamwork, and individual contribution.

From a CDIO perspective, this challenge directly affects the implementation of Standard 7 (Integrated Learning Experiences), Standard 8 (Active Learning), and Standard 11 (Learning Assessment). As AI becomes embedded in PBL workflows, assessment practices must be adapted to ensure that learning outcomes, professional competence, and fairness are preserved.

This study therefore investigates how engineering students use AI within PBL environments and examines the implications for assessment practices. Building on prior work in PBL assessment, technology-enhanced learning, and generative AI in higher education, the paper proposes an AI-aware assessment framework that supports responsible AI use while maintaining alignment with CDIO learning objectives.

AIM OF THE STUDY

The aim of this study is to investigate how engineering students use AI tools within PBL environments and to examine the implications for assessment fairness, authenticity, and individual accountability. The study analyzes student perceptions of AI-supported learning and uses these insights to propose strategies for redesigning PBL assessment practices in AI-rich

educational settings. Given its exploratory nature, this paper is positioned as a CDIO implementation and design-based contribution rather than a fully validated intervention study. It proposes an AI-aware PBL assessment framework informed by student perceptions, instructor reflection, and existing CDIO-aligned assessment practices. Future work will focus on implementing and validating the framework across additional cohorts and PBL contexts.

Research Questions

1. How do engineering students use AI tools during different stages of a PBL course, including planning, coding, documentation, design, and reporting?
2. What are students' perceptions of the benefits, limitations, and risks of using AI in PBL activities?
3. What assessment strategies can support fairness, authenticity, transparency, and individual accountability in AI-supported PBL environments?

METHODOLOGY

PBL Course Context

The study was conducted within an undergraduate PBL course offered in the Electrical Engineering program for students in Year 3–4 at the Australian University-Kuwait. PBL is a core pedagogical component of the curriculum, with students completing five PBL courses across their degree. In this course, students work in teams to apply CDIO framework (Conceive, Design, Implement, Operate) and document a complete engineering solution over a full academic semester. A project brief is provided at the start of the semester, after which students are divided into groups and are required to develop their solution collaboratively.

During weekly sessions, students engage in structured teamwork and receive formative feedback from the instructor, who serves as a facilitator rather than a traditional lecturer. Students are expected to work independently, troubleshoot problems autonomously, and consult external experts or industry professionals when needed. All consultations must be documented through meeting minutes, while external work completed by practitioners is strictly prohibited and results in loss of marks. Students maintain reflective workbooks, record team meetings, and progressively build project documentation over the semester.

Permitted Use of AI Tools

In this iteration of the course, students were explicitly allowed to use AI tools to support their project work. This included AI tools for coding, documentation, debugging, design, and simulation support. However, students were clearly informed that while AI may assist their work, they remain entirely responsible for the accuracy, validity, and reliability of all project outcomes. Students must be able to validate, justify, and demonstrate full understanding of any AI-assisted component during presentations, evaluations, or technical questioning. No restrictions were placed on specific AI platforms; students could freely use tools such as ChatGPT, GitHub Copilot, or other AI generative systems as long as they maintained complete ownership and comprehension of their submitted work.

Assessment Structure

The course assessment is distributed across five components spanning the semester as shown in table 1:

Table 3. Course assessment elements

Assessment	Type	Description	Week	Weight
Assessment 1 – Deliverables	Individual / Group	Individual report (10%) and project plan (5%)	Week 4	15%
Assessment 2 – Presentation	Individual / Group	Interim presentation	Weeks 7–8	15%
Assessment 3 – Comprehensive Evaluation	Individual / Group	Final presentation (15%) and final report (15%)	Weeks 3–14	30%
Assessment 4 – Portfolio	Individual / Group	Technical evaluation (20%) and final code/simulation/prototype (10%)	Weeks 13–14	30%
Assessment 5 – Participation	Individual	Attendance and class engagement	Weeks 1–14	10%

Survey Design and Purpose

A structured survey was designed to examine students' use of AI tools within the PBL process and to capture their perceptions of learning impact, teamwork dynamics, and assessment fairness. The survey supports the study's research questions by providing empirical evidence on how AI is integrated into PBL activities and how students believe assessment practices should adapt in response.

The instrument included Likert-scale items addressing AI usage frequency, perceived benefits and challenges, and impact on teamwork, as well as open-ended questions to gather qualitative insights and recommendations. The survey was reviewed for clarity and alignment with the research objectives and was administered anonymously during the final weeks of the semester via Microsoft Teams after completion of major PBL milestones. Participation was voluntary and had no impact on course grades, with a total of 38 student responses.

Quantitative data were analyzed using descriptive statistics, while open-ended responses were examined through thematic analysis to identify recurring themes related to AI integration, learning processes, and assessment fairness.

RESULTS AND DISCUSSION

Thirty-eight upper-level electrical engineering students participated in the survey, the majority with prior PBL experience. About 88% reported using AI tools during the course, primarily ChatGPT, across most PBL stages including coding, report writing, brainstorming, and design development.

Overall, students viewed AI as beneficial, reporting improved understanding of project tasks and greater confidence when presenting AI-assisted work. Learning outcomes were perceived as comparable to or better than those in previous non-AI courses, suggesting that students did not perceive AI use as reducing their engagement with engineering concepts.

However, concerns about assessment fairness were prominent. Students emphasized that AI-assisted work should be assessed equally only when accompanied by clear explanations and demonstrated conceptual understanding. Suggested strategies included oral assessments, AI-use declarations, reflective explanations, and peer evaluation.

While students acknowledged risks such as over-reliance on AI and reduced critical thinking, they noted that responsible use and independent validation could mitigate these issues. Overall, the findings highlight the need for transparent, explanation-based assessment approaches to ensure fairness and academic integrity in AI-supported PBL.

Table 2. Summary of Student Survey Results on AI Use in PBL (N = 38)

Category	**Variable**	**Summary of Findings**
Participant Profile	Major	100% Electrical Engineering students
	Year of Study	Majority Year 3–4 (upper-level students)
AI Usage	Used AI in PBL	~88% Yes, ~12% No
	Frequency of AI Use	Mostly Occasionally → Frequently → Almost Always
AI Tools Used	Tools	ChatGPT dominant; some DeepSeek
AI-Related Tasks	Tasks	Coding, report writing, brainstorming, flowcharts, formatting
Impact on Learning	Understanding	Majority reported improved understanding (Yes/Partial)
	Confidence	Majority felt more confident presenting AI-assisted work
	Learning Level	Most said About the same or Learned more
Fairness of Assessment	Equal assessment	Majority: Only fair if explanation of AI use is provided
	Preferred Strategies	Oral discussions (viva), AI-use declarations, reflections, peer evaluation
	Declaration Requirement	Majority Yes or Only for major tasks
Perceived Risks of AI Use	Risks	Over-dependence, wrong answers, reduced writing/critical thinking, shallow understanding
Student Suggestions	Recommendations	Oral questioning, testing understanding, AI-use declaration, ensuring comprehension

The survey findings directly informed the proposed framework. Students' emphasis on explanation and oral questioning supports the inclusion of micro-vivas; their support for AI-use disclosure informed the AI declaration requirement; and their concerns about over-reliance, incorrect AI outputs, and shallow understanding informed the focus on validation, reflection, and individual accountability. The framework presented in the following section is therefore interpreted as a proposed assessment design rather than a fully validated intervention. It is grounded in the exploratory survey findings, the existing PBL assessment structure, and reflective instructor experience in managing AI-supported project work.

PROPOSED AI-AWARE PBL ASSESSMENT FRAMEWORK

Building on the survey findings, the existing PBL assessment structure, and reflective discussions among instructors teaching PBL courses, this section proposes an AI-aware assessment framework designed to preserve fairness, authenticity, and alignment with learning outcomes while recognizing AI as a legitimate and increasingly unavoidable tool in engineering education.

Rather than restricting AI use, the framework rebalances assessment priorities, shifting emphasis away from polished outputs, such as well-written reports, formatted documentation, generated code, or visually refined presentations, toward understanding, validation, and individual contribution.The central premise is that meaningful learning in AI-supported PBL environments can be ensured when assessment focuses on *how* students use AI and *what* they understand, rather than *what* AI produces.

The proposed framework is structured around four guiding principles, each supported by concrete assessment mechanisms that can be integrated into existing PBL courses with minimal structural change.

Principle 1 – Transparency of AI Use

To ensure assessment fairness and accountability, students must explicitly declare how and where AI tools are used throughout the project lifecycle. Transparency reduces ambiguity regarding authorship, clarifies individual contribution, and enables instructors to make informed assessment decisions.

Operational Mechanism: AI-Use Declaration and Documentation
Each major deliverable includes a short *AI Use* section in which students specify:

- Which AI tools were used (e.g., ChatGPT, DeepSeek, Copilot),
- For which tasks (e.g., brainstorming, debugging, drafting report sections),
- How AI-generated outputs were reviewed, modified, or validated.

In addition, individual reflective workbooks are extended with prompts such as: *“Describe one instance where an AI-generated response was incorrect, incomplete, or unsuitable, and explain how you identified and corrected it.”*
This requirement reinforces critical engagement with AI rather than passive acceptance.

Principle 2 – Assessment of Understanding Rather Than Output

Since AI tools can generate technically correct code, designs, and documentation, assessment must prioritize students’ ability to explain, justify, and adapt AI-assisted outputs. Understanding, not output quality alone, becomes the primary indicator of learning.

Operational Mechanism: Embedded Individual Oral Checks (Micro-Vivas)
At key project milestones such as interim presentations, final presentations, and technical evaluationsbeach student participates in brief, targeted oral questioning focusing on:

- Specific components of the design or code for which they claim responsibility,
- The rationale behind design decisions, parameter choices, or control strategies,
- The role AI played and how its outputs were verified or refined.

These *micro-vivas* are assessed using a simple rubric emphasizing conceptual clarity, technical reasoning, and responsiveness to follow-up questions, ensuring that learning remains demonstrable even when AI is used.

Principle 3 – Multiple Sources of Evidence for Individual Contribution

Fair assessment in team-based PBL requires triangulation across multiple evidence sources rather than reliance on a single group deliverable. This principle is particularly important in AI-supported environments, where outputs may not reliably reflect individual effort.

Operational Mechanism: Process-Oriented Artefacts and Logs Students continue to submit meeting minutes and reflective workbooks, but with explicit prompts to document:

- Major project decisions and the individuals involved,
- How AI contributed to brainstorming, analysis, or problem-solving,
- The evolution of drafts, highlighting where AI-generated content was adapted or replaced.

Where feasible, instructors may also consider artefact histories such as version control logs or annotated drafts to further support contribution tracking.

Principle 4 – Proportional Weighting of AI-Prone Tasks

Assessment weightings should reflect the degree to which tasks can be automated by AI. Activities that require judgment, validation, adaptation, and real-time reasoning should carry greater weight than tasks that AI can perform with minimal student input.

Operational Mechanism: Rebalanced Rubrics and Weighting Rubrics for reports, presentations, and technical evaluations are revised to:

- Increase emphasis on explanation, justification, and validation of results,
- Reduce emphasis on surface-level features that AI can readily generate (e.g., basic formatting or boilerplate code),
- Allocate a small but explicit portion of marks to responsible and transparent AI use, rewarding critical and ethical engagement with AI tools.

Application to the Existing PBL Assessment Structure

The proposed framework can be integrated into the current assessment plan without changing the overall weights, but by modifying what is assessed within each component.

Assessment	Proposed AI-Aware PBL Assessment
Assessment 1 – Deliverables	• Mandatory “AI Use” subsection in the individual report. • Reflective questions on independent vs. AI-assisted work. • Emphasis on logic, calculations, and validation rather than writing fluency.
Assessment 2 – Presentation	• Each student presents a defined section. • 1–2 targeted questions per student verifying understanding of AI-supported content. • Marks emphasize real-time explanation.
Assessment 3 – Comprehensive Evaluation	• AI declaration table in the final report. • Structured micro-viva with randomized technical questions.

	• Reduced weight on polished report; increased weight on demonstrated reasoning.
Assessment 4 – Portfolio	• Focus on interpreting results, diagnosing issues, and adapting designs. • Live modifications during evaluation to test understanding. • AI assistance allowed in preparation, but marks awarded for independent technical reasoning.
Assessment 5 – Participation	• Includes brief in-class tasks performed without AI. • Provides a baseline of individual understanding.

The proposed framework aligns closely with student perspectives captured in the survey. Students overwhelmingly supported:

- The usefulness of AI for learning, productivity, and confidence.
- The need for oral questioning and explanation to ensure fairness.
- Transparent disclosure of AI use.

By integrating declarations, micro-vivas, process documentation, and rebalanced rubrics, the framework directly addresses the central challenge identified in this study: AI can support learning in PBL without compromising the integrity, fairness, or validity of assessment provided that assessment is redesigned to reward understanding and accountability rather than AI-generated output.

CONCLUSION

This study examined how engineering students use AI tools within a PBL course and considered the implications for assessment design in CDIO-based engineering education. The findings show that AI was used across several stages of the PBL workflow, including coding, report writing, brainstorming, formatting, flowchart development, and design support. Students generally perceived AI as beneficial for productivity, understanding, and confidence. However, they also identified risks such as over-reliance, incorrect AI-generated outputs, reduced critical thinking, and shallow understanding. These findings suggest that AI can support PBL learning, but students must remain responsible for checking, explaining, and validating AI-assisted work. In response, this paper proposed an AI-aware PBL assessment framework based on transparency of AI use, assessment of understanding, multiple evidence sources for individual contribution, and proportional weighting of AI-prone tasks. The main takeaway is that AI use in CDIO-based PBL does not need to be prohibited; instead, assessment should be redesigned to reward reasoning, validation, accountability, and responsible AI use. Since this study is exploratory and based on one cohort, future work should implement and evaluate the framework across additional PBL offerings.

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AI Usage Declaration

During the final editing phase, the authors used generative AI (ChatGPT) solely for English language editing and clarity. The tool did not influence the study design, analysis, or conclusions.

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BIOGRAPHICAL INFORMATION

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A PRACTISE OF A CREATIVITY-CENTERED PEDAGOGICAL MODEL FOR CHINESE DESIGN EDUCATION

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ABSTRACT

Based on a doctoral research project on pedagogical innovation in higher design education for Generation Z in China, this paper examines how international exemplary educational models can be effectively integrated and localized within the Chinese educational context. An innovative teaching framework was researched, developed, verified and validated to meet the needs of Chinese design education in the study. The approach cultivated student's creativity as its central goal, the research integrates international advanced educational theories such as interdisciplinary teaching, CDIO framework and student-centered pedagogy. Also, aligned the student learning experience with the characteristics of China's education system and societal development needs. The resulting framework is systematic, structured, and highly adaptable, aiming to promote students' comprehensive development in creativity, critical thinking, collaboration, application ability, communication, and social responsibility through the integration of interdisciplinary knowledge and project-based practice. Drawing on students' learning process experiences and self-evaluations, this paper evaluates the proposed teaching model and examines the adaptability of the CDIO approach in design education within the Chinese context.

KEYWORDS

Chinese higher education, interdisciplinary learning, project-based learning (PjBL), CDIO implement, Standards: 2, 3, 8

RESEARCH OVERVIEW

In the context of the deep convergence of globalization and digitalization, design education is undergoing profound systemic and structural transformation. The rapid evolution of global economic forms, scientific and technological advancement, and social demands has imposed increasingly complex and multidimensional requirements on the competency structure of design professionals. Contemporary designers are expected not only to possess solid professional knowledge and technical skills, but also to demonstrate systems thinking, interdisciplinary integration, and sustained capacities for creativity and practice within real and complex contexts, alongside a strong sense of responsibility toward society, culture, and sustainable development (Buchanan, 1992; Cross, 2006).

Although Chinese design education has gradually shifted toward a competency-oriented paradigm, moving beyond traditional skill-based training toward educational models that emphasize comprehensive capability development and authentic learning contexts (Ministry of Education of the PRC; Xie et al., 2021), the learning experiences of many Chinese students have still largely been shaped by lecture-oriented and assignment-driven instructional models (Biggs, 1996). In such environments, knowledge transmission and individual task completion often occupy a central position in classroom activities. While this approach supports the development of disciplinary foundations, it may provide limited opportunities for open-ended exploration, collaborative problem-solving, and experiential learning. Consequently, students may initially encounter challenges when adapting to project-based and student-centred learning environments.

In this study, creativity is understood as the capacity for problem discovery and problem solving within authentic contexts. Rather than focusing solely on the generation of novel ideas, creativity in design education also involves the ability to identify meaningful problems, frame design opportunities, and develop viable solutions through iterative processes (Runco & Jaeger, 2012; Sawyer & Henriksen, 2024).

From a pedagogical perspective, creativity development is often supported through experiential learning, interdisciplinary knowledge integration, and collaborative problem-solving environments (Amabile, 2018). Previous studies in design education have suggested that project-based learning, studio-based learning, and interdisciplinary curricula can provide meaningful contexts for students to develop creative and professional competencies (Lupton & Miller, 1991; Visser, 2010). Meanwhile, the CDIO framework provides a structured educational approach that aligns well with these pedagogical principles. Through the “Conceive-Design-Implement-Operate” cycle, the framework integrates disciplinary knowledge, professional skills, and experiential learning processes. In particular, the pedagogical design of this course corresponds to several CDIO standards, including integrated curriculum development (Standard 3), active learning strategies (Standard 8), and the development of personal and professional competencies (Standard 2).

Within this context, the teaching experiment reported in this paper was conducted at an University in China, with the research framework supported by Canterbury Christ Church University in the United Kingdom. Based on students’ classroom performance and post-course questionnaire and interviews feedback, this study examines how international pedagogical frameworks can be adapted to the Chinese higher design education context. The research aims to explore how creativity-oriented design pedagogy can be implemented through interdisciplinary learning environments and CDIO framework, while generating insights that may inform broader innovation-driven curriculum development.

RESEARCH METHODOLOGY

This study adopts pragmatism as its overarching philosophical paradigm. Pragmatism supports multi-method integration and results-oriented inquiry, emphasizing the practical use of knowledge (Morgan, 2007). This orientation aligns closely with the core aim of the study, which is to develop and validate an innovative teaching model within the context of Chinese higher design education to effectively cultivate students' creativity and comprehensive design literacy.

In the research process, the researcher participated fully in the teaching practice through multiple methods, including student questionnaires, student interviews and participatory observation to class, to comprehensively collect multidimensional feedback during the implementation of the teaching model. The questionnaire was administered offline using a six-point Likert scale, and all responses were collected anonymously to encourage honest and unbiased feedback. To further reduce potential bias, several items were designed as reverse-scored questions. Student interviews were conducted by a third party to minimise the influence of the researcher on participants' responses. The interviews were subsequently transcribed and anonymised before analysis to ensure confidentiality. In addition, classroom observations were carried out throughout the course. All observational records were processed with identity masking to avoid identifying individual students. These measures ensured ethical compliance and enhanced the reliability and validity of the collected data.

This triangulated design enhances the validity of educational research findings, as recommended by Creswell and Cohen (Creswell & Creswell, 2017). The study has obtained formal ethics approval from the Canterbury Christ Church University Ethics Review Committee in the United Kingdom and the Communication University of China Nanjing where the experimental course was implemented. All research participants were fully informed of the purpose, procedures, and confidentiality principles of the study before participation. The entire research process strictly adhered to the ethics of educational research, ensuring participants' rights to informed consent, privacy, and voluntary participation.

This paper primarily evaluates the effectiveness of the experimental course through an in-depth analysis of students' learning practices and multidimensional post-course feedback.

THEORETICAL SUPPORT

The theoretical foundation of this study draws on perspectives from the cross-cultural development of design education, which emphasise that educational reforms should be understood within their specific sociocultural contexts rather than being transferred directly across systems (Steiner-Khamsi, 2004). In China, the evolution of design education reflects broader historical and cultural influences. Earlier models were shaped by craftsmanship traditions and ideological education, while more recent reforms have gradually shifted toward approaches that emphasise interdisciplinary integration, systems thinking, and creative practice (Li, 2021). At the same time, Chinese educational practices continue to be influenced by Confucian learning traditions that value discipline, respect for teachers, and knowledge transmission, as well as by socialist educational ideals emphasising collective responsibility and social development (Zhang 2017; Zhao, 2019).

These cultural and institutional conditions shape how international pedagogical models are interpreted and implemented within Chinese higher education. In particular, the introduction of student-centred and project-based pedagogies may require adaptation, as students often

transition from lecture-based learning environments toward more open and collaborative learning structures.

Building on this theoretical perspective, the curriculum model developed in this study consists of three interrelated components: interdisciplinary knowledge integration, project-based practice structured through the CDIO framework, and student-centred pedagogy embedded throughout the learning process.

Interdisciplinary knowledge integration aims to expand students' cognitive perspectives by connecting knowledge from multiple domains, such as design, social sciences, and cultural studies. Such integration supports systems-level understanding and enables students to approach design problems from broader social and contextual perspectives.

Project-based practice in this model is organised according to the CDIO framework. Through the learning cycle of "Conceive-Design-Implement-Operate", students engage in authentic design projects that integrate conceptual thinking, technical development, and real-world application. This approach corresponds to several CDIO standards, particularly integrated curriculum design (Standard 3), active learning methods (Standard 8), and the development of personal and professional competencies (Standard 2), thereby supporting the cultivation of both creative and practice-oriented capabilities (Edström & Kolmos, 2014).

PEDAGOGY FRAMEWORK

Course framework

The curriculum model developed in this study aims to cultivate students' critical thinking, interdisciplinary integration, and sustained capacities for creativity and practice through a structured teaching framework. The course combines interdisciplinary knowledge integration with project-based learning organised within the CDIO framework, forming a learning environment in which theoretical exploration and practical experimentation continuously reinforce each other.

The course is organised into two sequential stages which can be seen in figure 1.

The first stage focuses on interdisciplinary lectures and discussions designed to broaden students' cognitive perspectives and stimulate creative thinking. Design education research emphasises that interdisciplinary exposure can significantly enhance students' innovative capacity and systems thinking by enabling them to approach design problems from multiple knowledge domains (Rong et al., 2025).

The course is organised around the core theme of "Memory". Using an abstract and conceptually rich theme encourages students to engage in deeper analysis and interpretation while transcending disciplinary boundaries (Manovich, 2002; Norman, 2007). Eleven interdisciplinary lectures were delivered by scholars from different fields−including architecture, sociology, psychology, literature, biology, medicine, economics, philosophy, pedagogy, drama and film, and computer science. These lectures introduced diverse perspectives on memory, ranging from spatial narratives and collective identity to neurological mechanisms and digital technologies. Following each lecture, students engaged in guided discussions and completed reflective journals to consolidate their learning. This process supported the gradual construction of interdisciplinary connections and provided a conceptual foundation for the subsequent design projects.

The second stage centres on project-based learning implemented through the CDIO framework. Students work in groups to investigate real-world issues related to the theme of memory and develop innovative game-based solutions. The design process follows the CDIO learning cycle:

Conceive (C): Students analyse design problems and contextual knowledge to develop initial game concepts and conceptual design frameworks.

Design (D): Students refine the concepts and translate them into structured game mechanics and design plans.

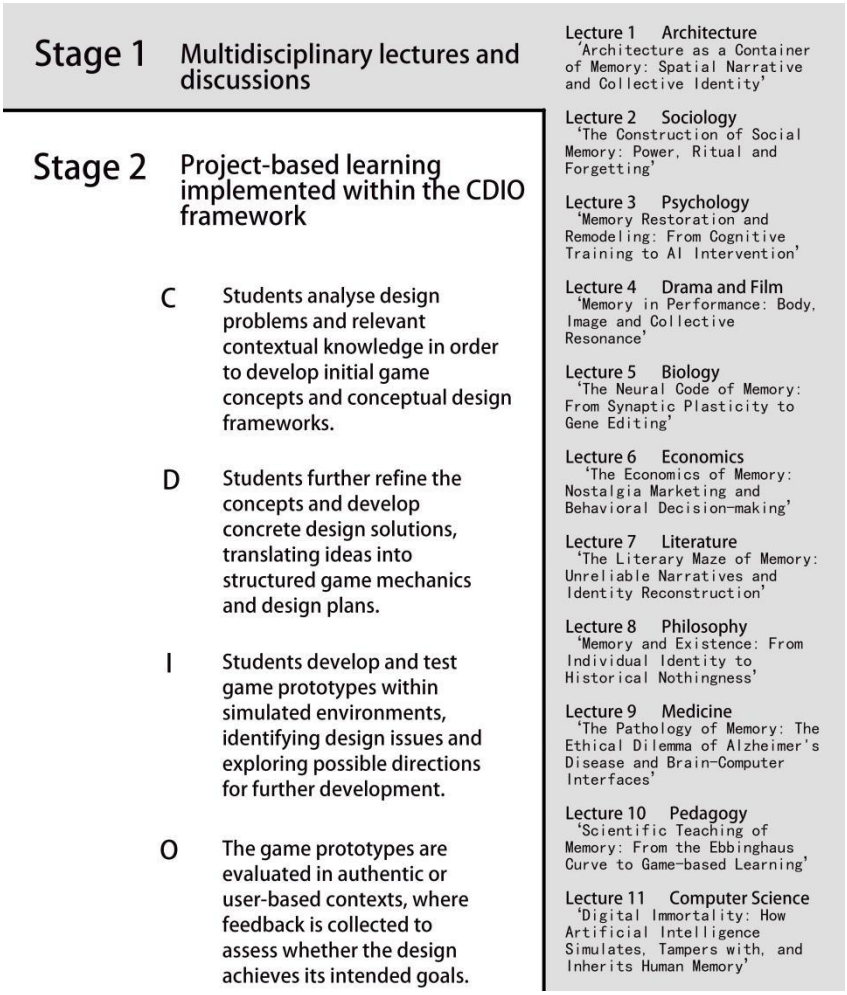
Implement (I): Students develop and test game prototypes within simulated environments, identifying design issues and exploring directions for improvement.

Operate (O): Game prototypes are evaluated in authentic or user-based contexts where feedback is collected to assess whether the design achieves its intended goals.

Each group is required to develop a playable game prototype addressing a specific issue related to memory. The prototypes undergo iterative testing and refinement before culminating in a final game artefact.

Through this process, students apply interdisciplinary knowledge and design thinking to analyse complex problems, generate solutions, implement design ideas, and continuously improve their work through iterative development. The learning process therefore supports the development of critical reflection, collaborative problem solving, creative thinking, and engagement with authentic design practice.

Figure 1. The two stages of course framework



Grouping mechanism

The course adopts a two-stage grouping mechanism. In the first, self-directed learning stage, students freely form groups based on their interests during interdisciplinary lectures and discussions. This open structure fosters autonomous exploration, knowledge construction, and communication skills, laying the groundwork for diverse perspectives and innovative ideas in the subsequent project-based phase. In the second, design-oriented stage, the instructor assigns structured teams of four to five students according to their prior performance and disciplinary strengths, ensuring complementary skill sets. This arrangement supports students throughout the full process from “Conceive-Design-Implement-Operate”, reinforcing the systematic progression of tasks and enabling the efficient transformation of concepts into deliverable outcomes.

Assessment system

The course assessment system emphasises process-oriented and reflective learning, aligning with the iterative nature of design practice and the competency development goals highlighted in the CDIO framework. Rather than focusing solely on the final outcome, the assessment also evaluates students’ learning performance throughout the entire project development process.

The final grade combines formative and summative assessment, accounting for 60% and 40% of the total grade respectively. The formative assessment consists of six components corresponding to key stages of the project development process, including concept development, design planning, prototype implementation, iterative refinement, testing and evaluation, and reflective learning. These assessments are conducted continuously through instructor feedback, group discussions, and prototype reviews. Feedback generated at each stage provides students with clear and actionable directions for improvement. Drawing on iterative, multi-source feedback, students continuously refine their design solutions by revising concepts, improving technical implementation, and enhancing user interaction. The final project outcome constitutes the summative assessment component. This evaluation approach not only examines the quality of the final game product but also assesses students' engagement in design iteration, problem-solving, and critical reflection throughout the development process.

The assessment methods integrate instructor evaluation, peer assessment, and self-assessment, forming a multi-source feedback mechanism that enhances transparency and fairness in the evaluation process. This assessment structure encourages students to reflect on teamwork processes and individual contributions, thereby promoting the development of communication skills, collaboration, and a sense of responsibility (Nortcliffe et al., 2022), which are also the core competencies emphasized in the CDIO framework.

MODEL IMPLEMENTATION AND REFLECTION

This course was part of the Integrated Product Design program within the Art and Technology major at the Communication University of China Nanjing, and is a compulsory module for fourth-year students in the same major. The implementation of this course was approved by the university's ethics review committee. All participating students were fully informed about the course and research procedures and participated voluntarily, with the right to withdraw at any time.

The course includes about twelve weeks of classroom instruction followed by four weeks of independent study. The experimental class used in this research is a naturally formed cohort, ensuring the generalizability of the findings. All students were admitted through the standard progression from general secondary education to higher education and had completed three years of full-time undergraduate study prior to participating in the course. This relatively homogeneous educational background provides a consistent basis for evaluating the effectiveness of the teaching intervention. Based on the course implementation and student interviews, this paper analyzed the progression of students' learning. The results show a clear developmental pattern: students moved from initial unfamiliarity and uncertainty to increasing engagement and adaptation, and ultimately to active exploration and creative production. Throughout the project, they exhibited notable growth in learning, creativity, and overall design competence.

In the early stages of the course, students showed low familiarity with the course content and learning approach, accompanied by limited willingness to participate. This pattern was evident both during the initial interdisciplinary lecture phase and at the beginning of the second-stage project collaboration. Such phenomena are consistent with the characteristics of the initial stage of the learning curve, which is marked by high uncertainty and low performance (Anderson, 2005). As one student reflected to the question "How would you evaluate your performance in this course?":

> “At the beginning, I really did not adapt well to this learning approach. I did not know what I was supposed to do, and the teacher did not give us very specific task requirements.”

As the course progressed, students gradually developed an understanding of the course structure and learning logic, and began to adjust their learning strategies more autonomously by actively seeking information and engaging in discussions. As another student noted in the same question:

> “If I did not actively expand the knowledge needed for learning, it was hard to keep up with the course and participate in group discussions, so I started to explore areas I was interested in after class.”

This transition reflects a shift from externally regulated learning toward internalized motivation, aligning with self-determination theory (Deci & Ryan, 2013), and also resonates with Rogers (2003)’ diffusion of innovations model, which describes the progression from resistance to acceptance.

In terms of teamwork, the quality of group collaboration improved markedly following adjustments to grouping strategies and assessment mechanisms. In the early phase, some groups experienced unclear task allocation and uneven participation, with one student stating:

> “At the beginning, the group organization was quite chaotic, and some group members did not really participate.”

After the introduction of peer assessment and rotating leadership roles, students’ sense of responsibility and willingness to communicate increased significantly. As one student explained in question “To what extent did group-based learning in this course contribute to your personal and professional development?”:

> “I became clearer about which part I was responsible for and more willing to join discussions, and I also realized the importance of teamwork.”

These changes support team learning theory, which emphasizes the role of feedback and accountability in effective collaboration (Senge & others, 1990), and also indicate the development of students’ self-regulated learning abilities (Zimmerman, 2002).

Students also improved in time management and learning organization. Early in the course, they lacked systematic planning and often relied on last-minute work. Through iterative project tasks and continuous feedback, they gradually formed more efficient working habits, consistent with habit formation theory and evidence that project-based learning strengthens self-management (Lally et al., 2010).

Regarding the development of students’ personal competence and creativity, students gradually developed more effective learning habits, interdisciplinary ways of thinking, and authentic project-based experience. Students reported a shift from “rushing to complete tasks close to the deadline” to “breaking tasks down, setting schedules, and continuously reflecting and adjusting during the process,” highlighting the positive role of project-based learning in fostering time management and self-management skills (Lally et al., 2010). At the same time, students demonstrated the ability to transfer and integrate interdisciplinary

knowledge in their design practice. As one student remarked in the question “What do you think you gained from participating in this course?”:

> “Memory is not only a personal experience but can also be understood at social and cultural levels.” which was subsequently translated into design decisions, such that “design was no longer just about making something visually appealing.”

This process illustrates the core value of project-based learning under the CDIO framework, where repeated cycles of conceiving, designing, implementing, and operating promote originality and integrated competence through authentic learning experiences.

QUESTIONNAIRE RESULTS AND CONCLUSION

The post-course questionnaire employed a six-point Likert scale for measurement and analysis. To minimise response bias and enhance data reliability and validity, several items were randomly designed as reverse-scored questions, and some statements were intentionally phrased in reverse to reduce mechanical responding and encourage more careful responses. The scale ranged from 1 (strongly disagree) to 6 (strongly agree).

All 36 student questionnaires were returned and considered valid for analysis. The result of questionnaire see Table 1 shows that students responded very positively to the experimental course. Most expressed strong satisfaction with the teaching quality, course structure, learning experience, and instructional organization, noting that the content was clear, well-structured, and engaging, and that the overall experience surpassed previous courses. In self-assessments, students widely recognized the course's impact on enhancing creativity, critical thinking, and interdisciplinary understanding, viewing the design of the module as both innovative and practical in supporting their overall development. Although the questionnaire revealed some differences in perceived challenge, autonomy, and gains in reflection and communication, these variations were largely linked to individual learning styles rather than negative evaluations. Overall, students affirmed the high quality of the course and its positive, lasting influence on creative design thinking and comprehensive competence.

Table 1. The table of the mean values of each category in the questionnaire

Category Mean Value	N	Mean Value	Std
Teaching on the course	36	5.24	0.63
Learning opportunities	36	5.16	0.50
Assessment and feedback	36	5.10	0.85
Organization and management	36	4.81	0.89
Student voice	36	5.17	0.78
Personal development	36	5.43	0.66
Overall satisfaction	36	5.06	1.1
Employability and skills	36	4.86	1.1

Post-course student questionnaires and in-class observations indicate that the experimental course successfully established a coherent teaching framework suited to the Chinese educational context. By integrating interdisciplinary knowledge development with real-world projects, the curriculum effectively enhanced students’ interdisciplinary thinking, collaborative

awareness, practical project experience, and reflective abilities as key components of comprehensive talent development.

The strong alignment between the theoretical framework and empirical evidence further supports the feasibility of localizing international design education paradigms in China. The study also confirms that the CDIO framework, originally developed for engineering education, can be successfully extended to design education, offering valuable support for innovation in contemporary higher education.

Overall, this research offers an innovation-driven pathway for advancing the reform and modernization of design education in China and contributes valuable insights into how international educational theories can be adapted and expanded across different cultural contexts.

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BIOGRAPHICAL INFORMATION

Yufan Zheng is a doctoral researcher in Canterbury Christ Church University. Her research focuses on pedagogical innovation in higher design education for Generation Z learners, with particular interest in interdisciplinary curriculum design, creativity cultivation, and the localization of international educational frameworks within the Chinese context.

Anne Nortcliffe, Dean of the Faculty of Arts, Computing, and Engineering at Wrexham University, is a Professor of Inclusive Engineering and Technology with over 30 years of experience in Engineering, Technology and Design education, pedagogical practice development and research. Previously, she was the Founding Head of Engineering at Canterbury Christ Church University, establishing an inclusive engineering program. An advocate for diversity in engineering, Anne is an internationally published researcher and educator.

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Stuart Lambert is Course Director for Product Design Engineering and holds a BA (hons) Industrial Design, an MBA and PhD candidate researching design skills at the interface of design and engineering and a Fellow of the HEA. He has worked in product design consultancy in London and Milan with 25 years of design, managerial and director experience and currently 6 years in academia

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ENSURING INDIVIDUAL ACCOUNTABILITY IN AUTHENTIC TEAM-BASED ASSESSMENTS

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ABSTRACT

Effective teamwork is a critical skill for engineering graduates to demonstrate both during their studies and in their future careers. The requisite personal attributes, skills and behaviours may be cultivated through structured teamwork activities applied to authentic scenarios. However, team-based assessments may be perceived as failing to reflect individual contributions, leading to concerns about fairness and disengagement. This paper presents an approach to authentic team-based assessment designed to develop professional skills while ensuring individual accountability within a team context. Foundation Year students collaborated over four weeks to design a product addressing an accessibility need and create a business plan for a start-up company producing and selling the product. The inclusion of an individual component based upon assigned roles together with peer assessments and progress tracking motivated engagement of all team members. Survey feedback indicated students valued the opportunity to demonstrate personal contributions, and improved pass rates suggested increased engagement.

KEYWORDS

Authentic Assessment, Active Collaborative Learning, Team-Based Learning, Experiential Learning, CDIO Standards: 1, 2, 3, 4, 5, 7, 8, 11.

INTRODUCTION AND LITERATURE REVIEW

The ability to work effectively in a team is a crucial skill that engineering students must develop and demonstrate (Chowdhury & Murzi, 2019; Ercan & Khan, 2017; Herrera et al., 2017; Kimpton & Maynard, 2025). Many universities incorporate team-based learning to foster collaboration and promote deeper understanding of engineering concepts and their application (Sousa & Fontão, 2025). Reported benefits include improved test performance, greater conceptual understanding, and enhanced engagement and interest (Swanson et al., 2019). Team-based learning also appears particularly effective in supporting students with lower entry-level attainment (Sena-Esteves et al., 2024). Accrediting bodies reinforce the importance of teamwork development; for example, AHEP 4 in the UK specifies that graduates should "function effectively… as a member or leader of a team" (Engineering Council, 2020, p.31). Furthermore, employers increasingly demand more than technical expertise from graduates: they must be able to work collaboratively and communicate effectively, attributes consistently identified as essential for employability (Baird & Parayitam, 2019; Hirudayaraj et al., 2021). The required personal attributes, skills and behaviours are not innate but may be actively cultivated through structured, purposeful activities that require students to exercise and refine these capacities in authentic contexts (Kimpton & Maynard, 2025; Orih et al., 2024).

Authentic assessment requires students to demonstrate their knowledge and skills through the performance of tasks reflecting real-world situations or professional practice (Gulikers et al., 2004; Wiggins, 1990). These tasks typically demand the integration of a range of technical and interpersonal competencies. By simulating professional practice, these may be developed within a structured project environment, fostering teamwork, communication and project management capabilities (Villarroel et al., 2018). In an engineering context, authentic team-based assessments may be used to engage students in collaborative activities that require them to identify and define a problem, design a viable solution and communicate their ideas effectively. This approach aligns with the CDIO framework, particularly its emphasis on the ability to conceive and design real-world products in a team-based context, reinforcing both technical and interpersonal competencies (Kozanitis et al., 2009). Despite these benefits, team-based assessments may be criticised for failing to adequately reflect individual contributions. This may lead to perceptions of a lack of fairness in assessment or to disengagement as students become dependent on the most active team members (Hall & Buzwell, 2013; Michaelsen et al., 2004, p.16; Rasooli et al., 2025). While peer assessments may be used to address this issue, they may be influenced by personal biases, friendship networks, or a limited awareness of the contributions of other team members (Stonewall et al., 2024).

This paper aims to present and evaluate a case study of a Foundation Year project implementing an approach to authentic team-based assessment designed to improve engagement, perceptions of fairness and assessment outcomes, and aligned with the CDIO framework. Central to the assessment design was the inclusion of an individual component requiring students to produce role-specific output documents in addition to team deliverables. Students were also required to organise and conduct weekly team meetings outside scheduled teaching and to record individual progress and actions using structured meeting minutes. Combined with peer assessments, these measures enabled students to demonstrate personal contributions and promoted individual accountability while maintaining shared responsibility for project outcomes. Following completion of the project, students were invited to complete a survey examining perceived development of teamwork and presentation skills and whether the assessment enabled them to effectively demonstrate their personal contributions, alongside open-ended feedback on the project overall.

CONTEXT

The Integrated Cross-School Foundation Year at Nottingham Trent University (NTU) aims to equip students with the required skills, knowledge and personal attributes for successful progression to Year 1 of their undergraduate degree. The cohort includes students intending to study engineering, computer science, mathematics, physics, chemistry and forensics degrees. In the academic year 2024-2025, the cohort consisted of 348 students including 137 engineering students from across engineering disciplines: mechanical, aerospace, electronic & electrical, biomedical and sport engineering.

Table 1: Content and schedule for the module Practical & Professional Skills

	Teaching Week	Content	Assessments / Projects
Semester 1	1-3	**Unit 0: Introduction** Problem solving, teamwork, research and referencing, MS Office, professional behaviour.	
	4-6	**Unit 1: Sustainability & Technology** Sustainability & technology, UN's SDGs, renewable energy, integrating sustainability	**Project:** Sustainable Design
	7-9	**Unit 2: Evolution of Technology** History of technology, technology today, the future of technology	**Project:** Evolution of Technology Report
	10-12	**Unit 3: Information and Communications Technology** The internet & websites, html, telecommunications	**Project:** Science Website
	Christmas Break		
	Half-Year Exam Period		
Semester 2	19-23	**Unit 4: Technology and Business** Reflecting on feedback, business & marketing, effective presentations, statistics for business	***Group Presentation Assessment***
	24-26	**Unit 5: Technology and Computers** How computers work, VR & AR, Smart technology, artificial intelligence	**Project:** C Coding
	27-28	**Unit 6: Dissecting Technology** Making technology, operating technology, how technology fails	**Project:** Reverse Engineering
	Easter Break		
	31	**Unit 6: Dissecting Technology (cont.)**	
	32	**Progression** Final submissions for Project Portfolio & reflective journals, progression to Year 1	***Project Portfolio & Reflective Journals***
	End of Year Exam Period		

Alongside core technical modules in mathematics, science and engineering, all students complete the year-long module Practical & Professional Skills which aims to bridge theoretical learning with practical application and to support the transition into higher education through the development of professional and related skills. The module is delivered through a combination of lectures and laboratory sessions across the year and incorporates a range of individual and team-based projects. Table 1 outlines the module content and schedule.

While most projects are assessed through a portfolio submitted at the end of the academic year, students also complete a **group presentation assessment** at the start of the second semester. This evaluates their ability to collaborate effectively on a project combining design development with creation of a detailed business plan, while demonstrating strong presentation and communication skills, reflecting key professional competencies expected of engineering graduates. By simulating a product development process and business pitch, this provides an authentic team-based assessment mirroring real engineering practice. Details of this assessment as implemented in 2024/2025 are provided in the following section.

ASSESSMENT DESIGN

The cohort was divided across six laboratory groups based upon progression degree, with each laboratory supported, where possible, by a lab leader from the same academic department. During the first laboratory session, students were placed in teams of 5 or 6 students. They then had four weeks to design a product and produce a business plan for a proposed start-up company producing and selling the product. The product was required to relate to the theme *Accessible Design*: a product, app or service that ensures all users, regardless of age, disability or other characteristics, are able to live and/or work without restrictions to their everyday activities.

Table 2: Timeline for Group Presentation Assessment

Week	Content
1	• Team forms, assigns roles, sets up Microsoft Team and generates ideas. • Initial research performed. • First team meeting arranged by teams and documented with team meeting minutes form.
2	• Finalise design concept. • Begin preparation of individual documents. • Second team meeting.
3	• Complete individual documents. • Begin preparation of presentation. • Third team meeting.
4 / 5	• Submission of individual and group documents. • Delivery of presentation. • Submission of peer assessments.

Table 2 shows the timeline for the project. At the beginning of the project, students assigned themselves roles within their team: Designer, Head of Operations, Head of Finance, Market Researcher, Market Strategist, Risk Analyst. Teams subsequently discussed these roles with the lab leader to ensure each student was aware of the requirements of their role and how the roles related to one another. An output document was associated with each role (see Figure

3). Each student had individual responsibility for production of their document while ensuring that all documents were consistent.

During subsequent laboratory sessions, students worked in their teams, with targeted activities set by the lab leader and aligned to the project timeline. The lab leader circulated between teams to monitor progress and team functioning, note engagement issues where observed, and provide formative feedback on project work.

In addition to attending scheduled teaching sessions, teams were expected to independently organise and conduct a weekly team meeting. These were documented using a templated meeting minutes form, capturing team progress, individual contributions and agreed actions for the week. Teams were also expected to create a dedicated Microsoft Teams space for communication and document sharing. These measures ensured students took responsibility not only for the project outputs but for effective management of the team and the project.

Using their individual documents as a basis, each team prepared and delivered a 10-12 minute PowerPoint presentation outlining their product design and associated business plan to their lab leader acting in the role of a potential investor. All students were expected to contribute except in cases where a student had an accessibility need affecting their ability to present, in which case alternative arrangements were made. The presentation was followed by a question-and-answer session in which the assessor examined aspects of the design and proposed business. The television programme *Dragon's Den* was used as an illustrative example to help students understand the format and expectations.

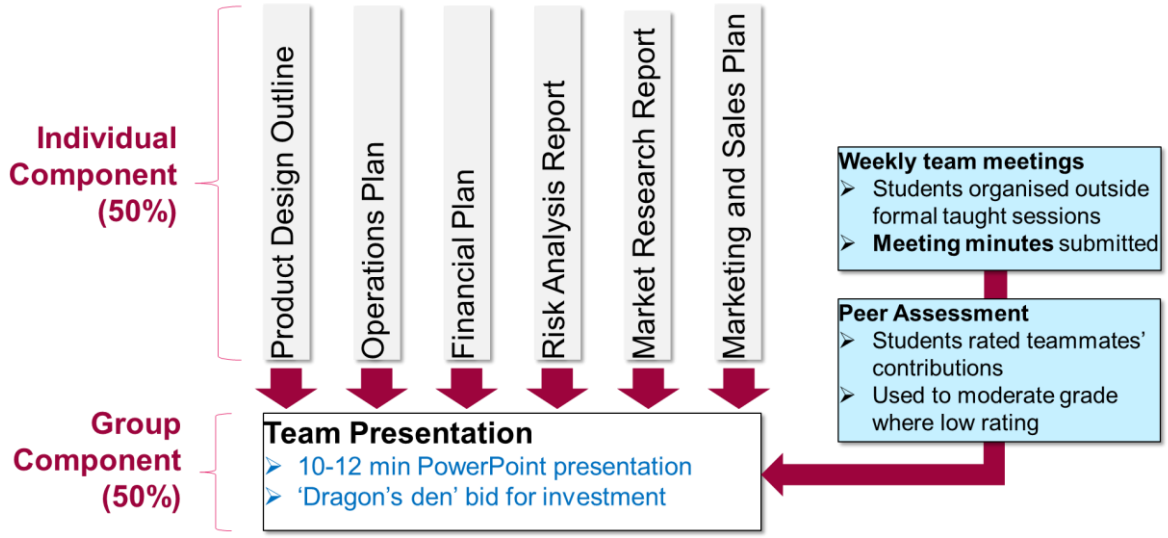


Figure 3: Group Presentation Assessment components

Figure 3 shows the components of the assessment. Individual output documents accounted for 50% of each student's grade and were awarded individually i.e. they did not depend upon the work of other students in the team. Furthermore, if a student did not achieve a passing grade for the individual component, their overall grade was capped at that of their individual component. This ensured each student must engage with the project and contribute to the team. The remaining 50% of the grade was awarded to the team as a whole: 10% for the team meeting minutes, 20% for the presentation quality and 20% for the overall quality of the project including the design concept and business case put forward. Upon completing the project,

students undertook peer assessment to evaluate the contributions of other team members. Where peer assessments consistently indicated limited contribution, meeting-minutes, attendance records and notes recorded by the lab leader on student engagement were examined for supporting evidence. Affected students were asked to provide evidence of their contributions. Where this could not be demonstrated, their group-component grade was moderated downwards, including zero credit where no contribution was evidenced.

RESULTS

Figure 4 shows examples of student designs. A passing grade was achieved by 89% of students in 2024-2025 versus 79% in 2023-2024. Cohort size and composition in 2023-2024 were similar to 2024-2025, as was the assessment design; however, an individual component was not included. Therefore, improvements in pass rate occurred despite a reduction in students' ability to rely on the contributions of teammates and thus increased rigour of the assessment. The majority of fail grades (9% versus 19% in 2023-2024) were due to students not submitting any work. This suggests a marked improvement in student engagement with the assessment.

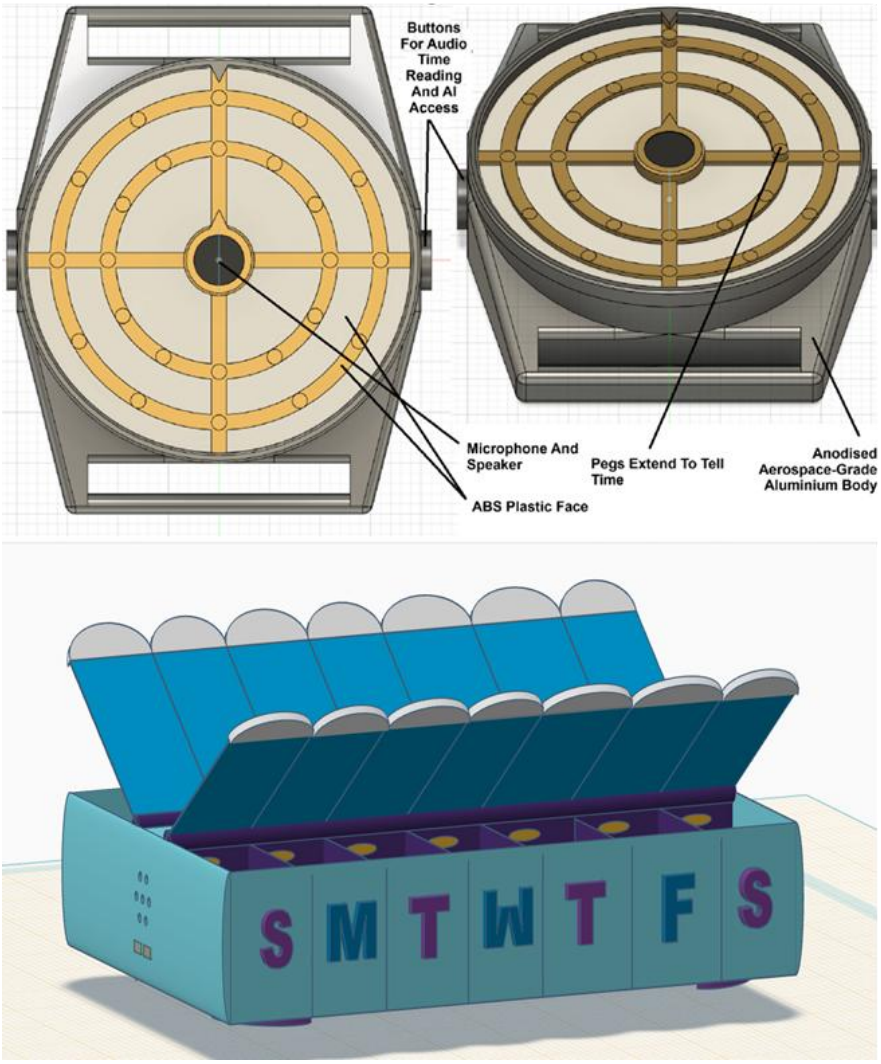


Figure 4: Examples of student designs. *Top:* 'NovaDot' accessible watch for the visually impaired. *Bottom*: 'PillProd' smart pill dispenser.

After the assessment had been completed, feedback was collected through a Microsoft Forms survey comprising several Likert-style questions and space for further comments about the project. The survey was approved by the School of Science and Technology non-invasive ethics committee and was conducted during a taught session after assessment completion to encourage engagement, while making clear that participation was entirely voluntary and had no impact on assessment outcomes. Responses were pseudonymised to allow participants to withdraw their data. Responses were received from 26 students including a mix of male and female students and diverse ethnicities. Of these, 70% agreed or strongly agreed that the project helped develop their presentation skills, 73% agreed or strongly agreed that it helped develop their teamwork skills and 77% agreed or strongly agreed that it allowed them to demonstrate their contributions to the team. Due to the small number of respondents, no demographic patterns could be identified. Feedback comments received indicated that students valued the addition of an individual component to the assessment:

> "Overall the individual project idea was excellent as there are people who have done more work than others"
>
> "I liked the fact that there was an individual element so that my work can be judged on its own as well as with regards to my contribution to the team."
>
> "The Individual output being the majority of the grades has made me confident that I will receive a pass grade, however the team assessed aspect makes me less confident in getting a high grade because some team members didn't contribute as much"

As indicated in the last comment above, students still had reservations about the teamwork component. Several referred to issues relating to teamwork:

> "Attendance of team mates was a reoccurring issue."
>
> "… stressing because team members haven't turned up or done anything to contribute"
>
> "I prefer solo projects as working with a team is difficult when nobody is free all at the same time and you can't work at your own pace"

It appears, therefore, that while inclusion of an individual component went some way to alleviating student anxiety regarding fair evaluation of their contributions, this was not eliminated and students continued to find issues with teammates frustrating, especially lack of attendance and contribution.

DISCUSSION AND CONCLUSION

This paper demonstrates how individual accountability can be embedded within authentic assessment without undermining collaboration in a team-based context, supporting the effective use of integrated learning and active engagement (CDIO Standards 7 and 8). The inclusion of an individual component within the assessment required all students to engage meaningfully with the project and mitigated the risk of individuals relying solely on the contributions of others. Improvements in pass rates and assessment completion and performance suggested increased engagement. Student feedback further indicated the inclusion of an individual component was perceived to result in fairer assessment of contributions.

Individual outputs were subsequently used as a basis for team presentations, supporting a balance between individual accountability and collective responsibility for the project. This was further reinforced using peer assessments to moderate grades. By requiring teams to establish their own communication channels and organise regular meetings outside of scheduled taught sessions, students were encouraged to take responsibility not only for project outputs but also for the management of the team and the project, thus integrating assessment of personal and interpersonal skills with disciplinary knowledge (CDIO Standard 11).

Despite these benefits, several challenges were identified. The inclusion of an individual component significantly increased the marking workload as individual submissions were assessed alongside team presentations. This was partially mitigated through the use of relatively prescriptive criteria for individual documents enabling short marking times for each. Feedback was primarily provided at the team level.

In many cases, students continued to report frustration with the lack of contributions of teammates and difficulties in communication. While this can provide a valuable preparation for future university and professional teamwork, the lower engagement levels typical of Foundation Year cohorts may compound the problem and, in some cases, led to a single student assuming responsibility for the production of most team outputs. Although this was reflected in marks awarded, frustration with the process remained. While students did perceive assessment to be fairer, additional mechanisms may be required to identify low engagement students early and enable timely intervention.

Finally, the assessment criteria required careful planning to ensure an appropriate balance between individual and team components. The additional complexity of this assessment approach necessitated clear communication of criteria and expectations to students to maintain transparency.

In conclusion, use of multiple assessment mechanisms within this innovative authentic team-based assessment supported individual accountability while maintaining collective responsibility for the project. In particular, the inclusion of an individual component appears to have been effective at improving student engagement and perceptions of fairness. However, more effective monitoring strategies may be required to address disengagement at an earlier stage.

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DESIGNING AUTHENTIC INDUSTRY-ENGAGED ASSESSMENT FOR PROFESSIONAL COMPETENCE IN BUSINESS INTELLIGENCE

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ABSTRACT

Engineering programs increasingly seek to align student learning with professional practice, yet meaningful industry collaboration often exposes misalignment between academic assessment norms and workplace expectations. This paper presents a CDIO Implementation case describing the redesign of an undergraduate business intelligence course to strengthen industrial relevance while supporting student professional development. The redesign integrated semester-long, industry-inspired project work structured around team-based learning and competence-oriented assessment, emphasizing authentic data, reproducible workflows, and professional collaboration tools. A single industrial partner contributed real-world datasets, problem framing, and feedback, enabling students to engage with constraints and quality standards characteristic of professional practice. Assessment and feedback were redesigned to balance team performance with individual contribution through visible artifacts (e.g. version control activity) and structured reflection, addressing persistent challenges related to workload, accountability, and fairness. Evidence from iterative course evaluations, student reflections, graduate feedback, and industry partner input indicates increased student engagement, improved coherence across learning activities, and clearer alignment between assessment criteria and professional expectations. At the same time, the collaboration revealed tensions between academic tolerance for developmental errors and industry demands for reliability and trustworthiness, highlighting the importance of explicitly preparing students to communicate differently with academic and professional audiences. The paper reflects on these tensions and outlines design principles for industry-engaged CDIO courses, including expectation alignment early in the course, sustained use of a shared industrial context, and assessment practices that foreground professional standards without sacrificing formative learning space. The case offers transferable insights for CDIO programs seeking to leverage industrial collaboration as a catalyst for student professional development through innovative assessment and feedback.

KEYWORDS

Industry collaboration, professional competence, assessment and feedback, team-based learning, CDIO Standards: 5, 7, 8, 11

INTRODUCTION AND MOTIVATION

Engineering education increasingly emphasizes alignment between academic learning and professional practice. Within this agenda, CDIO integrates disciplinary knowledge with personal, interpersonal, and system-building competencies enacted in realistic engineering settings (Malmqvist et al., 2022). In parallel, industry expects graduates to handle authentic data, collaborate effectively, justify methods, and deliver credible, reproducible outputs.

Despite broad agreement on these goals, tensions persist between academic assessment practices and professional standards. In higher education, assessment often functions developmentally: students are encouraged to explore, iterate, and learn from error. By contrast, professional evaluation foregrounds data provenance, limitations, reproducibility, stakeholder relevance, and the business implications of uncertainty–sometimes more than mastery of specific algorithms. These differences surface most clearly in industry-engaged courses where academic norms meet workplace expectations and where credibility and trust become explicit evaluation criteria grounded in industry expectations of reliable, decision-supporting analysis, assessed through reproducibility, transparency, and the justification of analytical choices. This aligns with authentic assessment, which emphasizes realistic tasks, explicit criteria, and feedback that supports improvement toward professional performance (G. Wiggins, 1998).

Business Intelligence (BI), spanning data analysis, information systems, and organizational decision support, provides a revealing context for examining these tensions. Practitioners must combine sound analytical method with professional judgment, transparency about assumptions and limitations, and effective communication with non-technical stakeholders. This paper reports a redesign of a BI course to strengthen industrial relevance through competence-oriented assessment and sustained collaboration with an industry partner. We analyze how assessment and feedback support professional competence development in this context and reflect on resulting tensions, trade-offs, and transferable design principles for CDIO-aligned programs.

COURSE AND INDUSTRY CONTEXT

BI is a 6 ECTS elective for advanced undergraduate and early graduate students in Industrial Engineering and adjacent programs. The course typically enrolls 10–15 students working in two larger teams and runs over one semester in five thematic two-week modules followed by a capstone project. A single industry partner contributes authentic data and domain framing and has participated across two consecutive offerings, enabling comparison of coherence and professional relevance.

DESIGN FRAMEWORK AND ALIGNMENT WITH CDIO

The course redesign adopts a CDIO-inspired approach in which assessment and feedback function as developmental mechanisms guiding students toward professional standards rather than serving as terminal checks of attainment. While prior CDIO work has examined challenges in assessing interpersonal competencies in project courses–using peer assessment or logbooks (Hansen & Sindre, 2023; Huet et al., 2008; Junaid et al., 2018)–there has been comparatively less attention to how such practices interact with industry-facing expectations of credibility and trust in sustained collaborations.

Professional competence in a CDIO perspective

Professional competence is understood as the integrated ability to analyze open, data-rich problems, locate and critically evaluate information, and collaborate effectively under realistic constraints. This aligns with the CDIO Syllabus 3.0 emphasis on personal, interpersonal, and system-building competencies alongside disciplinary knowledge (Malmqvist et al., 2022).

To operationalize these competence goals, the redesign used the LOUIS (Learning Outcomes in University for Impact on Society) competence framework (Aurora Universities Network, 2022). LOUIS structures broad competences into observable elements at increasing levels of proficiency. In this redesign, it was used to make competence expectations explicit and to support prioritization: rather than addressing a wide range of competences simultaneously, a small number of key domains (e.g. critical thinking, information literacy, and teamwork) were selected and reinforced across the course. This focus enabled clearer alignment between learning outcomes, activities, and assessment within an authentic project context (Biggs & Tang, 2015).

Learning, assessment, and feedback design principles

The redesign is organized around three principles that structure collaboration, guide method use, and ensure that feedback supports progressive improvement.

Team-Based Learning as structure: TBL provided the organizational backbone, with each module moving through preparation, readiness assessment tests, team application, and individual reflection (iRAT, tRAT, tAPP, iREF; following standard TBL terminology) (Fink, 2013; Michaelsen et al., 2004; Sibley & Ostafichuk, 2014). The team application phase (tAPP) involved collaborative analysis of authentic, industry-inspired data.

Problem- and experience-oriented learning: Activities were framed as open-ended, data-intensive problems in a sustained industrial context, drawing on problem-based and experiential learning (Barrows, Tamblyn, et al., 1980; Bruce & Bloch, 2012; Kolb, 2014). This continuity enabled students to refine analytical approaches rather than repeatedly onboarding to new datasets.

Assessment-as-development: Assessment prioritized reliability, transparency, and reproducibility while retaining space for formative learning (Hansen & Sindre, 2023). Version-control artifacts and code reviews supported traceability, and rubrics aligned with the selected LOUIS domains were reused across modules to make quality criteria explicit (Biggs & Tang, 2015; G. P. Wiggins & McTighe, 2005).

Pedagogical mechanisms and tooling choices

Figure 1 provides an overview of the course structure and interaction between modules, reflection, and the capstone project.

Preparatory materials and method overviews were assigned outside scheduled class time, reserving contact time for application, discussion, and feedback (flipped classroom; (Tucker, 2012)). Within each TBL module, individual readiness activities (iRAT) required students to propose context-specific uses of analytical methods, while team readiness discussions (tRAT) consolidated approaches prior to team application (tAPP).

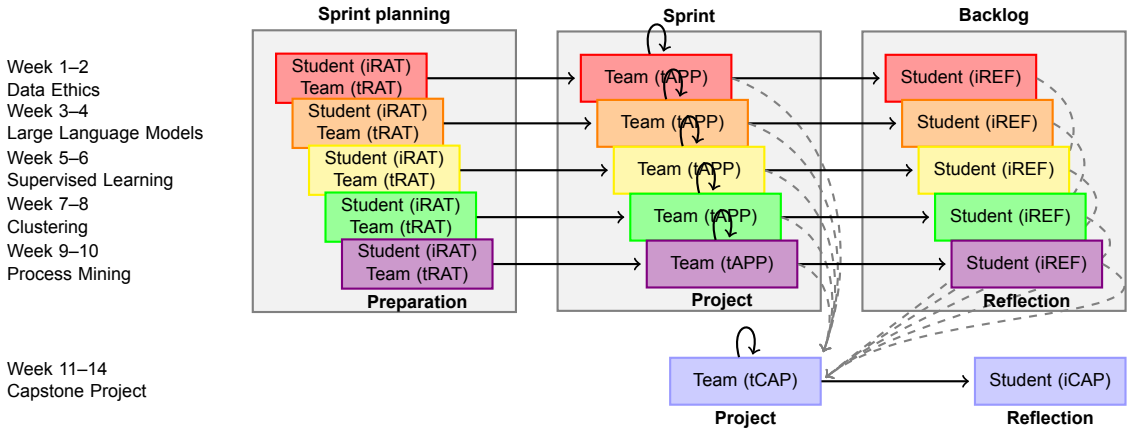


Figure 1. Course flow illustrating the structure of thematic team-based learning modules and their integration into the capstone project. Each module includes preparation (iRAT/tRAT), team application (tAPP), and individual reflection (iREF). Reflections serve as forward-oriented notes and backlogs that inform the capstone project (tCAP), supporting continuity, iteration, and professional competence development across the semester.

GitHub Classroom was adopted as the primary collaboration environment, reflecting common professional practice. The platform supported version control, peer review via pull requests (PRs), and reproducibility, enabling assessment to recognize both team outcomes and individual contributions through observable work traces. PRs provide a mechanism for proposing, reviewing, and discussing changes to a shared codebase, commonly used in professional software and data workflows. Ingimundardóttir (2026) provides a detailed account of how PR-centric workflows function as assessment architecture within this structure.

Each two-week module was aligned with agile development practices (Schwaber & Beedle, 2001). Planning activities in tRAT functioned as lightweight sprint planning, tAPP as execution, and individual reflection (iREF) as a structured retrospective. Reflection was forward-oriented: students documented unresolved issues, methodological limitations, and improvement ideas that they revisited during the capstone project.

Course flow and iterative integration

The course flow integrates five thematic TBL modules into a final capstone project (Figure 1). Each module comprises preparation (iRAT/tRAT), team project work (tAPP), and individual reflection (iREF). Dashed connections indicate how both team outputs and individual reflections contributed to the capstone project (tCAP). The capstone project functioned as a sustained integrative task in which teams revisited and consolidated insights, feedback, and unresolved issues from earlier modules, enabling assessment and reflection to accumulate toward professional standards rather than reset between tasks.

By explicitly carrying insights, constraints, and unresolved questions forward into the capstone, the course avoided treating assessment tasks as isolated events. Instead, assessment and feedback accumulated across modules, reinforcing learning as an iterative, developmental process aligned with professional practice.

Alignment with CDIO standards

The redesigned course aligns with CDIO Standards in several ways. Standard 5 (Design–Implement Experiences) is addressed through semester-long, industry-inspired project work that requires students to design analytical approaches and implement reproducible solutions. Standard 7 (Integrated Learning Experiences) is reflected in the intentional integration of professional competencies with BI methods within a sustained industrial context. Standard 8 (Active Learning) is operationalized through TBL modules, flipped preparation, and in-class application requiring reasoning, collaboration, and decision-making. Finally, Standard 11 (Learning Assessment) is addressed by competence-aligned rubrics, artifact-based accountability, and iterative feedback loops that balance formative learning with professional expectations. Together, these elements position assessment and feedback as central drivers of development toward professional standards in a CDIO-aligned project-based course.

COURSE REDESIGN: ASSESSMENT AND FEEDBACK ARCHITECTURE

This section outlines how assessment and feedback were reconfigured to function as developmental mechanisms supporting professional competence, rather than primarily summative evaluation. The redesign is informed by qualitative evidence from two course iterations with a single industry partner, drawing on observations, reflections, and partner feedback. The following subsections detail the key elements of this assessment architecture.

From assessment as measurement to assessment as development

We adopted a developmental view of assessment, in which criteria and feedback guided progression toward professional standards over time. The final rubric was introduced early and reused formatively with scaled weight across project modules, allowing students to rehearse expectations while retaining space for revision. Early exploration and errors were acceptable if recognized, documented, and addressed. Rubrics covering analytical soundness, transparency, reproducibility, and stakeholder relevance were applied consistently across modules and the capstone so that feedback accumulated across modules through explicit revisiting and resolution of prior comments, rather than fragmenting across tasks, with detailed rubric design and application discussed in Ingimundardóttir (2026). Version-control histories and pull-request records provided concrete evidence of whether and how teams responded to feedback between iterations.

Industry-engaged project structure

A key element of the assessment architecture was the use of a shared, industry-inspired project context spanning the entire semester. A single industry partner provided an authentic dataset and participated in problem framing, milestone discussions, and final presentations. Students were free to augment the provided data with additional sources, but all work remained anchored in the same organizational and analytical context.

This design choice addressed two recurring challenges observed in earlier course iterations: repeated onboarding to unrelated datasets and weak coherence between modules. By maintaining a stable context, students could progressively deepen their understanding of the domain, refine analytical approaches, and revisit earlier assumptions as new methods were introduced.

Assessment requirements emphasized reproducibility and traceability. All analyses were developed in shared repositories, and deliverables consisted not only of reports and presentations, but also of executable code and documented workflows. This structure mirrored professional expectations in data-intensive work and reinforced importance of credible, transferable results.

Industry feedback emphasized trustworthiness and usability, making visible how even minor analytical flaws can erode confidence–a clear contrast to academic tolerance for developmental error that students learned to navigate.

In parallel, the partner emphasized a preference for receiving the final deliverables in a GitHub-based format, reflecting their familiarity with working in that environment. For professional audiences, a concise slide deck summarizing key insights, assumptions, and business implications was considered the most useful final product, with the option to explore the underlying codebase in the repository if the results appeared promising. By contrast, the more extensive technical report was produced primarily to satisfy academic assessment requirements, ensuring transparency of methods and providing the instructor with sufficient detail to evaluate attainment. This distinction further highlighted how professional and academic audiences value different forms of evidence, documentation, and communication.

Balancing team performance and individual accountability

Team-based project work was central to the course, mirroring professional practice in BI. However, team assessment introduces well-known challenges related to unequal contribution, free-riding, and perceived unfairness, as widely recognized in CDIO project courses (Huet et al., 2008). Rather than relying solely on peer grading or individual exams, the redesign adopted a dual assessment strategy.

Team deliverables were assessed collectively with respect to analytical quality, coherence, and professional relevance. In parallel, individual contribution was assessed through visible artifacts generated during project work, including version-control activity, code reviews, and documented design decisions. Structured individual reflection complemented these artifacts by requiring students to articulate their contributions, uncertainties, and learning needs.

This approach allowed individual accountability to be supported without fragmenting team outcomes. Students reported that this transparency clarified expectations and reduced uncertainty about how their individual efforts were recognized within the team context.

Feedback loops and iterative learning

Feedback was integrated at multiple levels and stages of the course. Instructor feedback focused on methodological soundness, alignment with competence criteria, and progression across modules. Peer feedback occurred primarily within teams, through code review and collaborative problem-solving, and across teams during selected review moments.

Throughout the semester, the instructor served as the primary point of contact, emphasizing methodological and implementation aspects, while industry input was concentrated at key milestones and emphasized domain relevance and decision context. This separation of roles made differences in evaluation criteria explicit and required students to adapt their communication to distinct stakeholders.

Individual reflection (iREF) functioned as a forward-oriented practice: students documented unresolved issues, limitations, and improvement opportunities that were revisited during the capstone. This is consistent with CDIO approaches to reflection as professional practice rather than retrospective reporting (Junaid et al., 2018). As illustrated in Figure 1, these reflections formed a personal backlog that students returned to during the capstone, enabling feedback from earlier modules to inform later design decisions.

Industry feedback was gathered through discussions of intermediate results and final presentations, informing expectations across iterations. It was interpreted in relation to professional competence, emphasizing justification of analytical choices, clear communication of assumptions and limitations, and credible, decision-supporting results. In contrast to academic tolerance for developmental imperfection, industry feedback foregrounded trustworthiness, clarity, and usability, requiring students to adapt their work and communication accordingly.

STUDENT AND INDUSTRY RESPONSES

Evidence of the impact of the redesigned assessment and feedback architecture indicates three main themes: (i) engagement and perceived relevance remained high without formal attendance requirements, reflected in consistently high attendance and active participation among current students, consistent with Freeman et al. (2007), who link engagement to a strengthened sense of belonging; (ii) early-career transfer was evident in graduates' use of reproducible workflows, collaborative problem-solving, and explicit documentation of assumptions and limitations; and (iii) industry partner feedback valued improved coherence and credibility of outputs while highlighting that small analytical flaws can undermine trust—an expectation difference we now make explicit to students. From an academic perspective, this was also reflected in increasingly ambitious, student-driven project scope, enabled by the sustained structure of the course rather than direct instructor steering.

TENSIONS, TRADE-OFFS, AND LESSONS LEARNED

Industry engagement exposed productive tensions central to the redesign. Most prominently, academic tolerance for developmental error contrasted with industry expectations of reliability and trustworthiness. Accepting developmental error proved pedagogically valuable, but it also complicated students' calibration of when exploratory imperfection was acceptable and when it conflicted with professional expectations of reliability.

Team-based assessment presented a second trade-off. Large collaborative projects supported professional skill development but heightened concerns about workload distribution and fairness. Visible artifacts and structured reflection reduced ambiguity around individual contribution, though increased transparency also amplified student sensitivity to perceived inequities.

Tooling introduced a further tension. Professional collaboration platforms enhanced authenticity and reproducibility but imposed both an initial learning burden and substantial instructor effort through ongoing review and feedback. This front-loaded investment, however, streamlined final assessment by making revisions and responses to feedback clearly visible across iterations. Relocating tool onboarding earlier in the curriculum emerged as a pragmatic adjustment to preserve realism while reducing cognitive load during complex project work.

Collectively, these lessons indicate that industry-engaged assessment requires deliberate negotiation between realism and pedagogical support. Designing explicitly for such tensions–rather than attempting to eliminate them–proved essential for maintaining both learning quality and professional credibility.

TRANSFERABLE DESIGN PRINCIPLES FOR CDIO PROGRAMS

The redesign surfaced several principles that may support other CDIO programs implementing industry-engaged, competence-oriented assessment. These principles highlight how authenticity, developmental assessment, and clear competence structures can be integrated to reinforce professional learning in data-intensive project contexts.

1. **Anchor assessment in a sustained industrial context.** Maintaining a shared, semester-long industry context supports coherence across learning activities and enables cumulative competence development, reducing fragmentation between project modules.
2. **Design assessment as a developmental process.** Align assessment criteria across formative and summative tasks so that feedback accumulates over time and guides students toward professional standards rather than functioning as isolated judgments.
3. **Make individual contribution visible within team work.** Combine team-level outputs with artifact-based indicators and structured reflection to support accountability and fairness without undermining collaborative learning.
4. **Use reflection as forward-oriented professional practice.** Frame reflection as documentation of unresolved issues and improvement opportunities that inform subsequent design decisions, rather than as retrospective self-evaluation alone.
5. **Explicitly manage academic–industry expectation gaps.** Surface differences between developmental learning tolerance and professional reliability requirements early, and prepare students to adapt quality standards and communication to audience and context.
6. **Introduce professional tooling with intentional scaffolding.** Select tools that support authenticity and reproducibility, but ensure early alignment and onboarding to prevent tool mastery from overshadowing learning objectives.

CONCLUSIONS AND FUTURE WORK

This paper presented a redesign of an industry-engaged Business Intelligence course in which assessment and feedback function as central mechanisms for developing professional competence within an authentic project context. The approach combines team-based learning, sustained industry collaboration, and competence-oriented assessment to enhance coherence and professional relevance. The redesign surfaced productive tensions between developmental learning space and workplace expectations of reliability and trust, illustrating how assessment structures and forward-oriented reflection can help students navigate these expectations.

Two targeted refinements follow from iterative delivery. First, to reduce cognitive load and keep thematic modules in focus, mastery of collaboration tooling (e.g., GitHub) will be addressed in a prerequisite course. Second, to support early collaboration and credibility, the opening session will prioritise team formation, trust-building, and exploratory engagement with the industrial context before readiness activities and application work.

Future work will examine how this revised sequencing influences team dynamics, the credibility of student deliverables, and competence development across cohorts. It will also explore how the assessment architecture can scale to additional partners and related data-intensive courses.

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BIOGRAPHICAL INFORMATION

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IDENTIFYING THE FOUR CORE BENEFICIARIES OF INDUSTRY-DRIVEN CDIO PROJECTS

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ABSTRACT

Industry sourced and supported CDIO projects achieve beneficial outputs for all internal and external stakeholders including students, higher education institutions (HEI), industry partners, and society. For students, these projects provide exposure to authentic, real-world challenges rather than purely academic or hypothetical problems. In addition, to the standard learning outcomes and critical-analysis skills developed through CDIO projects, students gain technical and work-related skills experience in project management, market analysis, budgeting, quality assessment, and working with industry standards. Engagement with industry professionals, enhance their graduate employability through interactive and presentation skills. HEIs benefit in teaching and learning frameworks, research impact, knowledge exchange and networking with local commercial sectors. These activities support institutions in achieving professional accreditations, quality benchmarks and contributing to regional developments as civic anchor institutions. Industry partners gain access to academic knowledge, development of local workforce, new business ideas, collaborative funding opportunities, and expanded professional networks. Society ultimately gains from positive regional economic impact on businesses, socioeconomic improving and students' future through enhanced career opportunities, production of skilled professionals, and development of sustainable relationships between all four beneficiary groups. At Canterbury Christ Church University, students have completed more than 25 industry-sourced CDIO projects across various engineering courses from foundation year to final year supported by a diverse range of industries, including manufacturing, design, healthcare, shipping, and construction etc. The projects have not only strengthened students' learning and technical skills but also supported employability, with an average of 75% securing graduate jobs, placements, or internships. Participation in these projects has enriched students' academic and professional portfolio. Overall. this paper analyses how such industry-sourced CDIO projects generate multidimensional benefits across key stakeholder groups.

KEYWORDS

Industry-source projects, quality assessment, industry standards, professional accreditation, graduate employability, Standards – 2-8,11,12

INTRODUCTION

CDIO projects have been very effective in implementing project-based learning (PJBL), problem-solving, with experimental analysis in higher education sectors. PJBL (Ramírez de Dampierre, 2024) aims to improve learning outcomes and competencies in technical and non-technical areas (De Dampierre *et al.*, 2024). The CDIO model adopted globally in engineering education but covers wider curricula frameworks (Lingling *et al.*, 2012). The multi-stakeholder approach (Armstrong *et al.*, 2005) that the CDIO framework leads to varying impacts on various entities. This study identifies four core beneficiaries: students, HEIs, industry, and society. Through imitating the lifecycle of real-life engineering projects, CDIO provides unique exposure through which learners familiarise themselves with industry standards and access wider network pools. They acquire hands-on experience with industry practice (Rigden, 2022).

Applying PJBL through CDIO enables engineering students to learn from reality "rather than generalisation" (Hong *et al.*, 2024). Teaching through CDIO aims to train students comprehensively in terms of knowledge, skills, attitudes, and core competencies linked to their profession. This emerging practice also enhances curriculum relevance and supports the alignment of programs with professional accreditation requirements, including the development of industry-standard competencies in quality assurance, sustainability, and regulatory practice.

Canterbury Christ Church University is among the HEIs that actively use the CDIO framework as a structured approach that encompass the entire life cycle of engineering projects, from conception, design, implement to operation, (Edström & Kolmos, 2014). The institution emphasises the need for early students' exposure to industry-sourced projects and collaboration. In addition to student-centred benefits, the institution reports experiencing positive CDIO impacts in the form of improved pedagogy, enhanced knowledge exchange capacity, strengthened accreditation readiness, and research and outreach potential. Industry partners and society also benefit from better innovation and more sustainable relationships.

The primary aim of this article is to identify the key beneficiaries of industry-supported CDIO project-based curriculum and to evaluate its impact beyond the educational domain. In particular, the study examines its broader socio-economic and environmental contributions. The outcomes are intended to demonstrate the significance of the CDIO approach not only in advancing technological capability but also in fostering responsiveness to evolving industry demands and promoting environmental sustainability.

Based on these premises, the present study explores the impact of CDIO projects on students, HEIs, industry, and society. The mixed-methods study sources information from an array of sources, including documentation from the 25 projects, student artefacts, staff and industry partner feedback, and project key outcome artefacts, among others. A thematic analysis pattern helps identify recurrent benefits to various stakeholders of interest in the study. By considering each stakeholder separately, the study distinguishes the unique benefits that the CDIO-PJBL approach brings to each of the stakeholders considered.

METHODOLOGY

This study employs a mixed-methods approach grounded in project records, stakeholder reflections, and institutional performance indicators. Evidence was gathered from:

- Documentation from 25 industry-sourced CDIO projects.
- Student reflective reports, presentations, and assessments.

- Staff and industry partner feedback.
- Graduate Outcomes and progression data from CCCU.

IMPLEMENTATION OF INDUSTRY-SOURCED CDIO PROJECTS

To enhance graduate employability and adapt to real-world engineering problems, CDIO projects in our curriculum are sourced from local industry partners. A robust process (Figure 1) has been created to transform those real-world engineering problems into CDIO projects (Manna *et al.*, 2023). Those engineering problems from local industries have been obtained through various channels and converted into student projects integrated with modules.

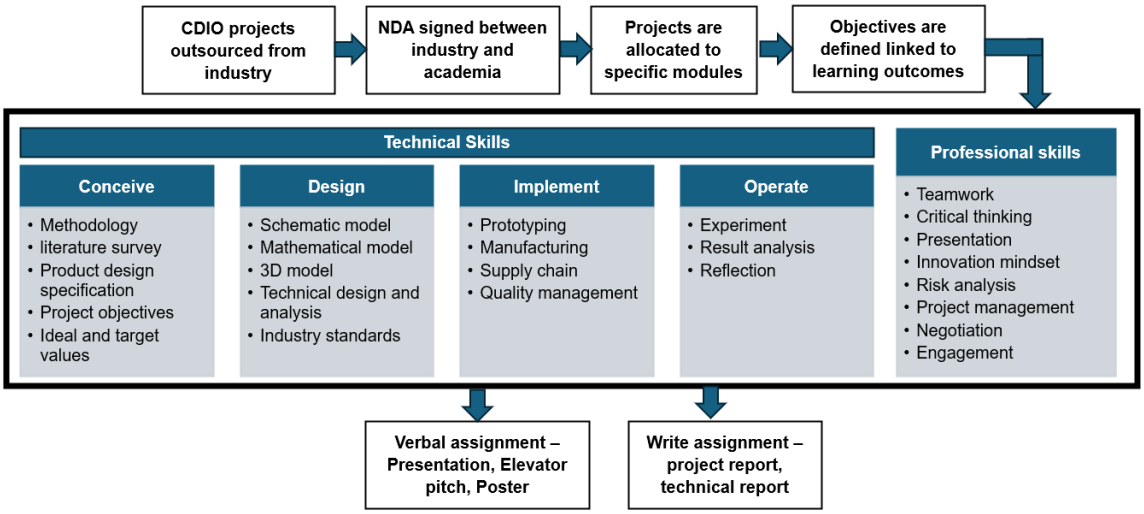


Figure 1. Industry sourced CDIO projects

Project allocation is determined by the complexity and technical demands of the problem, the level of the students, and the expertise of tutors and technical staff. Based on these factors, each project is assigned to an appropriate cohort within a specific course and year group.

Tasks in conceive stage

In this stage, students develop the methodology for the industry-defined projects, including the Product Design Specification (PDS) sheet and the Bill of Materials (BoM). They determine the technical specifications of the proposed solutions along with their structural components. The specifications for the CDIO project are defined using three metrics: ideal, target, and achieved values. The ideal values are derived from the literature review, the target values are set based on business factors such as cost and time, and the achieved values are established after the prototype has been developed.

Tasks in the design stage

In this stage, students design the foundational framework of the CDIO project, including the schematic model, mathematical model, and 3D model. They also explore various technical designs such as electronic circuits and virtual prototypes. To develop these designs, students use several software tools. For example, Fusion 360 was used to create the 3D model; Arduino IDE for programming the Arduino board; Tinkercad for designing electronic circuits and virtually embedding and verifying the programmed logic; MATLAB for developing the mathematical model of the proposed solution; and ANSYS for conducting finite element

analysis and computational fluid dynamics when required. Depending on the complexity of the project, the types of software used may vary. Throughout this process, students conduct risk assessments and comply with relevant industry standards.

Tasks in Implementation stage

In this stage, students manufacture the models using various processes such as 3D printing, laser cutting, and machining in the mechanical workshop; develop electronic circuitry by soldering discrete electronic components and programmable modules. Throughout this phase, they also follow quality management procedures.

Tasks in Operate stage

In this stage, students execute the project and reflect on the outcomes. They create a controlled environment and conduct real-time experiments to evaluate the performance and effectiveness of the prototype. A critical analysis is carried out by comparing the experimental results with the theoretical predictions, and the findings are documented in a comprehensive report. Finally, students present their work, either individually or as a group, to an academic and industrial panel and submit the final reports for assessment.

The objectives of the project have been transformed into various assessments (coursework, lab and presentations) of the associated module so that students can achieve the module learning outcomes while meeting the project objectives. As part of their assessments, students prepared both written and visual outputs, including technical and business reports, risk assessments, posters, and elevator pitches to present their findings. Beyond developing technical competencies, students strengthened key professional and soft skills such as teamwork, critical thinking, creativity, innovation, and active engagement.

FOUR BENEFICIARIES OF CDIO PROJECTS

Since 2019/20, engineering students at Canterbury Christ Church University have already worked with more than 25 industry-sourced CDIO projects, mostly from small and medium-scale industries. In this process, students have liaised with internal and external stakeholders, including academics, technical team, industry personnel and sponsors. There are mainly four stakeholders who have benefited from these projects (Figure 1). Through delivering real-world CDIO projects, the team have explored good academic practices to reduce the complexity of industry-standard processes for adaptive learning and graduate employability. Besides, students gained familiarity with current industry standards (Figure 2).

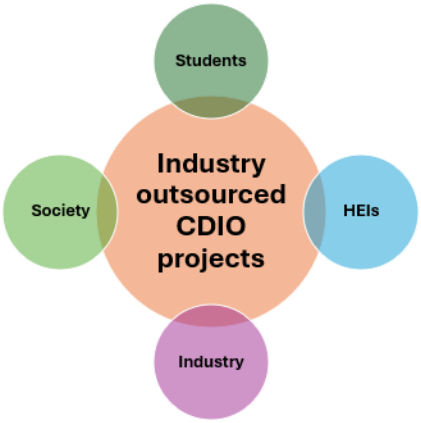


Figure 1. Four core beneficiaries

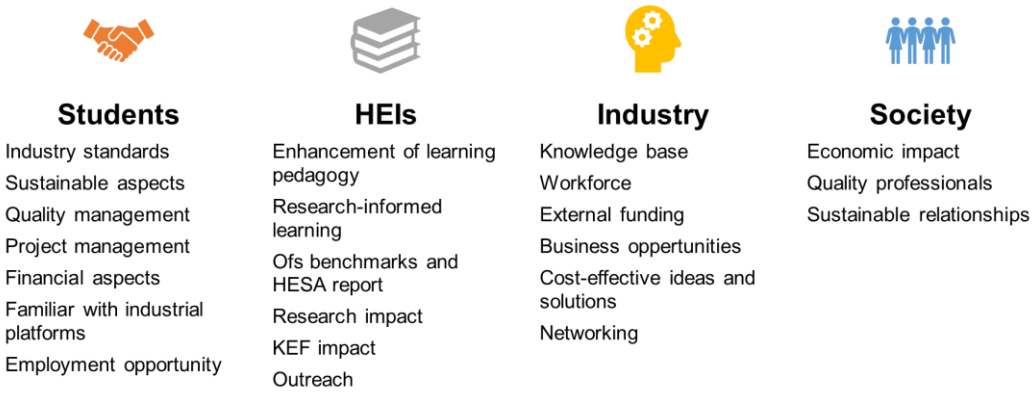


Figure 2. List of benefits

BENEFITS FOR STUDENTS

Industry standards

While working on the industry-sourced CDIO projects, the prospective solutions will aim to achieve industry standards and regulations such as BSI and ISO. This approach would make the solution closer towards the market standard while students' perspective. Keeping the objectives of projects aligned with industry standards, students will continue their design, implementation and operation process.

Sustainable aspects

To reduce environmental impact and carbon footprint, students are encouraged to design and implement sustainable elements in their CDIO projects (Steuer-Dankert, 2023). This has also become a learning requirement set by professional accreditation and regulatory bodies across the UK HEIs. Wherever possible, project solutions (Jaca *et al*., 2021) should align with the UN Sustainable Development Goals (SDGs). As part of this effort, students calculate the carbon footprint of the overall development and manufacturing process, design for sustainable end of life, make use of recyclable materials and design environmentally friendly products or systems.

Quality management

While completing industry-sourced CDIO projects, students have also followed the QMS (quality management system) since it is required by the industry for further investigation, testing and launching the products/systems. During the QMS process, students will study the quality of the solutions, robust testing, risk assessments, and sustainable supply chain etc.

Project management

Most of the projects are group work with 3-4 students and the role of each usually possesses a significant contribution while supporting each other, like an industrial platform. A Gantt chart is produced with a timeline of completion for each task and students also reflect on the issues they faced and how they overcame them. In this process, they coordinate with peers while liaising with academics and industry personnel, enlightening their multi-team working model.

Financial aspects

To understand the market compatibility of their proposed and developed solution, students will do a comparative cost analysis of existing products. At the beginning of the project, students

were allocated a specific budget for the project. They also complete a thorough costing of the solution, starting with designing, building, testing and production. The costing will include the cost of components, manpower, supply chain, manufacturing etc. This kind of analysis is helpful to maintain the cost-effectiveness of the proposed solutions.

Familiar with industrial platforms

While pursuing CDIO projects, students interact with industry personnel, visit their platforms and are continuously guided by their expert advice. Sometimes, students also approached prospective industries to secure sponsorship for project finance. In this process, they learn how to professionally communicate with the industry both verbally and in writing and how to present their ideas and solutions in a more convincing way.

Employment opportunity

The outcome of CDIO projects leads to both direct and indirect impact on student employment. Completing the CDIO projects boosts their confidence and portfolio while applying for jobs. These industry sourced projects enriched their industrial experience, CVs and fulfilled the industry expectations. Sometimes, they also receive recommendations from industry personnel. Pleased by the performance of students, the industry sometimes offers internships, placement and contractual job roles. So far, the collaboration opportunities with eXroid have supported five interns, two KTP associates and one full-time and one part-time role and are currently supporting one part-time contractual role. In a few scenarios, students also received with monetary contributions from industry as a token of appreciation.

BENEFITS FOR HEIS

Enhancement of teaching and learning pedagogy

Through collaborative work with academics, technical team, learning skills team and industry partners, students can practice most of the required learning methods such as problem-based learning, project-based learning and experimental learning. Therefore, having those projects onboard supports their teaching and learning framework as required for professional accreditation and quality framework (Penttila and Kontio, 2016), thus helped students to realise how complex, industry-standard engineering products can be designed from a simple idea with appropriate technical expertise and hands-on skill. Through this process, students can use their previously gained knowledge and skills, which also help them to retain the knowledge, one of the major concerns for current education.

Research-informed learning

Transforming the best practices of teaching and learning into research can show strong evidence of its impact. Following the CDIO projects, the developed research mindset may drive students to pursue research in future rather than going for traditional jobs, eventually getting them in a research and development organisation or academics. Sometimes, it also fosters their entrepreneurial mindset for startups and spinouts (Norrman *et al.*, 2014).

Ofs benchmarks

There are certain measures defined by Office for Students (Ofs, 2022) to measure outcomes of HEI providers for example, Continuation and Completion measure the percentage of

students who remain on their course and successfully achieve their qualification, while Progression captures graduate outcomes such as employment, further study etc.

Industry-sourced CDIO project supports the students to enhance their graduate employability, which also has a direct impact on progression statistics of Ofs benchmark in the UK. It also appears that the performance of the students is much better in project-based modules when they are industry-sourced. For biomedical engineering, the course continuation rate is high (91.7%), the retention rate is 84% and progression rate is 100% with graduate employment in NHS, eXroid, BAE etc whereas average progression rate for engineering courses is 75%.

Research impact

The research-oriented CDIO project can also contribute to the research framework in UK HEIs. With appropriate support, those student-based CDIO projects can be transformed into large-scale, impactful research projects supported by internal or external funders. One of our student-based CDIO projects supported by eXroid in 2020, which eventually led to a mini-KTP project and later an accelerated KTP project funded by Innovate UK. The outcomes from CDIO projects will be used a REF (research excellence framework) impact case study.

Knowledge exchange

Liaising with local industry as a part of CDIO projects, universities will deliver knowledge transfer to local businesses, which has a direct impact on local economy and society in terms of value and workforce. This approach will also build a sustainable relationship with HEIs. In the current scenario, universities need to build courses to support the industry expectations; therefore, the local industry always play a major role in developing industry-oriented courses, eventually contribute in the UK-wide knowledge-exchange framework.

Outreach

Through collaboration with industries, even at the academic level, the outreach of HEIs can be expanded, especially in commercial sectors. This, in turn, enhances institutional reputation and rankings. In addition to establishing national and international footprints, such engagement can also help to increase student recruitment.

BENEFITS FOR INDUSTRY

Knowledge base

Since industry partners typically do not allocate funding for student-based CDIO projects, these initiatives are primarily supported by academic institutions. On the other hand, industries receive new ideas, prospective solutions and working prototypes for their proposed engineering problems. Industries are open to taking those ideas to implement in their platform. At the beginning of collaboration, a Non-disclosure Agreement (NDA) is signed between industry and institutions to preserve any developed ideas or solutions.

Workforce

The local industry, which is mainly small and medium scale, engagement in the CDIO projects enable them to develop their future workforce in collaboration with HEI without going through the extensive and costly recruitment process. In one of our previous projects, students from the project have been recruited by the industry.

Business opportunities

It has been found that while working on CDIO projects, there are new ideas and product concepts that have evolved and developed, which have also led to new business opportunities for industries. Usually, students are not familiar with the current market scenario; sometimes, those ideas are not biased and affected by pre-existing information. For example, while working on the CDIO project on electrotherapy, students managed to build a software solution for tracking and monitoring the tissues, which has led to a new product.

Cost-effective ideas and solutions

CDIO projects do not incur any financial liability on industries. The only commitment for them is to make a few engagements with the students to clear their queries and provide guidance along with academic team. On the other hand, it would enable industry to crowd source new potential viable new ideas, feasibility studies or a working prototype of their engineering problems, which will result a huge cost savings on their research and development.

Networking

Through engagement with CDIO projects, industries can network and collaborate with world-class academia to support their continuous professional training and development in both technical and business areas from manufacturing to supply chain management. Industry personnel can receive Institutional training as a form of CPD (Continuous Professional Development) for growing their business model and product market fit. Sometimes, researchers from academia can work as consultants in industry to provide support.

External funding

Building on the outcome of the CDIO project, the industry can pursue external funding (InnovateUK, NIAB, British Council etc) to support its projects. Having a track record of working with CDIO projects helps the industries to provide evidence of their achievements.

BENEFITS FOR SOCIETY

Economic impact

The local economy of the society is indirectly influenced by the growth in education and industry sectors. Additional income through a rise in recruitment numbers and in the industry through sources of income from products could lead to more investment in society. Besides, by securing graduate-level jobs at the end of their course, the quality of life for graduates will be improved and they will further contribute to society through taxes, benefits etc.

Quality professionals

Early training and interaction with industry from the start of their course make students industry-ready professionals. Since the industry has certain expectations where skills in both technical and professional sectors are equally important, CDIO projects provide the scope of learning from an early stage. This will further reduce the wastage of resources in society.

Sustainable relationships

Building sustainable relationships between industry and academia through CDIO projects has long-term implications for society since it keeps current education aligned with industry

requirements to reduce the gap between the real-world challenges and academic world for long term goals in education and industry.

RESULTS

Since 2019/20, the engineering courses (Biomedical, Product Design, Mechanical and Chemical) at Canterbury Christ Church University have incorporated approximately 25 CDIO projects (Figure 3), typically sourced from industry (healthcare, real estate, construction, shipping, sport, manufacturing, education, agricultural technologies and so on) to all levels, including Foundation Year to Final Year. Figure 4 shows the distribution of these projects across the various engineering disciplines and academic levels.

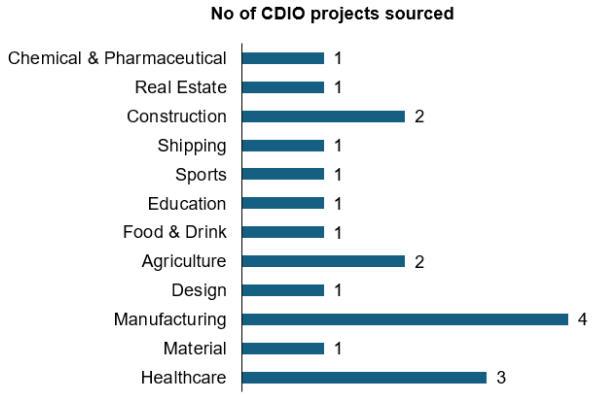


Figure 3. Types of industries supported by CDIO projects

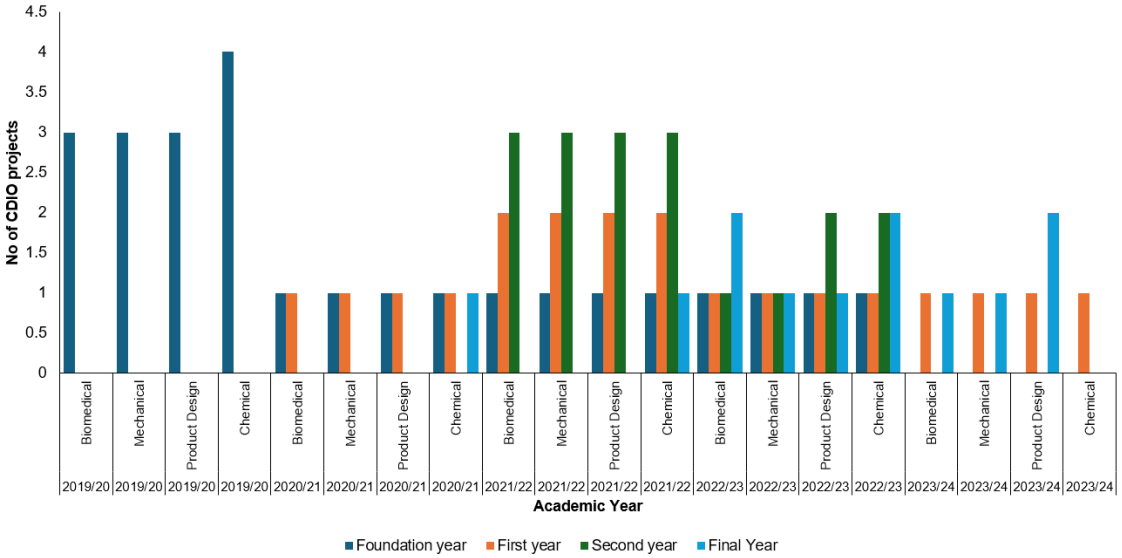


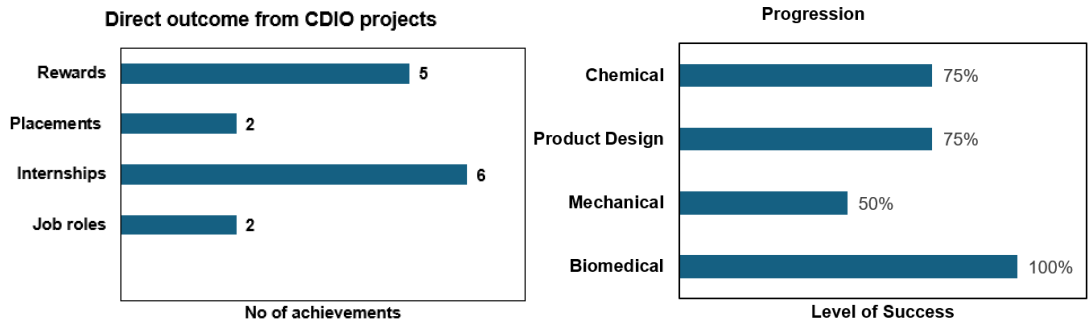
Figure 4. Project allocation across courses and Years

Both short-term and long-term opportunities are shown in Figure. 5a. For example, a manufacturing company awarded £3,000 to the best first-year student group working on a SLAM lock project for delivery vans and has incorporated their innovative ideas into the next version of its product. Another organisation awarded £1,500 to the top Foundation Year group for an inclusive, flexible easel design. Students have also received individual awards; for instance, one Product Design student was awarded £500 for a Pickleball racket project.

Furthermore, several students have secured internships through these industry-funded projects. In terms of long-term goals, some students have obtained commercial employment

with partner organisations. For example, one graduate is currently employed by a healthcare company after working with them on a project. Overall graduate employability (Figure 5b) has also improved and is reflected in national graduate outcomes data for UK students. The data was collected from university platforms such as Power BI and the Careers and Enterprise team, the average progression rate across all four engineering courses is approximately 75%, with Biomedical Engineering achieving the highest rate at 100%.

The analysis adopts a structured and systematic approach to evaluating CDIO project activity and its impact on graduate employability. Data relating to the number of CDIO projects is first collected and organised on a course-specific, year-wise basis. Each project is then categorised according to its thematic focus, area of research, and associated industry or provider company, enabling a coherent mapping of academic activity to industry engagement and research domains. In parallel, project outcomes are analysed using defined employability indicators. These include student progression rates as a primary measure, alongside short-term success metrics such as awards and recognitions, internships secured, placement achievements, and the nature of job roles obtained. This dual-layered analysis facilitates a more comprehensive understanding of how CDIO project participation contributes to both immediate student success and longer-term graduate employability outcomes.



a. Short-term and long-term opportunities b. Progression of graduate students

Figure 5. Impacts of CDIO projects on student employment

Students and industry partners have also shared their personal experience while working on the industry-sourced CDIO projects.

Quotes from students

Student 1 - 'While doing the CDIO project I've been able to improve upon my CAD (computer-aided design) skills. For these two subjects I've gained a lot of self-confidence and the ability to speak with confidence during team presentations'.

Student 2 - 'I feel that as a future professional engineer I have gained a lot of new skills as well as helped contribute to my team'.

Quotes from industry partners

'The talent and resources at Canterbury Christ Church University are very impressive. It's been an absolute pleasure to work with both the students and lecturing staff on innovations that will continue to transform our potential, as well as the University management for their approach to partnerships with industry.'- Managing Director, healthcare company

'The CDIO framework is acknowledged by WBCL as being effective in both education and the design of real-world products and systems in due course hopes to benefit from the investment through recruitment of CCCU graduates.' - UK manufacturing company

CONCLUSION

The study demonstrates that CDIO projects are not only impactful to students, but their impact radiates across HEIs, society, and industry partners. Integrating real-life engineering problems into the framework imparts technical and critical employability capabilities such as project management, communication, sustainability analysis, quality assurance and professional engagement. In summary, the study reports multi-stakeholder benefits emerging from CDIO projects. HEIs like Canterbury Christ Church University should continuously improve their PJBL by integrating emerging industry trends into CDIO to prepare students for current and future industry trends. Integrating emerging trends and techniques would also lead to more innovative solutions across disciplines. The multi-stakeholder approach to this PJBL method helps address any challenges that emerge in the profession. Students become part of the solution while still in their training and learning stages. Industry-sourced CDIO projects are, therefore, an ideal approach through which the goals of PJBL are achieved.

The main challenge lies in identifying appropriate industry projects. Most partner organisations are SMEs, and they have their own business operations. As a result, the projects they offer are often non-commercial in nature, with little or no financial support available. This means that HEIs have to rely on their own internal funding and resources to deliver such projects. Another limitation is maintaining the quality of projects to meet industry expectations. This is often constrained by students' limited knowledge and the restricted resources available within the institution. Consequently, many projects result in working models or conceptual designs rather than fully developed commercial prototypes. Embedding these industry-based projects into appropriate modules presents an additional challenge. Projects must align with module learning outcomes and depend on the expertise of academic staff, which can vary. Furthermore, projects are typically time-bound, requiring solutions to be developed within strict academic timelines, which may not always align with industry expectations.

In spite those limitations, findings from the 25 CDIO projects at Canterbury Christ Church University show how learners become better prepared through improved self-confidence and better professional portfolios. These educational and professional advancement opportunities prepare engineering students for industry, eliminating employability challenges. The study also links CDIO projects to numerous social, industry and HEI benefits. Among HEIs, for example, the evaluation reveals the evidence of robust pedagogical frameworks, evidence-informed practice, better knowledge exchange programs, and innovative pathways for impact generation. At the industry level, stakeholders acquire innovative ideas, low-cost research and development, talent sourcing, and sponsorship opportunities. The study also links CDIO projects to further social benefits, such as the development of high-quality professionals and long-term sustainability. To strengthen support systems, it would be beneficial to introduce dedicated support for HEIs to collect CDIO-based projects and industry engagement activities. Financial support would enable institutions to better resource these projects and reduce reliance on internal budgets. In addition, establishing a more structured industry–academia collaboration model within the curriculum could significantly improve outcomes. This could include designated personnel or liaison roles responsible for identifying, sourcing, and maintaining relationships with industry partners, as well as coordinating project opportunities. Such an approach would reduce the burden currently placed on academic staff and streamline communication with industry and ensure a pipeline of suitable industry-linked activities.

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INTEGRATING CDIO AND TEAM-BASED LEARNING IN A MANAGEMENT COURSE: ACTION RESEARCH STUDY

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ABSTRACT

Current management education faces challenges including low student motivation, digital distractions, and superficial team interactions. Traditional didactic teaching often fails to cultivate talent capable of practical problem-solving. This study addresses these pedagogical pain points by cross-disciplinarily applying the engineering-based CDIO (Conceive, Design, Implement, Operate) framework to a first-year Management course, integrated with Team-Based Learning (TBL) strategies. Adopting an action research approach with 68 first-year students, the study utilized mixed methods for data collection. The instructional design implemented CDIO standards and TBL mechanisms (iRAT/tRAT) to facilitate active learning through strategic planning projects based on real-world corporate scenarios. The results indicated that: (1) learning motivation significantly improved ($p < 0.05$), demonstrating that CDIO and TBL can positively influence student motivation; (2) team learning effectiveness surpassed individual learning, with tRAT scores consistently exceeding iRAT scores; (3) guided by the CDIO process in executing corporate case analyses, students showed increased confidence in practical skills; and (4) TBL fostered a positive collaborative environment, enhancing students' sense of participation within their teams. The study concludes that combining CDIO with TBL effectively improves practical abilities and collaboration satisfaction, assisting students in transitioning from passive knowledge receivers to active learners. These findings provide a reference for future curriculum design in business education.

KEYWORDS

CDIO, Team-Based Learning (TBL), Action Research, Management Education, Learning Motivation, Standards:3, 4, 5, 7, 8

RESEARCH MOTIVATION

In the landscape of contemporary management education, cultivating management talent equipped with practical problem-solving skills and higher-order thinking is crucial (Ahmad et al., 2025). Industry practitioners have also reflected on the prevalent "gap between theory and practice" in traditional business education. However, an examination of current pedagogical practices reveals that students face multiple challenges regarding learning motivation and effectiveness, creating significant pedagogical pain points. The instructional setting must shift from merely transmitting knowledge to cultivating students' ability to navigate real-world work environments in the future.

Observations from the course indicate that students' lack of autonomous learning ability is a significant issue. Students are generally accustomed to a passive, lecture-listening mode of receiving knowledge and lack the willingness for independent exploration and critical thinking. This phenomenon primarily stems from the influence of traditional didactic teaching, which diminishes students' agency in constructing knowledge and hinders the development of autonomous learning habits (Grangeat, 2016).

Secondly, distraction and fragmented attention interfere with learning outcomes. With the ubiquity of mobile devices, students are easily distracted by messages on phones and tablets during class. Such distractions not only affect individual cognitive absorption but also create an adverse effect on the overall learning atmosphere of the classroom. Furthermore, team interactions often remain superficial. In group collaboration tasks, students rely on AI tools to quickly obtain answers. Although responsibilities are divided, the outcome often becomes a fragmented collection rather than a genuinely collaborative effort. There is a lack of deep analysis of management issues and a failure to build consensus, which compromises the quality of reports. Groups often lack in-depth dialogue and dialectic engagement, missing the connection between reflection and theory.

To address these challenges, the instructional setting must introduce a teaching framework that is both systematic and practical. Compared to traditional lecture-based teaching methods, Team-Based Learning (TBL) uses structured group activities to promote student engagement (Bingjie et al., 2022; Jeno et al., 2017), requiring students to apply concepts in realistic contexts (Chen et al., 2018; Azim et al., 2018). TBL's emphasis on collaboration stimulates members' intrinsic motivation. Students become more invested in the learning process due to their accountability to peers. Many students report a preference for team activities over traditional lectures, which helps enhance their learning experience (Azim et al., 2018; Shoair et al., 2023).

CDIO is an integrative and practice-oriented educational framework that provides a new pathway for transforming the classroom in business education. Over the past several years, Feng Chia University has actively institutionalized the CDIO (Conceive, Design, Implement, Operate) approach within its pedagogical practices, integrating it comprehensively across diverse disciplines and educational levels, from first-year courses to graduate programs. Although the CDIO educational model originated in engineering education (Crawley et al., 2014; Worldwide CDIO Initiative, n.d.-a), its emphasis on "learning by doing" and experiential learning aligns seamlessly with management concepts such as planning, organizing, leading, controlling, and business models. Therefore, this teaching practice research adapts the CDIO framework for a management course to strengthen learning motivation and address observed pedagogical problems:

- Conceive: Guide students to start with secondary data to understand the enterprise, define corporate problems, and comprehend market demands and management issues, thereby addressing the problem of passive learning.
- Design: Connect classroom management theories (e.g., Porter's Five Forces, SWOT, organizational structure, strategic management) with practical experiences in corporate case analysis. Students apply management theories to plan solutions or business models, enhancing their focus.
- Implement: Concretize theories through actual plan execution, prototyping, or corporate case simulations.
- Operate: Assess the feasibility and sustainability of the plan. Students are required to collect feedback during the implementation phase and make iterative corrections.

Using the CDIO framework combined with the TBL model, the course transforms classroom participation into small-group collaborative learning to analyze its impact on students' learning motivation and teamwork effectiveness in the management course.

RESEARCH PURPOSES

Based on the aforementioned problems in the management education setting—such as low student learning motivation, distraction, and superficial team interactions—this study applies the CDIO pedagogical framework, combined with TBL strategies, to construct an innovative teaching model suitable for first-year students in the College of Business. Referencing the 12 CDIO Standards (Worldwide CDIO Initiative, n.d.-a), this study sets the following research purposes:

- To establish a practical management teaching model guiding students from "Conceive" to "Implement." This purpose aims to provide first-year students with an introductory framework that offers a comprehensive view of management practices, sparking their interest in the professional field. Simultaneously, by guiding students to shift from passive listening to active environmental scanning and strategic design, they experience the complete cycle from "Conceive" to "Implement," cultivating the ability to solve real-world problems. This purpose responds to the content of Standard 4 (Introduction to Engineering/Management) and Standard 5 (Design-Implement Experiences).
- To explore the impact of the TBL mechanism on learning motivation. To address issues of student distraction and passive learning, the course employs the TBL pedagogy to investigate its impact on student learning motivation. This study examines how the TBL mechanism encourages students' willingness to engage in active learning, thereby influencing their motivation. This purpose relates to Standard 8 (Active Learning).
- To investigate the impact of CDIO and TBL on learning effectiveness. Addressing the issue of superficial group interaction, this instructional design utilizes the CDIO framework and TBL to enhance peer dialogue and consensus-building, resolving the problem of "division of labor without collaboration." By observing changes in communication quality, conflict resolution skills, and collaboration patterns during the implementation of the CDIO project, the study aims to increase students' confidence in problem-solving and cultivate management talent equipped with collaborative skills. This purpose aims to examine whether the course achieves Standard 7 (Integrated Learning Experiences)—that is, fostering students' Standard 3 (Interpersonal and Teamwork Skills) while teaching professional management knowledge.

Corresponding to the purposes of this teaching research and the CDIO Standards (Worldwide CDIO Initiative, 2020), the specific implementation practices in the course are shown in Table 1.

Table 1: Course Implementation Goals and Practices Based on CDIO Standards

CDIO Standard	Summary of Definition	Specific Course Implementation
Std 3: Interpersonal and Teamwork Skills	To cultivate personal and interpersonal skills. Focuses on developing students' ability to work effectively in teams and communicate.	Adopting TBL mode: Students collaboratively analyze cases, solve problems, and present group reports to practice interpersonal dynamics.
Std 4: Introduction to Engineering* *(Adapted as Introduction to Management)*	To provide fundamental knowledge of management theories. Serves as the introductory framework for the discipline.	Bridging theory and practice for first-year students: Assisting students in applying theories to real-world cases at an introductory level, thereby stimulating enthusiasm for the management field.
Std 5: Design-Implement Experiences	To provide opportunities for case analysis and practical implementation. Emphasizes learning through the creation and operation of products/processes.	Guiding the strategic planning process: Teams are guided through the complete cycle of problem definition, data analysis, and strategic design for specific corporate cases.
Std 7: Integrated Learning Experiences	To integrate disciplinary knowledge with professional skills. Merges academic content with personal and interpersonal competencies.	Reflective and collaborative integration: Through collaborative learning, the course requires groups to complete case analysis reports and team reflections, alongside individual learning reflections, to integrate analytical experiences with professional knowledge insights.
Std 8: Active Learning	To employ TBL to engage students in thinking. Engages students directly in thinking and problem-solving activities.	Implementing TBL with iRAT/tRAT mechanisms: Utilizing readiness assurance tests to facilitate deep peer discussion and immediate feedback, effectively addressing issues of distraction and passive learning behavior.

RESEARCH METHODOLOGY

This study employs an action research approach to investigate the impact of the CDIO-integrated TBL pedagogical model on university students' learning motivation, team interaction quality, and learning effectiveness.

Research Subjects

The research subjects were first-year students from the Department of International Business, enrolled in the compulsory "Principles of Management" course. A total of 68 students participated in the course. The gender distribution was 85% female and 15% male. This sample was selected because first-year students are in a critical transition period of their learning patterns, and management serves as an introductory course to the business field, making this group highly representative for this study.

Course Design and Implementation

This study structured the course around the CDIO (Conceive, Design, Implement, Operate) framework and integrated Team-Based Learning (TBL) into the weekly management classes. To ensure systematic progression, this study divided the 18-week teaching activities into four phases: Conceive, Design, Implement, and Operate. This study was deliberately designed to address persistent pedagogical challenges in traditional management education, including the gap between theory and practice, low student motivation, and free riding in team-based tasks. Through group collaborative projects focused on analyzing corporate cases, this study guided students through a comprehensive cycle of applying management concepts to real-world problems. The detailed implementation framework is presented in Table 2.

Table 2. Course Operation Framework

Phase / CDIO Standards	Goal	Pedagogical Focus	Practical Task	TBL Mechanism
Conceive (Weeks 1-4) *Std 4: Intro to Mgmt* *Std 8: Active Learning*	Field Exploration and Problem Definition	Establishing foundational management theory; Environmental scanning.	Students actively search for and select a Small and Medium-sized Enterprise (SME) to conduct secondary data collection and analysis.	iRAT/tRAT (Individual/Team Readiness Assurance Tests): Ensuring comprehension of foundational vocabulary and reinforcing pre-class study motivation through active learning.
Design (Weeks 5-9) *Std 3: Teamwork Skills* *Std 4: Intro to Mgmt*	Theory Application and Strategic Planning	Systematic diagnosis using analysis tools (PEST, Porter's Five Forces, SWOT).	Groups transform market information into structured analysis reports, proposing analytical results and defining case problems.	Positive Interdependence: Members discuss, complete individual analysis dimensions, report back to the group, and integrate findings to establish task interdependence.
Implement (Weeks 10-14) *Std 5: Design-Implement* *Std 7: Integrated Learning*	Concretizing Action Plans	Strategic evaluation and recommendations for the case study.	Producing specific analysis reports. Students propose recommendations for marketing, HR, and strategy, converting abstract strategies into actionable Action Plans.	Group Deliverables: The team collaborates to produce tangible analytical outputs and specific solutions.
Operate (Weeks 15-18) *Std 3: Teamwork Skills* *Std 7: Integrated Learning*	Outcome Presentation and Field Verification	Professional communication, persuasion, and reflection.	Holding a final presentation, simulating a professional briefing to business owners.	Peer Evaluation & Reflection: Conducting peer evaluations and writing reflective journals on the collaborative process.

Data Collection Instruments

This study employs a mixed-methods approach, utilizing methodological triangulation to ensure the reliability and validity of the data:

Quantitative Measures

- Motivated Strategies for Learning Questionnaire (MSLQ): Adopting the scale developed by Pintrich et al. (1991), this questionnaire was administered at the beginning and end of the semester. A paired-samples t-test was used to analyze differences in students' learning motivation and learning efficacy dimensions.
- Team Interaction Assessment: This study employed Michaelsen's Method, utilizing peer evaluation scores from TBL sessions to assess individual contributions and the collaborative climate. Individual impact was quantified by calculating the mean deviation of these peer scores.
- Learning Performance Tests: Including scores from iRAT and tRAT, as well as assessments of the final project.

Qualitative Measures

- Reflective Reports: Students wrote reflective journals after the conclusion of each CDIO phase, documenting the difficulties encountered and the strategies used to resolve them.
- Focus Group Interviews: A purposive sampling approach was employed at the conclusion of the semester. Teams were selected from both high-performing and low-performing clusters to explore the nuanced impact of the CDIO project on their teamwork models. A total of 16 students participated in semi-structured interview sessions, each lasting 20–30 minutes, providing diverse perspectives across varying achievement levels.
- Team Interaction Assessment: To assess team interaction, students were required to provide a concise qualitative peer feedback for each teammate, specifically highlighting their individual contributions to the collective task. This approach facilitated a deeper understanding of the team's interpersonal dynamics and the specific collaborative behaviors of the students.

Data Analysis

- Quantitative Analysis: This study utilized SPSS 24.0 statistical software to conduct data analysis. It performed descriptive statistics to examine sample characteristics, applied t-tests to assess changes in learning motivation and learning outcomes, and employed regression analysis to evaluate the significance of relationships among variables.
- Qualitative Analysis: Transcripts from interviews and reflective journals were subjected to coding and inductive analysis to extract key themes affecting learning outcomes. These findings were then cross-referenced and interpreted in conjunction with the quantitative data.

RESEARCH RESULTS

Sample Structure and Gender Difference Test

This study involved a total of 68 students, comprising 85% females and 15% males. To examine gender differences, this study conducted an independent-samples t-test. The analysis revealed no significant differences between male and female students in learning motivation or learning outcomes ($p > 0.05$). These findings suggest that the CDIO and TBL

pedagogical models implemented in this course exhibit generalizability, indicating that their effectiveness is not contingent upon student gender.

Effectiveness of TBL Learning and Immediate Feedback

Analysis of the iRAT and tRAT data reveals that the average scores of the tRAT were significantly higher than those of the iRAT. The results demonstrate that through peer discussion and cooperative learning, students were able to correct misconceptions and achieve the effect of knowledge construction (Figure 1).

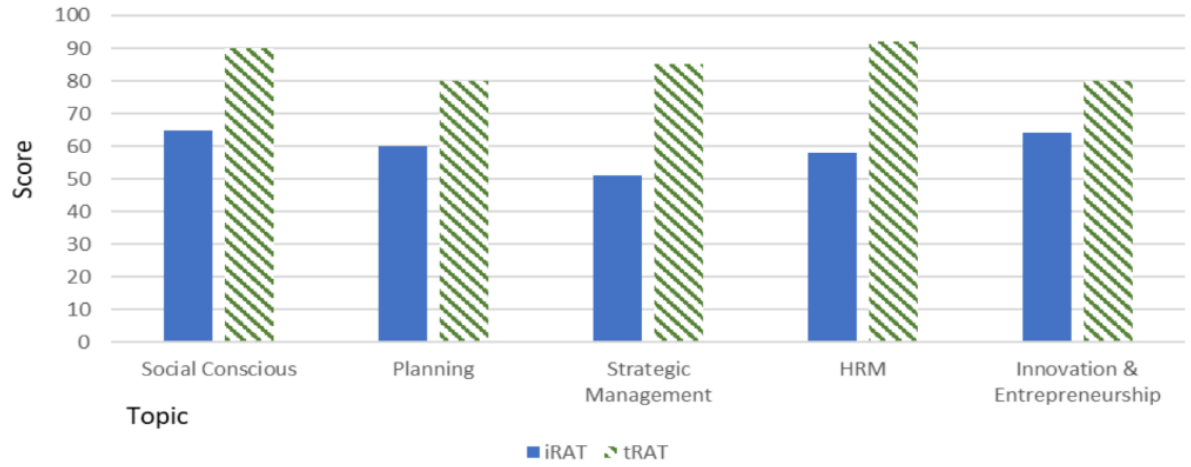


Figure 1. Comparison of iRAT and tRAT Scores

Analysis of Learning Motivation

Regarding the verification of instructional effectiveness, the results indicate that students' learning motivation at the end of the course was significantly higher than at the beginning ($p < 0.05$). Specifically, facilitated by TBL and group discussion mechanisms, students' post-course learning motivation was significantly superior to their pre-course motivation (Figure 2). The result demonstrates that, in this pedagogical research, the introduction of team learning mechanisms effectively enhanced students' sustained motivation for learning. The study further analyzed the relationship between learning motivation and learning outcomes. The results reveal that learning motivation has a significant positive influence on learning outcomes ($p < 0.05$).

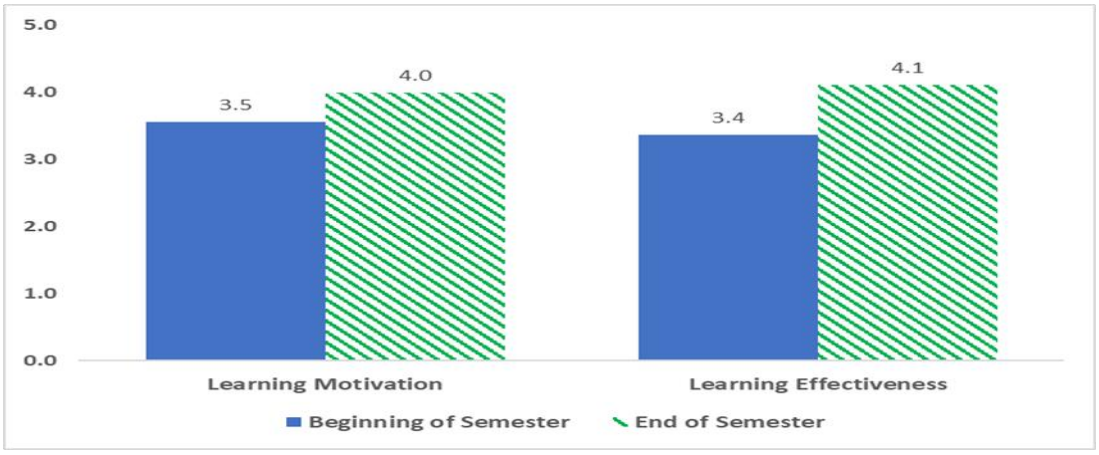


Figure 2. Changes in Learning Motivation and Learning Outcomes: Pre-test vs. Post-test

Impact of Classroom Participation

This study categorized students into a High Participation Group (4-5 points) and a Low

Participation Group (1-3 points) based on their self-assessed classroom participation (scale of 1-5). Independent samples t-test results indicated that the High Participation Group scored significantly higher than the Low Participation Group in both learning motivation and engagement in group discussions ($p < .05$).

Furthermore, comparing the High Motivation Group (score≥7) and Low Motivation Group (score≤6) based on self-assessed learning motivation (scale of 1-10), findings revealed that high-motivation students performed significantly better in weekly course completion and the quality of group interaction.

Notably, the data showed that regardless of individual motivation levels, students exhibited high satisfaction with group participation. Qualitative results further clarified that the primary reason for low-motivation students' satisfaction was their positive evaluation of the group discussion process. Students noted:

"Team members participated actively, made efforts to share ideas, and cherished each other's diverse viewpoints."

"The diverse insights brought by members not only sparked more creativity but also made the conclusions more comprehensive."

"The discussion atmosphere was harmonious, with smooth interaction and mutual respect."

"Although there were occasional communication challenges, I enjoyed the overall interaction experience, which aided personal growth and deepened thinking."

"Discussions made me braver in expressing myself."

The result demonstrates that the TBL mechanism successfully created a positive atmosphere of peer mutual aid, allowing even low-motivation students to find a sense of belonging and participation within the team.

Specific Effectiveness of the Implementation Project

Regarding CDIO implementation outputs, teacher grading indicated that 65% of the groups were able to propose specific analysis content and recommendations for their research cases, demonstrating students' understanding of course content and their ability to apply it to practical scenarios. Grading results also showed improved scores in environmental analysis and SWOT analysis.

However, some group project reports remained superficial and lacked in-depth analysis. These limitations point to an area for future improvement, suggesting that instructors should provide targeted guidance to underperforming groups. Additionally, student feedback indicated an increase in self-confidence regarding practical skills such as secondary data collection, environmental analysis, SWOT analysis, and report writing (Figure 3).

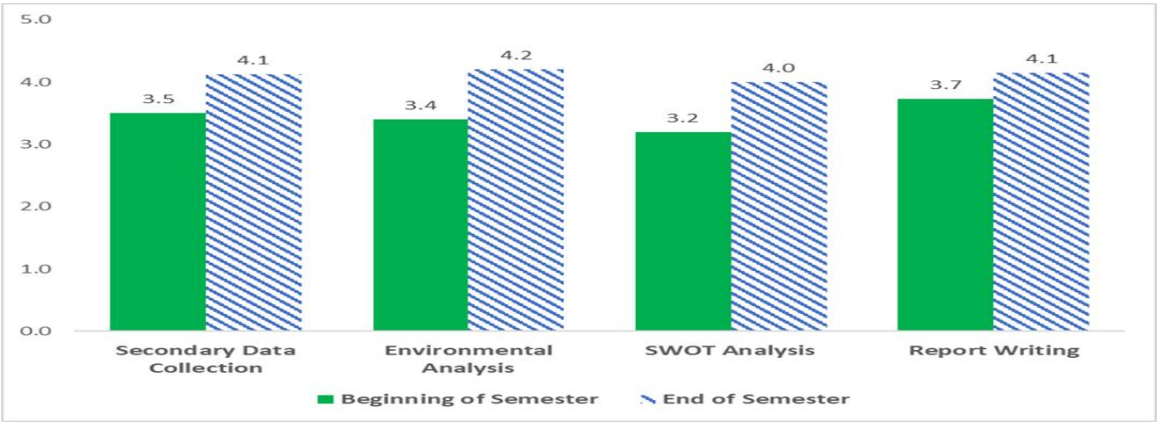


Figure 3. Changes in Student Confidence Levels Regarding Group Project Skills: Pre-semester vs. Post-semester

CONCLUSIONS AND SUGGESTIONS

Conclusion

This study aimed to explore the effectiveness of integrating the CDIO engineering education framework with Team-Based Learning (TBL) in a first-year Management course.
Synthesizing the quantitative data and qualitative analysis results, the study summarizes the following four core conclusions:

- The CDIO framework and TBL mechanism ameliorate passive learning and deepen students' knowledge construction (Responding to Standard 8). The results indicate that TBL significantly enhanced students' learning motivation and satisfaction with interaction quality. The fact that tRAT scores consistently surpassed Individual iRAT scores demonstrates that peer cooperative learning promotes a more profound understanding of knowledge. Addressing the challenge of fragmented attention, this study found that the appropriate introduction of real-time digital feedback tools (e.g., Kahoot, Quizizz) can foster student interaction and engagement, effectively refocusing student attention within the instructional context.

- CDIO implementation projects strengthen the link between theory and practice. Through the introduction of Small and Medium-sized Enterprise (SME) analysis projects, students experienced the complete cycle from environmental scanning and strategic planning to the formulation of action plans. The implementation outputs evidence that students have acquired the ability to transform abstract theories—such as environmental analysis and SWOT analysis—into concrete solutions. The result shows that the CDIO model effectively acts as a bridge for "integrating learning and application," achieving the goals of Standard 5 (Design-Implement Experiences) and Standard 7 (Integrated Learning Experiences).

- Team discussion enhances cooperative motivation (Responding to Standard 3). The study found that even students with lower learning motivation maintained high satisfaction with "group participation," primarily influenced by their willingness to engage in group interactions. Furthermore, the CDIO-integrated TBL model demonstrates good generalizability; this framework enhances learning motivation and effectiveness, making it suitable for comprehensive promotion within business schools.

- Assisting first-year students in establishing foundational management knowledge (Responding to Standard 4). As an introductory course for first-year students, this model not only imparted management knowledge but, more profoundly, helped students undergo an identity transformation from "passive receivers" to "active learners." Through the CDIO pedagogical architecture, students established a cognitive framework for management practices early on, laying the groundwork for autonomous learning throughout their four years at university.

Reflections and Suggestions

To address these limitations and inform future teaching research, the following recommendations are proposed:

- Reinforce the Scaffolding Mechanism for Reflection. Instructors should provide more detailed reflection guidelines or structured assessment rubrics to support students in transitioning from descriptive accounts of activities (i.e., what was done) to critical

reflection (i.e., what was learned and how improvement can be achieved). This approach aims to deepen the development of personal and metacognitive skills.

- Intervention for Underperforming Project Groups: Results showed that some group project reports remained superficial and lacked in-depth analysis. To address this, instructors should intervene earlier with groups that are lagging to understand their difficulties in the learning or case analysis process, guiding them to reinforce group dynamics and momentum.

- Longitudinal Tracking of Learning Transfer: Future research could further track this cohort of first-year students trained under the CDIO model to observe whether they continue to demonstrate superior project implementation and teamwork capabilities in advanced courses during their sophomore and junior years, thereby verifying the long-term benefits of this model.

Since this study employed a single-cohort design without a control group, a potential limitation involves self-reporting bias. Students might have exhibited social desirability bias, providing overly positive responses to reflect their support for the new instructional model. To minimize this effect, all surveys were conducted anonymously, and students were explicitly informed that their feedback would not influence their final grades. Furthermore, qualitative insights from the focus group interviews were used to cross-verify the depth and authenticity of the survey results, ensuring a more robust interpretation of the pedagogical outcomes.

While traditional engineering CDIO emphasizes technical reliability, this research demonstrates that Management CDIO prioritizes 'Adaptive Resilience'—the ability of a team to pivot their business model effectively under simulated market volatility. These findings suggest that the CDIO standards can evolve into a cross-disciplinary pedagogical framework, successfully integrating technical systems with human-centric organizational dynamics to prepare business students for complex, real-world environments.

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SUST*A*/NABILITY CONSIDERATIONS IN ENGINEERING CURRICULUM

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ABSTRACT

A comprehensive definition of sustainability encourages implementers to consider what they aim to sustain in terms of individuals, organizations or systems, and the outcomes of their actions. Sustainable development is a continuous transformation at global, regional, and local levels to secure good living conditions for current and future generations. It requires decisions and actions that balance environmental, social, and economic factors within Earth's carrying capacity and biodiversity. Integrating sustainability into Master's-level engineering education is essential for strengthening the knowledge base of future engineering leaders. This paper outlines the development of two new Master's degree programmes within the Faculty of Technology at LAB University of Applied Sciences, highlighting how sustainability has been embedded in their design. The aim is to establish a foundation for future initiatives in sustainable curriculum development. One degree programme focuses on circular economy solutions, while the other addresses technological leadership transformation, embedding sustainability as a core element of future leadership. Both programmes were developed in parallel to offer scholars flexible opportunities to design their own study paths, culminating in two Master's degrees with sustainability at the heart of their core competencies.

KEYWORDS

Sustainability, Sustainable development goals, Curriculum development, Standards: 2-4

INTRODUCTION

Engineering education aims to equip future engineers with the knowledge and skills necessary for successful careers in the field (Routaharju 2025). In a constantly changing world, the understanding of future skills also evolves. However, no one can deny the importance of sustainability understanding. Engineers play a central role in shaping a more sustainable future, and therefore, the sustainability perspectives of engineering education require attention.

Sustainability, especially environmental sustainability, is featured in the Conceiving - Designing - Implementing - Operating (CDIO) approach (Edström et al. 2020). To support holistic sustainability and align with the United Nations (UN) Sustainable Development Goals (SDGs), an even more comprehensive approach is needed. This article presents the inclusion of sustainability in Master level engineering education curricula at LAB University of Applied Sciences (LAB) in Finland.

LAB's strategy aims to develop "Responsible, sustainable, and regenerative growth" (LAB 2025a). This is achieved through developing key competences in Intangible Value Creation, Multipurpose Materials and Human Well-being. Sustainable development and responsibility are in the core of the strategy; thus, the joint goal is to integrate sustainability perspectives in all curricula over time.

The concept of sustainability originates from the concern about poor resource management and environmental degradation (Kopnina 2017). In 1972, after the publication of 'The Limits to Growth' by the Club of Rome, environmental awareness emerged even stronger (Meadows et al. 1972). An ongoing debate about the earth's capacity to sustain human economic growth started. Sustainable development as a term was introduced from a political perspective in 1987 by the United Nations (UN) (Sneddon et al. 2006; UN 1987). Here sustainable development is defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs', thus underlining that it comprises environmental, social and economic aspects (UN 1987).

Since sustainability was introduced, it has been commonly understood that the linear economy for generating economic growth in which raw materials are extracted, manufactured, used and thrown away cannot lead to sustainable development (Hoekstra and Wiedmann 2014; Millar et al. 2019). The concept of circular economy arose as a way to increase effectivity while reducing the use of resources (D'Amato et al. 2017). The holistic perspective of the circular economy emphasizes all aspects of sustainable development: environmental, social and economic (Desing et al. 2021). Especially, the circular economy has been seen as a solution for combining the possibilities of economic growth and environmental sustainability (Vanhamäki et al. 2021). The circular economy presents a context for concretizing the implementation of sustainability in an economic model and bringing the context closer to practice.

In 2015, the UN General Assembly established the Agenda for Sustainable Development, which defined 17 SDGs outlining urgent and essential actions required globally (UN 2015). These goals and targets address interconnected ecological, social, and economic challenges that are vital for the future of humanity and the planet (UN 2015). LAB has identified seven UN SDGs as key focus areas in its 2030 strategy (LAB 2025a; 2025b). Through its education and research, development, and innovation (RDI) activities, LAB aims to contribute to these goals in various ways:

- SDG 3: Good health and well-being – LAB trains healthcare professionals who integrate sustainability principles into their practice, contributing to more sustainable healthcare solutions.
- SDG 8: Decent work and economic growth – LAB promotes sustainable economic growth by supporting RDI initiatives and fostering collaboration between students and businesses.
- SDG 9: Industry, innovation, and infrastructure – LAB encourages eco-friendly technological solutions by incorporating circular economy principles, innovation, and design expertise.
- SDG 11: Sustainable cities and communities – LAB actively participates in designing safe, sustainable, and livable environments that meet societal and individual needs.
- SDG 12: Responsible consumption and production – LAB focuses on developing methods for sustainable consumption and production, emphasizing resource efficiency and waste reduction.
- SDG 13: Climate action – LAB takes action against climate change by increasing awareness and innovating technological solutions to reduce environmental impact.
- SDG 17: Partnerships for the goals – LAB fosters collaboration between researchers, students, and businesses to drive sustainable innovation and scale impactful solutions. (LAB 2025b.)

By concentrating on these seven SDGs, LAB strategically aligns its efforts to make a tangible impact on sustainability and global development. This paper looks at two Master level engineering degrees, and their sustainability. The research question of the study is: How is sustainability integrated into the curriculum of Master level engineering programmes? The aim of the paper is to present a case example of how sustainability is embedded in the curriculum of two Master's level degrees, as defined by the UN SDGs.

METHODOLOGY

Empirically, this study is based on a qualitative analysis of two Master's level engineering programmes developed at LAB during 2024. The data consists of the two programme and course descriptions, curriculum documents and the author's' reflective observations as program developers, analyzed through a case study and action research approach. This study adopts a qualitative and contextual approach. In other words, it explores the perspectives of selected university representatives, focusing on their emotions, preconceptions, and motivations within the framework of research, development, and innovation (RDI) activities related to the development of online Master's degree programmes (Gray 2017). Two approaches were applied in this study: a case study approach and an action research approach. Case studies are an adequate and necessary method for certain research tasks. The case study method has been used extensively across fields, particularly in education, and is well suited to solving complex problems (Montes-Rodríguez et al. 2019). The study was conducted ex post by systematically examining the completed curricula and mapping course content and learning objectives against the SDG's. This was done to identify how sustainability themes are embedded across the programme's and to assess the extent the SDG's are addressed at the programme level.

While sustainability and the UN SDGs are explicitly emphasized in LAB University of Applied Sciences' institutional strategy, the degree programmes were not designed through an explicit SDG-by-SDG curriculum planning process. Instead, sustainability principles guided programme development at a strategic level. The systematic mapping of course content against the SDGs was conducted ex post as part of this study. The ex post analysis therefore

serves both as a reflective evaluation of curriculum alignment with strategic sustainability objectives and as a tool for identifying development needs for future curriculum iterations.

The action research approach is a method of systematic inquiry that university lecturers perform as researchers of their own practice, constantly questioning the practices and methods in use and being active drivers for change. The inquiry involved in action research is often visualized as a cyclical process, as shown in Figure 1.

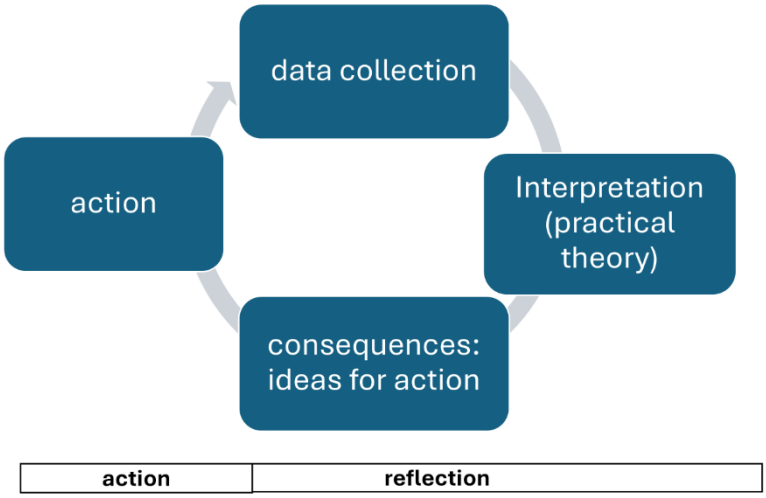


Fig. 1: The circle of action and reflection (Altrichter et al. 2007)

Action research focuses on problems, problem-solving abilities, and community. It influences the functions and environment of the researched phenomenon by enhancing and developing the community's problem-solving skills. Active participation in the community's practices related to the research phenomenon is essential for conducting action research. It begins with practical actions that provide data through scientifically recorded observations (Brusila-Meltovaara et al. 2022).

This study was undertaken within LAB and it covers the construction of two new multidisciplinary Master's degree programmes specifically during the new curriculum design period spanning the entire year 2024. The completed curriculums were officially approved in December 2024. The overall strategy of LAB gave the framework for the degree development. The strategy is constructed on enabling responsible, sustainable, and regenerative growth (LAB 2025a). Sustainability and responsibility are promoted by LAB in education, RDI activities, stakeholder cooperation, and also operating methods in everyday life at campuses. Climate change mitigation and carbon neutrality in 2025 are also seen as strategic choices by LAB. (LAB 2025a).

The degrees in focus of the study are 1) Circular Economy Solutions (CES) and 2) Technological Transformation Leadership (TTL). The development of these two multidisciplinary degrees began at the beginning of 2024, where the degree titles and participating faculties were decided upon by the board of directors of LAB. Both multidisciplinary degree programmes are led by the Faculty of Technology. CES was planned

and will be implemented together with the faculties of business and design, while TTL is carried out in cooperation with the faculty of health and wellbeing. (Brusila-Meltovaara et al. 2025) The scope and length of the Master's degree studies in accordance with the length of the first degree i.e., the Bachelor's degree. The total amount of credits one obtains by completing both a Bachelor's and Master's level degree is 300 ECTS. The credits required for completing the design or technology Master's degree are 60 ECTS as the Bachelor's degree consists of 240 ECTS. Each course is 5 ECTS.

RESULTS

LAB aligns its education and research activities with the SDGs, emphasizing seven key objectives in its 2030 strategy (LAB 2025a; LAB 2025b). The TTL and CES programmes integrate these sustainability goals into their curriculum, ensuring that graduates are equipped with the knowledge and skills to drive sustainable change in organizations.

The TTL and CES curriculums incorporate sustainability aspects into multiple courses, contributing to selected SDGs through practical applications, theoretical frameworks, and industry-relevant case studies. Tables 2 and 3 illustrate potential ways in which these goals are reflected in TTL and CES courses. Furthermore, students are encouraged to consider SDG perspectives in their thesis projects, ensuring that sustainability themes are integrated into their research and practical work.

Table 2: Integration of SDGs in TTL courses

Course	SDGs	Example
Change Mgmt Knowledge Mgmt	SDG 8 SDG 17	Students will analyze company case studies that have successfully navigated workforce transitions through digital transformation while ensuring employee well-being and career development.
Modern Technologies & Megatrends	SDG 3 SDG 9 SDG 13	Students will assess the impact of key megatrends and explore how emerging technologies contribute to better medicines, improved health outcomes, & enhanced healthcare accessibility.
Process and Project Mgmt	SDG 8 SDG 12	Students will explore sustainable project mgmt methodologies ensuring resource-efficient & ethical business practices.
Emerging Technologies in Innovative Solutions	SDG 9 SDG 13	Students will develop business models that integrate technology-driven sustainability solutions, such as smart infrastructure and resource-efficient industrial processes.
Lean Innovating of Digital Solutions	SDG 9	Students will innovate strategic solutions, apply Lean thinking and evaluate their added value from sustainability perspectives.
Leading Digital Trans-formation	SDG 8 SDG 17	Students will work with industry partners to design digital transformation strategies that promote both economic growth and social responsibility.
IoT and Cloud Services	SDG 3 SDG 9 SDG 11 SDG 12 SDG 13 SDG 17	Students will develop smart IoT and cloud-based solutions, enhance wellness technologies, & improve industrial efficiency through predictive maintenance. They will design energy-efficient infrastructures & create global collaboration platforms, promoting sustainable practices and partnerships.
Data Analysis and Visualization	SDG 8 SDG 9 SDG 13	Students will analyze & visualize datasets to develop models improving energy efficiency & supporting climate action & sustainable industry practices. Data analysis & visualization skills will be developed to foster sustainable growth & promote decent work.
Machine Learning and AI	SDG 9 SDG 12 SDG 13	Students will design machine learning models to optimize material usage & reduce waste in manufacturing processes, while applying techniques to predict maintenance needs & minimize waste & energy consumption.

Table 3: Integration of SDGs in CES courses

Course	SDGs	Example
Circular Economy for Global Sustainable Transformation	SDG 8 SDG 9 SDG 11 SDG 12 SDG 13 SDG 17	Students will get an understanding of the connections between sustainability and circularity from regional strategy and industry perspectives, and the importance of design in implementation of sustainable and circular practices.
Circular Economy R&D Methods&Cases	SDG 9 SDG 11 SDG 12	Students will increase abilities in circular economy RDI, while enhancing project preparation skills with strategic and innovative insights.
Sustainable Processes and Product Development	SDG 9 SDG 12 SDG 13	Students will assess and develop organisational/industrial and product related processes to align with sustainability and circular economy principles & identify business opportunities. Students develop renewable energy solution skills.
Materials in Circular Economy	SDG 9 SDG 12	Students will understand material circulation in the circular economy for sustainability, focusing on polymers & biobased materials. Students will learn to utilize audits, implement waste solutions, maximize reuse, consider extended producer responsibility & identify sustainable alternatives from production & consumption perspectives.
Circ. Economy Technologies & Data Mgmt	SDG 9	Students will understand the role of technologies & data in the circular economy.
Climate Change Mitigation and Adaptation	SDG 11 SDG 13 SDG 17	Students will be able evaluate urban climate interactions, compare mitigation strategies, assess climate change effects & adaptation strategies & understand climate-smart governance.
Impact Assessment of Circular Economy	SDG 9	Students will be able to apply life cycle assessment, carbon footprint & nature impact assessments, understand reporting requirements, utilise & develop circular economy metrics.
Managing Urban Sustainability Change	SDG 11	Students will apply sustainable change mgmt methods & circular economy principles at the community level, use forecasting techniques & understand sustainability strategies & smart city technologies.

While the TTL programme contributes to several SDGs, the strongest emphasis is placed on SDG 9 and SDG 13. These goals align with the core themes of the programme, which focuses on leveraging technology for sustainable technological transformation. Furthermore, the programme highlights SDG 8, SDG 12, and SDG 17 to ensure that technological

transformation supports inclusive economic growth, sustainable practices, and cross-sector collaboration. Similarly, the CES programme also emphasizes SDG 9. However, a strong focus is also put on SDG 11 and SDG 12. All these are central in developing a circular economy. Furthermore, SDG 13 is also fundamental in the sustainable circularity change, which also shows through the curriculum analysis. Table 4 summarizes how frequently each SDG is addressed across the courses.

Table 4: Integration of SDGs in TTL and CES courses

SDGs chosen in LAB's strategy.	Number of courses addressing the SDG	
	TTL (n=9)	CES (n=8)
SDG 3: Good health and well-being	2	0
SDG 8: Decent work and economic growth	4	1
SDG 9: Industry, innovation, and infrastructure	6	6
SDG 11: Sustainable cities and communities	1	4
SDG 12: Responsible consumption and production	3	4
SDG 13: Climate action	5	3
SDG 17: Partnerships for the goals	3	2

At programme level, SDGs are embedded across core courses, while the specific SDG focus may vary depending on course implementation and elective choices. As the programmes are in their early implementation phase, initial observations indicate strategic alignment with sustainability, while future iterations are needed to ensure consistent SDG integration at course and teaching practice level.

CONCLUSIONS AND IMPLICATIONS

This study provides a case example of how SDG's can successfully be incorporated in the curriculum of master level engineering studies. Both CES and TTL have the SDG's incorporated into their curriculum in line with the overall strategy of the university. The CES programme, is constructed around the perspective of fostering sustainable development through promoting circular economy, thus, especially the resource efficiency-related SDGs are integrated to the entire content. In contrast, the core competences gained through TTL often contribute indirectly, yet significantly, to achieving the SDGs, as the degree focuses on leveraging technology for sustainable transformation. However, further work needs to be undertaken with respect to finding synergies between the two degrees. As course implementation varies by teacher, the actual embedding of SDG related topics in each course is not certain. Future research should be directed towards the actual SDG topics in the course implementations and towards examining student feedback in relation to the SDG content, which should be followed by continuous yearly improvement with regards to course content based on the received feedback. Engineers are central in shaping a sustainable future, which calls for an integrated and holistic approach to sustainability within engineering education. Beyond technical expertise, curricula must encompass environmental, social, and economic dimensions to prepare engineers as responsible leaders capable of addressing complex global challenges.

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BIOGRAPHICAL INFORMATION

Kristiina Brusila-Meltovaara, has a PhD degree in business. She acts as a Principal Lecturer at the Technology Faculty of LAB University of Applied Sciences. Kristiina has extensive industry experience and experience in lecturing, curriculum development, e-learning, development of teaching materials, and commercializing training and university services. Current research interests include innovation, commercialization, leadership and management, ethics, sustainability and the leadership thereof.

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SINGAPORE POLYTECHNIC AND POLIBATAM TRANSNATIONAL COLLABORATIVE STUDENT PROJECT: INITIAL EXPLORATION

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ABSTRACT

This paper describes the insights gained from a transnational learning collaboration of a capstone project between Singapore Polytechnic (SP), School of Mechanical and Aeronautical Engineering (MAE) and Politeknik Negeri Batam, Indonesia or Polibatam (PB). It highlights the constraints and the benefits using framework outlined by Augouri (2023, p.9) for a deeper academic collaboration in an international setting. It emphasises the importance of cross-cultural sensitivities, transdisciplinary coordination and practical learning experiences in institute of higher learning, and how synergies could be forged in an international collaboration. Both institutions involved being members of the CDIO (Conceive, Design, Implement, and Operate) international network, therefore the CDIO Framework lends itself readily to facilitate such cross-border collaboration. The deployment of the CDIO framework and its relevance and the benefits in bringing about the learning outcomes needed to prepare graduates in an interconnected global working environment were discussed. 13 students comprise of 3 nationalities were grouped to observe their collaboration process, guided by faculties from SP and PB. The student teams from both countries aimed to use their domain knowledge to solve the problem faced by a household in a village in Batam, Indonesia.

KEYWORDS

Transnational Collaboration, Transdisciplinary, Capstone Project, CDIO Standards: 5-8

INTRODUCTION

Internationalisation of curriculum has been a common feature in many schools globally for many years. This can be observed by the many students social and cultural exchange programmes before and after the COVID-19 pandemic period. Many Institutes of Higher Learning (IHL) also allow students to gain credit by reading a few courses abroad, usually via credit transfer. Overseas capstone programme is also well documented. Bovill C. et al (2015, p.13) observed that “internationalization are often responding to national and global pressures to maximise knowledge transfer, where knowledge is viewed as a global commodity.”. While the advantages from the learning outcomes are obvious, the resource intensive nature of such learning can be challenging when educators have to work in a different environment culturally. In Singapore recently, there has been a strategic shift from the Singapore’s Ministry of Education (MOE, 2024) with a "70-70" initiative which aims for 70% of local IHL students to have some form of overseas exposure, and 70% of these students to have exposure to ASEAN countries, China or India (ACI). The authors feel that transnational learning fosters collaborative and cross-cultural competence by enabling students to work in multi-disciplinary, transnational teams, engage in international projects, and develop strong communication skills. Innovation and systems thinking are emphasized through design thinking, sustainability integration, and understanding the global impact of engineering solutions. The author also feels that such collaboration affords good opportunity to bring about transdisciplinary learning outcomes among participating students. McPhee *et al* (2018, p.3) described the difference between transdisciplinary, multidisciplinary and interdisciplinary innovation. Transdisciplinary approaches place disciplinary interaction “in an integrated system with a social purpose, resulting in a continuously evolving and adapting practice”. He pointed out that a “by-product of transdisciplinary innovation is that the integrated solution contributes back to the disciplines it drew upon to evolve them, too”. Angouri (2023, p.9) highlighted the benefits of transnational collaboration illustrated in figure 1.

Angouri (2023) noted that: “The complexity of problems faced by modern society requires universities, as generators of new knowledge and educators of the future global citizens, to find ways to transcend national, discipline and linguistic borders in research, innovation, teaching and learning. The changing population demographics, skills gap agenda and geopolitical changes also necessitate a rethink of the types of education and the modalities of the offering that should be available to the citizens of the future”. (p.8)

Attempts were made to link these benefits from the CDIO skillsets perspective and how transnational collaboration can be an effective strategy in bringing out the CDIO skillsets.

In terms of transnational learning collaboration, it is one notch higher and hence resource intensive. The CDIO (Conceive, Design, Implement, Operate) framework lends itself an effective milestones and skillsets for planning and executing transnational collaborations. Due to policy and culture differences, many blind spots have to be uncovered. To forge for a deeper transnational collaboration with as part of curriculum design, a capstone project would be a good start to explore academic and resource requirements and constraints faced by partnering institutes. This will eventually pave the way for a sustainable scaling up of the collaboration.

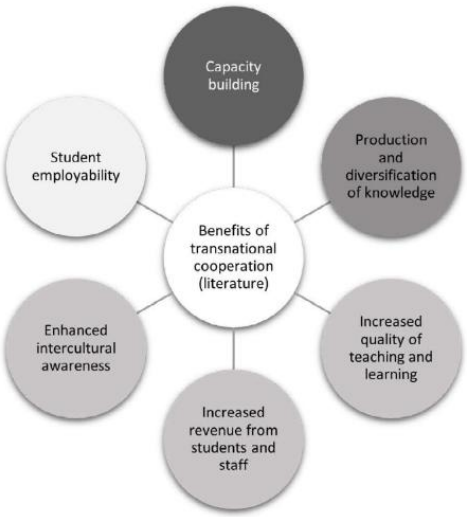


Figure 1: Benefits of transnational collaboration (Angouri 2023, p.9)

BACKGROUND ON JOINT SP-PB CAPSTONE PROJECT

SP is an early adopter and had piloted with CDIO in 2004 to transform its engineering education. This was later expanded to all engineering programs in 2008 with the objective of transforming unmotivated and uninterested first-year engineering students into engineering graduate who are innovators with a social cause. To this end, empathy studies to uncover unmet needs of stakeholders (using Design Thinking) was infused into the C-D stages of the framework. Since then, CDIO has continued to be an important part of education in SP. For examples, Soh (2010, 2011) had demonstrated that the CDIO is a meaningful framework in capstone projects in SP. SP recognizes that key learning outcomes for polytechnic education are to equip students with both technical competencies and global collaboration skills. Given the increasing importance of transnational learning, these outcomes should align with preparing students to work effectively in an interconnected world. Soh et al (2014) for example explored a 2-week transnational programme, engaging multidisciplinary students, using their domain knowledge to solve real-world social issues. However, the geographical distance between institutions posed significant logistical challenges to bring together students from different IHLs for relatively longer periods of time to work together to complete the full CDIO cycle. The advent of technology especially affordable online video conference call now made such endeavours more realizable.

This transnational collaboration with Polibatam (PB) is therefore a renewed effort to execute a transnational program. Both are members of the international CDIO community. A relatively newcomer, PB adopted the CDIO Framework in 2021 as a pilot to enhance the quality of project-based education and learning in the Applied Bachelor of Robotics Engineering Study Program. This initiative was later expanded to 18 study programs at PB. The collaboration between the School of Mechanical and Aeronautical Engineering (MAE) from Singapore Polytechnic (SP) and Polibatam (PB) is a natural fit due to their geographical proximity to one another and an emphasis on project-based learning while teaching relevant disciplinary skills and knowledge.

The SP-PB collaboration aims to provide students with cross-cultural, multidisciplinary and practical learning experiences. The project involves students and staff from both polytechnics working together on a social project to help a household in Batam produce banana chips with improved safety and productivity. The project involves transdisciplinary collaboration involving engineering students from Electronic Engineering, Mechatronic Engineering, Instrumentation Engineering and Aeronautical Engineering.

TRANSNATIONAL PROJECT COLLABORATION FRAMEWORK

The project was divided into four phases: Conceive, Design, Implement, and Operate. As illustrated in Figure 2, both institutions had decided to meet in-person at the end Conceive and Operational phases. Online milestone meetings were set before the project "kick off" and the end of Design phase. MS Team and Zoom were used for online milestone meetings although students often rely on messaging tool such as WhatsApp for communication. Katsumata et al (2020, p.20) observed that "Intercultural telecollaboration projects increase cultural knowledge and skills". Hence, online mode of collaboration can be an economical and effective tool. In a trans-national setting, it is highly possible that divergence of ideals and solutions would occur. The supervisors from both institutions adopted a flexible approach by allowing a possibility of delivering multiple solutions to the stakeholders. From the bold central arrow, as shown in figure 2, attempts were made to guide students to converge (thin arrows) as best as possible at every stage. If divergence (thin arrows) were unavoidable, the team could possibly end up with 2 sets of solutions. By working closing with each other, the team decided at the Implementation stage to deliver one solution, but each group will take care of fabricating different portion of the final product. Throughout the whole process, business students would have to rework their analysis based and marketing plans based on the latest Engineering updates. Design students focus on packaging while the media students came up with good storyline to develop a video documentary of the product creation process. Face-to-face meeting in Indonesia for assembly and delivery, and training were provided to the stakeholder premise.

The project timeline is as shown in Figure 3. While students from both SP and PB started on week 1 by meeting online, actual work from SP students started on week 3 after their examination. Hence, they missed the on-site empathy studies using the Design Thinking process and both teams will do their own ideation separately based on established data points. Occasionally, students communicated remotely (e.g. WhatsApp) to update each other. They meet in-person on week 5 to share their outcomes and to finalise their design direction. Students from SP are progressing with the end of design phase by themselves as BP students are preparing for their mid-semester test from week 8 to week 11.

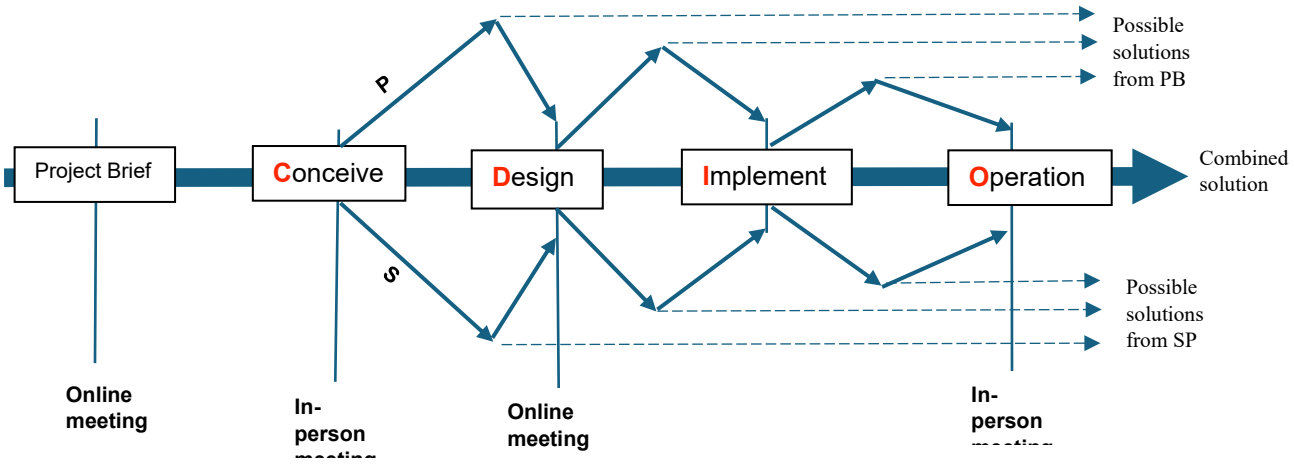


Figure 2: Divergence and convergence of ideas at each project phase

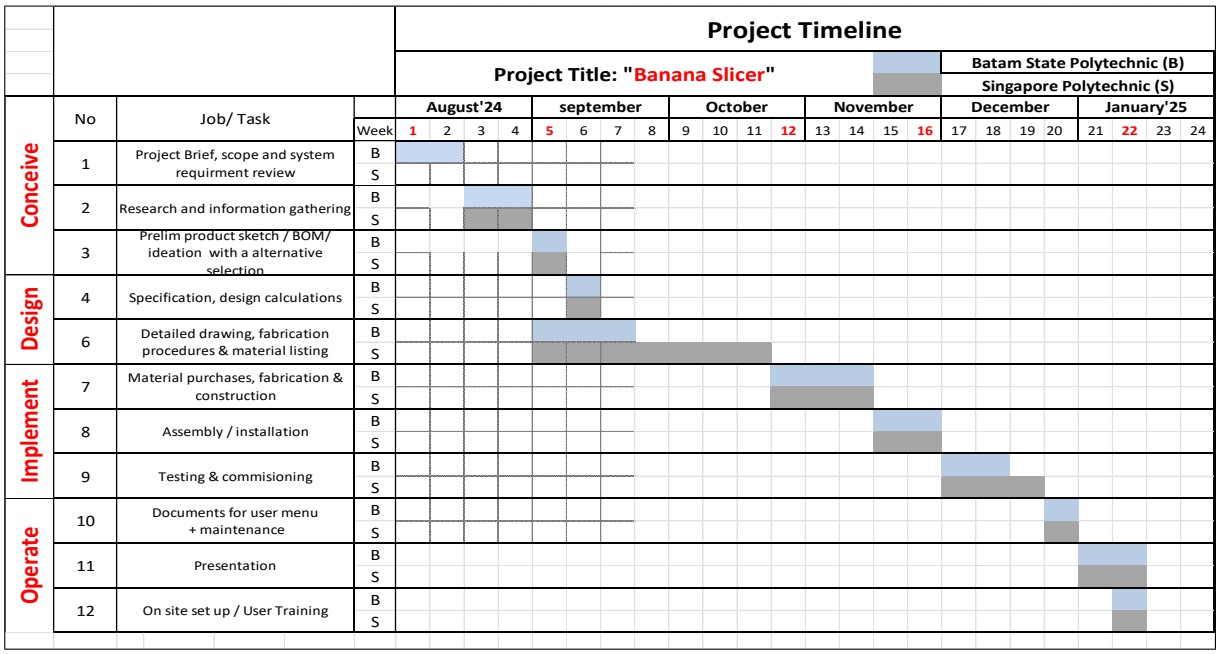


Figure 3: Project timeline of Polibatam

Students' Feedback

Students were asked to provide their views on the benefits of an international collaboration, what went well and what can be further improved on. This is to gain insights from the project, challenges faced and how they were overcome, and the impact of the collaboration on their personal and professional development. The main results are summarized in Table 2, and the major findings discussed.

When asked if they find international collaboration useful for executing their project, all responded positively. The students' feedback highlights the significant benefits of their transnational learning experience. Working with international partners brought innovative ideas, enriched design and functionality, and provided new perspectives, especially in engineering and the CDIO framework. This collaboration improved their cross-cultural communication, teamwork, and problem-solving skills while exposing them to diverse

standards and approaches, contributing to their professional development. The experience facilitated valuable knowledge exchange and offered insights into different work cultures and technological approaches. Even initial unsuccessful attempts served as valuable learning experiences, reinforcing the importance of cultural nuances and interpretation.

The students indicate that their collective project faced significant challenges, primarily due to misinformation and technical issues. Additionally, incomplete information and misunderstandings during the conceive stage led to improper tool selection. Delays in budget planning and issues with storage of materials further complicated the project, highlighting the need for better coordination and expertise in future attempts. To improve the flow of the project, students suggested that it is essential to enhance communication within the team, conduct more detailed research on machine requirements, and engage experts to refine the machine's functionality. Testing prototypes early will identify and address issues, while better understanding of materials and tool compatibility through direct surveys will minimize errors.

The most frequently reported challenges in remote international collaboration were language barriers, lack of face-to-face interaction, and time zone differences. Despite these challenges, most students rated communication and overall teamwork effectiveness as 'Well' or 'Very Well', indicating that teams were generally able to overcome barriers and collaborate successfully.

Table 2. Students' feedback on their transnational collaboration

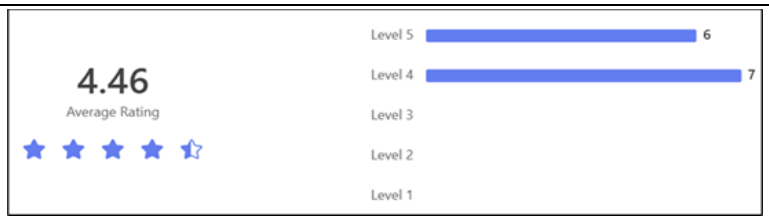
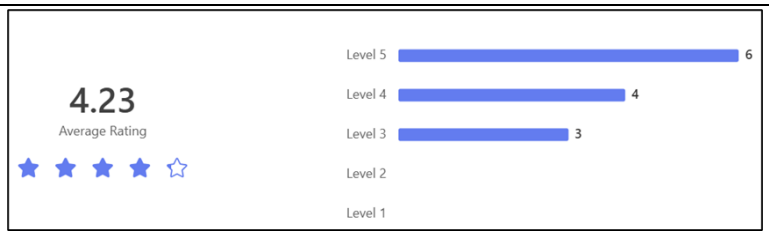
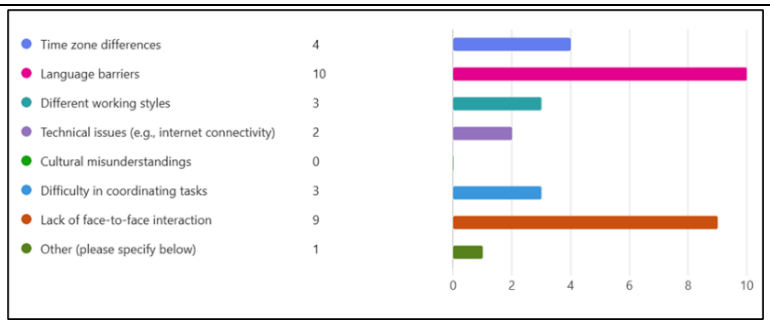
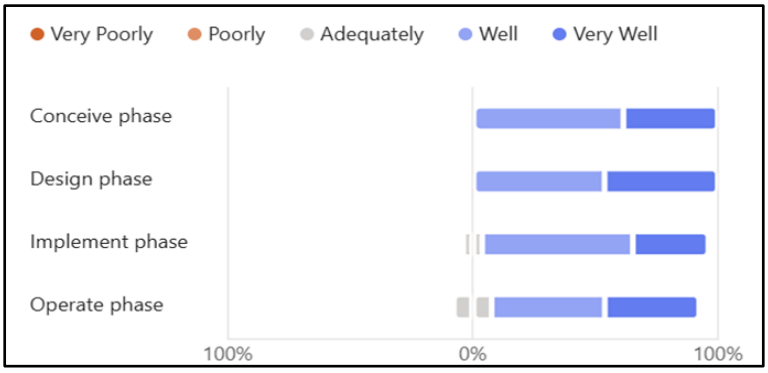
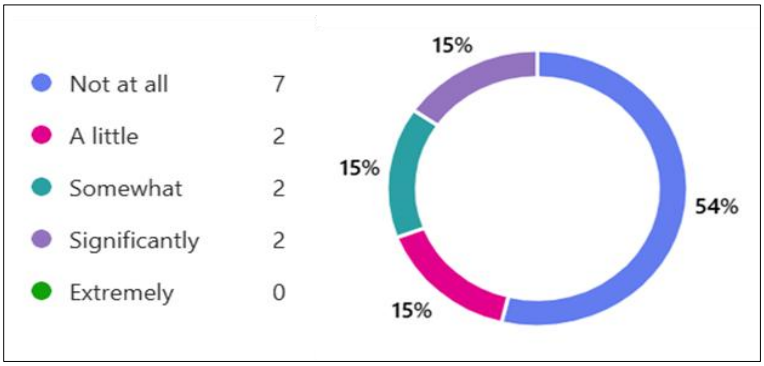
Effectiveness of teamwork between Singapore Polytechnic and Batam state Polytechnic students?	
How effective was the communication among team members during the project?	
Challenges you faced while working remotely with team members from a different country and discipline.	

Table 2 (Cont'd)

How well did the team collaborate during the different project phases?	
To what extent did cultural differences influence your team's dynamics and project work?	
Suggestions to improve future international and interdisciplinary collaborations?	

LEARNING POINTS FROM FACULTY REFLECTIONS

The transnational project served as a powerful catalyst for both student growth and institutional learning. The collaboration between students from PB and SP has many advantages for students. Students can improve their interpersonal skills, such as teamwork and communication skills. Because this project was conducted by two different institutions coming from different countries, Indonesia and Singapore, communication skills, especially in English, are essential for students and educators.

Transnational capstone project can be resource intensive. A trip from Singapore to Indonesia Batam involved additional budget for ferry tickets, working permit (even for a few hours of physical meeting) and travel insurance. Angouri (2023, p.42) concluded that "true international collaboration is achieved when it is deeply and fully embedded in the daily experience of students and staff. To build on momentum, we need to approach internationalisation with a new holistic approach which must cut across resourcing, careers, administrative/pedagogical support, and infrastructure". Faculty reflections affirmed that transnational collaboration successfully delivers broad academic and professional benefits to both institutions and students, validating the 6 benefits outlined by Angouri (2023).

Capacity Building

The international collaboration between Polibatam and Singapore Polytechnic in the implementation of Project-Based Learning has contributed significantly to capacity building, particularly within Polibatam. Several lecturers and laboratory technicians gained new experiences and insights that can be applied to institutional development at Polibatam.

One notable example is the application of design thinking in the implementation of project-based learning. A sound understanding of design thinking is essential for lecturers, laboratory technicians, and students, as it supports the development of innovative products and services.

In addition, this transnational project has had a positive impact on improving the quality of laboratory equipment and materials. The collaborative initiative created opportunities for laboratories—especially mechanical and electrical laboratories—to acquire new equipment and components. Internally, Polibatam provided institutional support to enhance the capacity of selected laboratories in order to effectively support the collaborative project with Singapore Polytechnic.

Production and Diversification of Knowledge

Working across national borders facilitates a "by-product of transdisciplinary innovation" where solutions contribute back to the original disciplines, evolving them further. By integrating engineering, business, and media disciplines in a transnational setting, students and staff generate new knowledge that transcends linguistic and national borders. This diversification is essential for addressing the complexity of problems faced by modern society.

Increased Quality of Teaching and Learning

The collaborative project contributed to the enhancement of teaching and learning quality for lecturers, laboratory technicians, and students at Polibatam. Polibatam lecturers and laboratory technicians gained valuable knowledge regarding project management practices and idea development through communication and joint project implementation with lecturers and students from Singapore Polytechnic. This collaborative activity also served as a benchmarking reference for Polibatam in the development of curricula within relevant study programs, particularly by providing insights into the implementation of capstone projects in the teaching and learning process.

Furthermore, students from the Electrical Engineering program at Polibatam benefited substantially from collaboration with students from Singapore Polytechnic, who came from a different discipline, namely Mechanical Engineering. Knowledge and exposure to mechanical design and fabrication processes offered new learning experiences for Polibatam students. Improvements in teamwork and communication skills were also evident among Polibatam students as a result of their participation in the collaborative project.

Increased Revenue from Students and Staff

Essentially, lecturers, laboratory technicians, and students from Polibatam did not receive direct financial benefits from the implementation of this collaborative project, as it was specifically designed as a community engagement initiative. The products developed through the project were donated to Micro, Small, and Medium Enterprises (MSMEs) in Batam. Nevertheless, Polibatam lecturers, laboratory technicians, and students gained substantial

indirect benefits, including valuable experience, enhanced insights, skill development, and the establishment of new professional networks.

Enhanced Inter-cultural Awareness

The transnational project between Polibatam and Singapore Polytechnic enhanced awareness of the importance of cultural differences brought by lecturers, laboratory technicians, and students from both institutions. Polibatam lecturers, laboratory technicians, and students became more aware of the cultural diversity embodied by their counterparts from Singapore Polytechnic, allowing differences in culture and background to be recognized as natural and non-disruptive to the collaborative process. Such intercultural awareness facilitates students' development of knowledge, perspectives, and skills, particularly in preparation for future opportunities to study, work, or travel abroad in environments characterized by different cultural contexts.

Student Employability

Polibatam students involved in the collaborative project with Singapore Polytechnic gained numerous benefits, including improved English language proficiency, adaptability skills, teamwork, intercultural awareness, and communication competence. Several of the skills developed through participation in this transnational project constitute valuable elements of students' professional portfolios, which can be leveraged when applying for employment after graduation. This is particularly relevant in the context of Batam, where most industries operate as multinational companies with strong international working cultures. Students who are already accustomed to, or have prior experience in, international collaboration are therefore more likely to have enhanced employment opportunities within these industries.

AREAS OF IMPROVEMENT

From the authors' experience supervising this project, the following points are recommended:

- Administrative and Policy support: As highlighted by Angouri (2023), a well-structured policy enables sustainable collaborations in the future. Partnering institutions need to establish comprehensive administrative protocol (e.g. signing of a Memorandum of Cooperation and IP agreements), to streamline the operation of transnational learning projects. Fulfilling national policies such as the 70-70 initiatives and targeting on ASEAN, China and India institutions would provide rationale to push forward the implementation of such learning projects.
- Resource allocation: Transnational collaborations for design and implement experiences are resource intensive. For continual engagements with strategic partners, special funding must be set aside beyond hardware and software development. Expenses for transport, working visas, food and insurance coverage must be considered. In situation where students need to bring fabricated parts overseas for final assembly of the project, it would be good to prepare relevant documents for the custom clearance (see appendix) and to check for any cost incurred.
- Pedagogical Synchronisation: Despite a staggered in academic calendar by 2 weeks and the difference in cultures, both institutions had coped well mainly because both are CDIO collaborators and students were taught the Design Thinking methodology. Future collaborations should emphasise more on the "social" dimension so that students would understand the purpose of their endeavours and not just fulfil the technical requirements.

CONCLUSION

This transnational capstone collaboration between Singapore Polytechnic (SP) and Politeknik Negeri Batam (PB) demonstrates the potential of international, cross-cultural, and transdisciplinary project-based learning in engineering education. Anchored in the CDIO framework, the project brought together students from diverse nationalities and disciplines to address a real-world problem faced by a household producing banana chips in Batam. With emphasis on empathy studies during the Conceive phase of the project, the team was able to meet the stakeholder's technical expectations. Furthermore, the collaboration succeeded in achieving important learning outcomes related to communication, empathy, teamwork, and iterative problem-solving.

The challenges encountered—including cultural differences, misaligned academic calendars, remote coordination, and technical setbacks—highlight the complexity and resource-intensive nature of such initiatives. Nevertheless, the students gained valuable exposure to global work practices and intercultural collaboration. Faculty reflections affirmed that the project deepened student learning through stakeholder engagement and iterative prototyping and laid the groundwork for sustained partnerships. To scale and sustain such collaborations, future efforts should focus on streamlining administrative processes, aligning academic timelines, and enhancing remote collaboration tools. Ultimately, this model offers a meaningful pathway to prepare graduates for an interconnected and complex global landscape.

ACKNOWLEDGEMENTS

The authors from SP and PB received no financial support for this work.

The GenAI tool Gemini was used in the review of the AREAS of IMPROVEMENT section of this paper. It essentially entails the use of Gemini to "read up" some papers from the author's own manual keywords search of the Internet using Google, whereby Gemini then provide key summaries that are of relevance to this paper. The author then writes this part of the paper using his own words. The prompts used and responses obtained can be found in the LINK.

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BIOGRAPHICAL INFORMATION

Hendawan Soebhakti is an Assistant Professor in Robotics Engineering Technology and Expert Staff to the Vice Director for Academic Affairs at Politeknik Negeri Batam. He is a lead driver of Project-Based Learning (PBL) and the CDIO framework, overseeing the institutional CDIO Taskforce. His pedagogical interests include robotics for STEM education, while his research focuses on autonomous mobile robots and industrial automation.

Muhammad Arifin is the Coordinator of the Electronics Manufacturing Engineering Study Program at Politeknik Negeri Batam. He leads the curriculum development team and the institutional CDIO Taskforce, guiding multidisciplinary departments in the adoption of CDIO and Outcome-Based Education. His work focuses on aligning engineering education with institutional strategy and industrial standards.

Nanta Fakih Prebianto is the Coordinator of the Electronics Engineering Technology Study Program at Politeknik Negeri Batam. Drawing on his previous experience in the oil and gas sector, he focuses on strengthening the linkage between industry and academia. His pedagogical interests center on implementing CDIO-based learning and promoting Project-Based Learning as a tool for applied research with social impact.

Abdurahman Dwijotomo is a lecturer in the Mechatronics Study Program at Politeknik Negeri Batam. With a Ph.D. from Universiti Teknologi Malaysia, his expertise lies in control systems and automation. His research focuses on the development of Electronic Control Units (ECUs) and SLAM-based navigation systems for autonomous vehicles, integrating advanced automation technology into the engineering curriculum.

Kim-Fai Soh is the Senior Manager for the Teaching and learning unit in the School of Mechanical and Aeronautical Engineering, Singapore Polytechnic. He is also the Programme Chair for Common Engineering. His pedagogical interests include authentic and experiential learning with deep industrial participation and global collaborative learning, fostering real-world experiences that prepare students for the challenges of a globalized engineering landscape.

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Appendix: Document prepared for custom.

KEMENTERIAN PENDIDIKAN TINGGI,
SAINS, DAN TEKNOLOGI
POLITEKNIK NEGERI BATAM
Jalan Ahmad Yani, Batam Centre, Kecamatan Batam Kota, Batam 29461
Telepon +62 778 469856 - 469860, Faksimile +62 778 463620
Laman: www.polibatam.ac.id, Surel: info@polibatam.ac.id

No. 1626/PL29/VII/2025

Batam, 17th July 2025

To:
Mr. Soh Kim Fai
Singapore Polytechnic
Singapore

Subject: **Invitation for Educational Meeting**

Warm greetings,
Politeknik Negeri Batam (Polibatam) is pleased to invite you and group of students from Singapore Polytechnic (SP) to visit Polibatam and attend an educational meeting as detailed below:

Date : Thursday, 24th July 2025
Time : 08.00 – End
Place : BRAIL Lab Polibatam
Agenda : Educational Meeting on Learning Application
Delegation : 5 persons

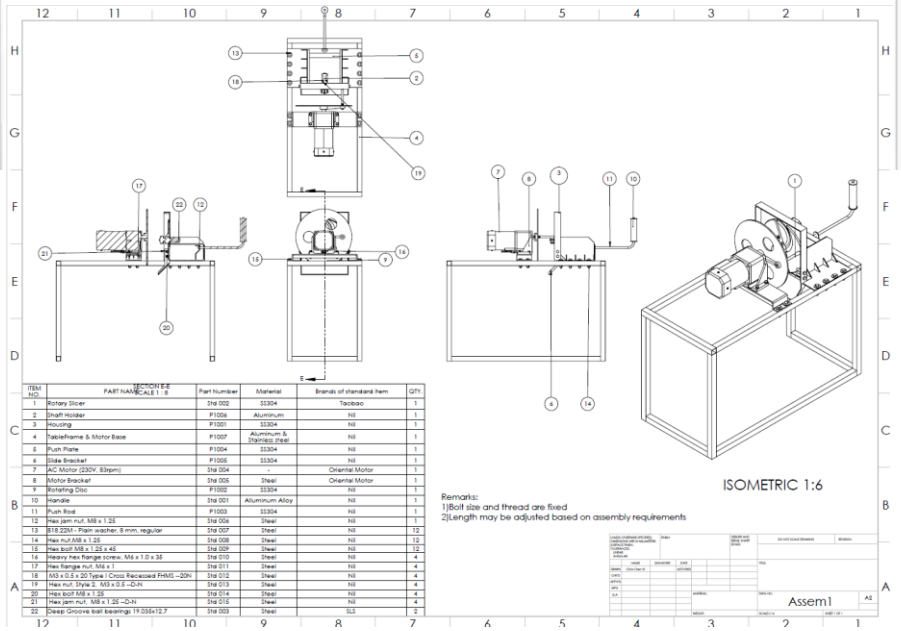
We expect you to bring along the learning equipment (attached here in this letter) for a demonstration, so students can have better understanding on how it works and how it can benefit to their expertise.

If you have any inquiries or further information, please do not hesitate to contact Mr. Muhammad Arifin, Head of Study Program for Electronics Manufacturing of Polibatam, via e-mail: arifin@polibatam.ac.id

We appreciate your understanding and cooperation in this matter.

Yours Sincerely,

Bambang Hendrawan
Director



ITEM NO.	PART NAME	Part Number	Material	Brands of standard item	QTY.
1	Rotary Slicer	Std 002	SS304	Taobao	1
2	Shaft Holder	P1006	Aluminum	Nil	1
3	Housing	P1001	SS304	Nil	1
4	Tableframe & Motor Base	P1007	Aluminum & Stainless Steel	Nil	1
5	Push Plate	P1004	SS304	Nil	1
6	Slide Bracket	P1005	SS304	Nil	1
7	AC Motor (230V, 83rpm)	Std 004	-	Oriental Motor	1
8	Motor Bracket	Std 005	Steel	Oriental Motor	1
9	Rotating Disc	P1002	SS304	Nil	1
10	Handle	Std 001	Aluminum Alloy	Nil	1
11	Push Rod	P1003	SS304	Nil	1
12	Hex jam nut, M8 x 1.25	Std 006	Steel	Nil	1
13	B18.22M - Plain washer, 8 mm, regular	Std 007	Steel	Nil	12
14	Hex nut,M8 x 1.25	Std 008	Steel	Nil	12
15	Hex bolt M8 x 1.25 x 45	Std 009	Steel	Nil	12
16	Heavy hex flange screw, M4 x 1.0 x 36	Std 010	Steel	Nil	4
17	Hex flange nut, M4 x 1	Std 011	Steel	Nil	4
18	M3 x 0.5 x 20 Type I Cross Recessed PHMS –ZDN	Std 012	Steel	Nil	4
19	Hex nut, Style 2, M3 x 0.5 –D-N	Std 013	Steel	Nil	4
20	Hex bolt M8 x 1.25	Std 014	Steel	Nil	4
21	Hex jam nut, M8 x 1.25 –D-N	Std 015	Steel	Nil	4
22	Deep Groove ball bearings 19.05Bx12.7	Std 003	Steel	SLS	2

INTEGRATING PROBLEM-BASED LEARNING INTO THE INCOME TAX THEORY AND SYSTEM COURSE AND EXAMINING ITS IMPROVEMENT ON LEARNING OUTCOMES

Sheng-Tung Chen

College of Finance, Feng Chia University

ABSTRACT

This study examined the teaching of income tax theory and systems at Feng Chia University by introducing Problem-Based Learning (PBL). Using quantitative and qualitative methods, it evaluated whether PBL improved students' learning outcomes and problem-solving skills. Quantitative data included pre- and post-tests and feedback questionnaires, while qualitative data assessed changes in problem-solving ability. The results showed improvements in self-directed learning, time management, logical reasoning, and teamwork. More than 66% of students performed better on the post-test, supporting the effectiveness of the PBL design. However, students also reported uneven group collaboration, information overload, time constraints, and difficulties integrating PBL with traditional teaching. Overall, the findings provide empirical support for the value of PBL in enhancing problem-solving ability and offer implications for teaching and curriculum design.

KEYWORDS

Problem-Based Learning, Qualitative Research Method, Solving Problem Ability, Active Learning, Standard 8

RESEARCH MOTIVATION AND OBJECTIVES

This study addressed issues in the current educational environment by implementing Problem-Based Learning (PBL), a student-centered approach organized around authentic problems and collaborative inquiry. Its primary goal was to enhance student engagement and interest by integrating PBL into the “Income Tax Theory and System” curriculum. Through these PBL modules, students were expected to improve learning outcomes and develop essential problem-solving skills. Using a mixed-methods approach, the study examined whether students’ problem-solving abilities improved after participating in PBL.

For students in Taiwan, although the transition from the traditional unified entrance examination system to the current multifaceted admission system has occurred, reliance on testing as the primary measure of achievement remains. If university education continues to prioritize examinations, students may have limited motivation to develop problem-solving abilities. Even with the introduction of educational technologies such as Zuvio and Kahoot, it remains unclear whether these tools effectively foster higher-order problem-solving skills.In particular, the “Income Tax Theory and System” course faced two major challenges: (1) insufficient learning motivation, as students often perceived tax theory as distant from daily life, and (2) difficulty integrating theoretical knowledge with real-world contexts. Although many tax concepts can be illustrated through current news and real-world issues, the dynamic nature of taxation has not been sufficiently incorporated into the curriculum.Therefore, this study integrates current economic issues into PBL scenarios, enabling students to analyze contemporary tax policies and understand how theoretical knowledge is applied in real-world contexts.

As Halmos et al. (1975) noted, the best way to learn is to do, while the worst way to teach is to talk. Dale’s (1969) “Cone of Experience” likewise suggests that direct experience leads to stronger retention and learning effectiveness. Therefore, integrating PBL with real-world contexts aims to bridge the gap between theory and application and strengthen students’ practical competencies.

Research Questions

(1). Does the implementation of PBL in the “Income Tax Theory and System” course improve students’ learning motivation?

(2). Does PBL help students better connect theoretical knowledge with practical and real-world issues?

(3). Does participation in PBL improve students’ problem-solving skills?

(4). How do students perceive the learning process, instructional facilitation, and overall effectiveness of the PBL approach?

LITERATURE REVIEW

In recent years, Problem-Based Learning (PBL) has been widely adopted across educational levels, including higher education (Yew & Goh, 2016). At the university level, its application has expanded beyond medical education to fields such as business education. PBL emphasizes student-centered and active learning, encouraging students to identify problems, determine necessary knowledge, and engage in “learning by doing” (Gibbs, 1992; Barrows, 1986).

Previous studies have shown that PBL enhances students' ability to apply analytical skills more effectively than traditional lecture-based instruction (Maxwell et al., 2005). In addition, active learning approaches such as PBL are associated with improved academic performance and engagement (Freeman et al., 2014). Overall, the literature suggests that PBL promotes knowledge acquisition and higher-order cognitive skills, particularly problem-solving ability.

The Instructional Process of the PBL Model

If PBL is introduced into the "Income Tax Theory and System" course only as a superficial activity, it may become formalistic rather than meaningful. Therefore, instructional design plays a critical role. This study adopts a mixed-methods approach to examine how instructional design facilitates student learning. Through group discussions, critical thinking activities, and instructor guidance, students engage more deeply with course content and ethical issues. Discussion topics should be closely related to students' real-life experiences. Heterogeneous grouping further promotes interaction by enabling students to contribute diverse perspectives.

Delisle (1997) outlined the PBL process in six steps: (1) connecting with the problem, (2) setting the structure, (3) visiting the problem, (4) revisiting the problem, (5) producing a product or performance, and (6) evaluating performance and the problem.

In this process, instructors act as facilitators, providing guidance without excessive intervention. Learning outcomes can be demonstrated through presentations, reports, and peer or self-evaluation.

Tools for Assessing Learning Effectiveness

To evaluate the impact of PBL on learning, this study adopted both quantitative and qualitative assessment methods. Sim et al. (2011) suggested that post-course questionnaires should focus on instructional design, learning objectives, and group interaction to generate meaningful data. Quantitative tools included pre- and post-tests, feedback questionnaires, and learning-related scales, generally based on the dimensions proposed by Delisle (1997) using a four-point Likert scale. The Feedback Evaluation Scale was used to identify areas for instructional improvement.

Qualitative data provided deeper insights into students' learning experiences and included group discussion records, peer- and self-evaluations, classroom observations, student reports, and interviews. Follow-up interviews were conducted when necessary to clarify student responses.

Biggs (1996) emphasized that combining multiple assessment methods improves the reliability and validity of evaluating learning outcomes. Therefore, this study adopts a mixed-method approach to assess the effectiveness of PBL instruction.

Instructional Outcomes of the PBL Model

Hsin et al. (2011) emphasized that integrating ethical considerations into professional education through PBL helps students explore and discuss moral issues, thereby enhancing both knowledge and positive attitudes. Prior studies have also shown that PBL effectively develops essential soft skills, including critical thinking, communication, and teamwork.

Under this approach, students become more engaged and take greater initiative in learning. Heterogeneous grouping further promotes interaction and deeper understanding through the exchange of diverse perspectives. However, some studies have identified challenges

associated with PBL. Chen et al. (2009) noted issues such as group conflict, increased time demands, and unclear task boundaries, while Wang and Song (2004) pointed out that insufficient guidance may lead to student frustration.

Accordingly, a hybrid instructional approach combining traditional lectures with PBL is often considered more effective. Overall, the literature suggests that PBL promotes active learning, knowledge application, and the development of interpersonal competencies. These characteristics align with the CDIO framework (Crawley et al., 2007), particularly in relation to learning outcomes (Standard 2), design-implement experiences (Standard 5), active learning (Standard 8), and instructors' pedagogical competencies (Standard 10).

RESEARCH DESIGN AND IMPLEMENTATION

This study examined whether the PBL model enhanced students' problem-solving abilities in the "Income Tax Theory and System" course at Feng Chia University. As the instructor of the course, I designed the following research steps to evaluate the effectiveness of the PBL model.

A. Research Framework

This study adopted a hybrid model combining traditional lectures and PBL. The instructional process consisted of three stages: traditional instruction with a pre-test, PBL implementation through group inquiry and project work, and post-implementation evaluation through post-tests, the Problem-Solving Rubric, and feedback questionnaires. Quantitative and qualitative methods were used to examine whether students' problem-solving abilities improved.

B. Research Problem and Scope

"Income Tax Theory and System" was a compulsory course for third-year undergraduate students. This study implemented PBL in the course and examined its effects on learning achievement and problem-solving competence. After the traditional lecture phase, three PBL modules were introduced, and student progress was assessed using the Feng Chia University Problem-Solving Rubric.

C. Research Subjects and Setting

Participants were third-year undergraduate students enrolled in the course in the Department of Public Finance at Feng Chia University. The study was conducted in regular classroom settings.

D. Research Methods and Tools

A mixed-methods approach was used to evaluate students' professional knowledge, engagement, problem-solving ability, critical thinking, and communication skills. Quantitative tools included: (1) a pre-test; (2) post-tests; (3) the PBL Learning Effectiveness Scale; (4) the PBL Teaching Facilitation Feedback Scale; and (5) the Problem-Solving Rubric. Qualitative data were collected from group discussions, peer- and self-evaluations, and interviews.

E. Teaching Intervention

The teaching intervention was based on the PBL model and included group discussions, peer collaboration, poster production, and oral presentations. These activities aimed to promote

collaboration and facilitate the application of course knowledge. Quizzes and examinations were also used to assess individual learning outcomes and support instructional adjustment.

Summary of Teaching Outcomes and Reflections

This PBL course aimed to enhance students' professional knowledge, engagement, problem-solving, critical thinking, and communication skills, assessed through pre- and post-tests, questionnaires, presentation rubrics, and qualitative data.

The findings indicate that PBL promoted active learning and deeper engagement. Through role-based research, tax calculations, policy analysis, and presentations, students developed a stronger understanding of tax reform from multiple perspectives and improved their analytical, communication, collaboration, and critical thinking skills. Qualitative results also suggested greater awareness of stakeholder perspectives and challenges in tax policymaking.

Some limitations were identified, including uneven group collaboration, information overload, and time constraints. Future teaching should provide clearer guidance and better pacing of PBL activities.



Figure 1: Student Engagement and Participation in PBL Instructional Activities

During this phase, student groups conducted research and analysis based on assigned roles, presenting their findings and recommendations through posters and oral presentations, as illustrated in Figure 1.

EVALUATION OF INSTRUCTIONAL EFFECTIVENESS

Comprehensive Analysis of Pre-test and Post-test Results

This course adopted a PBL-based instructional design, and learning effectiveness was evaluated by comparing pre- and post-test scores. A total of 66 students were included; after excluding zero scores, 60 valid observations remained.

The results showed that 40 students (approximately 66%) achieved higher post-test scores, indicating improved understanding of core course content. The maximum gain was 47 points, with an average improvement of 8.33 points. Notably, 18 students improved by more than 20 points, suggesting substantial progress, particularly among those with weaker prior foundations.

In addition to test performance, student feedback indicated enhanced higher-order learning competencies. High agreement was observed for items such as “I can fully utilize resources” (mean = 3.33) and “I can observe and accept classmates’ learning outcomes” (mean = 3.31), reflecting improvements in critical thinking and reflective learning. Responses related to contributing personal insights (mean = 3.20) and engaging in group discussions (mean = 3.02) further suggest development in communication and collaborative problem-solving skills.

Overall, the results suggest that the PBL approach improved both academic performance and competencies such as logical reasoning, critical thinking, and communication skills.

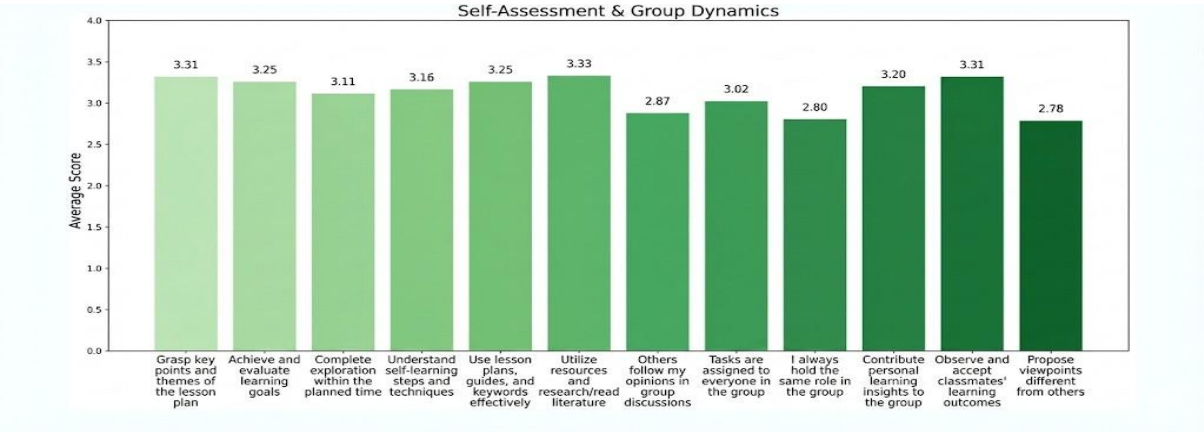


Figure 2：Feedback Evaluation Scale after PBL teaching

Student Learning Feedback :

As shown in Figure 2, on a 4-point scale, mean scores ranged from 2.78 to 3.33, indicating generally positive feedback. The highest-rated items were “I can fully utilize resources” (3.33) and “I can observe and accept classmates’ learning outcomes” (3.31), while most other items were around 3.25, suggesting support for structured and self-directed learning.

Lower scores were observed in group collaboration, particularly in fixed group roles (2.80), task allocation (3.02), and contribution of personal insights (3.20), indicating uneven participation. Overall, while the PBL model supported self-directed learning, future implementation should further strengthen group processes and role rotation.



Figure 3: Student Feedback on PBL Teaching Facilitation

Figure 3 shows that “Strongly Agree” and “Agree” accounted for the majority of responses across all items, while negative responses remained minimal (no more than five students per item), indicating positive feedback on instructional facilitation. These results suggest that the instructor effectively guided discussions, supported collaboration, and fostered a positive learning environment.

Future teaching should enhance the depth of student participation and increase the challenge of higher-order thinking tasks to further strengthen learning and policy analysis skills. While the PBL model improved engagement, collaboration, and practical application, differences in learning styles and adaptation should be considered. A hybrid approach is therefore recommended, in which traditional instruction establishes theoretical foundations and PBL modules reinforce practical application.

CONCLUSION

This study demonstrated that the PBL model can be effectively applied to the “Income Tax Theory and System” course to enhance students’ engagement, self-directed learning, teamwork, and problem-solving abilities. Evidence from pre- and post-tests, questionnaires, and qualitative data indicated improvements in both conceptual understanding and the application of knowledge to practical tax policy issues.

The findings also suggest that PBL supports higher-order learning by encouraging multi-perspective analysis, collaboration, and the development of reasoned policy recommendations, with notable gains among students with weaker initial foundations.

However, this study has several limitations, including the use of a single class, the absence of a control group, and the short duration of one semester.

Overall, PBL represents a meaningful pedagogical strategy in public finance education. Future research should consider broader samples, comparison groups, longer observation periods, and greater attention to individual differences and the pacing of PBL activities.

ACKNOWLEDGEMENT

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BIOGRAPHICAL INFORMATION

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AI CAPABILITY CULTIVATION SYSTEM FOR APPLICATION-ORIENTED INNOVATIVE TALENTS BASED ON OBE+CDIO

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ABSTRACT

To address the challenge of the lagging cultivation of AI composite competencies among traditional professional master's students in the context of industry upgrading and the integration of AI technology in the petroleum and petrochemical sector, this paper, guided by industry demands and based on the educational philosophies of Outcome-Based Education (OBE) and Conceive-Design-Implement-Operate (CDIO), systematically constructs an AI competency cultivation system for applied innovative talents. By examining industry talent competency requirements and analyzing existing issues in practical teaching, we propose an "AI-Engineering Integration" education system, a "Learning-Training-Competition-Innovation" quad-in-one "Three-Course Linkage" teaching model, and a "Multi-Collaboration" long-term operational and evaluation mechanism. Practice has shown that this system effectively enhances students' comprehensive AI application capabilities and innovation and entrepreneurship competencies, significantly improves teaching quality, and provides a replicable practical pathway for fostering interdisciplinary talent cultivation in traditional disciplines within industry-focused universities.

KEYWORDS

OBE, CDIO, Application-Oriented Innovative Talents, Artificial Intelligence, Petroleum and Petrochemical Industry, Standards: 1-3, 5-6, 8, 10-11

INTRODUCTION

Artificial intelligence serves as a crucial engine for developing new quality productive forces. AI technologies are rapidly permeating key industrial sectors such as petroleum and petrochemicals, driving the digital and intelligent transformation of industries. Consequently, there is an increasingly urgent demand for application-oriented innovative talents who possess both professional expertise and comprehensive AI capabilities. In 2018, the Ministry of Education issued the Action Plan for Artificial Intelligence Innovation in Higher Education Institutions (Jiaoke [2018] No. 3), encouraging the exploration of an "AI + X" talent cultivation model (Ministry of Education, 2018). In 2021, the Academic Degrees Committee of the State Council promulgated the Management Measures for the Establishment of Interdisciplinary Disciplines (Trial) (Academic Degrees Committee of the State Council, 2021), proposing that interdisciplinary disciplines represent new fields formed through the mutual penetration and integration of multiple disciplines. In 2022, the Academic Degrees Committee of the State Council and the Ministry of Education issued the Catalogue of Disciplines for Graduate Education (2022) (Academic Degrees Committee of the State Council, Ministry of Education, 2022), which added interdisciplinary disciplines such as Intelligent Science and Technology. In 2023, the Ministry of Education and four other departments released the Plan for Optimizing and Reforming the Establishment and Adjustment of Disciplines and Majors in General Higher Education (Ministry of Education and four other departments, 2023), advocating the breaking down of disciplinary barriers and deepening disciplinary integration. In 2025, industry applications of large-scale models, represented by DeepSeek and ChatGPT, became one of the hottest topics in higher education. In August 2025, the State Council issued the Opinions on Deepening the Implementation of the "AI +" Initiative, prioritizing "AI +" science and technology, strengthening the cross-disciplinary driving role of AI, and promoting multidisciplinary integration (The State Council, 2025). The introduction of this series of documents has advanced disciplinary integration and facilitated the formation of emerging interdisciplinary fields.

Traditional postgraduate courses primarily focus on theoretical knowledge instruction, with curriculum updates lagging behind industrial technology iterations (Chen, Li, & Li, 2023; Zhou, Lyu, & Guo, 2023). This makes it challenging for students to translate theoretical knowledge into practical problem-solving skills (Bi, Lan, & Wu, 2024; Chen et al., 2023). Algorithm design often occurs in isolation from real-world scenarios and lacks deep integration with AI technologies such as computer vision and deep learning. Consequently, students struggle to intuitively experience the functioning of algorithms (Liu, Zhang, & Weng, 2026; Huang, Jing, & Liu, 2025). Research indicates that traditional training models maintain clear disciplinary boundaries in fields such as mechanical engineering, chemical engineering, and control science, with weak interconnections of knowledge and insufficient integration of interdisciplinary courses (Li, Cui, & Yang, 2023; Zhou et al., 2023). There is also a lack of interdisciplinary projects based on real-world needs (Chen et al., 2023). Traditional evaluation systems tend to emphasize rote memorization and inadequately assess innovative and engineering practical abilities (Bi et al., 2024; Chen et al., 2023; Li et al., 2023; Liu et al., 2026). These evaluation mechanisms prioritize knowledge over competencies, highlighting significant shortcomings that fail to meet the industry's demand for cultivating interdisciplinary artificial intelligence talents.

Outcome-Based Education (OBE) (Xu & Zhan, 2025; Yang, 2025) centers on learning outcomes and emphasizes the precise alignment of educational goals with industry needs. The Conceive-Design-Implement-Operate (CDIO) philosophy (Huang, Wang, & Ming, 2023; Wu, Zhang, & Xu, 2021) focuses on the entire process of engineering practice, emphasizing

the cultivation of students' practical abilities and innovative thinking. The CDIO Standards were first introduced by Brodeur and Crawley (2005) and later elaborated further by Crawley, Malmqvist, Östlund, and Brodeur (2007). Recent international CDIO conference literature has focused on two core research directions: the adaptation of CDIO to digital and intelligent industrial transformation, and the cross-disciplinary and cross-institutional transferability of CDIO-based cultivation models. The 2023 International CDIO Conference emphasized that engineering education under the CDIO framework must embed emerging technologies such as AI into the entire talent cultivation process to meet the demand for composite talents in the digital age (CDIO International Committee, 2023). The 2024 International CDIO Conference further pointed out that the main challenge in the global promotion of CDIO is the lack of industry-specific customization of the general CDIO model, leading to poor adaptation in different disciplinary and institutional contexts (Kontio & Leong, 2024; Lyng & Nortcliffe, 2024). The integration of these two approaches provides a scientific educational framework for addressing the shortcomings of traditional training models. Existing research has demonstrated the effectiveness of the OBE+CDIO approach. International engineering education studies have verified that the OBE+CDIO integration model can effectively make up for the deficiency of single educational philosophy in talent cultivation, with some universities achieving remarkable results in the cultivation of mechanical and electrical engineering talents by applying this model (Yu & Ju, 2022). For example, in equipment systems engineering, "fast-response cumulative evaluation" has been implemented to provide real-time feedback on students' learning trajectories, addressing the lag in traditional assessment methods (Huang et al., 2023). In innovative practice courses on autonomous vehicles, the incorporation of "track competitions" and "competition-teaching integration" has stimulated students' motivation for innovation (Liu et al., 2026), achieving a precise match between talent cultivation and industry needs. However, existing domestic and international research on OBE+CDIO mostly focuses on general engineering fields, and there is a lack of in-depth exploration of the integration of this model with AI technology in industry-specific scenarios such as petroleum and petrochemicals, which is the research gap this paper aims to fill.

Analysis of the Current Situation and Issues in Cultivating AI Capabilities Among Postgraduates in the Petroleum and Petrochemical Field

Beijing Institute of Petrochemical Technology, as a university with distinct industry characteristics and engineering practice advantages, is one of the first pilot universities for the "Excellent Engineer Education and Training Program" by the Ministry of Education and a pilot university for CDIO engineering education reform. It joined the CDIO International Cooperation Organization in 2012. With the CDIO engineering education model as its core, the school focuses on cultivating students' engineering practice ability and innovative spirit. However, there are still three prominent issues in the current graduate student training at the school: First, the training objectives emphasize professional theory, with a vague positioning for artificial intelligence ability cultivation, and a disconnect between courses and industry needs, as well as technological frontiers. Second, the course content is outdated, lacking cases and practical training in the petroleum and petrochemical industry. There is a shortage of teaching resources such as computing power platforms and industry datasets, weak interdisciplinary integration, and students' weak ability to apply technology. Third, the evaluation system emphasizes knowledge assessment and neglects comprehensive literacy assessment. There is a lack of a school-enterprise-industry collaborative education mechanism, and the connection between theory and practice is not smooth, making it difficult to form a progressive training closed loop.

CONSTRUCTION OF A CULTIVATION SYSTEM UNDER THE OBE+CDIO FRAMEWORK

Based on the characteristics of the petroleum and petrochemical industry, this paper is guided by the OBE+CDIO concept, focuses on the capability requirements of artificial intelligence talents in the petroleum and petrochemical industry, reconstructs the artificial intelligence capability cultivation system, and clarifies the cultivation objectives of "solid professional foundation, outstanding intelligent capability, and strong practical innovation ability". Compared with the traditional CDIO model that focuses on the four-stage practice of general engineering projects, this system innovatively embeds AI technology training and petroleum and petrochemical industry scenario application into each link of CDIO, and adds an innovation and entrepreneurship link on the basis of the original CDIO process, forming a five-stage iterative cultivation process of "demand analysis-system conception-mode design-practical implementation-operation optimization". In addition, different from the single mentor guidance model in the international classic CDIO model, this study constructs a "three mentors" collaborative guidance system of on-campus professional teachers, corporate engineers and peer mentors, which adapts to the cultivation needs of AI composite talents in industry-oriented universities. This study constructs an "intelligent and industrial integration" education system, a "three-course linkage" teaching mode, and a "diversified collaboration" operation and evaluation mechanism, forming a comprehensive and full-chain cultivation system. The specific contents are detailed in Sections 3.1, 3.2 and 3.3 respectively.

Constructing a "Three Integrations and Three Mentors" Characteristic "Intelligence-Engineering Integration" Education System

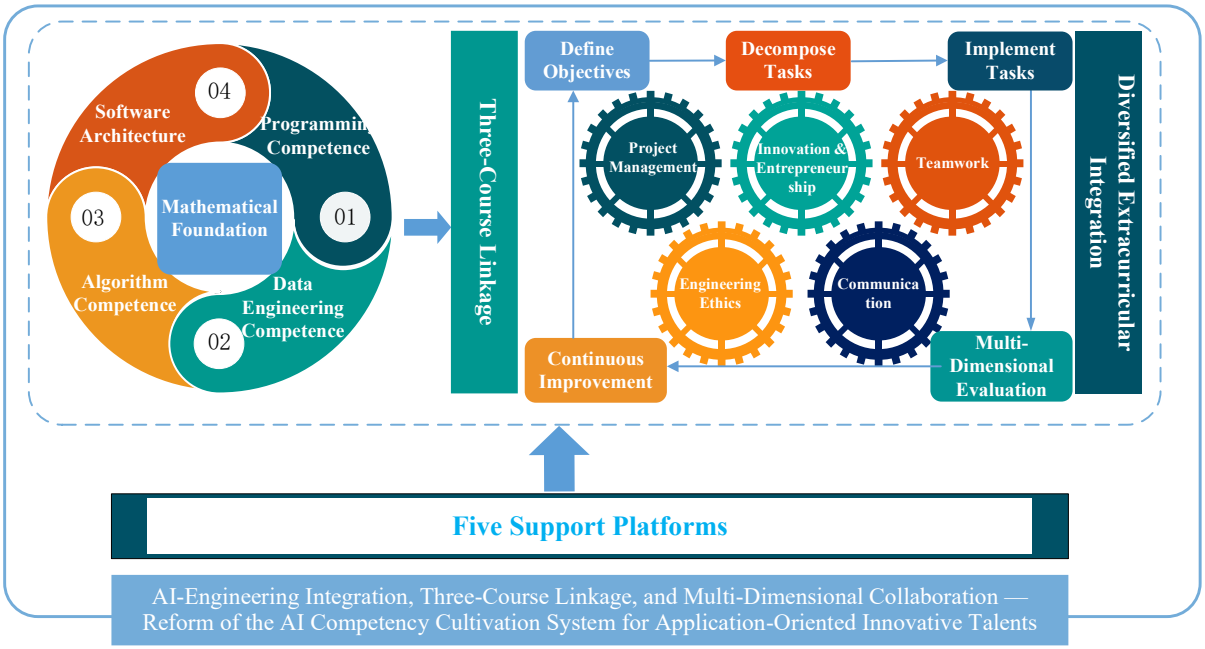


Figure 5. Cultivation Capability Framework Diagram

The core of the OBE philosophy is "backward design", which centers on student development by deriving talent cultivation objectives from industry demands. In cultivating AI capabilities across various disciplines required in the petroleum and petrochemical industry, we conducted in-depth research with leading enterprises and research institutes. The findings indicate that master's students in fields such as mechanical engineering, chemical engineering, control science, and electronic information, which represent key areas in petroleum and petrochemicals, not only need to consolidate their professional theoretical foundations but also

must master core AI competencies such as "mathematical foundations, programming development, data engineering, and algorithm application", as well as five key engineering literacies, including project management, teamwork, and engineering ethics. These elements collectively constitute the overarching goal of talent cultivation, as illustrated in Figure 1. The five supporting platforms are detailed in Figure 2, and the three-course linkage is elaborated in Figure 3.

Building on this, by integrating the CDIO philosophy, the cultivation objectives are decomposed into actionable process-oriented competency dimensions. This transforms the abstract "technical core" and "engineering literacy" into specific competency requirements embedded throughout the entire process of "demand analysis–system conception–model design–practical implementation–operational optimization". For example, addressing the core engineering challenge of "equipment fault prediction" in the petroleum and petrochemical industry, the OBE philosophy first clarifies the cultivation objective as "mastering the application of AI algorithms in fault diagnosis". Guided by CDIO, this objective is further refined into actionable implementation stages across the entire process: the ability to conduct fault data demand research and analysis (demand analysis), conceptualize the technical roadmap for fault prediction models (system conception), design data preprocessing and algorithm selection solutions (model design), implement model training and optimization using real equipment data (practical implementation), and iteratively improve model performance based on field operation feedback (operational optimization). The synergy between OBE and CDIO establishes a "goal-process" aligned competency coordinate system. This ensures that the cultivation direction remains aligned with industry demands while providing clear, process-driven mechanisms for competency development.

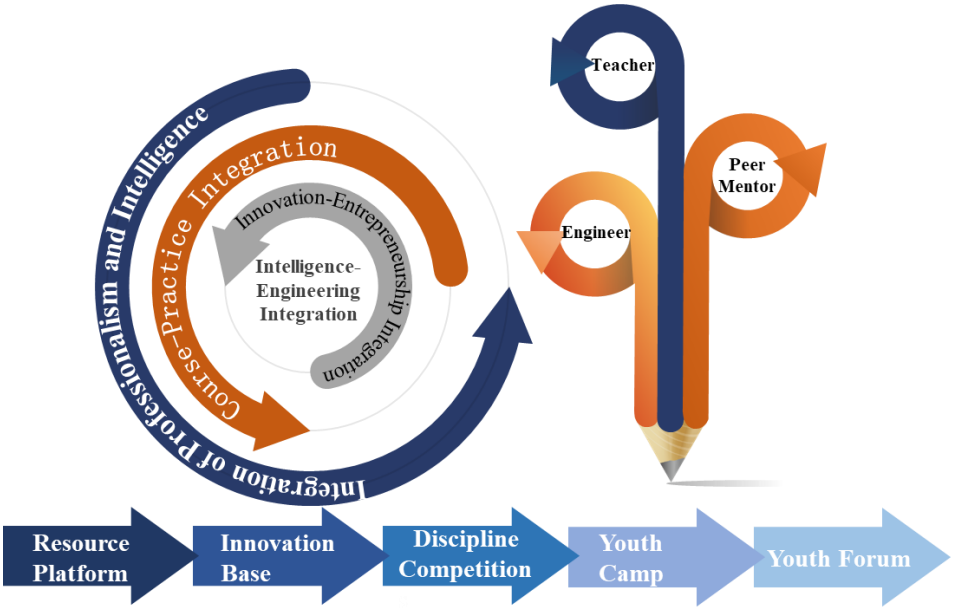


Figure 6. The Intelligence-Engineering Integration Education System

Specifically, driven by industry needs and supported by five key platforms—disciplinary competitions, youth camps, youth forums, innovation bases, and resource platforms—we have integrated critical components such as university-industry collaboration, curriculum instruction, practical training, and academic competitions. This framework establishes an "Intelligence-Engineering Integration" education system characterized by the deep fusion of "professional expertise with intelligent technologies, course content with practical application,

and innovation with entrepreneurship", as illustrated in Figure 2. In the actual implementation of this system, the university completed the construction of the five supporting platforms in a phased manner from 2015 to 2019. It then organized industry experts and in-house faculty to jointly develop typical industry cases of artificial intelligence for the petroleum and petrochemical sector, formulated the *Three-Mentor Management Measures*, defined the job responsibilities of each type of mentor, and thus ensured the efficient operation of the system.

(1) Integration of Professional Knowledge and Intelligent Technologies: A specialized AI case library for the industry has been developed, focusing on engineering challenges in the petroleum and petrochemical fields—such as equipment fault prediction, intelligent inspection, and process optimization. This initiative deeply integrates AI technologies into professional courses.

(2) Integration of Curriculum and Practice: By leveraging hands-on training projects, internship programs, and research initiatives, a comprehensive practical teaching system spanning the entire postgraduate training process has been established.

(3) Integration of Innovation and Entrepreneurship: Through platforms such as innovation bases, youth camps, and entrepreneurship forums, students' innovative awareness and entrepreneurial potential are effectively stimulated.

In terms of faculty allocation, an innovative "Three Mentors" follow-up model has been introduced, integrating on-campus professional teachers, corporate engineers, and outstanding peer mentors to form a full-cycle guidance team that covers "theoretical instruction, engineering practice, and experience transfer": **Professional teachers** are responsible for consolidating students' theoretical foundations and core knowledge of intelligent technologies. **Corporate engineers** focus on industry-specific practical issues, delivering case-based teaching and project guidance. **Peer mentors** assist students in quickly adapting to the learning pace and enhancing practical skills through experience sharing.

Additionally, to address the practical needs of petroleum and petrochemical engineering, typical industry application cases have been identified and integrated into a project-based teaching content repository. This approach achieves a deep fusion of artificial intelligence technologies with industry scenarios, cultivating students' ability to solve complex engineering problems.

Designing a "Learning-Training-Competition-Innovation" Quad-in-One and "Three-Course Linkage" Teaching Model

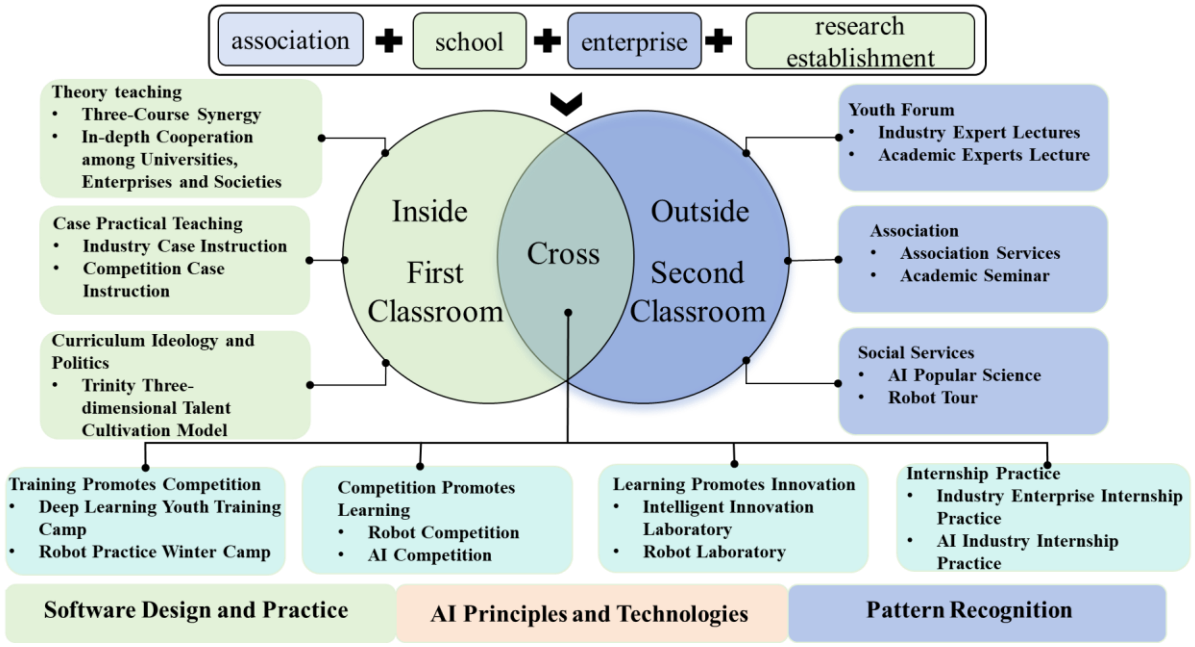


Figure 7. Three-Course Linkage Teaching Model

Guided by the CDIO concept as the logical framework, a progressive process of "theoretical courses - practical training and internships - disciplinary competitions - innovation and entrepreneurship" has been established. Meanwhile, OBE (Outcome-Based Education) focuses on competency outcomes at each stage, defining clear output requirements for every process to achieve precise alignment from "knowledge input" to "capability output". This approach fosters deep synergy between OBE and CDIO in terms of "process-outcome" integration, resulting in a "four-in-one" teaching model that combines "learning, training, competition, and innovation" with "three-course linkage", as illustrated in Figure 3. In the actual implementation of this teaching model, the university divides the three-year postgraduate cultivation program into three stages: the Foundation Consolidation Stage (Semesters 1-2), the Practice Enhancement Stage (Semesters 3-4), and the Innovation Advancement Stage (Semesters 5-6). Disciplinary competitions are leveraged to drive improvements across these three stages, thereby forming a progressive cultivation mechanism.

In the in-class component, the focus is on theoretical foundation and scenario empowerment. Practical application cases of artificial intelligence in the petroleum and petrochemical industry are introduced, and immersive scenario-based teaching is employed to enhance the understanding and application of new knowledge, methods, and technologies.

The extracurricular component expands the dimensions of practice. Through platforms such as academic conferences, professional annual meetings, and social services, renowned scholars in the field of artificial intelligence from both domestic and international backgrounds are invited to deliver lectures, broadening students' academic horizons.

The practical training component leverages robotics and artificial intelligence laboratories to establish university-enterprise collaborative training platforms. Driven by real-world engineering projects, students are guided to transform theoretical knowledge into practical operational skills.

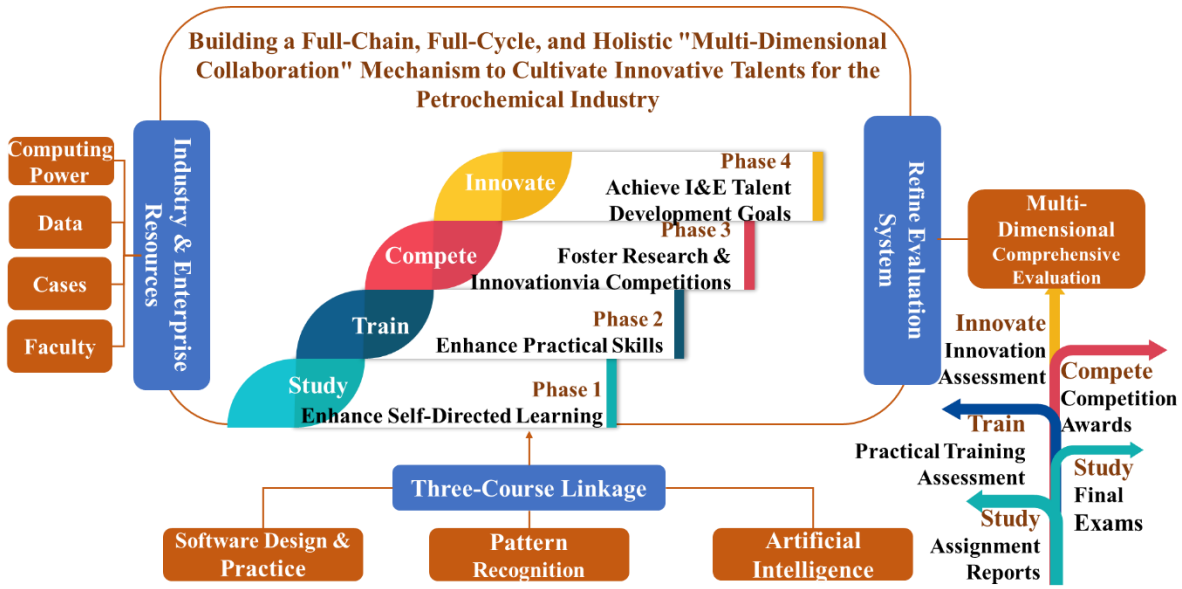


Figure 8. Multi-Collaborative Operation Mechanism

In the competition and entrepreneurship component, competitions serve as catalysts for learning and innovation. Interdisciplinary team participation in academic competitions is encouraged to cultivate teamwork and cross-disciplinary innovative thinking. Leveraging entrepreneurship incubation platforms, outstanding competition outcomes are transformed into entrepreneurial projects, achieving a leap from practical capability to innovative capacity.

The collaborative model ensures that each process component of CDIO implementation is no longer an isolated link but forms a progressive cultivation chain centered around OBE outcome objectives. The instructional implementation of each link is guided by clear outcome orientations, and the achievement of each outcome is supported by corresponding process components. This approach enables a teaching effect characterized by "controllable processes and measurable outcomes". However, the implementation of this teaching model faces certain practical challenges: first, the requirement of interdisciplinary team participation leads to increased difficulty in course organization and coordination; second, the transformation of competition results into entrepreneurial projects requires sufficient financial and policy support, and the school's current entrepreneurship incubation resources are relatively limited; third, the immersive scenario-based teaching in the in-class component requires high-level technical teaching equipment, which is insufficient in some professional courses.

Establishing a "Multi-Collaborative" Long-Term Operation and Closed-Loop Evaluation Mechanism

Building on the synergistic logic of OBE and CDIO, a diversified coordination mechanism for long-term operation and closed-loop evaluation has been designed. OBE defines core outcome standards, while CDIO provides full-process support. Together, they establish a comprehensive "multi-dimensional coordination" mechanism that spans the entire chain, cycle, and scope, forming a closed-loop evaluation system. This system fosters an "evaluation-feedback-optimization" cycle to ensure continuous improvement in talent development quality, as illustrated in Figure 4. This study clarifies the evaluation methods and evidence sources for student competencies and learning outcomes from the perspective of OBE outcome orientation, adopting a mixed evaluation method of quantitative indicators +

qualitative indicators, with all evaluation evidence derived from objective records and multi-stakeholder subjective evaluations with clear assessment criteria, to ensure the scientificity and credibility of the evaluation results.

Evaluation Methods and Evidence Sources for Student Competencies and Learning Outcomes

Student competencies and learning outcomes are assessed from three dimensions: professional foundation competence, AI application competence, and comprehensive engineering literacy, with clear differentiation of evaluation indicators and evidence sources for each dimension, as shown in Table 1.

(1) Quantitative evaluation indicators: All are objective measurable outcomes, with evidence sources from the school's official teaching management system, national intellectual property office official website, competition organizing committee official announcement and other authoritative channels, with traceable and verifiable data;

(2) Qualitative evaluation indicators: Focus on the assessment of non-measurable abilities, with evidence sources from multi-stakeholder evaluation results including on-campus professional teachers, corporate engineering mentors, peer team members and self-evaluation, and the evaluation adopts a 5-point scoring system with clear scoring criteria for each level to reduce subjectivity.

Table 1. Evaluation Indicators and Evidence Sources for Student Competencies and Learning Outcomes

Evaluation Dimension	**Quantitative Indicators**	**Qualitative Indicators**	**Evidence Sources**

25 YEARS WITH CDIO – A LINKÖPING PERSPECTIVE

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ABSTRACT

The CDIO Initiative is a community of practice aiming at improving and developing engineering education via the CDIO framework. Starting with a project with four participating universities 25 years ago, the CDIO Initiative has developed into a network of universities from all over the world. The framework is based on the fundamental documents the CDIO Syllabus, which supports the process of defining **what** an education program should aim for in terms of knowledge and skills, and the CDIO Standards which help define **how** the education program should be designed and run to enable the students to reach the learning goals. The paper gives a summary of the development of the CDIO Initiative over the 25 years, with emphasis on the first years, followed by a description of the adoption of the CDIO framework at Linköping University (LiU). The CDIO framework offers a common language for questions related to education, and it is, to various extent, implemented in all education programs within the Faculty of Science and Engineering at LiU. The CDIO Syllabus has been extended to also cover education programs in, for example, natural sciences, and the extended document, denoted the LiTH Syllabus, is a key component in the system for quality assurance via the use of course and program matrices, respectively. Most programs include an Introduction to Engineering course plus design-implement experiences on several levels. The fact that the CDIO framework is tightly integrated into the education has several possible explanations. First, there has always been strong support on the management level for the use of the CDIO framework. Also, the way to organize the management of the education programs plays an important role, and in the program boards as well as in individual courses there is close collaboration with industry and other parts of society.

KEYWORDS

25 years of CDIO, program development, quality system, Standards: 1- 12

INTRODUCTION

In October 2025 it was 25 years since the first meeting withing the CDIO Initiative, or the CDIO Project as it was called during the first years, was arranged at LiU. Thirteen people from the four participating universities met to start forming the project and planning the work forward. From that initial meeting, the CDIO Project has developed into the worldwide network of the CDIO Initiative with participating institutions from all parts of the world. See (CDIO Initiative, 2026) for an updated presentation of the framework and the network. Since LiU was one of the four original partners and has been active within the network since the start, it gives reasons to summarize and reflect upon the development over this period. The paper has two main purposes, and the first one is to give a summary of the development of the CDIO Initiative during the first years, since such a summary hasn't been presented before. The second purpose is to give an overview of how the CDIO framework has affected the engineering education programs at LiU and discuss which lessons that can be learned from that.

25 YEARS OF THE CDIO INITIATIVE

Background and motivation

For a thorough presentation of the background and motivation of the CDIO see Chapter 1 of (Crawley *et.al.,* 2014). Also, Chapter 10 of the same reference gives an excellent historical development of engineering education in different parts of the world, and CDIO is placed in a historical context. The emphasis in this paper is on the 25 years since the first meeting, but there were, of course, contacts and collaborations between the participating partners long before that, and these links were essential for forming the team and the application for funding of the project. These aspects are not treated in this paper.

The first years

One engineering education program was selected at each of the participating institutions, and these programs were

- MIT: Aeronautical Engineering led by Ed Crawley
- KTH: Vehicular Engineering led by Sören Östlund
- Chalmers: Mechanical Engineering led by Johan Malmqvist
- LiU: Applied Physics and Electrical Engineering led by Karl-Fredrik Berggren

There were three meetings per year, and normally two of those were arranged in Sweden and one at MIT. In addition to the activities at the meetings, considerable work was carried out at each of the participating universities between the meetings thanks to external funding. The work was organized in five working groups

- Curriculum
- Teaching and learning
- Workspaces
- Assessment
- Students

The first four working groups were formed at the meeting in October 2000, and the student group, which was very valuable for the project, was formed at a somewhat later stage. The work between and at the meetings involved, among other things, the following activities

Syllabus survey

This involves asking a selected set of stakeholders about their expected proficiency of the graduates. See Chapter 3 of (Crawley *et.al.,* 2014).

Curriculum benchmarking

This involves various activities for clarifying how the courses in a program fit together, how the courses are run, and how the assessment is carried out. One example of a mapping of connections between courses is given in Box 4.1 in Chapter 4 in (Crawley *et.al*., 2014).

Curriculum and course development

The development of several new courses started, plus revisions of existing courses. Of extra importance were various versions of Introduction to Engineering, inspired by Standard 4 in the CDIO Standards, and design-implement experiences, implied by Standard 5. Examples from both categories can be found in (Crawley *et.al.,* 2014) and in publications that can be accessed via the Knowledge Library at the CDIO-website (CDIO Initiative, 2026).

Workspace development

Parallel to the development of design-implement experiences, the need for new workspaces was identified and thereby developed, and some examples are given in (Crawley *et.al.,* 2014).

Expansion and consolidation

After the initial years, the project gradually shifted over to a network of interested institutions. The intention is not to give a complete overview of the development of the network, which after some years started to be named the CDIO Initiative, but to point out some of the highlights:

- Among the first institutions to join the network one can mention DTU (Denmark), USNA (USA), Queens University (Northern Ireland), University of Pretoria (South Africa) and Singapore Polytechnic.
- One of the first meetings with participants from new institutions was in Vadstena, just outside Linköping, 2003.
- During the following years, many more institutions from all parts of the world joined the network
- The first meeting held outside Sweden or USA was at University of Pretoria, South Africa in 2005.
- The 1st International CDIO Conference was arranged in Kingston, Canada, 2005 and the 2nd conference in Linköping the year after.
- The first version of the CDIO book was published in 2007, and the second edition (Crawley *et.al*., 2014) was published in 2014.
- Contacts and collaborations with other organizations within engineering education were established, and, for example, at the SEFI conference in Ankara in 2005, there was an entire session with papers from the CDIO community.
- After some years the governance structure was revised, and the first election of co-directors and members at-large of the CDIO Council, according to the new procedure, was held during the conference at MIT in 2013.
- There are of course many other milestones and highlights to mention, but that is left for future work.

Fun fact

As mentioned, the first meeting in the CDIO Initiative was held in Linköping, but there is another interesting connection between Linköping and the CDIO Initiative. André Oscar Wallenberg, shown in Figure 1, was born and grew up in Linköping. After some years in the Navy, he moved to Stockholm and initiated the activities of the Wallenberg family within banking and industry. Since the CDIO Initiative was funded by the Wallenberg foundation during the first years, his change of career had an impact on the development of engineering education worldwide almost two hundred years later.



Figure 1. André Oscar Wallenberg. Born in Linköping, 1816.

25 YEARS OF CDIO WITHIN LINKÖPING UNIVERSITY

Overview

During the first years the efforts within LiU were concentrated on the Applied Physics and Electrical Engineering program. After some years the program management working with the Engineering Biology program saw a need to strengthen the engineering aspects of the program, see (Kindgren *et.al*, 2005), and in that process the CDIO framework was found very useful. For example, an Introduction to Engineering course was introduced, see Box 11.2 in (Crawley *et.al*, 2014). During the first years, the framework was also adopted within two of the three-year engineering programs, as reported in (Granath & Bjerner, 2005). Examples of the impact of the CDIO framework within Mechanical Engineering are given in (Hallberg, 2016, 2018). The CDIO framework was also found to be useful during the Bologna process via the focus on learning outcomes for programs and courses. One component in this process was the introduction of course matrices (previously denoted ITU-matrices), as reported in (Gunnarsson *et.al.,* 2007). A few years later, it was decided that all five-year engineering programs should have a Bachelor's project during the second semester of the third year of the program, and this led to several design-implement experiences being introduced. With this step, most of the five-year engineering programs included an Introduction to Engineering course in year one, and design-implement experiences in year three and year five, i.e. according to Standards 4 and 5. Another important activity is the extension of the CDIO Syllabus into the LiTH Syllabus and the tight integration of this document into the quality assurance system. In the following section, some of the key components of the implementation of the CDIO framework are presented in detail. However, it should be stressed that one of the most important outcomes is that the CDIO framework has given a common vision of education

within the Faculty of Science and Engineering – a common terminology. Finally, the implementation and extensive use of the CDIO framework would probably not have happened without solid support from the top management, i.e. Dean and Board, of the Faculty of Science and Technology.

Introductory courses

Like within programs at other participating institutions, Introduction to Engineering courses was developed. The first one was developed for the program Applied Physics and Electrical Engineering, and it was given for the first time during the fall semester of 2002. See Box 4.4 in (Crawley, *et.al*, 2014). In addition to a series of lectures dealing with, e.g., group dynamics, oral and written communication, and the engineering role, the main part of the course is a project carried out in groups of six students. The course ends with a project conference where the students present their results in a conference-like format. Since the program has a wide scope, the project tasks range from Biomedical Engineering via Applied Physics to Automatic control. As mentioned above, similar courses were introduced in other programs, and one example of a project within Engineering Biology is given in (Wetterö, *et.al*., 2006).

Design-implement experiences

There were of course design-implement experiences within the engineering programs at LiU already before, but the CDIO Initiative meant a significant step in ambition and volume. A key step was the introduction of the design-implement experience in Electronics during the third year of the program Applied Physics and Electrical Engineering, which was introduced in 2002. The course became an immediate success and was highly appreciated by the students from the start. A thorough presentation of the course is given in (Svensson & Gunnarsson, 2012). As pointed out, in that paper the key success factors are clearly defined learning outcomes, a suitable and well-working organization of the course, suitable workspaces and equipment, and sufficiently challenging tasks. In addition to the course in Electronics, a set of almost ten different design-implement courses were developed or revised within the Applied Physics and Electrical Engineering program during the first years of the CDIO Initiative. The courses are connected to the specializations the students chose during the last part of the program. Examples of courses are presented in (Karlsson *et.al*, 2006) and (Larsson *et.al*, 2017). Nowadays, almost all programs include capstone courses connected to the specializations in the last years of the curriculum. It should be stressed that in the process of developing design-implement experiences, it was very valuable to have teachers with solid industrial experience involved.

LIPS project model

In the process of developing the design-implement experiences it was recommended by people with industrial experience to use some kind of project model in these courses. Therefore, the project model LIPS was developed and introduced. Detailed information about LIPS can be found via the web site (LIPS, 2026). The structure of LIPS is shown in Figure 2.

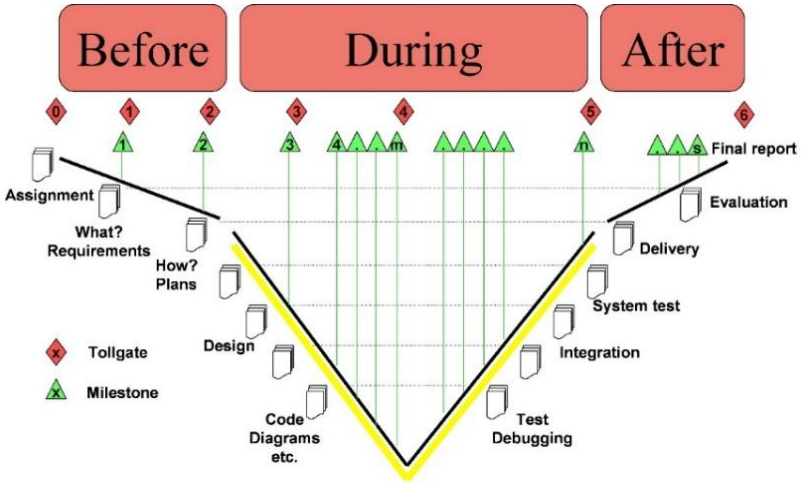


Figure 2. LIPS project model.

The project model provides a common structure for the work with suggested roles in the project teams, well defined decision points, and regular meetings for reporting and feedback. There are several other ways to manage development projects, like, e.g., agile methods, but LIPS provides a common language concerning the phases of the project and documentation. The model is flexible in the sense that, e.g., the amount of documentation can be chosen depending on the complexity of the task. One feature of using a project model with regular meetings between the project teams, the customer, and the supervisor is that it enables continuous assessment during the execution of the project. This is further elaborated in (Svensson & Gunnarsson, 2005). An important document in the LIPS model is the reflection document that is written at the end of the project. The purpose of this document is to give the student the opportunity to collect lessons learned from the project work. This involves technical issues as well as aspects related to the planning of the project and collaboration in the team. Also, the document gives feedback to the teacher responsible for the course, in addition to the regular course evaluation. Some observations from the use of reflection documents in project-based courses are given in (Gunnarsson *et.al.,* 2023). For example, the students point out that writing the document gives an opportunity to compare each other's impressions and opinions, and the document also marks the end of the project.

Reflection documents

The use of reflection documents in the project-based courses inspired the introduction of reflection documents as a mandatory part of the Master's or Bachelor's theses, giving the students one more opportunity for reflection, but also providing feedback to the program management about the contents and execution of the entire education program. Some initial experiences were presented in (Kindgren *et.al*, 2012). In 2023 a web-based system, Reflex, for managing the documents was introduced. Since all texts from the documents are stored in a searchable database, this enables systematic analysis of the reflections. The system Reflex and two case studies of how the contents of the documents can be analyzed and used for program development are given in (Gunnarsson *et.al*, 2025).

LiTH Syllabus

In addition to engineering programs, the Faculty of Science and Engineering offers Bachelor's and Master's programs in, for example, natural science subjects. To incorporate these programs into the system for program and quality management, a need to extend the CDIO Syllabus was identified. Since Section 4 of the CDIO Syllabus is based on a characterization

of the role of the engineer, a corresponding description of the role of the graduates was proposed, and Section 5 of the Syllabus was introduced. This extension, together with some additional modification, led to what is called the LiTH Syllabus.

Dissemination within LiU

The CDIO framework has also been disseminated to other disciplines. For many years LiU had been offering Bachelor's and Master's programs in Biomedicine, but around 2017 it was found that revisions and updates were needed. Until then the intended role of the graduate had been within academia or health care, and one important part of the revision was to put a stronger emphasis on roles in the life science industry. Based on these needs, it was found that the CDIO framework could be a useful tool. Some examples of outcomes of adaptation and use of the CDIO framework in this new context are given in (Fahlgren, *et.al,* 2018, 2019).

Quality assurance system

The LiTH Syllabus and the CDIO Standards are important tools in the quality assurance system that is used at LiU, and this is described in some details in (Gunnarsson, *et.al*., 2019). The key component of the quality system is a report that is written every sixth year for each program and is based on a set of criteria, which are defined on university level, but based on the European Standards and Guidelines (ESG). One criterion is about fulfillment of the learning goals at a program level and for that the course and program matrices, which are based on the LiTH Syllabus, are crucial. Another criterion is about the execution of the program, and for that part the components of the CDIO Standards are vital.

Collaboration with Brazil

LiU has had privilege to collaborate with colleagues in Brazil and share experiences of the use of the CDIO framework. Presentations have been given for guests visiting LiU, but also on several occasions in Brazil, including at IME in Rio de Janeiro, ITA in Sao Jose dos Campos, and SENai SIMATEC in Salvador. There have also been discussions with the working group dealing with the revision of the guidelines for engineering education in Brazil. During the fall and winter 2015/2016 two of the staff members from IME spent six months at LiU to learn more about engineering education at LiU and the use of the CDIO framework. This visit led to a joint plenary session at COBENGE 2016, which is the Brazilian national engineering education conference. Some results of the implementation of the CDIO framework at IME are presented in e.g. (Rezende, *et.al,* 2022). The paper points out how useful the CDIO framework has been in the process of adapting the engineering programs to the new guidelines. The collaboration with Brazil has continued with UFG in Goias as reported in, e.g., (Diaz & Gunnarsson, 2023).

REFLECTIONS

An obvious question to ask after 25 years with the CDIO framework is whether the engineering education within the Faculty of Science and Engineering has higher quality than it would have had without implementation of CDIO? It is of course impossible to give any certain answers to that question. Many things have changed in the surrounding world affecting the expectations of the industry concerning knowledge and skills of the graduates, the attitudes and expectations of the students, developments within engineering and science as well as general pedagogical approaches to teaching and learning practices.

Longitudinal study

During the first years a longitudinal study was carried out by Ellinor Stiwne and co-workers. The study followed two cohorts of students following the Applied Physics and Electrical Engineering program over several years using surveys and interviews. The data collected resulted in several conference papers and contributed to one PhD thesis. See (Jungert, 2009). One cohort of students carried out the studies before the changes implied by participation in the CDIO Initiative had been implemented, and one cohort of students followed the re-designed program. The survey gave strong indications that the students who had followed the re-designed program felt better prepared for professional life after graduation than the first cohort. More data is given in the reference mentioned above, but the overall impression from Stiwne's work is that the CDIO Initiative has had positive effects on the education program.

Engineering education program of the year - Årets Teknikutbildning

For some years, the association of Technology Industries of Sweden (Swe: Teknikföretagen) gave the award Engineering education program of the year (Swe: Årets Teknikutbildning), and 2007 it was given to the Applied Physics and Electrical Engineering program. In translated form, the justification of the award reads "The Applied Physics and Electrical Engineering program (Y) combines, in a successful way, deep and broad knowledge and gives a degree that is suitable for many different roles in industry. The CDIO framework and the experience of having worked in an industry-like project model LIPS give excellent understanding of the requirements in industry".

Contributing factors

As mentioned, it is not possible to "prove" the positive impact of the CDIO framework on the quality of the education programs within the Faculty of Science and Engineering, but since the framework has a strong position, it is worth pointing out some contributing factors behind this:

- There has always been solid support from top management, i.e. the Dean and the faculty management level, within the Faculty of Science and Engineering.
- The education programs are managed via Program Boards consisting of teachers, students, and representatives from industry, and there has always been strong support from industry concerning the fundamental ideas behind the CDIO framework.
- Within the Faculty of Science and Engineering, there is a long tradition of close interactions with industry and other parts of the surrounding society, and this is very valuable when it comes to finding suitable tasks for design-implement experiences.
- The development of the design-implement course in Electronics described above was led by a teacher who, in addition to being a brilliant teacher, had solid industrial experience. As mentioned, this course became an immediate success, and it served as an "early success" and a good example for others, which is very important in change processes.

Another thing that has been important is the systematic working method that has been built up. The development of the programs takes place according to an annual process that is known to everyone. It is crucial that all parties involved take responsibility for their parts, both at the Dean's office and at the different departments that the courses are commissioned from. So, when starting new educational programs, there is a basic idea to relate to, which facilitates the process. Not everyone needs to find their own solutions, since there is a structure that can be filled with different content.

CONCLUSIONS

The CDIO Initiative started 25 years ago, and it has grown from a project with four participating universities to a global network of institutions from all over the world. The paper has given a brief overview of the start and the development during initial years of the CDIO Initiative together with an overview of the impact of the CDIO framework within the education programs at the Faculty of Science and Engineering at LiU. The main lessons learned from these 25 years concerning the implementation of and use of the CDIO framework are strong and persistent support from the management level, a suitable organization for management of the education programs, including participation from students and representatives from industry, close contacts and interactions with industry and other parts of the surrounding society, and inspiring and well-designed learning activities. One of the key challenges for the future is the rapid development of artificial intelligence (AI) and the use of large language models (LLMs). This has a strong impact on both the goals for and the execution of engineering education. The starting point of the CDIO framework is the characterization of the role of an engineer (see page 50 of Crawley et.al, 2014), and a challenge for the future is to reformulate the role into an AI-supported one.

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USING PULL REQUESTS TO MAKE COLLABORATION VISIBLE IN CDIO PROJECT-BASED COURSES

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ABSTRACT

Assessing collaboration, individual accountability, responsiveness to feedback, and reproducibility remains a persistent challenge in open-ended, team-based project courses. Final deliverables often mask how work evolved, how responsibilities were shared, and how decisions were negotiated. This paper presents an assessment design in which pull requests (PRs), a mechanism for reviewing and integrating changes to shared project work, serve as the central mechanism for making collaborative practices visible and assessable within CDIO-aligned project-based courses. Rather than treating GitHub as a programming topic or tooling exercise, the approach positions PRs as assessment infrastructure that binds technical change to process evidence through review discussions, explicit responses to comments, and documented handover. The implementation spans two intentionally sequenced courses in Industrial Engineering. A second-year course introduces structured collaboration practices through short, skills-focused project cycles. A subsequent advanced course assumes GitHub fluency and organizes all project work within a single persistent repository maintained across the semester. Within this environment, PRs function as the primary unit of feedback, peer review, and evaluation. Students make their reasoning, revisions, and communication visible through routine workflow activity, and unresolved feedback carries forward across project cycles into capstone evaluation, enabling cumulative rather than fragmented assessment. Experience across multiple offerings shows that PR-centered assessment improves the scope and specificity of peer review, strengthens documentation and reproducibility practices, and fosters shared responsibility for evolving team artifacts. Students initially expressed concern about perceived overhead, but review quality, documentation habits, and disciplined handover improved markedly as the workflow became routine. Graduating students later identified PR-based communication and accountability as directly transferable to professional settings. The paper highlights key design decisions, trade-offs, and sequencing choices, offering practical and transferable guidance for educators seeking assessment methods that make collaboration, responsiveness, and reproducibility genuinely visible in CDIO project-based courses.

KEYWORDS

Pull requests, GitHub Classroom, assessment infrastructure, team-based learning, professional competence, CDIO standards: 5, 7, 8, 11

INTRODUCTION AND MOTIVATION

Team-based projects pose persistent assessment challenges: instructors must evaluate not only technical outcomes but also how teams coordinate work, share responsibility, respond to feedback, and hand over results in reproducible, trustworthy ways. In many courses, final deliverables reveal little about how work evolved or how responsibility was shared, motivating assessment approaches that make collaborative processes visible rather than relying solely on end products.

Existing uses of GitHub Classroom in CDIO and computing-education contexts focus on automated grading and assignment distribution (Glassey, 2019), leveraging test frameworks and repository templates to check correctness rather than to support collaborative review. Although richer GitHub features–particularly *pull requests (PRs)*, a mechanism through which proposed changes to a shared codebase/project are reviewed, discussed, and approved before integration–are considered promising for structuring critique and accountability, their pedagogical use in assessment remains limited, despite the broader adoption of GitHub in education. In contrast, Petre and Wilson (2014) emphasize that small, just-in-time reviews embedded in normal workflows surface reasoning and improve reproducibility, and practitioner guidance in scientific computing highlights documentation, version control, and transparent handover as foundational collaborative practices (Wilson et al., 2017).

Throughout this paper, PRs are treated as principal assessment artifacts. A PR couples a focused change set with a clear description of intent, threaded review comments, and documented responses to feedback. Unlike commits or standalone reports, PRs provide sustained visibility into how work evolves through critique and revision and how responsibility is distributed within a team. Relocating substantive communication from transient chat tools into *Issues* (task- and discussion-tracking threads within the repository) and PR threads further strengthens traceability and accountability.

The aim of this work is not the adoption of a particular platform, but the development of an assessment architecture that foregrounds collaboration, responsiveness to feedback, and reproducibility in project-based courses. This paper contributes such an architecture by positioning PRs as the core assessment unit and demonstrating its implementation across two intentionally sequenced courses, showing how PR-centered workflows create visible, attributable evidence of learning and support coherent, cumulative evaluation in CDIO-aligned curricula.

COURSE CONTEXT AND CURRICULAR PLACEMENT

The implementation spans two intentionally sequenced courses serving Industrial Engineering students, with regular enrollment from adjacent programs.

Information Engineering (IE) is a second-year mandatory undergraduate course built around short, skills-focused project cycles that consolidate foundational competencies. GitHub collaboration practices (Issues for task tracking, branches for isolated work, and PRs for review and handover) are explicitly introduced and scaffolded. Each cycle uses a separate repository to reset expectations, isolate errors, and manage cognitive load, emphasizing skill development and guided practice over long-term continuity. The course typically enrolls 20–25 students organized into small teams of 3–4 (6–7 teams).

Business Intelligence (BI) is a third-year undergraduate/first-year master's elective with larger, data-intensive projects organized in thematic cycles culminating in a final deliverable. GitHub is the primary collaboration environment, and proficiency is assumed. Assessment centers on *iterative, PR-based workflows* within a *single persistent team repository* used across the semester, enabling teams to revisit, resolve, and build upon feedback across successive PRs. The course typically enrolls 10–15 students working in two larger teams. Further detail on the BI course design appears in Ingimundardóttir (2026).

IMPLEMENTATION HISTORY AND IDENTIFIED LIMITATIONS

Early offerings of the BI course used one repository per cycle, with each cycle assessed independently. Although PRs supported review within cycles, work traces were fragmented across repositories: discussions, diffs, documentation, and decisions were split, making it difficult to audit how feedback was addressed. Instructor comments became effectively non-binding once a repository closed, and collaboration rules had to be repeatedly configured.

A further issue emerged in practice. In the first iteration of the course, the initial project cycle was consistently the weakest: teams struggled not only with problem framing and analytic skills but also with learning GitHub workflows from scratch. Students were simultaneously acquiring technical content, collaboration conventions, and version-control practices, and the combined cognitive load slowed early progress. Subsequent cycles improved markedly once basic GitHub fluency was established, indicating that tool onboarding was misaligned with the project's complexity.

This observation motivated a structural change in the curriculum. GitHub onboarding was moved to the prerequisite IE course, where collaboration workflows could be introduced through short, lower-stakes cycles. With these competencies in place, the BI course could assume fluency and shift attention to deeper analytic work and more substantive review practices. BI therefore adopted a single persistent repository with cumulative PR continuity, ensuring that feedback, decisions, and documentation remained visible and actionable across the semester. This design aligns with CDIO program practices that emphasize intentional sequencing and coherent integration of learning outcomes across courses (Malmqvist et al., 2006).

DESIGN RATIONALE: PULL REQUESTS AS ASSESSMENT INFRASTRUCTURE

The design objective is to make collaboration, responsiveness to feedback, and responsibility for shared artifacts *visible and assessable through normal project activity*. Prior CDIO work underscores that documentation habits only persist when they are explicitly structured and routinely reinforced; for example, Junaid et al. (2018) show that logbook keeping supports learning and traceability only when embedded in deliberate practice with clear expectations. We extend this principle from individual records to collaborative artifacts: when communication, critique, and decision-making occur within shared, version-controlled workflows, they become durable and auditable in ways that isolated deliverables do not.

Within this framing, PRs serve as assessment units that bind *technical change* to *collaborative process*. A PR couples a focused change set with rationale and scope, line-level review, threaded discussion, explicit responses to comments, and a visible merge or revise decision.

Because these traces are produced *in situ*–as part of the team's routine workflow–they provide integrated, assessable evidence of reasoning, critique, revision, and handover, aligning with recommendations on just-in-time review and reproducible practice (Petre & Wilson, 2014; Wilson et al., 2017).

Infrastructure context: GitHub Classroom

GitHub Classroom provisions standardized repositories from a common template and centralizes instructor-student interaction within Issues, pull request reviews, and feedback PRs (GitHub Inc., 2026, for documentation). Bennedsen et al. (2022) describe how GitHub Classroom has primarily been used to organize assignment distribution and feedback in repositories. More broadly, Glassey (2019) surveys Git/GitHub use in computing education and highlight its role in assignment management, batch cloning, and artifact-based review.

PRs as assessment units

PRs bind *technical change* to *collaborative process*. A PR couples a focused change set with rationale and scope, line-level review, threaded discussion, explicit responses to comments, and a visible merge or revise decision. Commits rarely expose intent, and standalone reports detach explanation from the evolving artifact. PRs provide integrated, assessable evidence of reasoning, critique, revision, and decision making (Glassey, 2019; Petre & Wilson, 2014).

ASSESSMENT ARCHITECTURE AND IMPLEMENTATION PRACTICES

Figure 1 illustrates the interaction structure of a typical project cycle. Students begin from a shared repository template and work on commits within separate branches. All changes to main must be integrated through PRs; direct commits to main are not permitted. Responsibility for integration is therefore distributed: the student responsible for a branch must request reviews from teammates, where peers are responsible for evaluating, commenting on, and approving changes before merging. One contribution is developed as a dependent branch and merged back into the core work stream, while another proceeds through a PR phase involving iterative revision before being merged into main. After the parallel feature is merged, the updated state of main is synchronized back into the core work stream, ensuring that subsequent integration reflects the current shared state. The final integrated result on main is then subject to instructor feedback.

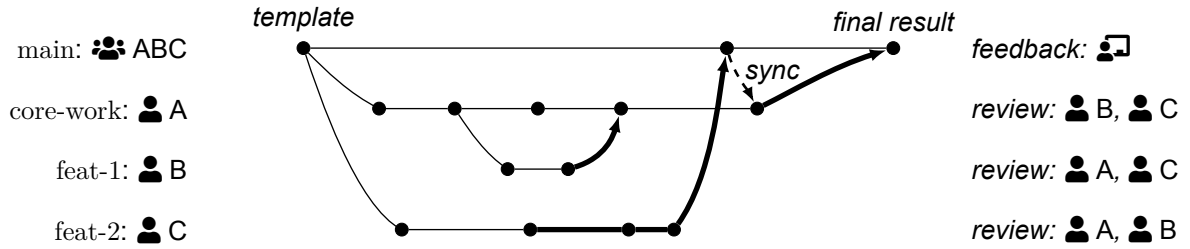


Figure 1. PR-centered interaction workflow for one project cycle. Students work on separate branches and integrate changes through reviewed pull requests. The PR phase is highlighted by thicker edges, indicating reviewed integration rather than independent work.

Assessable behaviors and required practices

The assessment architecture makes behaviors explicit and reviewable. Students must:

1. Submit focused PRs with clear descriptions and linked Issues when appropriate.
2. Provide at least two *substantive* peer reviews before merge.
3. Respond explicitly to peer and instructor comments (no silent fixes or private replies).
4. Merge only after approvals, documenting any deferrals as follow-up Issues.
5. Update README and run instructions when execution, data, or interpretation changes.
6. Participate visibly through authorship, co-authorship, and review.

These practices mirror industry norms, where PRs serve as the locus of communication, accountability, and reproducible handover (Petre & Wilson, 2014). They also reflect documentation-first workflows advocated in scientific computing (Wilson et al., 2017).

Assessment efficiency and reproducibility

Repository-based workflows keep all submission files *in situ* within a standard project structure, eliminating ad hoc packaging (e.g. ZIPs) and ensuring that code runs directly in that structure, with shared datasets explicitly included or referenced. This reduces non-pedagogical overhead (such as fixing paths, locating files, rebuilding contexts) and redirects effort toward evaluating method, documentation, and responsiveness. The repository becomes a stable execution and review environment, where diffs, run instructions, and documentation are co-located, improving reproducibility and assessment consistency.

Sequencing across courses

IE introduces collaboration conventions through short, skills-focused cycles. BI assumes fluency and leverages a *single persistent repository* to support cumulative iteration, sustained traceability, and efficient capstone evaluation. This sequencing shifts instructional effort from tooling toward collaboration quality.

ASSESSMENT FOCUS: REPRODUCIBILITY, HANDOVER, AND RESPONSIVENESS

Reproducibility. Documentation is maintained within the repository, especially the evolving README. Contributions that affect execution or interpretation must include run instructions, data-dependency descriptions, and concise summaries of analytical steps. Because documentation is reviewed through PRs, reproducibility is treated as a routine responsibility rather than a final-stage check.

Handover. Each PR functions as an explicit handover. Authors describe intent and scope, link Issues, and explain rationale at the moment of integration, making decisions and reasoning traceable.

Responsiveness. Students must engage directly in PR discussions to answer questions, clarify assumptions, and revise work where appropriate. Questions asked in threads are treated as positive evidence of engagement and shared responsibility. The depth of review and the explicitness of responses provide observable indicators of individual learning outcomes.

Substantive peer review is characterized by specific, actionable comments that address correctness, clarity, or design decisions, and by engagement in follow-up discussion when issues are raised. Superficial approvals without critique are not considered sufficient evidence of participation.

These dimensions operationalize professional competence in observable ways and align with formative, process-oriented assessment approaches: reproducibility through documentation practices, handover through structured PR descriptions, and responsiveness through engagement in review discussions, grounding assessment in observable evidence of attainment (Biggs & Tang, 2015). Taken together, they reinforce collective accountability and strengthen system-level responsibility. In earlier offerings of the course (and in comparable project-based settings) students frequently approached assignments as partitioned tasks, completing only their designated component while treating others' work as opaque. When later stages depended on prior work, students often expressed uncertainty about foundational steps, sometimes stating candidly that "someone else handled that part." This divide-and-conquer pattern is well-documented in team-based learning research, where strict task partitioning leads to superficial engagement and enables students to contribute minimally while relying on others' understanding (Börjesson et al., 2006).

A parallel dynamic is observed in engineering education more broadly: engineering students often delay engagement with conceptually demanding tasks until temporal pressure forces them to confront prior material, using procrastination as a coping mechanism that postpones understanding until "just-in-time" moments such as exams or later project milestones (Kim & Nembhard, 2019; Wilhelm & Nijman, 2023). These patterns reinforce the need for assessment structures that make intermediate understanding visible, distributed, and accountable throughout the project timeline rather than concentrated at high-stakes endpoints.

The assessment architecture makes shared responsibility explicit and ties evaluation to engagement with the evolving system, not isolated subtasks. PR authorship and co-authorship, review quality and documented follow-up provide attributable evidence of individual learning within team artifacts. These traces show whether students scrutinize and improve peers' work; superficial reviews or unexamined merges are visible, while substantive threads capture reasoning, error correction, and negotiated interpretation. Instructors gain actionable evidence of individual attainment and free-riding is deterred as weak collaboration surfaces in the PR history and impacts team performance.

Ultimately, the approach helps students see that effective teamwork requires shared understanding of system integrity, not merely completion of personal fragments. It also gives instructors visibility into misconceptions and reasoning processes, enabling targeted adjustments and coherent support across project cycles.

FEEDBACK CARRY-FORWARD AND CAPSTONE RE-EVALUATION

Project work in BI is organized in thematic cycles culminating in a capstone deliverable. Instructor feedback is delivered through PR reviews and is not closed at cycle boundaries. Unresolved comments automatically *carry forward*. Capstone evaluation checks whether previously identified issues have been resolved; if not, the corresponding assessment outcome remains unchanged. This makes feedback binding without requiring resubmission and enables efficient

Table 1. Rubric used to assess GitHub collaboration practices in the IE course

	Excellent	Good	Insufficient
GitHub usage	Branches are well organized with logical names tied to features. Commits are coherent and clearly describe changes. Documentation is complete and provides clear instructions.	Branches are used but naming or scope is sometimes inconsistent. Commits are mostly coherent with occasional issues. Documentation is present but incomplete.	Branches are absent or unclear. Commits are inconsistent with little structure. Documentation is unclear or missing.
Teamwork	All team members actively contribute. Contributions and responsibilities are distributed across the team. Decisions are shared through review and discussion.	Most members participate, but contributions are uneven. One or two members lead development, while others contribute through reviews or comments.	Work is largely carried out by one individual. Participation is minimal or uneven across the team.

summative assessment, as instructors can verify changes through diffs rather than rereviewing entire codebases. Early cycles may include exploratory or partial solutions, provided limitations are acknowledged and tracked. Capstone evaluation rewards teams that integrate feedback and deliver coherent, reproducible outcomes.

STUDENT RESPONSE AND ADAPTIVE REFINEMENT

Early student response highlighted perceived duplication of communication ("we already discuss work on Messenger"), additional overhead from writing PR descriptions, and delays caused by mandatory peer review. Instructional adjustments focused on behavior rather than tool mastery: review quality was explicitly graded, instructors modeled effective comments, and GitHub onboarding was moved to an earlier course to ensure fluency before advanced project work.

Over successive offerings, PRs became smaller and better scoped, documentation improved, and review discussions became more substantive. This progression is also reflected in rubric-based assessment data from the undergraduate IE course (cf. Table 1), where GitHub practices are introduced. Normalized scores (range $[0, 1]$) across eight team assignments (23 student observations) show a positive trend in both GitHub usage (slope = 0.019, $p = 0.023$) and teamwork and participation (slope = 0.047, $p < 0.001$), indicating increasing adoption of collaborative workflows and more active engagement in shared development practices. These trends are consistent with observed improvements relative to earlier course iterations without structured PR-based collaboration workflows.

ALIGNMENT WITH CDIO STANDARDS

This implementation aligns primarily with CDIO Standards 7, 8, and 11, with partial alignment to Standard 5 (Malmqvist et al., 2020). Integrated Learning Experiences (Standard 7) are realized through PR-centered workflows that integrate technical and interpersonal competencies. Active Learning (Standard 8) emerges through iterative contribution cycles in which students propose changes, receive critique, revise work, and integrate feedback *in situ*. Learning Assessment (Standard 11) is grounded in observable repository artifacts: shared responsibility is

reflected in participation in peer review and approval processes, responsiveness to feedback in explicit replies and revisions within PR discussions, and reproducibility in documentation and execution updates. These behaviors are assessed through rubric-based evaluation of GitHub usage and teamwork. Persistent repositories support aspects of Design-Implement experiences (Standard 5) in semester-long projects.

TRANSFERABLE DESIGN PRINCIPLES

These distilled principles articulate the aspects of the design most likely to transfer to other project-based courses seeking to make collaboration visible and assessable.

1. **Treat collaboration artifacts as assessment evidence.** Use PRs (or equivalent review units) as the basis for grading.
2. **Sequence tool learning before complex project work.** Teach collaboration workflows in a lower-stakes course; assume proficiency later.
3. **Prefer persistent artifacts over fragmented tasks.** Use a single repository for sustained projects to accumulate documentation, decisions, and feedback.
4. **Grade review quality and responsiveness.** Reward substantive critique and explicit responses; penalize cursory approvals or off-platform clarification.
5. **Carry feedback forward.** Treat unresolved comments as work-to-be-done and re-evaluate them at key milestones.

Boundary conditions and limitations. In practice, the approach depends on student readiness for collaborative workflows and familiarity with version control, and introduces overhead from documentation and review requirements, particularly early on. Scalability to larger cohorts requires coordination of review responsibilities, and transferability to non-technical domains depends on the availability of analogous tools supporting transparent iteration and review.

CONCLUSIONS

This paper presented a CDIO implementation in which pull requests (PRs) serve as assessment infrastructure for team-based project courses. By anchoring evaluation in PR authorship and review, explicit responsiveness to feedback, and reproducible handover, the design makes collaboration and individual participation visible within routine project activity. A single persistent repository supports continuity across project cycles and enables efficient capstone re-evaluation through diffs rather than repeated whole-artifact review.

The contribution lies in the assessment architecture rather than in a particular tool: PRs become the unit of feedback and grading, peer review is an assessed responsibility, and unresolved feedback carries forward in a systematic way across the semester. This structure reduces fragmented grading, concentrates attention on reasoning and revision, and embeds documentation and handover as normal habits rather than as end-stage compliance.

Beyond course-level logistics, the approach provides a structural safeguard for individual attainment in team settings. Because PR authorship, critique, and documented follow-up are

attributable to specific students, individual engagement becomes visible even within tightly coupled group work. This helps mitigate free-riding and opaque task ownership and enables instructors to evaluate how each student contributes to the evolving system, not only to isolated deliverables.

At the same time, the workflow aligns closely with professional collaborative practice. PR-based review, documentation, and handover are widely used in industry across software, data science, and technical analysis contexts. Students therefore gain both a fair and transparent assessment structure and sustained practice with a competency directly transferable to modern workplaces. This dual benefit—reliable evidence of individual attainment and authentic preparation for professional collaboration-motivates the design and supports its relevance for CDIO programs.

This work reports practitioner experience rather than controlled experimentation, and its findings should therefore be interpreted as design insights rather than empirical evaluation. Future refinements will explore lightweight review rubrics that calibrate "substantive" critique across teams, clearer PR and issue templates to standardize rationale and handover, and strategies for balancing mixed undergraduate–graduate cohorts.

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BIOGRAPHICAL INFORMATION

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NORDIC INSTITUTIONAL RULES AND REGULATIONS IN THE LIGHT OF GENERATIVE AI

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ABSTRACT

Generative artificial intelligence (GenAI) is rapidly becoming embedded in students' study practices, challenging universities to balance innovation with academic integrity, equity, and valid assessment. For the CDIO implementation community, the key question is which institutional mechanisms help programmes and teachers integrate GenAI while protecting intended learning outcomes and assessment credibility. We analyze GenAI rules and guidelines at six Nordic CDIO institutions using Diffusion of Innovations Theory (compatibility, trialability, observability). **Key findings**: (1) baseline principles converge on student/teacher accountability, growing expectations for disclosure, and GDPR-driven steering toward sanctioned tools (e.g., Microsoft Copilot); (2) trialability is operationalized through implementable "rules-in-use" (traffic-light models, course templates, declarations) that translate policy into course practice and support CDIO Standards 9 and 11; and (3) observability varies with organizational context: multi-faculty universities depend on recurring cross-faculty partners (central pedagogical units, AI labs/policy labs, working groups) to diffuse and update guidance, while more centralized or single-faculty settings emphasize streamlined recommendations and teacher-led, course-specific implementation. **Implementation implications for CDIO**: (i) adopt shared course-level decision artefacts to enable consistent yet discipline-sensitive implementation; (ii) resource faculty support for assessment redesign (Standard 9); and (iii) build feedback loops for continuous improvement and assessment transparency (Standard 11).

KEYWORDS

Generative AI, Assessment, institutional rules, higher education governance, assessment design, Diffusion of Innovations, Standards: 9,11

INTRODUCTION

The advent of ChatGPT in November 2022 sparked a very rapid growth in the availability and capability of GenAI. Many other GenAI-based applications (Mistral, Perplexity, Co**P**ilot, etc.) and integration of AI in other tools (e.g. grammar and spell checking in Microsoft Word, or tools that can write code from a specification in programming environments) followed the ChatGPT trend. When searching the web today (if you "Google" something), we automatically get an AI-generated answer – AI is everywhere in the digital domain.

Students are bright and have quickly started using GenAI when doing their assignments, exams etc. It becomes difficult to find out if it is the student or the GenAI who created a solution. This gives rise to many questions, such as: Is it acceptable to use GenAI in my assignments? If it is acceptable, how and for what can I use it? What is the environmental impact of GenAI? How do I cite work created by GenAI? What about privacy? Can more privileged students have unfair advantages (afford better versions of GenAI)?

The increased adoption of GenAI places significant pressure on universities to develop policies and guidelines in response. Luo (2024) argues that "*A more inclusive approach needs to be reflected in the policies to address issues around originality in students' work. Rather than stressing originality from a surveillance angle, policies can place more emphasis on the available support to students in producing original work that is meaningful to their learning."* (p. 662).

Several international organizations like UNESCO (Sabzalieva & Valentini, 2023) and OECD (OECD, 2023) have published guidelines on the use of Gen AI. These guidelines are quite generic (e.g. digital poverty) and are not specific to higher education (HE). UNESCO has also published AI competence frameworks for students and teachers (UNESCO, 2024a; UNESCO, 2024b). Furthermore, UNESCO calls for national AI strategies to include HE explicitly and stresses the need to train university faculty and researchers in GenAI use, including prompt engineering, ethical considerations, and pedagogical integration (UNESCO, 2023).

All these questions have made it clear to institutions that they need an institutional policy to help individual teachers. In addition, many institutions offer detailed guidance for the use of GenAI in the classroom

RELATED WORK

Although only slightly more than three years have passed since the launch of ChatGPT, a substantial body of research on GenAI policies in HE has already emerged. A Google Scholar search for "institutional policies" guidelines "generative" "AI" returned approximately 6300 results (December 19, 2025), reflecting the rapid expansion of the field. As expected, much of this literature is recent and thus unevenly cited; among the five most cited publications, citation counts range from 269 to 17, with one study still available only as a non-peer-reviewed preprint. The following paragraphs summarize four peer-reviewed contributions that are particularly relevant to this study.

Jin, Yan, Echeverria, Gašević, and Martinez-Maldonado (2025) analyzed GenAI policies from 40 universities worldwide using Diffusion of Innovations Theory (Rogers, Singhal, & Quinlan, 2019), focusing on compatibility, trialability, and observability. Their findings show that most institutions emphasize academic integrity, ethical AI use, enhancement of teaching and learning, assessment design, transparency, privacy, and human-centric competencies. In

contrast, relatively few policies address continuous evaluation, collaboration, or ongoing monitoring.

McDonald, Johri, Ali, and Collier (2025) examined documents from 116 U.S. research-intensive (R1) universities using open coding. They found that 73 institutions encouraged the use of GenAI, typically accompanied by extensive guidance, while 43 discouraged its use. Their analysis highlights the strong relationship between institutional stance and the level of practical support provided to staff and students.

Spivakovsky et al. (2023), based on interviews and discussion platforms at Kherson State University, proposed four key recommendations: revising syllabi to integrate GenAI and promote critical thinking, educating faculty and educational support staff in GenAI, conducting information campaigns on AI literacy, and including guidance on GenAI use in scientific publishing.

Finally, An, Yu, and James (2025) analyzed GenAI guidelines from the top 50 U.S. universities using topic modeling, sentiment analysis, and qualitative thematic analysis. They identified recurring themes related to syllabus statements, assessment redesign, ethical use, AI detection tools, and transparency. For staff, policies emphasize privacy, security, and limitations of GenAI, while for all stakeholders, they highlight academic integrity, disclosure, and responsible use.

CASE STUDIES

The following sections present cases from six Nordic CDIO institutions on their policy and guidelines for GenAI.

Method

We have used the same theoretical lens as Jin, Yan, Echeverria, Gašević and Martinez-Maldonado (2025), namely Diffusion of Innovations Theory (Rogers, Singhal, & Quinlan, 2019), to present the cases in the same way (see table 1 in (Jin et al., 2025) p. 4). We therefore focus on the characteristics (Compatibility (C), Trialability (T) and Observability (O)) and themes:

Academic Integrity and Ethical Use of AI (C): Use Gen AI tools in ways that uphold academic integrity and align with principles of originality and honesty.

Enhancing Teaching and Learning (C): GenAI is a tool to improve teaching methodologies, enhance learning experiences, and foster continuous learning.

Compatibility Fostering AI Literacy and Skills for the Future (C): Develop AI literacy and responsible use of AI tools to prepare students for a future where AI is ubiquitous.

Information Security and Data Privacy (C): Safe and secure use of AI technologies, compliance with policies, and protection of sensitive information.

Support for Diverse Educational Needs and Equity (C): Ensure equitable access to AI tools and support diverse educational needs, including personalized learning and support for students with disabilities.

Integrating AI into Educational Practice (T): Encourage the use of AI for content creation, interactive learning, and adapting teaching and assessment strategies.

Critical Evaluation and Human-Centric Perspectives and Competencies (T): Promote a critical stance toward AI-generated content and prioritize human-centric skills, including information verification and critical evaluation.

Transparency and Privacy (T): Transparency in AI use, proper citation of AI-generated content, and protection of privacy.

Policy Communication (T): Clear communication regarding AI use policies and guidelines for faculty and students.

Assessment Design and Authentic Assessments (T): Design assessments that evaluate higher-order thinking skills and are resistant to being solved solely by AI.

Continuous Evaluation (O): Test and evaluate the effectiveness of AI tools through new assessment methods and periodic evaluations involving various stakeholders.

Collaboration and Discussion (O): Foster collaboration and dialogue among educators, students, and stakeholders to address AI-related challenges and opportunities.

Ongoing Monitoring (O): Continuously monitoring AI technologies and adapting policies and guidance as understanding and technologies evolve.

Case Finland: LUT Universities and Turku UAS

The integration of AI into HE in Finland is guided by ethical, pedagogical, and strategic principles. The Finnish National Agency for Education emphasizes AI literacy for both students and educators, advocating for responsible use of AI in teaching, assessment, and personalized learning. Institutions are encouraged to develop clear policies and ensure equitable access to AI tools, while educators are supported through professional development.

ARENE, the Rectors' Conference of Finnish Universities of Applied Sciences (UAS) (https://arene.fi/en/), serves as a cooperation forum for universities of applied sciences. ARENE has recognized the importance of a structured approach to AI. Arene has published recommendations on the use of AI in education, with the latest update released in October 2024. These recommendations are publicly available (ARENE, 2024a, ARENE 2024b). The recommendations have been defined at the organizational, teacher, and student levels, with each university of applied sciences preparing its own guidelines independently. The objective is to promote ethical, transparent, and competent use of AI, enhancing both educational and professional competencies. In addition, the recommendations include a traffic light model that clearly communicates when and how AI tools may be used in course assignments.

Turku UAS follows the ARENE recommendations, and concrete guidelines are published on the university intranet. Another practical example is the LUT Universities that include two independent parts, LUT University and LAB UAS. Most of the guidelines and policies, e.g. The AI-based tools policy (for students), are common for both HE institutions (LUT Universities, 2025).

Compatibility

Academic Integrity and Ethical Use of AI: Turku UAS emphasizes responsible use of AI, stressing that authors remain fully accountable for any outputs and must report their use according to assignment instructions; undisclosed use is considered fraud. Ethical principles, originality, and transparency define expected academic conduct. LUT Universities similarly require responsible and ethical use, obligating students to document how AI was used. Any use against instructions or attempts to conceal AI involvement is regarded as academic misconduct, and AI must never be used for dishonest purposes.

Enhancing Teaching and Learning: At Turku UAS, AI is encouraged as a supportive learning assistant, with teachers guiding its use through the traffic light model. AI is positioned as a tool that enhances learning rather than replaces it. LUT Universities echo this approach by promoting AI as a learning and work-life skill. Teachers can either require or prohibit AI use, and AI is framed as a helpful tutor while ensuring that student learning remains central.

Fostering AI Literacy and Skills for the Future: Turku UAS identifies AI literacy as a strategic institutional goal, encouraging all staff and students to strengthen their AI competencies. LUT Universities also emphasize AI literacy, expecting students to reflect on how AI supports their learning and contributes to the development of future-oriented expertise.

Information Security and Data Privacy: Turku UAS instructs users not to input confidential or personal data into AI systems unless using secure institutional tools like Microsoft Copilot, stressing compliance with data-protection guidelines. LUT Universities similarly require the use of university credentials when accessing Microsoft Copilot to ensure data security. Students bear responsibility when using external AI tools and must avoid entering sensitive information into any AI service.

Support for Diverse Educational Needs and Equity: Turku UAS highlights AI as a tool that can support diverse learning needs and promote equitable access by offering tools and training. LUT Universities likewise encourage the use of AI to support learning, emphasizing responsible and equitable practices.

Trialability

Integrating AI into Educational Practice: Turku UAS integrates AI into education using the traffic light model, which clarifies whether AI is required, allowed, or prohibited in each assignment and ensures staged implementation across programs. LUT Universities also allow teachers to define assignment-specific AI rules, requiring students to follow these instructions and document any AI use.

Critical Evaluation and Human-Centric Perspectives and Competencies: Turku UAS trains students to evaluate AI critically, verify accuracy, and maintain strong human-centric competencies such as critical thinking. LUT Universities reinforce this expectation: students must verify AI outputs, cannot present AI-generated text as their own, and must clearly demonstrate their personal contribution.

Transparency and Privacy: At Turku UAS, AI use must be reported according to assignment requirements, with the traffic light model ensuring transparency. Privacy is safeguarded through institutional guidelines. LUT Universities similarly require students to document AI use and emphasize privacy and data-security practices, encouraging reliance on secure institutional tools.

Policy Communication: Turku UAS disseminates policies through institutional platforms, offering detailed guidance for both staff and students, including instructions related to the traffic light model. LUT Universities publish and regularly update policies on their intranet, complementing them with assignment-specific instructions from teachers.

Assessment Design and Authentic Assessments: Turku UAS designs assessments to ensure originality and higher-order thinking, treating undisclosed AI use as fraud and regulating AI use at the assignment level. LUT Universities ensure that assessments clearly reflect the student's own work; AI use must never compromise learning objectives, and teachers may prohibit AI where necessary.

Observability

Continuous Evaluation: Turku UAS maintains feedback and monitoring mechanisms and updates policies as AI technologies evolve. LUT Universities likewise conduct periodic updates and encourage students to request guidance and share feedback on AI use.

Collaboration and Discussion: Turku UAS fosters collaboration and dialogue among staff and students, enabling open exchange about AI practices and experiences. LUT Universities similarly encourage both students and teachers to discuss and reflect on their AI use, supporting collective learning.

Ongoing Monitoring: Turku UAS continuously monitors AI developments and updates policies accordingly, while encouraging participation in national discussions. LUT Universities also follow both internal and national AI developments, ensuring that guidelines remain current and responsive.

Umeå University, Sweden

Umeå University is a comprehensive university in the northern part of Sweden with research and education distributed over four faculties, 150 study-programmes at first and second cycle level and over 1600 courses. Out of the courses, some 25 include "Artificial Intelligence" in the name, and these are distributed over all faculties. By tradition, the faculties are rather autonomous with different traditions when it comes to assessment etc., making it hard to present a clear view of all actual pedagogical activities related to GENai.

Compatibility

Academic Integrity and Ethical Use of AI: Umeå University's guidance states that existing rules for grading and disciplinary cases also govern AI use, and teachers must specify permitted aids during tests and examinations (UMEAA 2025b). The policy further requires transparent labelling of AI-generated material and stresses the legal ambiguity of copyrighted input - promoting caution and documentation. This stance dovetails with the EU AI Act's risk-based framework—human oversight, accountability, and robustness - anchoring AI use within academic norms and legal compliance.

Enhancing Teaching and Learning: Institutional initiatives seek to enhance pedagogy without displacing human judgment. TaiGA (2026) provides venues and support for educators and students across faculties, framing "AI for the Good of All" and maintaining a focus area on Education and AI. Faculty seminars (e.g., #fraiday talks (UMEAA n.d. a)) and medical faculty teaching days explore ethical, technical, and practical dimensions—from CoPilot-assisted grading to responsible use in health education—consolidating a culture of reflective adoption.

Fostering AI Literacy and Skills for the Future: Umeå University fosters AI literacy through many formal courses (e.g., Introduction to AI in Schools (UMEAA 2024a), and Digital Dilemmas: Feminist Perspectives on Artificial Intelligence (UMEAA 2026) to mention only a few) and through participation in Erasmus+ Teacher Academies aimed at strengthening teacher education in the AI era (UMEAA 2025a). At the research/policy interface, the AI Policy Lab (UMEAA n.d.b) advances governance literacy—training scholars and decision makers to navigate compliance and societal impact—thereby bridging technical skills with trustworthy AI competencies (UMEAA n.d. c).

Information Security and Data Privacy: Internal guidance emphasizes confidentiality, data protection, and copyright compliance in AI development and use. Reference frameworks - including DIGG's AI trust model (DIGG 2026) - are recommended to build trust and transparency, and the human in the loop requirement is highlighted to ensure monitoring and accountability for outputs. Complementarily, European ethical guidelines foreground privacy and data governance as conditions for trustworthy educational applications.

Support for Diverse Educational Needs and Equity: University policy and European guidance converge on fairness, non-discrimination, and inclusivity—recognizing AI's promise to support diverse learners and the parallel obligation to mitigate algorithmic bias. TaiGA's (UMU TaiGA) transdisciplinary posture and education focus signal a commitment to equity-oriented design and adoption across programs, including domains beyond computing.

Trialability

Integrating AI into Educational Practice: Umeå University cultivates pilotability through workshops, seminars, and faculty teaching days that invite practical experimentation with generative tools and automated feedback, paired with peer exchange and critical appraisal (UMEAA 2024b). Research on no-code AI in HE provides tested methodologies for integrating machine learning into non-technical courses, thereby lowering barriers and expanding participation.

Critical Evaluation and Human Centric Perspectives and Competencies: The AI Policy Lab7 explicitly orients toward human-centred AI, developing tools and governance practices that uphold ethical, legal, and social values. As part of a broader scholarly mission, Umeå University advances responsible AI through leadership in ethics and policy; this institutional capability frames educational use as inseparable from human agency, societal wellbeing, and democratic accountability (UMEAA 2025c).

Transparency and Privacy: Policy requires clear disclosure when interacting with AI systems (e.g., chatbots) and mandates labeling of AI generated outputs. Privacy safeguards and risk classification under the AI Act anchor institutional expectations, while European ethical guidance equips educators with practical questions for classroom deployment—supporting transparency by design in teaching and assessment.

Policy Communication: Umeå University communicates policy via dedicated pages for AI in education and AI in professional practice, reinforcing the message that academic integrity rules apply to generative tools. TaiGA's web presence and news items amplify these messages with events, training, and research updates—helping staff and students to contextualize policy in daily teaching.

Assessment Design and Authentic Assessments: Institutional discourse acknowledges that GenAI complicates traditional examinations, pointing toward authentic and process-

oriented assessments that elicit higher order judgment and originality (UMEAA 2026b). External scholarship underscores the tension between workforce relevant digital skills and preserving scholarly autonomy—suggesting assessment redesign to reconcile these duties within credible academic standards.

Observability

Continuous Evaluation: Guidance on developing AI systems at the university stresses ongoing risk assessment, documentation, and data governance—tools that enable continuous evaluation of both systems and practices. This complements external frameworks that call for iterative monitoring of fairness, safety, and privacy, especially in educational deployments. In a near future Umeå University's digitalization policy (UMEAA 2023) is to be complemented with an AI-policy for GenAI and Digitalization (including AI) will be made a permeating perspective for all education at Umeå University.

Collaboration and Discussion: TaiGA's interdisciplinary model and the AI Policy Lab's advisory and training functions institutionalize collaboration—bringing educators, researchers, and external stakeholders into sustained discussions about emerging issues. European projects (Erasmus+ Teacher Academies) extend this dialogue internationally, strengthening observability and shared learning.

Ongoing Monitoring: The university's "Using AI at work" policy emphasizes human oversight ("human in the loop") and compliance with the EU AI Act's risk categories, supporting ongoing monitoring of deployed systems. This governance posture—linked to labeling requirements and disclosure duties—cultivates institutional habits of accountability and traceability in educational contexts.

KTH Royal Institute of Technology, Sweden

KTH Royal Institute of Technology (KTH) is a single-faculty institution. Up to the time this paper is being produced, KTH only has recommendations (not a policy) in line with DIGG's guidelines for GenAI in public administration, adapted by the E-learning team to be more relevant for teachers at KTH. This approach was suggested by a working group, initiated by the KTH faculty council on 6 March 2024.

Compatibility

Academic Integrity and Ethical Use of AI: KTH advocates for the effective use of GenAI, taking into consideration its legal and ethical aspects. This is done by highlighting considerations on the use of different tools. In addition, users are strongly recommended to read the terms of service before using a GenAI tool. These can be summarized in the following five points:

1. Only use GenAI when it is relevant and appropriate.
2. Have a human-centric and respectful approach to GenAI.
3. Work critically and with human review ("human-in-the-loop").
4. Take GDPR and copyright into account.
5. Be transparent about how you use GenAI.

Enhancing Teaching and Learning: Through clear information early on in a course, students are expected to be told how and when they are to use GenAI in graded course activities. For this reason, each course at KTH is recommended by the Faculty Council to have course-specific information about GenAI published in both Canvas (current Learning Management

System) and the course memo. To speed up and simplify scientific information retrieval, researchers are also made aware of the risks of inaccurate information and fictitious references.

Fostering AI Literacy and Skills for the Future: For students, Openai "Study mode" has been suggested for a more structured way of studying while being interactive and supporting a more active and reflective approach to learning. For staff, a hands-on workshop with focus on GenAI tools (mainly Chat GPT) aims to streamline work tasks. Among different examples, the topic of sustainability and GenAI has been raised to bring awareness of the energy consumption and ecological footprint of a GenAI tool. This was done through a discussion in a Lunch 'n' Learn, led by KTH faculty.

Information Security and Data Privacy: Information on the intranet is found with regards to how to handle intellectual property rights and copyright, the General Data Protection Regulation (GDPR) and the AI act from the EU. People are advised to have clear prompts from personal data when using GenAI tools. Most institutions in Sweden follow reference frameworks such as the DIGG's guidelines.

Support for Diverse Educational Needs and Equity: To promote fair treatment and equal opportunities, KTH recommends first and foremost that staff use tools that are supported by the institution. This is done by suggesting teachers to: 1) Only allow the use of GenAI for tasks where the versions produce similar results or do not have a major impact on the end result. 2) Specify which versions of GenAI tools are allowed to be used. 3) Give access to the paid version of a GenAI tool to everyone in the course. For example, all KTH students and researchers can now use Scopus AI, a tool that provides AI-generated summaries, concept maps, and in-depth reports from the Scopus database.

Trialability

Integrating AI into Educational Practice: With 31 different programmes in the first and second cycle, the approach taken by KTH is for teachers to provide course-specific information about GenAI to the students for each course. It is up to the teachers of each course to specify both restrictions of GenAI use as well if such use needs to be disclosed. To help teachers create this information, four different templates were developed (further described below) by KTH e-learning, where each template represents a different approach. These templates are automatically included in each course room in Canvas

Critical Evaluation and Human-Centric Perspectives and Competencies: KTH highlights the importance of human review, suggesting that material created by GenAI should be checked and edited before publication, both for quality purposes and to meet certain legal requirements. For example, human involvement is required to comply with copyright and the AI act. This allows users to argue that the prompt and the response from the AI are drafts and therefore do not have to be saved according to the principle of public access to official documents.

Transparency and Privacy: To support teachers creating the course-specific information about GenAI, KTH e-learning has developed four different templates, which can be seen as four different levels of allowed GenAI use:

1. No use of GenAI tools allowed – Can be used when GenAI has a risk of negatively impacting the students' ability to meet the course's intended learning outcomes

2. GenAI tools only allowed in specific assignments – Can be used when a course has certain assignments where the use of GenAI would help the students reach the intended learning outcomes. If not specified, the use of GenAI is not allowed.
3. GenAI tools allowed according to given guidelines – Can be used when GenAI is allowed for certain things, but not for others. E.g. allowed for generating ideas and correcting grammar errors, but not to fully generate a full text for an essay.
4. Free use of GenAI tools – This could, for example, be courses where GenAI is the topic of the course.

Policy Communication: Information is found on the institution's intranet, under education and system support. Staff are recommended to be transparent and model expected behavior. Continuous discussions are suggested to combat over-reliance on AI tools and help students avoid common problems. A page with FAQs related to GenAI is constantly updated.

Assessment Design and Authentic Assessments: As assessment has become one of the biggest issues in this area, KTH faculty and students are discussing how to approach the necessary changes. One of the workshops offered triggered discussions and reflections on the effects of GenAI on examination, how to handle the risk of AI-related misleading during examinations, and how we can communicate about AI with our students.

Observability

Continuous Evaluation: The KTH E-learning team, consisting of DL (Digital learning), IT and the Support unit, constantly revises the different tools being used and their effectiveness. This often involves a number of stakeholders.

Collaboration and Discussion: The Faculty Council of KTH Royal Institute of Technology emphasizes the importance of university-wide exchange and learning as part of the systematic quality work. To strengthen the exchange of experience and continuous quality development of our educational programmes, the Storträffen meetup is arranged every semester for all staff and students. In the autumn, the main language of the Storträffen meetup is Swedish. On 1 December 2025 the main theme of the meeting was: Education with and without AI.

Ongoing Monitoring: As agile as possible, KTH tries to work on current issues involving different stakeholders. Between the big meetings that occur twice a year, working groups (known as PriU, dealing with prioritized issues) meet on a more regular basis to keep track of what is going on.

Aarhus University, Denmark

Aarhus University (AU) is a comprehensive university and the second largest university in Denmark. It has five faculties; each faculty has between three and fifteen departments. Engineering war quite recently included at the university.

Like many other Nordic universities, there is a large degree of freedom for the individual teacher/researcher in the way she uses GenAI in her teaching and assessment. Three years back, a working group with representatives from all five faculties was established and it came up with the first version of the rules for the use of GenAI in exams. The overall conclusion was “GenAI is forbidden unless it is clearly stated that it is allowed”. Less than a year later, this was changed to “GenAI is allowed unless it is stated that it is not allowed” (AU 2024). Since the first version of the rules, the student must declare the way they have used GenAI (AU 2026a).

Compatibility

Academic Integrity and Ethical Use of AI: Existing rules for grading and disciplinary cases also govern GenAI use. In all courses, the course-responsible teacher must specify restrictions on permitted aids during examinations. AI-generated material must be labeled and cited, and a declaration for the use of GenAI must be submitted with students' written work.

Enhancing Teaching and Learning: In the support materials for students and teachers, there is a focus on how to use GenAI to enhance learning. The declaration of the use of GenAI was done to make students reflect on their use and how it enhanced their learning.

Fostering AI Literacy and Skills for the Future: Three years ago, a university-wide initiative started with a focus on the "digital competent candidate". (AU 2022). Here, GenAI got a central focus. No central initiative has been taken for the inclusion of a specific GenAI course, but many study programmes include courses focusing on the responsible use of GenAI.

Information Security and Data Privacy: AU stresses that the use of GenAI might disclose sensitive information. It is highly recommended that students and teachers alike consider GDPR when prompting. AU has a data agreement with Microsoft (CoPilot), ensuring that all students and staff can use it securely.

Support for Diverse Educational Needs and Equity: There is no direct focus on this in the AU guidelines or policies. There have been discussions among teachers that students who can afford access to better GenAI tools will have an advantage.

Trialability

Integrating AI into Educational Practice: AU has a central pedagogical unit (https://ced.au.dk/en). They have websites for students and teachers with case studies and advice for the use of GenAI. A university-wide course focusing on teachers' course redesign to include the use of GenAI (AU 2026b) was given. Several local and faculty arrangements have been made where ideas are shared.

Critical Evaluation and Human-Centric Perspectives and Competencies: There is a general focus on "AI for good". Many departments and study programmes have discussed how one can "keep the human in the loop"

Transparency and Privacy: The declaration required from students is a way to ensure a transparent use of GenAI. Teachers are instructed to cite correctly, which includes citing correctly when using GenAI.

Policy Communication: The policies are available on the intranet. It is communicated via the educational hierarchy; the study director discusses with the course representatives on how to include it, e.g. in the assessment.

Assessment Design and Authentic Assessments: There has been a requirement that all courses decide on the use of GenAI. The board of studies ensures that all course descriptions include information about the use in the exam.

Observability

Continuous Evaluation: The central pedagogical unit continuously evaluates GenAI tools. There is no structured collection of GenAI usage across the university.

Collaboration and Discussion: This is done in different fora: Many departments have devoted half or a full departmental day to discussing how to use GenAI, there have been workshops organized by the central pedagogical unit, etc.

Ongoing Monitoring: There is no formal structure for ongoing monitoring.

Jönköping University, Sweden

Academically, Jönköping University (JU) is organized into four schools (faculties) offering a wide range of bachelor's, master's, and doctoral programmes across business, engineering, computing, education, health sciences, and social sciences. This structure supports interdisciplinary collaboration, particularly in innovation, digitalization, and sustainability.

In recent years, JU has actively addressed the development and use of AI in both education and assessment. The university has established institution-wide guidance on the responsible use of AI tools, focusing on ethics, academic integrity, legal compliance, and transparency for both staff and students (JU 2025a). These guidelines clarify how AI may be used in learning activities, research, and examinations, and emphasize the examiner's responsibility in defining permitted tools and assessment formats. In parallel, AI-related education is embedded in several programmes, particularly in engineering and computing, and supported by initiatives such as the Jönköping AI Lab (JaiL) and courses on AI ethics and responsible design, reflecting JU's commitment to developing AI competence while safeguarding fair and valid assessment practices.

Compatibility

Academic Integrity and Ethical Use of AI: From an ethical use perspective, AI should support learning rather than replace human judgment. Academic Integrity and clear instructions in course guides about what constitute acceptable AI use.

Enhancing Teaching and Learning: In JU, AI should enhance, not diminish, teacher competence; it should empower knowledge. Students benefit from AI to enhance learning; however, students are encouraged to engage with AI tools responsibly, understanding their role as complementary rather than authoritative sources.

Fostering AI Literacy and Skills for the Future: For JU, it is important to use AI to innovate and continuously improve staff work in Education. JU launched structured workshops on AI literacy and assessment design.

Information Security and Data Privacy: JU stresses that staff and educators need to ensure that AI systems are reliable, fair, safe, and trustworthy, and that the management of educational data is secure and protects the privacy of individuals. Safe systems like Microsoft Copilot are integrated.

Support for Diverse Educational Needs and Equity: According to JU guidelines, employ AI tools to support fairness and inclusion in education, while avoiding bias or discrimination. Fairness and inclusion are key principles included.

Trialability

Integrating AI into Educational Practice: In JU, the teacher must explain how and why AI tools are used in grading, providing feedback, or supporting learning materials.

Critical Evaluation and Human-Centric Perspectives and Competencies: Regarding a Human Centre perspective, students are expected to uphold academic integrity by ensuring that the work they submit is their own and to avoid over-reliance on AI for academic tasks. The use of AI boots is encouraged as a tool; however, it should be supervised by a human (JU 2025b).

Transparency and Privacy: The declaration states that students are expected to be transparent about how AI affects their learning and assessment.

Policy Communication: The policies are available on the intranet and updated regularly.

Assessment Design and Authentic Assessments: There has been a requirement that all courses decide on the use of GenAI. For students, the policy emphasizes responsible use, avoiding plagiarism and cheating, and understanding that generated text may still count as misconduct if misused (SVT 2024; JU 2025a).

Observability

Continuous Evaluation: JU, through EDUCATE (JU 2025b), offers workshops and guidelines to integrate AI responsibly, demonstrating institutional commitment.

Collaboration and Discussion: Students, teachers, and supervisors are encouraged to discuss, share, and participate in various events related to AI.

Ongoing Monitoring: Continuous monitoring, updating and innovating, including the new platform (JU AI network) to foster interdisciplinary collaboration and policy.

CONCLUSIONS

This paper examined institutional rules and guidelines for GenAI at six Nordic CDIO institutions, using Diffusion of Innovations Theory as an analytical lens. Despite differences in organizational structures and governance traditions, these institutions share an aligned understanding of the challenges and opportunities posed by GenAI in HE. GenAI is considered a transformative technology that requires pedagogical, ethical, and organizational responses.

From a compatibility perspective, the findings show a consistent emphasis on academic integrity, transparency, and data protection. Across all cases, GenAI use is anchored in existing academic norms and regulatory frameworks, reinforcing the principle that responsibility and accountability remain with students and staff.

Regarding trialability, there is a tendency toward contextual and pedagogically grounded implementations. Traffic light models, course-specific guidelines, templates, and declarations of use exemplify mechanisms that allow experimentation while maintaining clarity and fairness. This flexibility enables teachers to integrate GenAI in ways that are appropriate to disciplinary practices and assessment goals. From a CDIO perspective, these mechanisms are particularly relevant to Standard 9 (Enhancement of Faculty CDIO Skills). Rather than treating GenAI as an external disruption, institutions invest in developing teachers' competencies to design learning activities, assessments, and guidance that meaningfully integrate AI.

In terms of observability, the results are more heterogeneous. While all institutions acknowledge the need for continuous evaluation, dialogue, and policy updates, the level of

formalization seems to vary. Some institutions have established structured mechanisms for monitoring developments, whereas others rely more on ad hoc discussions and local initiatives. This dimension connects closely to CDIO Standard 11 (Learning Assessment). GenAI challenges traditional assessment practices by blurring boundaries between individual and assisted work, thereby increasing the importance of transparent assessment criteria, authentic tasks, and reflective documentation of learning processes.

Overall, the findings suggest that Nordic HE institutions are moving toward pragmatic and adaptive governance models for GenAI. Rather than attempting to fully control or prohibit its use, institutions focus on setting clear boundaries, supporting informed experimentation, and strengthening faculty competence and assessment practices. From a CDIO standpoint, this approach reinforces the interconnected nature of curriculum, pedagogy, faculty development, and assessment. GenAI thus becomes not only a policy challenge but also a catalyst for advancing CDIO-aligned practices that emphasize authentic learning, professional skills, and continuous improvement.

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ASSESSING STUDENTS OR THEIR AI TEAMMATES? CASE STUDIES IN THE GAI ERA

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ABSTRACT

The widespread adoption of Generative AI (GAI) since 2022 has fundamentally challenged traditional assessment methods in engineering education, exposing the weakness in assuming submitted artefacts reliably represent student thinking. This article's purpose is to provide concrete examples of how GAI has changed formative and summative assessment in engineering courses. Through comparative case studies across five CDIO institutions in Norway, Denmark, Finland, France, and Singapore, we examine GAI implementations involving over 400 students. All cases are characterized using the Traffic Light Model by Arene (2024), which categorizes AI use as required (blue), prohibited (red), reported (yellow), or allowed (green). Our findings reveal that effective GAI integration requires thoughtful assessment redesign—structured implementations with clear pedagogical frameworks demonstrated positive outcomes, whilst less structured approaches can lead to student over-reliance and reduced learning. The evidence indicates thoughtful assessment redesign grounded in constructive alignment is required, where AI use decisions are tied explicitly to learning outcomes. Effective integration demands shifting from product-based to process-based assessment methods, emphasizing evaluation of student reasoning, judgement, and capacity to work responsibly with AI.

KEYWORDS

Generative AI, assessment, learning paths, CDIO Standards 2, 3, 11.

INTRODUCTION

Since the release of ChatGPT in November 2022, Generative AI (GAI) has been on everybody's lips. Especially in teaching and learning, it has been clear that the traditional assessment formats are deeply challenged by GAI. This is particularly so in Higher Education (HE), where essays, technical and managerial reports, programming problems, math problems, etc. can all be easily solved and answered by one of the freely available GAI tools. Recently, we have seen a bigger integration of the tools in many software products, e.g. an AI answer when using Google Search, correction of grammatical errors and suggestions for improvement of a text in your text editor.

Many of the GAI tools are free of charge and very easy to use; thus, many students found these tools attractive and started using them. Sakirin and Said (2023) "*found that 70% of users chose ChatGPT-powered conversational interfaces over traditional techniques, citing convenience, efficiency, and personalization*." (p.22). Although many institutions banned these tools in the beginning, many have since shifted towards a more positive view of seeing GAI as an effective learning tool (McDonald, Johri, Ali, & Hingle Collier, 2025). In 2026, more and more Universities start to have their own sovereign RAG LLM servers.

Especially within assessment, the GAI tools have challenged our conventional ways. As Niels Lauritzen (2025) notes in his debate post "*With a simple prompt, uploading my notes and exam assignments to Google AI Studio, I saw for the first time generative AI produce a correct answer with completely correct references to the syllabus*.". Jens Bennedsen (2025), in his reply to Niels Lauritzen's post, wrote "*We evaluate the students' process (how they solve a task) by evaluating their product. The problem is that with GAI, we now have a digital assistant that can produce a product of a quality that will typically result in the highest grade. In other words, we cannot assume a correlation between the students' process and the product they create. What is the solution? We need to develop types of examinations that allow us to evaluate the students' processes directly. This requires that we can observe the process or at least get the student to discuss it based on questions such as: What did you do to make the product? What alternatives are there? What considerations led you to choose this product? Why does it make sense to use this theory?*"

The Traffic Light Model published by the Rectors' Conference of Universities of Applied Sciences in Finland (ARENE, 2024) categorizes AI use as required (blue), prohibited (red), reported (yellow), or allowed (green) (Figure 1). Students at universities of applied sciences are recommended to use AI in learning and studying. The model is used in Finnish Universities of Applied Sciences to clearly communicate when and how the use of AI tools applies to course assignments (Kontio, 2025).



Figure 1: The labels of the Traffic Light Model.

Based on the Traffic Light model, this paper gives examples from teachers at five CDIO institutions on how they allowed and used GAI for formative and summative assessment in 2025. A short pedagogical discussion on the assessment of product or process in the GAI new era is given, then impacts on educational frameworks for quality enhancement (as accreditations and CDIO) are questioned.

RELATED WORK

Growing student involvement in assessment and feedback with GAI

The growing use of GAI by students is changing how assessment and feedback take place. For teachers, this phase is often stressful and time-consuming. Could teachers make their workload lighter and boost student learning by guiding students to evaluate their own outcomes and engage in peer review with GAI?

Research by Zhan et al. (2025) suggests that GAI has the potential to enhance student feedback engagement with its rapid personalized feedback, ongoing interaction and practice. Nonetheless, significant challenges and ethical concerns also arise. Without proper training, students might misuse GAI, which could inhibit their engagement and learning. To support students, teachers should assist students in defining their individual feedback goals before seeking feedback and create ample opportunities to interact with GAI tools.

While students generally consider teacher feedback to be more helpful and trustworthy, GAI feedback stands out for being much easier to access, more understandable, less negative, and better at aiding sense-making and understanding. The findings suggest that these feedback modes are not an either/or; students can and do engage with both, because they serve different functions (Henderson, et al., 2025).

FIVE CASE STUDIES IN ENGINEERING EDUCATION

The following case studies shed light on different ways to tackle the “problem” that GAI has made clear when assessing students – are we assessing the students or the GAI?

Developing Critical Thinking Practices Interwoven with Blue GAI usage at NTNU

In a study published by Styve et al. (2024), a first-year bachelor's 7.5 ECTS engineering course designed to foster critical thinking skills was adjusted to integrate the use of GenAI. Present day software development is largely characterized by assembling premade blocks of code, rather than creating and coding algorithms. If students perceive the task to be the delivery of a well-functioning code, there is a risk that coding blocks found on internet forums are uncritically assumed to perform what they claim to do. The recent establishment of generative AI tools exacerbates this challenge.

The course design - formative assessment

For the study, one of four mandatory assignments in the course was redesigned and titled “AI with Critical Thinking”. (In addition to the four assignments, students had to finish and deliver a portfolio project.)

The students were instructed to solve a programming assignment by using GitHub Copilot to generate code, and then analyses the code suggested by Copilot with respect to the quality and robustness criteria taught in the course. They were then instructed to ask ChatGPT to analyses the code generated by Copilot, compare the output with their own analysis, and write down their observations and reflections on the process so far. Based on their own analysis and that of ChatGPT, they were then instructed to refactor the generated code to the required level of quality and robustness. For the final part, they were also required to describe and explain their changes to the code and answer questions to reflect on the overall experience.

Results

Before and after this assignment, changes in the students' Critical Thinking skills were evaluated using a Critical Thinking Survey Questionnaire. The sample size was 90 students, with 55 that filled out the pre/post survey. In addition, 88 of 90 students submitted their assignments with reflective questions included. Overall, the results indicate that the students' awareness of the limitations of AI Tools, the importance of code quality and robustness, and of critical thinking practices were raised by the redesign.

The redesigned assignment did raise awareness among the students, as seen from the survey and the thematic analysis of reflective questions. The authors report that the positive effects on critical thinking from the pre- and post-surveys were positive after a single iteration. The most notable change in the survey was for the claim "*I use a piece of code in my program even if I do not fully understand it*" which declined from 'seldom' closer to 'never'. The reflective questions clearly indicate an increased awareness among the students with respect to limitations in the trustworthiness of AI. For further in-depth analysis the reader is referred to the original paper.

Accessing the programming process instead of the program using blue-green GAI at Aarhus University

One of the areas GAI is believed to deliver a significant reduction in the man-hours needed is programming. The LLMs are trained on a huge amount of source code etc., making them very good at producing code for the kind of problem very often used in introductory programming courses.

The context

An introductory programming course (5 ECTS) at a professional bachelor's programme (3,5 years). The class size is around 175. The students are divided into eight groups of 20-25 students. There is a lecture (2*45 minutes, all students in an auditorium) and problem-solving class (2*45 min in their group) each week. There is a final exam at the end of the course with a pass/fail grade.

Previously, the final exam was a "traditional" written exam containing programming problems where the students should implement programs solving the problems. The grading of their programming competencies was based on the product, i.e. the source code. Any of the GAI tools can create flawless implementations of the programming problems, thus making it problematic to use their product as a proxy for their competencies.

The assessment

The students use GAI to create a solution (program) to the problems. Instead of using the source code as the basis for the assessment, the student must explain the program and how it solves the problem, i.e. it has changed from a written to an oral exam.

The students get 4-5 programming problems to solve. The time is the same as the previous written exam (two hours). Ten to twelve students sit in a large room at the same time. The examiner and co-examiner walk around in the room and ask the students about their solution and make small modifications (without the use of GAI) to their code. In this way, 10 students can be examined in two hours, making the form as efficient as the traditional written exam (previously, it took approximately 10 minutes to grade a student's solution).

Student feedback

After the first time we held this type of exam, we evaluated it with the students by sending them a questionnaire. It was a rather small cohort (approximately 70 students), and the response rate was 47%. In general, the students found that the form evaluated the course's learning outcomes; it was less stressful than a normal exam and resembled the way they envision programming will be in the future (you must understand and modify code made by GAI). On the negative side, the students would have liked more time to show their solutions to the examiner.

Teacher feedback

It was an effective exam, but quite stressful to keep track of 10-12 students at the same time. It took some time for the students to understand what we wanted when asking them about their solution (not "read C++ code aloud but explain the code using the correct terminology). We have therefore developed a more precise rubric to assess each student. To enhance their explanation skills (evaluative judgement of code produced by GAI), the problem-solving classes focus more on students explaining code to each other.

ICT tools in green-yellow-red GAI at Turku UAS

This case examines the implementation of GAI in a first-year engineering course, ICT Tools (2 ECTS), at Turku University of Applied Sciences. The approach reflects a shift toward a new learning culture emphasizing hybrid intelligence, shared responsibility in assessment, and the importance of AI literacy.

Pedagogical framework

Traditionally, assessment relies on teacher evaluation and feedback after submission. From a learning perspective, it is essential for students to analyze the feedback they receive and learn from it. Unfortunately, this process is often minimal, and students lack motivation after submission. In the model used in this course, AI acts as a mentor and sparring partner, enabling iterative improvement before final submission. Students engage in AI-assisted self-assessment based on the assessment criteria provided by the teacher, and maintain learning diaries, making the learning process transparent and enhancing learning and metacognitive skills.

At the beginning of the course, the teacher presents a slide with a title "AI as a mentor and sparring partner" among other topics, including instructions on peer review: "You can also use AI in peer review of your own performance. If necessary, give AI the evaluation criteria according to which your output should be evaluated."

Instructing the responsible AI use

At Turku UAS, the implementation of the traffic light model is part of the overall process of promoting and activating the use of AI in teaching and learning and strengthening AI literacy (Kontio, 2025). The Traffic Light Model is used in the instructions of each learning task to promote equity, AI literacy, and reduce fraud-related concerns. For example, independent weekly tasks in this course allow unrestricted AI use (green), while specific assignments require reporting (yellow), including prompts, AI outputs, and self-evaluation. In the final exam, the use of AI is prohibited (red).

A student example: good and bad practices

As an independent PowerPoint assignment for the ICT Tools course, the student can submit a presentation on a professional topic of interest. The assignment has a yellow traffic light. Before submitting the assignment, the student must check that the presentation contains all the elements required in the assignment and prepare a self-assessment using a ready-made assessment framework. The assessment is affected by whether the presentation contains the required elements. The task focuses on creating functional presentations that include the required elements. The process can be AI-assisted.

A student tested Microsoft 365 Copilot to generate an eight-slide presentation aligned with course criteria. While the output was visually appealing, it lacked required elements (hyperlink, table, chart, video, and graphic objects). The student gave Copilot an assessment framework used by the teacher, and as a result, Copilot told the student about the shortcomings and gave development suggestions. However, the student submitted the AI-generated version with self-evaluation but without revisions, resulting in a lower grade. In an ideal situation, the student would have made the changes after receiving the AI peer review, for example, with the help of AI sparring, learning in the process, and finally submitting the improved presentation, which would have led to a higher grade. This would also have reduced the teacher's workload in the final assessment and final feedback.

Project management planning using blue GAI at IMT Atlantique

The MGP210 “Project Management Methods” course spans 16h30 over two months. Offered since 2007, it is mandatory for the 60 engineering students enrolled in the IT apprenticeship track during their first Master’s year. The cohort is divided into three classes of 20 students, organized in teams.

The course is structured on a project-based learning model (11h15), in which students first delineate a project idea and match it with a real funding call (e.g. regional, Horizon Europe). Then they elaborate a project management plan (no implementation).

Seven intended learning outcomes (LO) are used for assessment: (LO1) identify and formalize project objectives, strategic issues, main activities and deliverables, (LO2) define a work breakdown structure with task assignment, (LO3) estimate effort & task durations in a schedule sequencing activities, (LO4) identify, qualify and quantify project risks, with mitigations, (LO5) define SMART KPIs, (LO6) integrate environmental, social-societal dimensions as financial & legal concerns, and (LO7) structure and align project concerns in a logical framework. The grading model is competency-based, students are assessed for each LO with a rubric on a scale: not observed, not acquired, partially acquired, acquired, and beyond expectations. For crediting, three LOs must be acquired or higher, and none at not acquired or below.

In the 2024 session, 80% of the grading was based on student’s project management plan reports (approx. 60 pages) and 20% on a final oral presentation. Due to the increasing use of GAI by students in their reports, as an experiment, it was decided in Fall 2025 to let students an ‘open bar’ on the usage of GAI (Traffic Light Model “use of AI required”). Students elaborate their report with GAI somehow as a knowledge team member. The grading moved to 60% for oral and 40% on report. Still in 2025, the institution did not yet have GAI regulations formalized, and no GAI introductory course is in place.

In 2025, the assessment was threefold. First, an intermediate oral presentation (flipped-classroom model) of teams on their understandings of methods and tools on LO2-6 (1h15 for

5 teams of 4, one team per LO2-6 roles) is fully formative on lower Bloom levels. Slides are mostly generated with an AI tool by students. Secondly, a final oral presentation with Q&A (1h15 for 4 teams of 5) is summative, where both the teacher (50%) and students assess their peers (50%) on higher Bloom levels. This presentation allows for a more objective verification of skills. Via an online tool, each team is assessed on the seven LOs by another class of 20 students attending the presentations. Students also provide textual comments on each. Finally, the reports are assessed by the teacher with the help of GAI (Mistral 7B-instruct on a personal laptop), for 40% of the final mark. Each team report follows the same structure thanks to a LaTeX template of the project management plan, with a section for each LO1-6. LO7 is transversal. Selected document sections are ingested as a knowledge base (PM-BoK, Open PM² developed by the EU commission, and some dedicated ISO). Educationally, structured frameworks for LO1-LO7 prompts are used to guide assessment with the rubric criteria, 7W2H and PREPARED4ED (Verkuilena, 2025).

This sandboxed course clearly has no quality evidence of the use of GAI, it needs some pedagogical realignment in the Biggs sense. An evaluation questionnaire was filled by students at the end of the course. Quantitatively, their appreciation of full freedom to use GAI was rated above 7/10, but qualitatively, some students gave critical comments. In 2025, teams used mainly ChatGPT and Claude, which rely on a massive amount of data, and tend to limit students' reasoning via copy-and-paste answers. For the Fall 2026, a project management planning chatbot would pedagogically help to ensure coherence between guided responses and each LO. As a consequence, a chatbot is to be designed and a dedicated RAG with chunks from the knowledge base is to be envisioned.

Formative flipped learning assessment using yellow GAI at Singapore Polytechnic

Singapore Polytechnic has reduced reliance on high-stakes examinations by strengthening AI-enabled formative assessment as a core mechanism for preserving student cognition while maintaining assessment robustness. The institution implemented an AI-supported formative assessment model embedded within synchronous flipped-learning lessons. The approach was piloted in 2025 with 59 first-year diploma students across three classes, taught by three experienced lecturers, providing a realistic instructional context.

During each lesson, students completed an initial in-class quiz generated from approved learning materials. Conducted under supervised conditions, (1) first, this quiz functioned as a low-stakes, high-signal formative assessment, capturing authentic evidence of conceptual understanding. GAI analyzed student responses in real time, identifying misconceptions and patterns of difficulty at both individual and class levels. Lecturers then (2) adjusted instruction through just-in-time teaching, reallocating lesson time to address diagnosed gaps rather than pre-planned content coverage. A second in-class quiz followed, allowing both lecturers and students to observe immediate learning progression. Analysis of combined quiz results showed clear improvement for multiple students between the first and second quizzes, indicating measurable cognitive gains within a single lesson cycle. At the end of the lesson (3), GAI generated personalized learning reports for students, including targeted notes and follow-up tasks derived strictly from demonstrated performance. These reports were designed to support reflection and improvement, not to replace student thinking.

In this design, GAI functions as a cognitive amplifier rather than a cognitive substitute. This model preserves cognition in three ways. First, supervised, real-time sensemaking requires students to interpret questions and apply disciplinary principles without extended opportunities for AI outsourcing. Second, metacognitive regulation is reinforced through personalized feedback grounded in students' own errors and misconceptions; 72% of students used the

personalized notes, and 97% of these reported positive learning impact. Third, differentiated cognitive demand ensures foundational mastery for weaker students while extending higher-order application for stronger students, avoiding the cognitive flattening common in uniform assessments.

From an assessment quality perspective, the approach strengthens robustness across multiple dimensions. Task design aligned closely with learning outcomes enhances validity. Repeated formative checkpoints and aggregated performance patterns improve reliability. Supervised administration and process-level evidence (attempts, progression, misconceptions) strengthen academic integrity. Diagnostic reports and performance trends provide defensible evidence to support summative decisions where required.

Student perception data reinforces acceptability and feasibility. With an 80% survey response rate, over 80% of students rated the approach as engaging and effective, and 94% valued the structured quiz–lesson–quiz–feedback sequence, suggesting that cognition-preserving assessment design was well received rather than resisted.

This use case demonstrates that the response to GAI-disrupted examinations lies not in tighter surveillance or blanket AI prohibitions, but in intentional assessment redesign. By embedding AI-enabled formative assessment at the heart of teaching and learning, SP preserves student cognition, enhances instructional responsiveness, and maintains assessment robustness in an AI-rich educational environment.

DISCUSSION

This paper is twofold: experiences of GAI tools usage by engineering students and of GAI usage by faculty for their student formative and summative assessments. GAI disrupts a core assessment assumption: that the submitted artefact is a reliable proxy for the learner's thinking. In GAI-rich contexts, product quality alone becomes weak evidence of competence, shifting the problem from integrity to validity, specifically what claims can defensibly be made from the evidence collected (Zhao et al., 2024). Across the five cases, the practical implication for CDIO is consistent: assessment needs to generate process evidence, not only a final product.

What engineering students are doing with GAI, learning outcomes considerations

Graduate outcomes are disciplinary knowledge oriented, but also transversal for engineering professional competences. GAI as a teammate displays transversal skills: capabilities to understand, apply, analyze, evaluate, and create. It can offer instant results (e.g. text, source code, slides), but also guidance in student learning paths and journeys, as a teammate chatbot or a process-oriented formative sparring partner. As Stokkink (2025) concludes in the scope of GAI, "*proper adjustment of assessment methods to align with learning objectives is essential. [...] formative and summative assessment should be aligned*". All the case studies show that AI literacy and critical thinking are key competencies in the modern era of AI, and cognitive processes should not be outsourced to GAI. Hybrid intelligence (human-GAI collaboration) seems to optimise learning outcomes. This reframes competence as engineering with and around AI, including error detection, verification, and responsible disclosure (Zhan et al., 2025).

GAI with an assessment role: the process rather than the result

GAI has fueled the discussion of who the actual "person" is that produces the product we assess. But, did we previously know if it really was the student who created the product? One could argue that GAI has just changed “ghost-writing” (others creating the assessed product) from something only accessible to students with financial capabilities to all now.

Rethinking the roles of the student and the teacher has great potential. AI can enhance formative feedback, improve learning and grades, and reduce teacher workload, but risks require careful management and guidance. Clear guidelines on GAI use in learning tasks are essential to ensure equal and fair assessment and reduce fraud-related concerns. The Traffic Light Model (ARENE, 2024) on an organisational level is an example of a useful tool that supports shifting assessment toward critical thinking and judgment rather than end products alone (Kizilcec et al., 2024).

Feedback from students at IMT Atlantique case study in 2025 highlights several concerns (translated verbatim): “Abolish the 100% AI in favor of a better balance of personal reflection / AI writing”; “AI does the job for us too well […] we did not retain much of the concepts because they relied too much on AI, while the concepts covered are crucial and very relevant in business”, “the solution that we ended up finding, the AI didn't have it for us and couldn't have offered it to me”. This is illustrated also by student feedback: “starting from 0 with the AI, I could only accept what it said without critical thinking since I had no hindsight on what it said or knowledge. We should learn the fundamentals and then use AI as a tool rather than making it a substitute”. Another replied: “perhaps you could give us examples of relevant questions to ask so that we can better understand how to engage with the tool and what can actually be expected from it”.

Navigating the assessment, traffic lights of the 5 case studies

In the case of AU, the focus is on programming as a verb rather than a noun, i.e., the programming process rather than the program. The primary focus is students' demonstrated understanding of program logic, their ability to reason about behaviour, and their capacity to make targeted modifications without relying on GAI.

In the case of SP, the focus on formative assessment allows students to use GAI that provides feedback and pathways to enhance their learning under the supervision of the lecturers. While not affecting grades directly, open and green approaches remain credible when paired with designs that surface process, such as oral defence, staged deliverables, and critique-and-improve tasks.

In the case of NTNU, the students are required both to use GAI (blue light), and to comment on the use and how the output from the tools relates to their assignment (orange light), in line with recommendations by Haugan et al. (2017) to redesign mandatory coursework assignments as formative assessment exercises. One aspect of further work that may need to be addressed is feedback engagement. Feedback alone does not have intended effects without student engagement (Zhan et al., 2025). Another way of describing the same challenge is the phenomenon dubbed the “reflective zombie”, as outlined by de la Croix and Veen (2018).

DISCUSSION

AI is a disruption happening in a very rapid pace. In 2026, some institutions have GAI regulations, while others do not. Some are already engaged in their conformance with, e.g., the EU AI Act (data confidentiality, sovereignty, etc.), while others do not. Student and faculty AI literacies are at their early stages. GAI is a fast-moving topic where students in many cases are as competent as their teachers. QA agencies and accreditation bodies (e.g., US ABET, French CTI, EA, AACSB) for the higher education sector will take time to revise their reference criteria on GAI. Formal mandates might soon emerge. As of today, and to the best of our knowledge, in 2026, most international accreditation bodies for engineering education only prompt institutions to regulate their students and faculty's GAI use via internal policies.

Integrating GAI in educational programs is no small feat. It will take time to reach a coherent way of doing that free of inconsistencies. For example, within the non-normative CDIO framework several of the standards are affected by the impact of GAI use. The *CDIO Standard #2* needs to cover GAI use by students in their learning trajectory, both with respect to mentoring, and as an engineering and reporting tool. The *CDIO Standard #11*, covering the assessment of learning, needs to be explicit about assessment of processes rather than end products alone. Effective and reliable student assessments should use a variety of methods, constructively aligned with each type of outcome (Stokkink, 2025; Corbin et al., 2025). Furthermore, the *CDIO Standard #10* on enhancement of faculty competence will need to be revisited. Educators and teachers, disciplinary and pedagogical experts, need not be LLM specialists but they do need to figure out how GAI can be used to enhance learning. We suggest that we – the CDIO community – start revising our standards.

CONCLUSION

Generative AI has exposed a fundamental weakness in conventional assessment: the assumption that the quality of a submitted artefact can be treated as reliable evidence of student learning. Across the five cases presented, a common implication emerges—in GAI-rich environments, assessment must generate credible evidence of student thinking, including reasoning, judgment, and the capacity to work responsibly with AI.

The cases show there is no universal response. What is required is thoughtful assessment redesign grounded in constructive alignment, where decisions about when AI should be prohibited, allowed, reported, or required are tied explicitly to learning outcomes. Whether through oral examinations, reflective critique, or supervised tasks, the direction is clear: engineering education must increasingly assess how students think and learn, not only what they produce.

From a CDIO perspective, this extends beyond individual courses to programmatic alignment of GAI-related learning outcomes, faculty capability, and assessment practices across curricula. The central question is no longer whether engineering education should respond to GAI, but how it can do so while preserving cognition, strengthening professional judgement, and sustaining assessment validity in an AI-rich era.

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A TWO-MODULE APPROACH TO ACHIEVING CDIO STANDARD 4 IN INTRODUCTORY ENGINEERING EDUCATION

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ABSTRACT

This study examines the implementation of a two-module structure for the introductory course Introduction to Engineering Education at D. Serikbayev East Kazakhstan Technical University, aligned with CDIO Standard 4. The first module, Business Creation, focuses on fostering students' creative and entrepreneurial thinking, while the second module, Fundamentals of Engineering, emphasizes project-based application of engineering principles. A comparative survey-based study was conducted to evaluate the effectiveness of the redesigned course structure, analyzing student engagement, motivation, understanding of engineering practice, teamwork, and acquisition of basic engineering and digital competencies. The descriptive survey results suggest that the two-module approach is associated with higher self-reported cognitive readiness, professional awareness, and practical skills compared to the traditional single-module format. Findings highlight the importance of early exposure to both creative and technical aspects of engineering education and demonstrate the potential of modular course design in promoting professional identity, problem-solving abilities, and project-based competencies within the CDIO framework.

KEYWORDS

introductory engineering education, two-module course structure, creative thinking, project-based learning, entrepreneurship education, CDIO Standard: 4.

INTRODUCTION

Modern engineering education must prepare specialists for complex professional tasks. Engineers should not only apply fundamental knowledge. They should also solve ill-structured problems, think creatively, work across disciplines, and collaborate in teams (Felder & Brent, 2016; Johri & Olds, 2011). These skills are especially important in the context of digitalization, Industry 4.0, and complex engineering systems. Therefore, cognitive and metacompetencies are becoming essential, including critical thinking, generation of non-standard ideas, and transformation of creative solutions into engineering projects (Cropley, 2015; Altshuller, 1999).

One widely recognized approach to modernizing engineering education is the CDIO initiative. CDIO means Conceive–Design–Implement–Operate. Unlike general active-learning approaches, CDIO uses the lifecycle of engineering products, processes, and systems as the educational context (Crawley et al., 2014). The framework is implemented through CDIO Standards. These standards guide curriculum design, integrated learning experiences, design–implement activities, active learning, assessment, and continuous improvement (Crawley et al., 2014; Malmqvist et al., 2020). Within this framework, introductory engineering courses play an important role. They introduce students to authentic engineering practice and prepare them for later project-based and team-oriented learning (Edström & Kolmos, 2014; Malmqvist, Hugo, & Kjellberg, 2015).

CDIO Standard 4 is especially important for introductory engineering education. It focuses on personal and professional skills and attributes. These include teamwork, communication, problem solving, reflection, and professional growth (Rugarcia, Felder, Woods, & Stice, 2000; Dym, Agogino, Eris, Frey, & Leifer, 2005). Integrating these skills into the curriculum helps prepare graduates who are technically competent, able to address ill-structured problems, and effective in multidisciplinary teams (Felder & Brent, 2016; Cropley, 2015).

This study proposes and analyzes an original two-module approach to the course “Introduction to Engineering Education” within the CDIO Standard 4 framework. The first module develops students’ creative engineering thinking. It includes creative and TRIZ-based tasks, idea generation, and activities for overcoming cognitive barriers (Altshuller, 1999; Cropley, 2015). The second module focuses on an engineering project. In this module, students apply creative and analytical skills to move from conceptual ideas to technically substantiated solutions (Dym, Agogino, Eris, Frey, & Leifer, 2005).

The aim of this study is to compare one-module and two-module models for organizing an introductory engineering course. The comparison is based on student questionnaire data. The study evaluates how the preliminary creativity module affects students’ cognitive readiness for project work, confidence in generating engineering solutions, engagement in learning, and self-assessed quality of completed projects.

The originality of this study lies in the curriculum architecture and competency staging of the course. The paper does not present creativity or project-based activities as isolated elements. Instead, it proposes a sequenced two-module model. In this model, creative and entrepreneurial preparation comes before introductory engineering implementation. The contribution is not a new assessment instrument. It is a structured curriculum model that operationalizes CDIO Standard 4 through staged development of problem framing, value awareness, teamwork, and concept-level engineering design. Unlike conventional introductory CDIO courses, which often combine orientation, teamwork, and projects in one block, this model separates creative problem identification from technical project work (Cropley, 2015; Dym, Agogino, Eris, Frey, & Leifer, 2005).

LITERATURE REVIEW

Engineering education has shifted toward closer alignment with modern industry needs. Traditional discipline-centered curricula have been criticized for weak engagement and limited exposure to engineering practice (Sheppard et al., 2009). Within the CDIO framework, introductory engineering courses are expected to motivate students, introduce authentic engineering activity, and prepare them for later design–implement experiences (Crawley et al., 2014).

A common approach is a single integrated module that combines engineering design, teamwork, communication, and basic technical content. Such courses are valued for compactness and administrative simplicity. They often include short design projects, hands-on activities, and problem-based learning, giving students early experience of engineering practice (Dym et al., 2005; Prince & Felder, 2006). Studies report positive outcomes, such as higher motivation, better understanding of engineering professions, and stronger first-year engagement. However, many objectives must be addressed in limited time. This creates trade-offs between breadth and depth and may constrain the development of engineering fundamentals and higher-level design competencies (Goldberg, 2020; Borrego & Newswander, 2008; Subramaniam et al., 2024).

In response, some institutions use multi-module or staged models. These models distribute learning objectives across modules and support gradual competency development. Pedagogically, this is consistent with constructivist learning and cognitive load management. It reduces the need to address technical, creative, and organizational skills at the same time (Prince & Felder, 2006). Multi-module models also make it easier to align learning outcomes with specific CDIO standards, especially when introductory orientation is separated from hands-on engineering implementation (Crawley et al., 2014).

Recent CDIO studies show that introductory courses often provide early exposure to engineering practice, teamwork, professional roles, and design–implement activities (Crawley et al., 2014; Malmqvist et al., 2020; Medina, 2023). However, many CDIO implementations combine orientation, creativity, teamwork, and projects within one course block. The preparatory stage of idea generation, entrepreneurial framing, and value-oriented problem formulation is often less explicit. This stage is important for engineering identity formation. First-year students begin to see themselves as future engineers when they define meaningful problems, understand user needs, and create value through engineering solutions (Jackson et al., 2022; Rodriguez et al., 2018). Therefore, the proposed two-module structure links entrepreneurial engineering education with early engineering identity formation by placing creativity and value-oriented problem framing before technical project work.

Entrepreneurial and value-creation competencies are also important in introductory engineering education. Modern engineers must solve technical problems and understand market needs, stakeholder expectations, and social context. Therefore, early engineering curricula increasingly include idea generation, business modeling, and innovation thinking (Barba Sánchez & Atienza Sahuquillo, 2018; Snihur, Lamine & Wright, 2021; Makai & Dőry, 2023). These concepts can strengthen systems thinking and help students view engineering as a value-driven activity, not only as a technical profession.

Despite growing research on introductory engineering courses, project-based learning, and entrepreneurial education, their modular architecture remains insufficiently studied. Existing studies usually focus on course outcomes, teaching methods, or specific pedagogical tools. Systematic comparisons between one-module and multi-module models are still limited

(Sheppard et al., 2009; Jamieson & Lohmann, 2012). In particular, little is known about how a two-module structure, separating entrepreneurial orientation from foundational engineering implementation, can support staged competency development within the CDIO framework.

This gap motivates the present study. It compares one-module and two-module structures of the course “Introduction to Engineering Education.” The proposed model separates a creativity- and entrepreneurship-oriented module from a fundamentals-oriented engineering project module. This separation aims to improve learning effectiveness and better align the course with CDIO principles and first-year students’ learning needs.

EXPERIENCE OF EKTU IN IMPLEMENTING CDIO STANDARD 4

At D. Serikbayev East Kazakhstan Technical University, CDIO Standard 4 is implemented through the mandatory first-year course Introduction to Engineering Education. The course is taken by students from engineering, architecture, construction, energy, earth sciences, and ICT programs. It introduces them to engineering thinking, professional roles, teamwork, and the CDIO lifecycle.

Before the redesign, Introduction to Engineering Education was mainly theoretical and orientation-based. It introduced students to the university environment, the engineering profession, and general principles of engineering education. Teaching was based on lectures, discussions, and short assignments. This format helped students learn basic concepts and professional roles. However, it included limited hands-on project work. It also did not guide students from problem identification and idea generation to engineering concept development and presentation. Therefore, the redesign changed both the course structure and teaching approach. The course moved to a two-module structure and activity-based learning. Theoretical content was shortened, reorganized, and embedded into creative tasks, teamwork, problem formulation, concept development, and introductory project activities.

The redesigned course is organized into two sequential modules. The redesigned course consists of two sequential modules. The Business Creation module develops creative and entrepreneurial thinking before project work. The Fundamentals of Engineering module focuses on concept-level engineering implementation in the Fab Lab.

Table 1. Structure of the two-module introductory engineering course

Module	Weeks	Main focus	Key activities	Expected outcomes
Business Creation	1–5	Creativity and entrepreneurship	Design thinking, idea generation, contradiction solving, preliminary business model, product viability testing	Creative thinking, problem framing, value awareness
Fundamentals of Engineering	6–15	Project-based engineering implementation	Team project, problem analysis, concept development, sketching/design, prototyping or visualization, presentation	Engineering thinking, teamwork, basic design skills, communication

Although the course includes many activities, the expected project depth is introductory. The course has three contact hours per week. It is also supported by guided independent teamwork. Students are not expected to develop fully engineered or market-ready products. The intended outputs are a clear problem statement, analysis of existing solutions, a preliminary value proposition or business model, a concept sketch, basic engineering justification, a low-fidelity prototype or visual model, and a final presentation. Thus, the course

focuses on early engineering formation, problem framing, teamwork, communication, and understanding of the CDIO lifecycle. It does not aim at comprehensive technical design or complete product development.

The transition between the two modules follows a structured idea-to-project process. At the end of the Business Creation module, teams prepare an idea portfolio. It includes the problem statement, target users, value proposition, preliminary solution, and feasibility considerations. Ideas are screened by relevance, user value, feasibility, available Fab Lab resources, and potential for concept-level engineering development. Selected ideas are then transformed into engineering project briefs. These briefs include functional requirements, constraints, expected outputs, and a prototyping or visualization plan. In the Fundamentals of Engineering module, students develop these briefs into engineering concepts through analysis, sketching, basic justification, prototyping or visualization, and final presentation.

Assessment is aligned with the staged course outcomes. In the Business Creation module, students are assessed on problem identification, idea originality, user needs, value proposition, feasibility, and teamwork. In the Fundamentals of Engineering module, assessment focuses on engineering concept development, analysis of existing solutions, design sketches, basic engineering justification, prototype or visual model quality, use of engineering and digital tools, teamwork, and final presentation. Peer evaluation supports individual accountability in team projects. Instructor assessment is based on rubrics aligned with each module and CDIO Standard 4.

The creativity-first sequence is based on scaffolding and constructivist progression. First-year students often have limited experience with ill-structured problems. They also struggle to connect technical solutions with user needs. Therefore, the Business Creation module acts as a preparatory scaffold. It develops problem awareness, idea generation, and value-oriented thinking before technical project work. This sequence may reduce cognitive load. Students do not have to learn engineering tools, teamwork, and project development at the same time. It also supports cognitive readiness for project-based learning (Wood et al., 1976; Sweller, 1988; Bransford et al., 2000).

EVALUATION OF THE TWO-MODULE COURSE STRUCTURE IMPLEMENTATION

Evaluation methodology

To evaluate the redesigned two-module structure of Introduction to Engineering Education, a comparative survey-based study was conducted. The course was aligned with CDIO Standard 4. The study assessed changes in student motivation, perception of the engineering profession, and self-assessed competencies. It focused on the transition from a traditional introductory format to a modular structure with active and project-based learning.

The study used a pre- and post-implementation comparative design. The pre-implementation survey involved students who completed the course before the redesign. At that time, the course was mainly theoretical and orientation-based. The post-implementation survey involved students who studied the redesigned course with the Business Creation and Fundamentals of Engineering modules.

Participants and cohort characteristics

The study involved two cohorts of first-year undergraduate students enrolled in the mandatory course Introduction to Engineering Education. The pre-implementation cohort included 85

students. The post-implementation cohort included 92 students. The first cohort completed the course before the redesign. The second cohort studied the redesigned course with the Business Creation and Fundamentals of Engineering modules. Both cohorts were comparable in academic level, year of study, institutional context, and field of study. Students represented engineering, architecture, construction, energy, earth sciences, and ICT programs. Since the course was mandatory, the samples consisted of regular course participants, not self-selected volunteers.

Survey instrument and construct mapping

The questionnaire measured students' self-reported perceptions related to CDIO Standard 4 and the two-module course objectives. It included Likert-scale items grouped into several constructs. These were engagement, understanding of the engineering profession, creative thinking, problem formulation, basic engineering and digital skills, teamwork, project-based learning experience, motivation, and perceived professional relevance. These constructs were mapped to CDIO Standard 4 outcomes. They covered early introduction to engineering practice, personal and interpersonal skills, teamwork, communication, and professional awareness. Closed-ended items used a five-point Likert scale. The percentages in Figure 5 show the proportion of students who selected "agree" or "strongly agree" for each survey dimension.

Data collection and analysis

The data were analyzed using descriptive and inferential statistics. Descriptive statistics summarized responses for each survey dimension before and after the redesign. Since the items used a five-point Likert scale, the Mann–Whitney U test was applied. This test is suitable for comparing two independent groups with ordinal data. Statistical significance was set at $p < 0.05$.

Effect sizes were calculated using the rank-biserial correlation coefficient, r. This helped estimate the practical magnitude of the observed differences. The interpretation followed conventional thresholds for small, medium, and large effects. The proportions of students selecting "agree" or "strongly agree" were also calculated for each survey dimension and used in Figure 5.

To support content validity, the questionnaire items were based on the course learning outcomes and CDIO Standard 4 competency areas. The items were reviewed by instructors involved in the two-module course implementation. This ensured alignment with course objectives and learning activities. Internal consistency was assessed using Cronbach's alpha. The result showed acceptable reliability, $\alpha = 0.82$.

Although the main dataset consists of student survey responses, the redesigned course also included performance indicators. These included project presentations, concept sketches, low-fidelity prototypes or visual models, and use of basic engineering and digital tools. These outputs were assessed using criteria such as problem formulation, feasibility, teamwork, engineering reasoning, prototype or visualization quality, and presentation clarity. However, these indicators were used mainly for course assessment. They were not fully included in the comparative statistical analysis. Therefore, the findings should be interpreted mainly as self-reported perceptions. Future research should combine survey data with rubric-based project assessment and objective competency indicators.

Results and discussion

A comparative analysis was conducted between two student cohorts. The first cohort completed Introduction to Engineering Education before the two-module redesign. The second cohort completed the redesigned course with the Business Creation and Fundamentals of Engineering modules. The comparison focused on professional self-determination, engineering thinking, motivation, and readiness for practical engineering activities.

The survey results show higher post-implementation values across all analyzed dimensions (Figure 1).

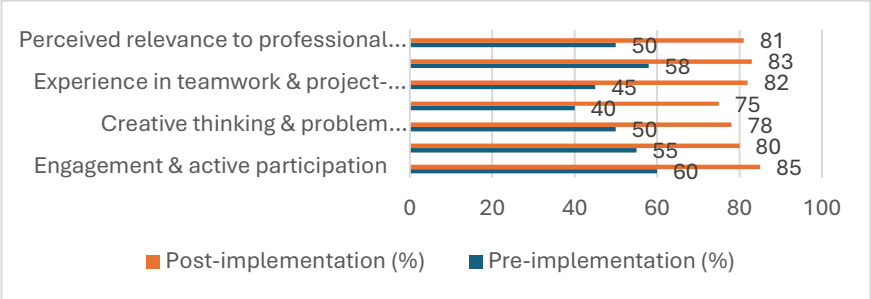


Figure 1. Percentage of students selecting “agree” or “strongly agree” (4 or 5 on a five-point Likert scale) for each survey dimension before and after implementation of the two-module course structure

The percentages in Figure 1 represent the proportion of students who selected “agree” or “strongly agree” on a five-point Likert scale. The largest differences were observed in engagement, understanding of the engineering profession, teamwork and project-based learning, acquisition of basic engineering skills, and perceived relevance to future professional practice.

Open-ended responses were used to contextualize these results. Post-implementation students more often referred to practical tasks, teamwork, project development, engineering tools, and professional roles. They also reported more reasoned career choices, stronger motivation, and clearer understanding of engineering practice. In contrast, pre-implementation students more often described engineering in general terms and reported limited experience with project work, teamwork, and engineering tools. These comments should be interpreted as self-reported perceptions, not as objective measures of learning outcomes.

The observed differences may be explained by the sequence of learning activities in the two-module model. The Business Creation module served as a preparatory stage. It developed problem awareness, idea generation, user orientation, and value-based reasoning before technical project work. This may have reduced the cognitive demands of the Fundamentals of Engineering module. Students entered the project phase with clearer intentions and more developed initial concepts. The second module then transformed these ideas into engineering outputs through teamwork, analysis, sketching, prototyping or visualization, and presentation.

Overall, the results suggest that the two-module structure improves the educational impact of Introduction to Engineering Education. The integration of Business Creation and Fundamentals of Engineering supports engineering identity, professional self-determination, practical engagement, and readiness for project-based learning. However, the findings should be interpreted mainly as evidence of students’ perceived learning experience, since the study relies primarily on survey responses and open-ended comments.

The two-module structure also creates implementation challenges. The Fundamentals of Engineering module depends partly on Fab Lab infrastructure, digital fabrication tools, engineering software, and spaces for teamwork and prototyping. This may limit transferability to institutions with fewer resources. The model also requires close coordination between instructors responsible for creativity, entrepreneurship, and engineering projects. This increases faculty workload during idea screening, project supervision, and assessment. For larger cohorts, the model may require teaching assistants, standardized rubrics, peer evaluation, and structured project management procedures. Thus, the approach is scalable but resource-sensitive and should be adapted to each institution's infrastructure and teaching capacity.

CONCLUSIONS

This study examined the redesign of the first-year course Introduction to Engineering Education. The redesign used a two-module structure aligned with CDIO Standard 4. The model combines the Business Creation module and the Fundamentals of Engineering module. The first module focuses on creativity, entrepreneurial awareness, problem framing, and value-oriented thinking. The second module focuses on introductory project-based engineering implementation. The main contribution is the staged curriculum architecture. In this structure, creative and entrepreneurial preparation comes before concept-level engineering design and project work.

The results suggest that the two-module structure was associated with higher student engagement, clearer understanding of engineering practice, stronger motivation, and greater readiness for teamwork and project-based learning. These outcomes may be explained by the sequence of learning activities. Students first developed problem awareness and initial ideas. They then transformed these ideas into engineering concepts through teamwork, analysis, sketching, prototyping or visualization, and presentation. Thus, the model may support early engineering identity formation. It also provides a structured introduction to engineering practice within the CDIO framework.

At the same time, the findings should be interpreted with caution. The study was conducted in one institutional context. It also relied partly on students' self-reported perceptions. Survey results and course-based observations provide useful evidence of perceived effectiveness. However, further research is needed to strengthen the empirical basis of the model. Future studies should include larger and more diverse cohorts. They should also use longitudinal tracking, objective assessment of project performance and prototype quality, rubric-based competency evaluation, and comparison across programs or institutions. Further attention should be paid to scalability, Fab Lab infrastructure, and instructor workload.

Overall, the study shows that a staged two-module approach can help operationalize CDIO Standard 4 in introductory engineering education. Its effectiveness, however, depends on careful curriculum design, aligned assessment, available infrastructure, and institutional support.

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CO-LOCATION LABS FOR AUTHENTIC LEARNING: EXPERIENCES FROM SINGAPORE POLYTECHNIC'S ENGINEERING CLUSTER

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ABSTRACT

The rapid evolution of technology presents constant challenges for Institutes of Higher Learning (IHLs) in maintaining curriculum relevance whilst ensuring graduates possess industry-ready competencies. This paper examines how Co-location labs (Co-labs) within Singapore Polytechnic (SP)'s Engineering Cluster address these challenges through systematic industry-academia collaboration, exploring how students achieve authentic learning within Engineering Learning Workspaces under the CDIO framework. The paper first provides a literature review on different approaches to industry-academia collaboration, namely internships and Co-location arrangements, discussing their relative merits in affording real-world learning experiences. This work further examines Co-lab implementation within SP's Engineering Cluster, which comprises the Schools of Electrical and Electronic Engineering (EEE) and Mechanical and Aeronautical Engineering (MAE). Through the Cluster Industry Engagement Centre (CIEC), strategic partnerships have established physical industry presence on campus featuring Industry 4.0 applications, 5G and aioT systems, Smart Energy Technologies, and Advanced Manufacturing solutions that emphasize hands-on learning and collaborative environments. Survey results based on stakeholders' feedback and focus group discussion are shared to examine experiences with Co-location learning environments. The study investigates how these engineering workspaces enhance students' learning outcomes, develop their skill attributes, and improve their industry readiness, whilst several implementation challenges are identified and elaborated upon. Findings demonstrate that Co-labs provide a means to advocate CDIO Standards 6 and 7 through industry-integrated environments supporting concurrent skill development. This approach enhances faculty competence (Standard 9) through direct industry exposure and collaborative opportunities with professional practitioners. The paper concludes with reflections on Co-labs as effective mechanisms for supporting authentic learning in IHLs. Key success factors are identified, and strategies for overcoming implementation challenges are proposed using guidance from the CDIO Framework, providing a roadmap for other institutions seeking to implement similar initiatives in engineering education.

KEYWORDS

Co-location Lab, Engineering Education, Academia and Industry Partnership, CDIO Standards 1-3, 6, 7 and 9.

INTRODUCTION

The accelerated evolution of emerging technologies is fundamentally transforming the industrial landscape (Gartner, 2024), presenting unprecedented challenges for tertiary education institutions globally. The imperative to maintain curriculum relevance amid rapid technological advancement has emerged as a critical concern for educational institutions. Recent data indicates a significant disruption in workforce skills, with 44% of workers' competencies projected to be disrupted within a five-year timeframe, and approximately 60% of the workforce requiring reskilling by 2027 (World Economic Forum, 2023). This dynamic environment necessitates a responsive and adaptive approach to curriculum development to prevent skills misalignment between graduates and industry requirements (Desha 2009, Chua 2020).

Authentic Learning in Higher Education Engineering

Creating learning environments that include engineering workspaces and laboratories to align to real-world tasks and context is an approach to authentic learning. The concept of authentic learning is likely to have first grown out from a body of work that sought to understand learning in workplace apprenticeships done by Brown, Collins & Duguid (1989). The study explained the importance of learning activities and environment are integral to cognition and learning. In this paper, the authors use the term "authentic learning" to describe learning that is supported by being situated in an environment that aligns learning objectives and activities with real-world tasks and context via Industry Academia Collaboration (IAC) (Kozanitis et al, 2009).

Authentic learning in higher education engineering is addressed notably within the CDIO Standards 3.0 framework as well. The CDIO framework facilitates authentic learning by immersing students in real-world engineering contexts that mirror professional practice. Standards 1 and 6 establish the conceiving, designing, implementing, and operating (CDIO) context and having suitable engineering learning workspaces respectively. The integration of appropriate learning environments and educating engineering students with the CDIO framework develops a holistic understanding of the challenges of engineering and the need to develop solutions in collaboration with others. Beyond setting the context and engineering workspaces to support authentic learning, Standard 12 (program evaluation) is important for authentic learning as well. A study by Cheah (2022) suggested the need to make reflective practices explicit in the CDIO framework. The Mirror-Microscope-Binoculars metaphor was introduced in the study to illustrate three levels of reflection for the continual improvement of academia programs. This emphasis on reflective practice is more important than ever, due to the rapid developments in technology and world events today. The following will review various studies of authentic learning in higher education through IAC:

A study by Mejtoft (2015) reported that students from Umea University, Sweden, successfully collaborated with media group VK Media to renew their digital news platform. The applied physics and electronics students developed digital platforms such as websites and mobile applications for the media company to keep up with technological changes. The author reported that the industry-academic collaboration following the CDIO framework led to higher levels of engagement from both students and industry. Standards like Active Learning and Design-Implement Experiences made students more aware of the actual problem and have a better professional attitude towards the project and results. Other than higher student engagement, another study by Tiewtoy et al (2019) reported that due to IAC, their agricultural engineering students have gained better employability and enhanced their faculty professional development to work with industry. The study highlighted their 5 steps IAC process: 1) university visit, 2) student internship, 3) industry visit, 4) industry-based co research and 5)

co-develop curriculum which incorporates CDIO standards like integrated curriculum, integrated learning experience and enhancement of faculty competences to be key reasons why the IAC was successful. Many industry companies are classified as Small and Medium Enterprises (SMEs), and unsuccessful IAC can be costly to their finances. As such Bridgewood and Sorensen (2020) reported a successful IAC between students from Technical University of Denmark (DTU) and manufacturing company, where the industry placed students are able to transfer their knowledge to subsequent students to ensure project continuity and success. The study reported that due to the increased IAC, the students met various CDIO standards like learning outcome, design-implement experiences and integrated learning experiences as well. Lastly, a study by Jaca et al (2021) reported their experience with IAC where their Industrial Engineering students from the University of Navarra, Spain worked with a machine tool company. The students visited the company and had specific sessions with the engineers of the company to reinforce their learning. The study reported that their students positively value the challenges posed by the company, and that the project was developed in the company's environment. The positive feedback encouraged the university to continue their IAC.

Alignment to SP Education Model

In Singapore Polytechnic, strategic partnerships with industry must be meaningful, purposeful and enable robust value exchange between parties. By integrating industry partners directly onto the campus, the institution ensures that students and staff are exposed to the latest technologies and practices. This aligns with one of the four key pillars of our SP Education model shown in Figure 1, supporting authentic learning and industry readiness across all SP courses. In essence, the overarching considerations for our SP Education Model are derived from the 3-pronged guidance given to us by Ministry of Education (MOE) namely PET (Pre-employment training), CET (Continuing Education & Training) and Industry Engagement (IE).

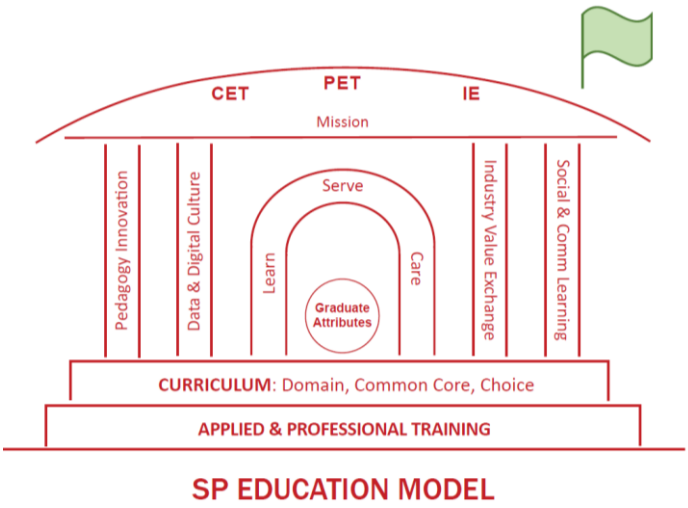


Figure 1. SP Education Model

The Co-lab approach ensures that we remain current with domain-specific trends and technological developments, enabling our students to experience curricula that are relevant to industry needs. Through authentic learning experiences, students develop knowledge and skillsets that are directly applicable to current industry practices, bridging the gap between academic theory and real-world application.

CDIO in Singapore Polytechnic and SP Engineering Cluster

Engineering education requires a structured framework that effectively guides the redesigning of our curriculum to constantly meet the learning needs of our students. The sustained implementation of CDIO has established it as a key approach in Singapore Polytechnic's Engineering Education Ecosystem. In the next section of the paper, a holistic review on the adoption of CDIO for Engineering Education referencing EEE, Diploma of Electrical & Electronic Engineering (DEEE) as case study is shared.

The 3-year DEEE programme in Figure 2 begins with a Common Core Curriculum (CCC) that equips students with essential human and digital skills crucial for success in a rapidly evolving world. As student progresses from this foundation, they advance through a comprehensive technical journey: starting with engineering fundamentals in Year 1, including mathematics, circuit analysis, and basic programming; moving to intermediate concepts like microcontroller programming and communication systems in Year 2. In the final year, students can choose from one of the seven specialisations to deepen their domain knowledge. This specialisation pathway, combined with industry internships, and flexible electives that allow students to explore their passions or tailor their study to specific career goals, ensures graduates emerge as well-rounded, industry-ready professionals with both technical expertise and practical experience.

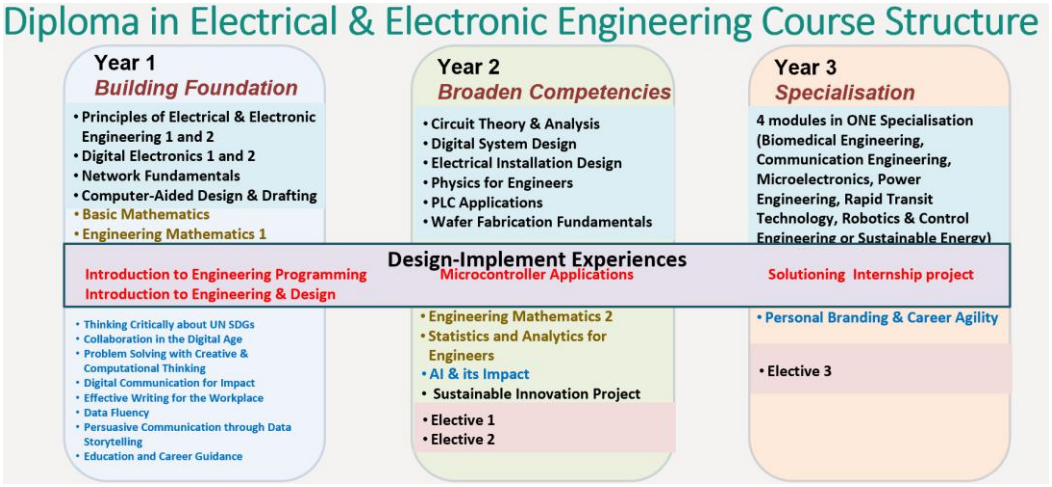


Figure 2. CDIO approaches across DEEE student learning journey

The integration of the CDIO framework across the 3-year curriculum in Figure 2 and Figure 3 demonstrate a progressive approach towards scaffolding the learning and building the students' competencies and confidence as they progress into their senior years of studies. While the first and second years establish foundational knowledge through structured laboratory settings, the third year marks a significant transition towards industry-focused learning. This culminates into a Solutioning Internship where students apply their specialised knowledge in real-world contexts. The Co-lab approach further enhances this authentic learning experience by bringing industry partners directly into the campus environment. This approach creates a seamless bridge between academic theory and professional practice, where students engage with genuine industry challenges whilst remaining within the supportive campus ecosystem.



Year 1: IED and IEP **Year 2: Microcontroller Application**	**CDIO Standard 4**: Introduction to Engineering **CDIO Standard 5**: Design - Implement Experience **CDIO Standard 8**: Active Learning	**CDIO Standard 3**: Integrated Curriculum **CDIO Standard 6:** Engineering Learning Workspaces **CDIO Standard 7**: Integrated Learning Experience
Year 3: Solution Internship	Students apply their specialised knowledge in real-world contexts	

Figure 3. DEEE students transition from lab to industry

The structured progression from controlled laboratory experiences to industry-integrated projects effectively transforms the traditional learning environment into an authentic workplace setting, preparing students for the complexities of real-world engineering challenges.

SP Engineering Cluster Industry Engagement

Singapore's RIE2030 strategic framework (National Research Foundation, 2025) recognises that navigating global economic shifts and technological disruptions requires sustained investment in research and innovation, particularly through intensified R&D efforts in high-impact sectors and horizontal enabling technologies with cross-sector applications. Singapore Polytechnic's Co-lab initiative aligns with this research and innovation focus by fostering industry-academia partnerships to build resilience and maintain Singapore's competitive edge as an advanced manufacturing and connectivity hub. The Ministry of Education's Planning Guidance for the Polytechnics and ITE for Financial Year 2026 further reinforces this alignment by establishing four key priorities that the Engineering Co-lab is uniquely positioned to address. The guidance's emphasis on industry relevance focuses on developing work-ready graduates with relevant skills in an AI-pervasive world through closer partnerships with employers and authentic work experiences through internship and Work-Study Programmes (WSP). The Co-Lab initiative exemplifies this approach by facilitating industry-academia collaboration. Similarly, the priorities of lifelong learning, comprehensive student support, and enhanced teaching practices create a framework within which the Engineering Co-lab can serve as a catalyst for continuous skills development, inclusive learning environments, and

innovative pedagogical approaches that prepare students for an evolving technological landscape.

The SP Co-lab initiative is operationalised for Engineering students through the Engineering Cluster Industry Engagement Centre (CIEC), which drives strategic partnerships with industry to achieve these objectives. By leveraging the combined expertise and resources of both schools (EEE and MAE), including lecturers, students, equipment, curriculum, and training materials, CIEC facilitates impactful collaborations across electrical, electronic, and mechanical engineering domains. CIEC adopts a structured engagement framework via its Industry Engagement Platform, starting with identifying value propositions, formalising partnerships through Memorandum of Understanding (MoU), allocating collaborative spaces, and assigning mentors. This is shown in Figure 4. Industry-relevant student projects and internships are supported through structured mentorship by both faculty and industry experts. The engagement approach presented could serve as a reference blueprint for SP future potential industry partnerships engagement in establishing Co-lab set up.

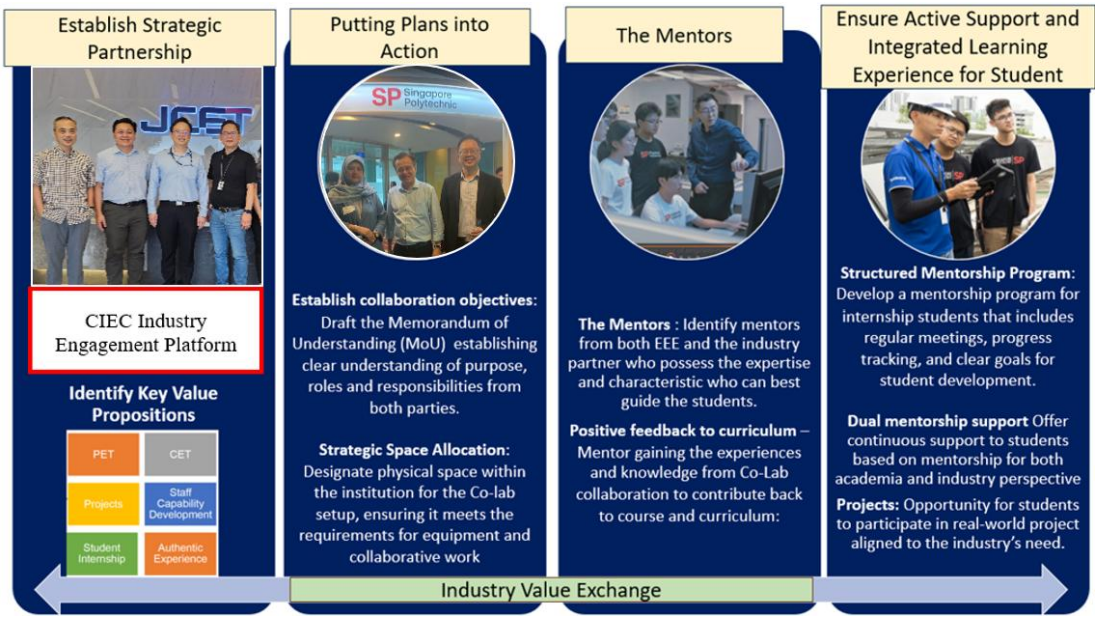


Figure 4. CIEC Industry Engagement approach

Co-lab Implementations and Benefits

Singapore Polytechnic's Engineering Co-lab addresses the challenge of providing authentic industry learning experiences by creating industry-integrated learning spaces that bridge the gap between academic theory and practical application. These centres and laboratories provide immersive learning and hands-on training, preparing students to meet the demands of the evolving technology landscape. Beyond just having a better holistic understanding of the industry, the continuous feedback from industry partners will enable staff (course chairs and teaching members) to constantly review their curriculum and materials ensuring relevancy to the industry.

The EEE Co-labs serve as a cornerstone for fostering technology-specific advancements and industry-academic collaborations, with each lab dedicated to a particular technology domain pertinent to its industry partner's needs. These labs are strategically integrated with EEE's eight tech hubs (SP EEE, 2025), which organise and allocate staff and resources based on

specific technological capabilities and domains, ensuring a focused and relevant learning environment. Similarly, the MAE Co-lab (SP MAE, 2025) creates value exchange through a collaborative ecosystem that nurtures both industry transformation and student development. Through the Advanced Manufacturing Learning Journey (SP-AMLJ), students engage in hands-on experiences that bring Industry 4.0, AI and sustainability concepts to life. Through these collaborations, students from SP's engineering cluster gain exposure to current industry trends and opportunities to engage in real-world projects. This enriches their learning experiences, building their competency in both technical and social skillset mimicking real job which is beyond their daily curriculum studies. To determine how different stakeholders (students, staff and industry) benefit from the Co-labs, a survey was conducted to gather views on the learning outcomes and experiences from the Co-lab initiative. The surveys looked at several areas, including authentic learning experiences, technology trend awareness, application of CDIO in projects and collaborative dynamics, providing insights into how the industry partnerships are improving student learning and skill development within the Co-lab environment.

SURVEY FINDINGS

In this section, the survey results from different stakeholders from Co-lab space will be discussed. Three distinct surveys were separately conducted across different stakeholder groups: Students, Lecturers, and Industry partners. The surveys were based on a 7-point Likert scale and examined the various dimensions outlined above, with particular focus on the bridging of academia-industry gaps and the facilitation of collaborative innovation, as well as project outcomes and organisational benefits.

Students in Co-lab workspace

From the student's perspective, a total of 43 students (EEE and MAE) from the past two semesters with interactions in Co-lab workspaces provided their input. Figure 5 presents the data for students' experiences in gaining better insight into technological trends of the industry. Analysis from the surveyed data reveals that most respondents (30 out of 43, 70%) indicated a "Somewhat large" to "Very large extent" of insights gained, while only a small fraction (4 out of 43, 7%) reported minimal impact.

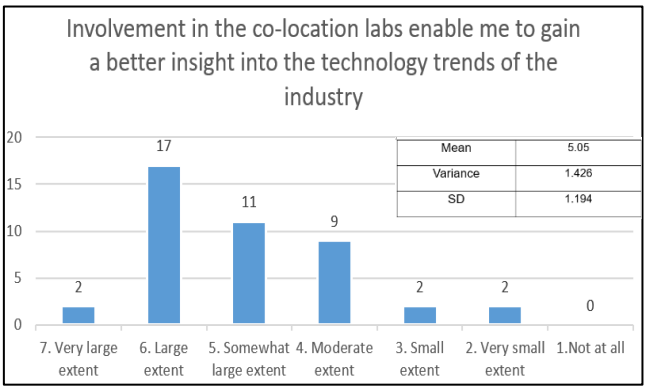


Figure 5. Student data (Insights into technology trends of the industry)

Due to the strong industry presence within the Co-lab workspace, the involvement by students significantly enhances participants' understanding of industry technology trends. This

reinforces the notion that Co-labs serve as an invaluable platform for institutions to keep students connected with industry technological advancements.

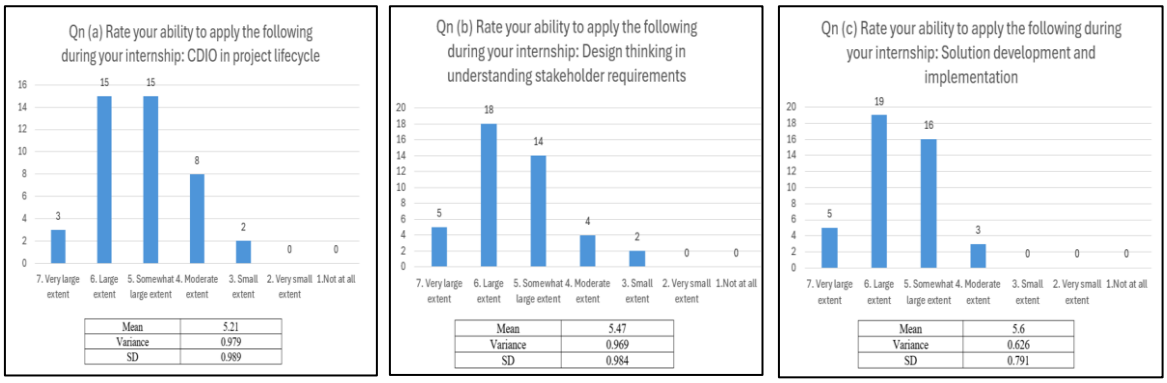


Figure 6. Student Data (CDIO in project lifecycle, DT and solution development)

Figure 6 Qn (a) examines the students' proficiency in applying CDIO for their projects during internships. This provides insights into how this framework addresses the fundamental challenge of integrating industry partnerships with authentic learning experiences. During internship, each student works on their projects through conceive, design, implement, and operate stages. The result reveals that most respondents (33 out of 43, 77%) indicated a “Somewhat large” to “Very large extent” of proficiency in the application of CDIO during internship, while only a small fraction (2 out of 43, 5%) reported minimal application. There are no respondents for options of “very small extent” and “not at all”. These findings strongly suggest that CDIO provides students with an effective framework to navigate and execute their internship projects. Figure 6 Qn (b) and (c) show a notably positive response on students’ self-assessment, their ability in application of Design Thinking, solution development and implementation. For application of Design Thinking skillset, 37 out of 43 interns (86%) rated their ability at "Somewhat large" to “Very large extent”. Similarly, in solution development and implementation, 40 out of 43 interns (93%) rated their ability at "Somewhat large extent" or higher. These results show that students developed foundational knowledge and skillsets through their earlier years of study reflected in Figure 2, effectively translate into practical competencies in design thinking and solution implementation during their internship.

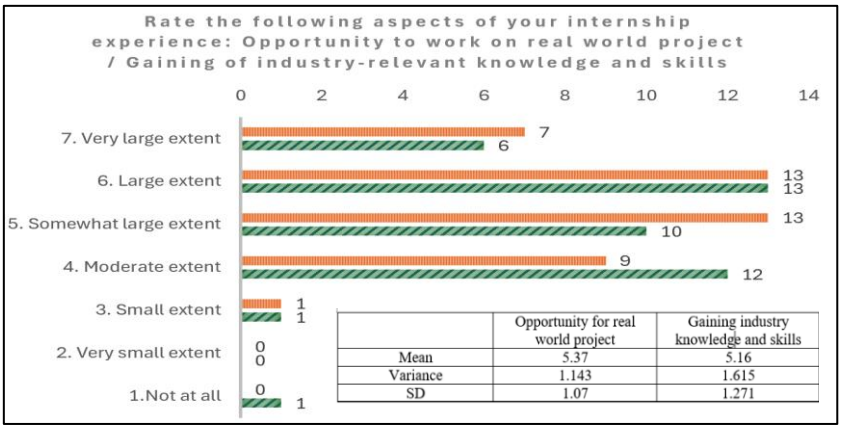


Figure 7. Student data (real-world project and industry relevant knowledge)

Figure 7 presents the students’ surveyed results on the opportunity to work in real-world projects and gaining skillset and knowledge relevant to industry while interacting in the Co-lab workspace. The results show that the responses generally cluster in the mid to upper range

(Likert 5-7, 77% - Opportunity to work on real world project, 67% - Gain Industry relevant skill and knowledge). The distribution shows a moderate positive skew, with mean ratings above 5.0 for both aspects. There are minimal responses in the lower ranges, with only one response each for "Small extent" and notably, one response for "Not at all" in gaining industry-relevant knowledge. These findings strongly support the strength of Co-labs in achieving authentic learning outcomes, where students are immersed in genuine industry environments enhancing their learning experience.

In the next section, the observations from the focus group discussions will be shared and discussed to gain a deeper insight and understanding of the survey data.

Focus group observation

A focus group discussion with 10 students was conducted with aim of gaining deeper insights into the survey responses and better understanding the underlying factors influencing students' learning experiences in the Co-lab. Through this qualitative approach, students were encouraged to share their perspectives on the authentic learning environment, industry project experiences and CDIO applications. The session was recorded and transcribed for analysis, with key themes and representative quotes extracted. The focus group discussion revealed several key observations as follows:

Authentic Learning: Participants noted that working in Co-labs differs significantly from traditional classroom learning. They emphasized the freedom to explore and tackle real-world problems, which enhances their learning experience.

Application of CDIO in Projects: The discussion highlighted the application of CDIO during the students' internship projects. Participants shared challenges faced during the conception and implementation stages, with many finding the implementation phase particularly difficult due to troubleshooting and design iterations.

Real-World Project Experiences: Participants discussed the challenges of working on real-world projects, including the need for self-directed learning and the importance of collaboration with peers and supervisors. They noted that real projects require them to bridge the gap between academic knowledge and industry requirements.

Skill Development: The focus group revealed that participants gained both technical skills (e.g., programming languages) and soft skills (e.g., communication and presentation skills) through their experiences in the Co-labs.

Collaboration and Peer Learning: The importance of exchanging ideas and seeking advice from peers and experienced staff was emphasized as a valuable aspect of their learning process.

Challenges in the Industry: Participants acknowledged the difficulties of adapting to industry standards and the need for continuous learning to keep up with technological advancements.

The focus group findings complement the quantitative survey results, providing deeper insight into how the Co-lab model facilitates authentic learning.

Staff for Co-lab workspace

From the stakeholder staff's perspective, a total of 24 (Engineering Cluster - EEE and MAE) staff provided their input. Table Qn 1(a) denotes the results from the staff survey. The data supports the Co-lab's notion in creating an authentic learning environment within the campus

ecosystem. With 92% of staff “Strongly agree” or “Agree” that the lab enables the staff to achieve desired learning outcomes with students. In addition, the positive response (100%) from Table Qn 1(b) regarding the lab's role in bridging academia-industry gaps indicates how this approach helps integrate academic theory with professional practice. This highlights the value of bringing industry partners into the campus environment to enhance student learning experience.

Table 1. Survey data from Staff on Co-lab

Questions	Responses	Stats
Qn (a) The industry co-location lab learning space enable me to achieve the desired learning outcomes for my students.	7. Strongly Agree (50%) 6. Agree (42%) 5. Partially Agree (4%) 4. Neutral (4%)	Mean: 6.38 Variance: 0.592 SD: 0.77
Qn (b) The industry co-location lab contributes to bridging the gap between academia and industry practices.	7. Strongly Agree (50%) 6. Agree (50%)	Mean: 6.5 Variance: 0.261 SD: 0.51
Qn (c)The industry co-location lab provides a means for staff to keep pace with latest industry trends.	7. Strongly Agree (67%) 6. Agree (25%) 5. Partially Agree (8%)	Mean: 6.58 Variance: 0.428 SD: 0.654
Qn (d) Industry co-location labs at SP enhance collaboration between academic and industry partners.	7. Strongly Agree (58%) 6. Agree (42%)	Mean: 6.58 Variance: 0.254 SD: 0.503

Table 1 Qn (c) demonstrates the lab's contribution toward staff development, with 67% “Strongly agree” and 25% “Agree” about the Co-lab providing a means for staff keeping pace with industry trends. Lastly, staff endorsement (Strongly agree, 58% and Agree, 43%) of enhanced academic-industry collaboration indicates that the Co-location model supports the progression from laboratory experiences to industry-integrated projects. These ratings across all dimensions suggest that Co-labs create an environment where staff and students can both benefit from the close engagement with industry, bringing closer the academia and industry gaps.

Below are some of the sampled qualitative comments from Staff:

Qn: Can you provide specific examples on significant project outcomes that is achieved with the collaboration of Co-lab with industry?

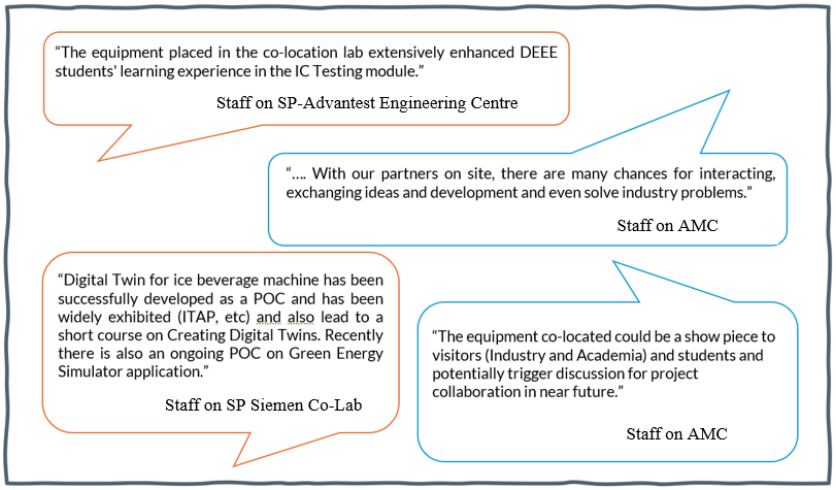


Figure 8. Qualitative comments from Staff

Industry partners for Co-lab workspace

From the stakeholder industry partner's perspective, 8 partners provided their quantitative and qualitative feedback.

Table 2. List of Participating Companies for Survey

Participating companies	
1. Aquapro Solutions Pte Ltd	5. Siemens Industry Software Pte Ltd
2. Advantest Singapore Pte Ltd	6. Haimer Singapore Pte Ltd
3. Chint Singapore	7. Shenhao (Singapore) Pte Ltd
4. Singtel	8. Astech Pte Ltd

Table 3 presented the survey data from Industry Partners on Co-lab. The industry partners' feedback indicates positive outcomes across the three survey questions and shown in Table Qn 3(a). For collaborative innovation, 75% (6/8) strongly agreed and 25% (2/8) agreed that the lab strengthens collaboration and innovative solutioning between stakeholders.

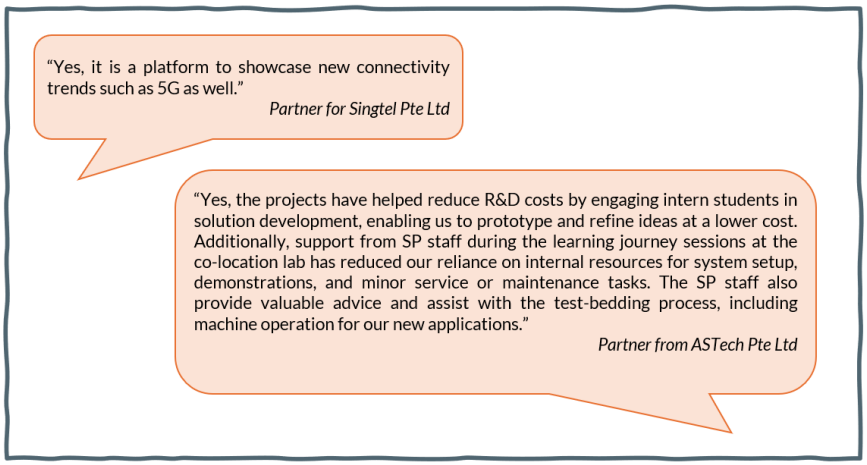
Table 3. Survey data from Industry Partners on Co-lab

Questions	**Responses**	**Stats**
Qn (a) The co-location lab approach strengthens collaboration and innovative solutioning between staff/ students and industry for the project.	7. Strongly Agree (6 out of 8) 6. Agree (2 out of 8)	Mean: 6.75 Variance: 0.214 SD: 0.463
Qn (b) The project/s outcomes delivered by SP students participating in project/s in the industry co-location lab meet my expectations.	7. Strongly Agree (4 out of 8) 6. Agree (4 out of 8)	Mean: 6.5 Variance: 0.286 SD: 0.535
Qn (c) The industry co-location lab strengthens SP Engineering Cluster (Consists of SEEE/ MAE)'s reputation for industry engagement and innovation.	7. Strongly Agree (6 out of 8) 6. Agree (2 out of 8)	Mean: 6.75 Variance: 0.214 SD: 0.463

Project delivery effectiveness shared in Table Qn 3(b) showed an equal distribution, with 50% (4/8) strongly agreeing and 50% (4/8) agreeing that student project outcomes met expectations. This balanced response on project outcomes reflects the challenging nature of industry projects, which require students to develop self-directed learning capabilities and acquire new technical skills independently to meet project requirements. Regarding institutional reputation in Table Qn 3(c), 75% (6/8) strongly agreed and 25% (2/8) agreed that the lab enhances SP Engineering Cluster's standing in industry engagement and innovation. These results demonstrate that the Co-location model successfully facilitates industry-academic collaboration while fostering student development through authentic industry project experiences. This integration of industry partnerships within the Co-lab has fostered mutually beneficial relationships, where companies gain access to innovative solutions while contributing to student development through authentic industry projects.

Sample Qualitative Comments from Industry Partners:

<u>The projects or initiatives undertaken with SP-EEE/ MAE's students and staff have been beneficial to my organization.</u>



Provide details on specific project/s or initiatives facilitated by the industry Co-lab that have led to tangible outcomes or intangible benefits to your organization?

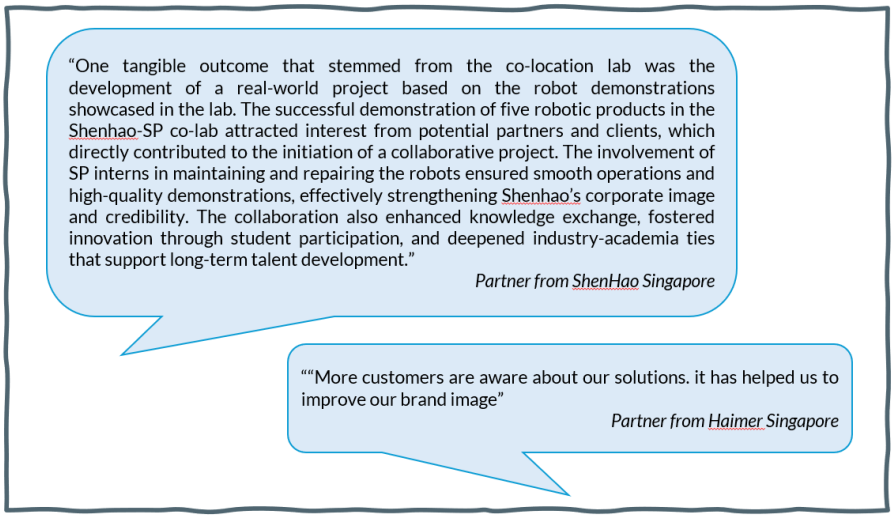


Figure 9. Qualitative comments from Industry Partner (benefits to organization)

The consistently positive feedback across all survey dimensions in Figure 8 and Figure 9 demonstrates a win-win collaboration model that strengthens both institutional and corporate brand reputation in the technology education space. This successful partnership between academia and industry creates sustainable value for all stakeholders, enhancing SP's standing as an innovation partner while providing industry partners with access to emerging talent and fresh perspectives.

In the next section, the reflection on the studies and discussion of future works is presented followed by the conclusion of the paper.

REFLECTION AND FUTURE WORKS

The survey findings from this study provide valuable insights into the effectiveness of the Co-lab in delivering authentic learning experiences. The results show that the Co-lab approach presents a strong alternative for SP students to gain authentic learning compared to traditional company internships. Key success factors include ensuring structured industry engagement

and forming strategic partnerships through careful evaluation of value propositions that benefit both students and the school, while maintaining clear alignment of collaboration objectives.

With the CDIO framework infused into our engineering curriculum, the scaffolding of foundational knowledge and skillsets enables students to take on more complex challenges, such as authentic real-world projects during their internship. The Co-lab approach provides the ideal engineering workspace, real-world problem from industry, and guidance from experts and mentors for students to undertake such projects during their internship.

Survey findings across students, staff, and industry partners validate that this integrated approach not only enhances students' technical competencies but also develops their professional skills through authentic industry exposure.

This sensing study, while informative, represents a preliminary exploration of the Co-lab model's effectiveness. The current findings suggest positive outcomes across stakeholder groups, but deeper longitudinal studies are needed to fully understand the impact on student learning outcomes and skill development.

1. **Tradition internship vs Co-lab (Student):** The relationship between traditional internships and Co-lab experiences requires further investigation. While both approaches aim to provide authentic learning experiences, their relative effectiveness in achieving specific course objectives and learning outcomes need more detailed examination. Future studies could compare learning outcomes and experience between traditional internship programmes and Co-lab-based learning. Initial findings suggest that Co-labs offer unique advantages in providing consistent, structured learning experiences while maintaining the benefits of industry exposure.

2. **Staff Development and Learning (Staff):** Reviewing the work from another perspective and viewpoint, the impact of Co-labs on staff development has emerged as an interesting area to further explore.

   From this work, some of the future research could examine:

   - Expanded studies on experiences of staff attachment programmes within Co-labs compared to company attachment
   - How industry exposure through Co-labs influences teaching methodologies
   - The development of industry-relevant expertise among academic staff

Moving forward, these areas of investigation could help in refining the Co-lab implementation and maximising its potential for delivering authentic learning experiences. A more comprehensive understanding of these aspects will enable better alignment between academic objectives and industry requirements, ultimately leading to more effective preparation of engineering graduates for their professional careers.

CONCLUSION

This work demonstrates that the implementation of Co-labs, guided by the CDIO framework, offers a systematic approach for tertiary institutions to address the challenges of delivering authentic learning experiences in engineering education. Through the implementation of Co-labs within the SP Engineering Cluster, we have observed how this industry-academia partnership approach effectively bridges the gap between theoretical knowledge and practical application. The survey results across different stakeholders supported by the focus group

studies demonstrate that Co-labs create an environment where students engage with emerging technologies, industry-standard equipment, and real-world challenges, thereby enhancing their learning experiences and industry readiness.

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PUTTING THE 'TECH' BACK INTO TEACHING TECHNICAL FUNDAMENTALS – UTILISING THE CDIO APPROACH

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ABSTRACT

The integration of practical skills with engineering theory are the foundation of the CDIO approach. However, challenges lie in rolling this out effectively in a university setting to large cohorts of students. This paper sets out to address how these challenges can be reduced to achieve CDIO standards 7, 9 & 10. Advancement of integrated learning experiences and enhancement of faculty competence and teaching competence requires input from staff members with extensive practical experience. As the changing landscape of engineering education moved towards prioritising an education based on maths, science and theory came at the cost of the fundamentals of practice. In addition, this caused a shift in the university faculty to a staff of academics with mostly research backgrounds and little industry experience. Academics who want to incorporate more CDIO elements to their modules must consider the practicalities of providing large numbers of students with safe and beneficial practical learning environments. This is where technical staff can bridge the gap in staff numbers and expertise. Technical staff possess the know-how and expertise of the skills being taught, alongside the health and safety awareness to get students involved in a safe and supportive way. While it is often argued that technical staff do not have any recognised teaching qualifications, the reality is that in the process of designing, developing and delivering practical workshops for large cohorts of students, technical staff are in effect undergoing teacher training through the very delivery of these modules in collaboration with academic staff. If this is viewed in a CDIO learning context as illustrated in this paper, the true potential of technical staff as educators could be realised. This could provide engineering faculties with more experienced, trained staff and serve to increase their compliance with CDIO Standards 7, 9 & 10.

KEYWORDS

Technicians, Technical Fundamentals, Practical Skills, Manufacturing Technology, Teacher Training, Standards: 7-10.

INTRODUCTION

The CDIO approach of Conceive – Design – Implement – Operate was created with the purpose of educating students to become successful engineers (Crawley, Malmqvist, Ostlund, Brodeur, & Edstrom, 2014). This was a reaction to the changing landscape of engineering education which had moved away from a more practical technical lead pedagogy towards a fully theoretical scientific approach. This move, towards prioritising an education based on maths, science and theory, though valuable, came at the cost of the fundamentals of practice. It also caused a shift in the university faculty creating a staff of academics with mostly research backgrounds and little or no industry or professional engineering experience before entering academia and teaching. These practical skills and experience are the foundation of the CDIO approach and therefore require input from university staff members with extensive practical and technical experience. Accrediting bodies also require that students are provided with these types of modules to meet mandatory learning outcomes (Cairns et al, 2024).

Technical staff have been contributing to the delivery of engineering education since its inception as a technical degree. Engineering education in the UK, seen as growing from practical skilled crafts, was viewed as a secondary trade and entered the universities much later than in other European countries such as France (Crawley, Malmqvist, Ostlund, Brodeur, & Edstrom, 2014). As the focus moved more towards a theoretical, science and research-based approach, the continued contribution of technicians became more invisible. However, this has changed in recent years as institutions, such as the authors', get on board with initiatives like The Technician Commitment, a UK wide initiative which is now getting more international recognition (Vere, 2024), and incorporate a CDIO approach into the syllabus. The core goals of the Technician Commitment are to ensure visibility, recognition, career development and sustainability for technicians working in higher education (HE). Technical staff are vital in the role of delivering practical skills. Giving students the opportunity to learn from experienced practitioners. These skills incorporate and apply the technical fundamentals that are often not retained when delivered only as transmissive learning. Despite this vital contribution in the delivery of education Wragg et al., (Wragg et al, 2023) state that technical staff's role within HE is still poorly understood and not widely recognised within their faculties.

Delivering CDIO modules to cohorts of 200+ students comes with its challenges. As student numbers increase this will only become more challenging (Cairns, Millen, Pick, & McCartan, 2024). This paper sets out to address how these challenges can be reduced to achieve better compliance with CDIO standards 7, 9 & 10. Academics who want to incorporate more CDIO elements to their modules must consider the practicalities of providing large numbers of students with safe and beneficial practical learning environments. This is where technical staff can bridge the gap in staff numbers and expertise to make these modules happen. Technical staff possess the know-how and expertise of the skills being taught alongside the health and safety awareness to get students involved in a safe and supported way.

Teaching is a discipline of its own. A separate skillset to both the practical and theoretical understanding of engineering. It is becoming more common for academic staff across universities to now undergo teacher training within the early years of their career such as a Post Graduate Certificate in Higher Education Teaching (PGCHET) in the UK (Kozanitis, et al., 2009). Savage, (2024), states in his chapter on Technicians as Educators that until recently the idea of technicians teaching was problematic, referencing the quote "you don't teach, you instruct" (Savage, 2024). The history behind this attitude is complex but includes the historical imbalance between the value placed on theoretical (mental) work and skilled (practical) work, despite, as Connelly states in his chapter on the history of technicians, the contextual

knowledge required for this skilled work, (Connelly, 2024), and the argument that technical staff do not receive formal training in the delivery of education. However, as this paper will argue, when viewed through the learning context of CDIO, technical staff are undergoing teacher training through the very delivery of these practical modules. Bui et al, (2025) proposed the CDIO approach as a context for teacher training because of its integration of theoretical knowledge with hands-on experiences, promoting active learning, problem-solving, and professional competency (Bui, Nguyen, Nguyen, & Nguyen, 2025).

Standard 10 of the CDIO approach is the Enhancement of Faculty Teaching. Power et al., (2019) wrote a paper on developing CDIO practitioners to address this standard. The paper suggests the gap be filled by postgraduate staff members by engaging them in formal teacher training at this stage of their career (Power, Tanner, Ryan, & Devitt, 2019). This works well to add to the cohort of staff who will deliver these modules with postgraduates well placed as an extension of academic staff to transfer and apply knowledge on theory during workshops. However, they are not best placed for transferring practical skills knowledge when compared to technical staff. In addition, the position of postgraduate is a stage in an academic career rather than a permanent role. These staff members will usually only spend a few short years in this role, and then new postgraduates will need to be trained. In engineering schools, technical staff are often full-time permanent members of staff. Recognising and investing in their educational contributions will have long term benefits for the whole school. New technical staff can build on this year upon year gaining valuable teacher training. Experienced technical staff already possess extensive teaching experience that isn't formally recognised by the University. Once this is recognised it can be better utilised for the benefit of all stakeholders involved in the CDIO approach.

BACKGROUND

What is a technician?

Wragg et al., (2023) state that because technicians occupy a huge range of roles and responsibilities within education and research, it is difficult to have one single definition (Wragg, Harris, Noyes, & Vere, 2023). However, they can be described as a highly skilled workforce with diverse expertise (Nottingham, et al., 2018). Table 4 adapted from Chapter 1 of Technicians in Higher Education and Research represents the varied roles and expertise of technicians highlighting seven key areas of responsibility (Wragg F. , 2024).

These responsibilities cover just some of the roles of technicians. A further definition in the chapter on defining technicians gives a more encompassing overview

"Technicians are trained and/or skilled in the techniques, tools and/or technology of their subject, providing the practical application of knowledge and/or the expertise to best utilise this practical application through managing, teaching, and/or training others to deliver it, and/or through maintaining and developing environments, standards, resources, and/or facilities required for this practical application to be delivered."

Multiple definitions are being included to illustrate the wide range of knowledge and responsibilities required by technical staff. As Winberg, (2021), states in her paper on The Making of Engineering Technicians, this is still a role not easily classified, disregarded by some and often misunderstood (Winberg, 2021).

Table 4: Variety of technical staff responsibilities, table adapted from (Wragg F. , 2024)

Preparing resources and materials	Operating equipment	**Research**	Training staff and students	Data analysis
Preparing resources and materials	Delivering instructions and teaching	**Teaching**	Providing 1-to-1 support and feedback	Patrol care of students
Arranging servicing	Preventative maintenance	**Maintenance**	Contractor checks	Fault finding
Carrying out audits	Statutory testing	**Health & Safety**	Writing risk assessments	Delivering training
Writing tenders	Budgetary planning	**Finance and Administration**	Purchasing and procurement	Asset registers
Management of infrastructure	Management of equipment and facilities	**Infrastructure**	Inspecting buildings	Planning new building projects and refurbishments
Inductions and training staff	HR processes	**People**	Pastoral care of staff	Line manager

What is their role in delivering education?

Technical staff play a significant role in the delivery of higher education and the enhancement of the student experience. The CDIO approach was born out a need for engineering graduates with better practical and interpersonal skills as detailed in Chapter 1 of Rethinking Engineering Education through feedback from industry on the desired attributes of an engineer (Crawley, Malmqvist, Ostlund, Brodeur, & Edstrom, 2014). Practical modules where students learn how to carry out skilled work both individually and in collaboration with their classmates address some of these desired attributes. These modules are delivered in the most part by technical staff. The Wragg et al. paper on Technicians as Educators emphasises the importance of practice-oriented, skills-based knowledge to create 'employment ready' graduates (Wragg, Harris, Noyes, & Vere, 2023). Survey data from this paper, carried out with a cohort of 1760 technicians in HE across the UK, showed that 83% of technical staff in engineering are involved in teaching. However, of the teaching technicians within engineering, 70% had not received any training with only 9% receiving formally recognised teacher training. Engineering showed the lowest percent of teacher training provided across the range of disciplines surveyed. In addition to limited recognised teaching accreditations for their contribution to education, technical staff often also go uncredited in their research contributions (Iliffe, 2008). Another area within HE where technicians are often the first port of call is in supporting the mental health of students. A survey carried out in 2019 with a cohort of 735 technicians across the UK showed that 22% of respondents said they provide pastoral support for students, 44% said they had discussed personal problems with undergraduate students and 51% with postgraduates. 60% said they had been approached or had approached a student to discuss their mental health. Despite so many technicians providing this type of support 68% said they had not received any training or were aware that training was available (Nottingham, et al., 2018). This is a vital but invisible role carried out by these staff members, often outside their job description, which hugely contributes to student wellbeing and the delivery of education.

How can this be utilised when incorporating a CDIO approach?

Large classes present significant challenges for student engagement. The Finn et al., study on student behaviour in small classes confirms that reducing group size increases engagement (Finn, Pannozzo, & Achilles, 2003). Having small class numbers for practical

modules promotes student engagement and allows for more 1-2-1 tuition helping to put students at ease and promote a safe work environment. A CDIO centred module also doubles as an opportunity for technicians to expand their skill set and gain teaching experience. This parallel track both delivers high quality CDIO based education to students while investing in future delivery of these courses through enhancing the teaching skills of the staff involved.

CASE STUDY – MANUFACTURING TECHNOLOGY MODULE

The School of Mechanical and Aerospace Engineering at Queen's University Belfast have a variety of technical staff involved in delivering both research and education. This paper will examine a case study of the Manufacturing Technology module as both a CDIO module for students and a CDIO learning context for teacher training of technical staff. A previous paper by Cairns et al. focused on the development of this module and how it impacted the student experience and their feedback. The focus here will shift to the parallel benefits of how CDIO modules provide technical staff with teacher training and experience through their delivery.

Module Overview

Manufacturing Technology 2 is a second-year undergraduate module for all students within the school, delivered over one semester. As detailed by Cairns et al., (2024) the school boasts a wide range of manufacturing technologies and processes with highly experienced technical staff. Capabilities include Laser Cutting, Hot Wire Cutting, 3D Printing, CNC machining, Lathe turning, a robot platform and various Composite and Polymer Processes (Cairns, Millen, Pick, & McCartan, 2024). The aim of the module was to create an artefact (*Figure 9*) which could be assessed and students would keep, which included a variety of manufacturing processes that students could both observe and experience hands on (*Figure 10* & *Figure 11*). As the practical workshops would be delivered primarily by the technical staff their input in the module design at every stage was essential.



Figure 9: Finished Artefact

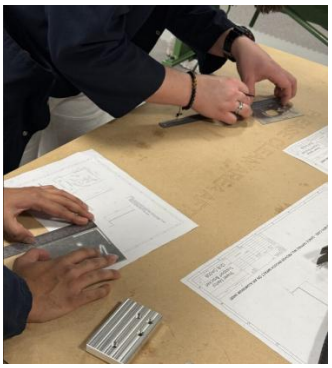


Figure 10: Students reading drawings for using hand tools



Figure 11: Students learning machining of parts in workshop

Complimentary learning material was provided during lecture sessions to both prepare the students and reinforce the learnings of the hands-on elements of the module. In the first year of the module 172 students were enrolled, these numbers have subsequently increased each year with no change in staff numbers. Students are divided into groups of five or six and scheduled to pass through five technician led workshops and demonstrations, along with two sessions of hand tool-based tasks.

Assessment is carried out once assembly has been completed. All parts must be present and working on the artefact. Assessment has been improved by observations by technical staff of common mistakes and incorporating elements to catch these errors. If parts get broken or are not manufactured correctly by the student they are given replacement parts which are a different colour to the original to make it clear to the final assessor that this has occurred and marks are deducted. This is made clear at the start of the module and motivates students to take their time and double check measurements and drawings.

The practical element of the module was conceived and designed by the senior technical staff in the school. This involved the design of the artefact and all its individual parts along with the breakdown of the technical knowledge that would be communicated during the sessions. Technicians with particular specialisms reviewed the lecture content for that part of the module to ensure cohesion with the knowledge and skill communicated in the practical session. This enabled a parallel CDIO path for both students and technicians through the module.

CDIO parallel track

Table 5 illustrates the parallel path students and technicians take through Conceive – Design – Implement – Operate gaining their respective outcomes in the process.

Surveys and Data

Vevox surveys are carried out each year with the students on their experience of this module. In addition, a short survey was completed by eleven technical staff in the 2025/26 academic year, on their perspective and experience of delivering the module. The technical staff who took part comprise of 4 education technicians, who work directly with students for both delivery of modules, support for final year projects and lab training, and 7 workshop technicians who run the in-house workshop manufacturing parts for all student project and research work done within the university alongside supporting practical modules. Most of these technical staff had delivered the module for three years consecutively. Technical staff were asked to rate the importance of engineering students learning hands on skills from experienced practitioners and the importance of their involvement in the design of the module. Staff were also asked several questions requiring a comment.

RESULTS

Both questions relating to the importance of students learning hands on skills and the importance of technician involvement in module design were rated very important by majority of staff (*Figure 12*).

A selection of comments from the open response questions are shown in *Table 6*

None of the technical staff delivering the module received any formal teacher training or were assessed on how they delivered their section of the module and so were under no obligation to make any adjustments to their delivery. However, when asked if they were making changes to improve the delivery of the module the answer was yes across the board. The comments illustrate how continual improvements are being carried out organically by each staff member, indicating an innate reflective approach to their own teaching practice. When asked if delivering the module was valuable for their professional development, the comments were very positive illustrating their interest and enjoyment in transferring their knowledge and skill directly to students despite no formal recognition of the teaching skills they are developing through this process.

Table 5 CDIO parallel track (Power, Tanner, Ryan, & Devitt, 2019) (Bui, Nguyen, Nguyen, & Nguyen, 2025)

	Student	Technical Staff
Conceive	Lectures on what the practical element of the module will involve and how students should approach each stage along with the theory behind the equipment	Stakeholder in conception of the module with a leading role in conception of practical elements and its assessment
Design	Create CAD for parts of the artefact. Learn how to read and understand drawings	Design of the artefact including decisions on what is possible, time involved in completing each stage, detailed descriptions of the learning objectives of each stage set out by senior technical staff
Implement	Making the parts, using hand tools, 3D printing, learning and observing how the machined parts are made.	Setting up the resources. Supplies and consumables for equipment. Determining staffing needs. Varied training to allow for cover of other staff. Providing PPE and health and safety talks. Setting out workshop and hand tool processes.
Operate	Assembly of final piece – understanding the importance of each stage and how each part is dependent on another to fit together for a finished piece.	Delivering the module. Managing the number of students. Module spread across number of locations and areas, technicians managing each space and health and safety.
Outcome	Gain practical skills and understanding in engineering learning directly from practitioners, contributes to more "employment ready" engineering graduates	Gain practical skills and understanding in teaching through delivering the modules and working through each stage of development with the academics. Opportunity to design the module, gain an understanding of factoring in assessment when designing the artefact, practical teaching skills of communicating detailed technical knowledge directly to students, adapting teaching style for each group and improving each year.

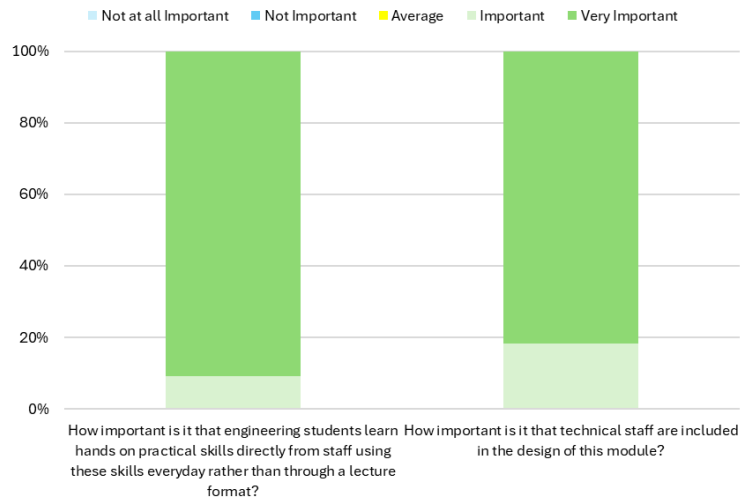


Figure 12 Technical Staff survey results

The benefits of being involved in teaching for technical staff from a career pathway point of view are unclear. Without formal recognition of this element of their work it is not a visible skill that is accounted for in career progression and pay scales. The appetite for more practical modules is clear in the final question illustrating the potential for extending the current CDIO offerings within the syllabus by utilising the expertise and teaching skills of technical staff.

Table 6: Staff survey comments

Have you made changes or improvements to how you deliver the module over the last three years based on what you have learned?	*"Yes, while delivering the theory parts of the lesson I have tried to introduce **structured opportunities** for students to **engage** via group participation in answers questions / brainstorming improvements. I find this helps **maintain interest** in the subject. We have also adjusted how the class is structured each year to improve the student experience."* *"Yes we have continually developed both the content of the module and the approach taken to deliver it; from a time point of view moving from a **structured format to a push/pull** that allows students to work on the elements within the technical lab continually through the class rather than being stuck waiting at a station waiting for others. We have increased the amount of equipment available, added additional processes and **improved the knowledge transfer between staff and students** by fine tuning dialogue to **improve the student learning outcomes/experience**."* *"Yes. Explaining more about the importance in manufacturing safety. The difference between a 3 Axis & 5 Axis milling machine, explaining their capabilities. **What an employer would be looking for** in manufacturing. The importance of designs & drawing using general tolerancing to keep the components cost effective"*
Do you think the opportunity to teach directly to students is valuable to your professional development?	*"I think its valuable to your **personal development**. Professional development, I'm unsure due to limitations within the University for technical staff progression"* *"Yes. Every year the students will ask a wide range of questions, some of which **I won't have considered before and need to seek out the answer to provide them**. Through this process **we all learn a bit more** and I am better placed to provide that information to the next group"* *"Yes, it helps **build rapport** with the students and also with other members of staff who are involved in the module."*
Would you be open to technical staff delivering more practical modules?	*"Yes, technical staff have the technical and practical expertise that would help improve the students experience and knowledge. Engaged students would definitely benefit from more practical classes as I know they enjoy this part of the degree."* *"Yes I would as I really enjoy the interaction with the students, I also think the students really benefit from the technicians one to one experience"*

The overall goal of the implementation of CDIO modules is to improve student engagement, experience and produce graduates ready for industry. These goals are reflected in the student data from the last three years of running this module. One example is that attendance has improved year upon as shown in *Figure 13* with well above 90% attendance in all practicals for the last 2 years. While improved attendance cannot be directly attributed to the CDIO

approach within the module alone. Additional student survey results from the module's first year as stated in Cairns et al., where students were asked open ended questions are shown in Table 7 indicating very positive student experiences of the practical elements of this module.

Table 7: Selected comments on module content and perception

How did you find the practical classes?	*"[It was] good to see all practical elements in person. The CNC practical was a lot of standing - too much information for the time spent. Technician support throughout was great."* *"I very much enjoyed the practical sessions – I did Technology and Design at school and missed the practical side in first year Aerospace. Seeing the workshop was great."*
How did you find the lecture material?	*"Very good lecture content with good links to our Design and Manufacturing module. Despite a couple of repeated lectures, I took different things from each."* *"[The] lecture content was interesting – clear layout and diagrams, One mechanical and one aero example would have been good."*
Did you feel you were learning when completing the practical classes?	*"Yes – more so when actually doing and when practicals complimented each other"* *"Yes – in some more than others. I don't feel I learned as much when only observing."*
How did you find the module overall?	*"Manufacturing Technology has been my favourite subject this year. I really enjoyed making the artefact and enjoyed [the] lectures. I appreciated how the subject could be applied to industry."* *"Happy overall with module - a good break from the theory heavy modules. I really like having the artefact on my desk and play with it when working."*

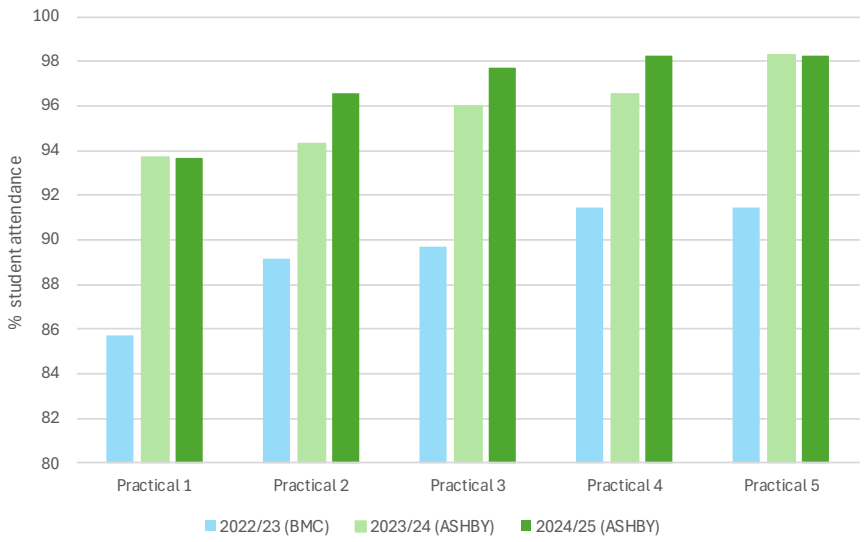


Figure 13: Student attendance for each practical for three consecutive years

CONCLUSIONS

The data and observations herein have shown that technicians are undergoing invisible teacher training in a CDIO learning context. If this could be formally recognised and utilised, it could provide engineering faculties with more experienced trained staff to expand on their delivery of the CDIO approach and benefit student learning. Improving CDIO modules to help students acquire disciplinary knowledge as well as personal and inter personal skills. This will increase their compliance with CDIO Standards 7, 9 & 10 and aid in facing down the challenge of increasing student numbers and lower academic staff to student ratios. In addition, this could provide potential professional development channels for technical staff that don't currently exist, giving more opportunities and recognised transferable skills. Most importantly extending a university's ability to offer CDIO modules will improve both the student experience

and the graduates produced. Addressing the very fundamentals of the CDIO approach to produce ‘employment ready’ graduates. Further to this, when the university values technical skills and knowledge they lead by example to produce graduates who do, ensuring respect, awareness and practical foundations in the many varied and complex skills that are involved in research, education and industry in the field of engineering.

LIMITATIONS

The published research exploring the role of technicians is limited. However, within the literature there is clear evidence of the importance of their contribution to both education and research and the need for it to be valued, visible and recognised. The above data is limited by number of technicians who took part in the survey, and is confined a single institution. Only attendance data for students was taken over multiple years. It would be beneficial to rerun the original survey from the inception of the module again now for comparison. Attendance data alone cannot be directly linked to a positive student experience in the module.

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CULTIVATING SUSTAINABILITY MINDSETS IN MECHANICAL ENGINEERING EDUCATION THROUGH DESIGN-IMPLEMENT EXPERIENCES

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ABSTRACT

This paper presents a comprehensive framework for cultivating sustainability mindsets within mechanical engineering education at Singapore Polytechnic through the integration of the CDIO (Conceive-Design-Implement-Operate) approach. Recognizing the urgent need for engineers to move beyond technical proficiency toward sustainable innovation, the initiative addresses the recurring challenge of limited value internalization, where students understand sustainability concepts but fail to act upon them. The proposed strategy employs the CDIO design-implement experiences structured around three vertical "pillar" courses – *Introduction to Engineering* (Year 1), *Design & Implement* (Year 2), and *Capstone Projects* (Year 3) – to progressively embed sustainability principles across the curriculum. These experiences are aligned with selected UN Sustainable Development Goals and guided by Isabel Rimanoczy's Sustainability Mindset Principles (SMPs), which emphasize cognitive, behavioral, and affective dimensions. Complementing these principles, the framework prioritizes two dominant Key Competencies for Sustainability (KCS) – Integrated Problem-Solving and Systems Thinking – while weaving in transversal competencies. Implementation plans for Year 1, and Year 2 illustrate how sustainability can be infused into cornerstone and intermediate projects through activities such as carbon footprint analysis, closed-loop system design, and reflective strategy proposals. The double-helix curriculum model highlights the interplay between SMPs, KCS, and SDGs, ensuring that sustainability is not treated as an elective theme but as a core pedagogical spine. By embedding sustainability into authentic design-implement experiences, the framework aims to transform student attitudes, foster ecological accountability, and prepare graduates to design resilient, circular, and socially responsible systems. Future directions include longitudinal studies to evaluate the impact of this model on students' professional identity formation and their ability to internalize sustainability values at both awareness and practice levels.

KEYWORDS

Sustainability Mindset, Key Competencies for Sustainability, Double-helix Curriculum, CDIO Standards 3, 5, 7

INTRODUCTION: ROLE OF MECHANICAL ENGINEERING EDUCATION IN SUSTAINABLE DEVELOPMENT

Sustainable development within polytechnic education entails cultivating the knowledge, skills, and attitudes necessary for graduates to contribute meaningfully to society. At the Singapore Polytechnic (SP), the Common Core Curriculum (CCC) provides students with a broad foundation for developing baseline emerging digital and human skills in students through the lens of the United Nation Sustainable Development Goals (UNSDGs), fostering awareness of real-world issues and their societal impacts (Cheah *et al*, 2022). While effective in building foundational understanding, these courses primarily operate at an introductory and awareness level. As noted by Alhasanni *et al* (2025):

> Engineers play a critical role in contributing to sustainable systems and infrastructure, they must be equipped with robust sustainability competencies. Further, integrating sustainability topics within the curricula should not just be surface level, but should go beyond to incorporate the transformative shift in pedagogical strategies, curriculum design, and institutional priorities. (p.2)

Within the School of Mechanical and Aeronautical Engineering (MAE), UNSDGs 3 (Good Health and Well-Being), 7 (Affordable and Clean Energy), 9 (Industry, Innovation and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), and 13 (Climate Action) are identified as most relevant to the mechanical engineering discipline. In the Diploma in Mechanical Engineering (DME), sustainability concepts are embedded through domain courses, electives and specialization courses. A summarized program structure of DME is as shown in Figure 1.

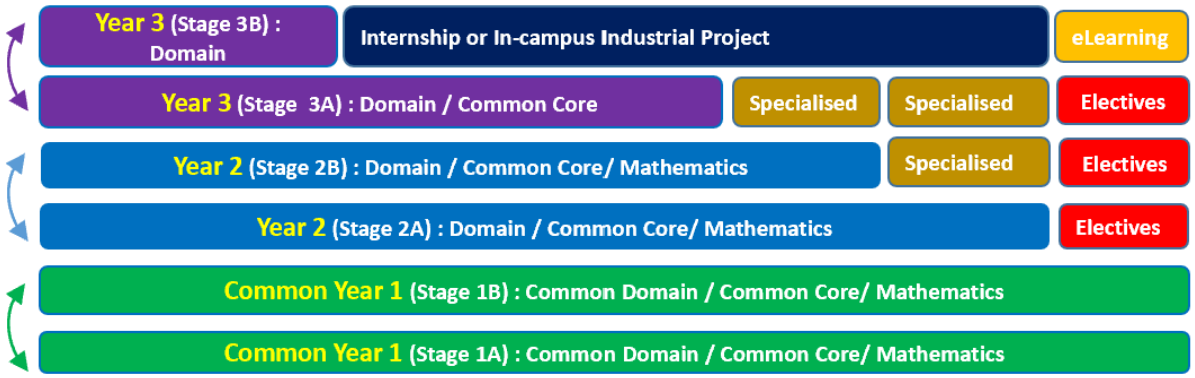


Figure 1. Program structure of DME

Despite this structured integration, a persistent challenge remains as students often demonstrate conceptual understanding of sustainability without translating it into meaningful action, reflecting limited internalization of sustainability values. Addressing this gap requires a more holistic pedagogical approach. The adoption of the CDIO (Conceive–Design–Implement–Operate) framework offers a robust foundation for outcome-based, authentic, and project-based learning around the full lifecycle of real-world products, processes, and systems. Cheah *et al* (2025, p24) pointed out that "CDIO Framework enable us to arrive at a plausible approach to integrate sustainable development into any educational program; by leveraging on the context-independence nature of key competencies for sustainability that "translate" (via the CDIO Standards) the more generic competencies (from the CDIO Syllabus) into context-specific scenarios where disciplinary knowledge is used alongside skills and attitudes to address sustainability issues". Azrai *et al* (2024, p323) concluded that "Project Based Learning models are effective in improving the pro-environmental behavior of high

school students. Students can take actions that are useful for the environment using a project-based learning model, so their pro-environmental behavior increases.”. This was further supported by Ayerbe et al (2024) who noted that:

> Project-based learning was shown to be an effective methodology for increasing environmental awareness in the participating students within the context described in this study, the environmental project was particularly effective in improving the affective dimension of environmental awareness.....Moreover, the project was quite effective in increasing the level of environmental literacy, an aspect linked to high levels of awareness. Therefore, the application of environmental projects is presumed as an effective educational strategy to increase attitudes of an environmental nature that are considered essential in the current global crisis. (p.16)

Scope of this Paper

This study explores how the DME curriculum systematically inculcates sustainability mindsets through a “project” spine of 3 Design-Implement Experiences (CDIO Standard 5): one in each year of study, via selected courses (Year 1: *Introduction to Engineering*, Year 2: *Design & Implement*, Year 3: *Capstone Projects*). The “project” spine features an Integrated Curriculum (CDIO Standard 3) addressing selected UNSDGs using the 2 key competencies for sustainability (integrated problem-solving and systems thinking) intertwined as a double-helix supported by other key competencies. The implementation plan for Years 1 and 2 are shared; and future directions, including plan for longitudinal studies to assess the impact of the proposed framework on students’ attitudes and value internalization at both awareness and professional levels, are shared.

DIPLOMA IN MECHANICAL ENGINEERING (DME) IN SINGAPORE POLYTECHNIC (SP)

A Short Summary of DME

The Diploma in Mechanical Engineering (DME) as shown in Figure 1 is Singapore’s first engineering program, providing a solid foundation in mechanical engineering since its inception in 1958. Current annual students’ intake is about 220 and they will undergo a three-year program with a common first year shared between Diploma in Aeronautical Engineering and Diploma in Mechatronics & Robotics. The program utilizes a swapping model, except for Mathematics and certain CCC courses, which follow a sequential structure. In a swapping model, courses across each year of study are organized into two stages. For instance, in Year 1, courses are assigned to either Stage 1A or Stage 1B. First-year students are divided into two groups, with one group commencing their studies with Stage 1A courses in the first semester, while the other group starts with Stage 1B courses. In the second semester, the groups swap stages. This swap model addresses resource/ facilities optimization, ensure relevant courses are gathered within the same stage, maintaining good staff to student ratio (1:20) and ensuring good study load balance.

The DME curriculum offers 6 specialization groups namely: (1) Automation & Robotics, (2) Energy & Facilities Management, (3) Engineering Design & Simulation, (5) Biomedical, (5) Precision Engineering and (6) Rapid Transit Technology. Each group has 3 specialized courses. Students in DME are to select one specialization from second year onwards. Students will be paired to relevant companies (for internship) or industrial projects based on their specializations. Teaching and learning are based on the CDIO Framework enhanced with design thinking methodology. Instructions are delivered through a blend of online

asynchronous lectures, in-person tutorials, and practical sessions for the majority of domain courses. Projects (CDIO design-implement experiences) is the dominant method of engaging students in learning.

Mapping UN SDG for DME

An exercise was mandated in SP for all programs to carry out mapping of the courses against relevant UNSDGs. The outcome for DME is shown in Table 1, for core courses and CCC courses. Servicing courses in other departments such as electrical and electronics and mathematics are not included in the mapping.

Table 1. Mapping of DME with UNSGDs

	Course Title	United Nations Sustainable Development (UNSDG) Goals					
		3	7	9	11	12	13
		Good Healthy and Well Being	Affordable and Clean Energy	Industry, Innovation, and Infrastructure	Sustainable Cities and Communities	Responsible Consumption and Production	Climate Action
Y1 - S1	Computer Aided Drafting						○
	Thermofluids 1		◉				
	Mechanics 1						
	CCC- Thinking Critically about the UN SDG	◉	◉	◉	◉	◉	◉
	CCC- Data Fluency	◉	◉	◉	◉	◉	◉
	CCC- Digital Communication for Impact	◉	◉	◉	◉	◉	◉
	CCC- Collaboration in the Digital Age						
Y1 - S2	Introduction to Engineering	◉		◉	○	◉	○
	Engineering Materials 1	○	○	◉	○	◉	○
	CCC- Problem Solving with Creative & Computational Thinking	◉	◉	◉	◉	◉	◉
	CCC- Effective Writing for the Workplace	◉	◉	◉	◉	◉	◉
	CCC- Persuasive Communication with Data Storytelling	◉	◉	◉	◉	◉	◉
Y2 - S1	Thermofluids 2		◉				
	Mechanics 2						
	Engineering Materials 2	○	○	◉	○	◉	○
	Computer Aided Machining		○	◉	○	◉	○
	CCC- Artificial Intelligence & Its Impact	◉	◉	◉	◉	◉	◉
Y2 - S2	Design and Build		◉	◉	○	◉	○
	Industrial Automation	○	○	◉		○	○
	CCC- Sustainable Innovation Project	◉	◉	◉	◉	◉	◉
Y3 - S1	Engineering Thermodynamics		◉	◉	○	○	○
	Mechanics 3						
	Fluid Mechanics						
	CCC- Personal Branding and Career Agility	◉	◉	◉	◉	◉	◉
Y3 -S2	Internship	◉	◉	◉	◉	◉	◉
	Industrial Project	◉	◉	◉	◉	◉	◉
	Workplace Safety & Health Management	◉					
Specialisation courses	Mechanical Assembly Design in CAD		○	◉	○	◉	◉
	Manufacturing Processes with Design for Manufacturing		◉	◉	◉	◉	◉
	Engineering Simulations		◉	◉	◉	◉	◉
	Refrigeration & Air-conditioning		◉	◉	◉	◉	◉
	Renewable Energy & Applications		◉	◉	◉	◉	◉
	Building Information Modelling for MEP Services		◉	◉	◉	◉	◉
	Digital Fabrication and Metrology		◉	◉	○	◉	○
	Multi-Axis Machining Applications		○	◉	○	◉	○
	Tooling Engineering		○	◉		◉	
	Railway Systems		◉	◉	◉	◉	◉
	Rolling Stock Design & Maintenance		○	◉	◉	○	◉
	Railway Infrastructures Design & Maintenance		○	◉	◉	◉	◉
	Smart Solution Development		◉	◉	○	○	○
	Robotics for Advanced Manufacturing		◉	◉	◉	◉	○
	Programmable Logic Controller						
	Assistive Technology & Rehabilitation Engineering	◉					
	BioMechanics						
	Biofluids						
	Contamination Controls & Clean Room	◉	◉	◉	◉	◉	○
Electives	Fundamental of Composite Repairs		○	◉		◉	◉
	Quality Engineering and Management		○	○	◉	◉	○
	Industrial Engineering		◉	◉		◉	○
	Introduction to Additive Manufacturing [3D Printing]		◉	◉	○	◉	○
	Introduction to Cobot		◉	◉	◉	◉	○

From Table 1, we note that DME has a good spread of mechanical courses with the potential of infusing sustainability topics. Bold circle "◉"represents greater ease of infusing the relevant

UNSDG into the course, based on current learning activities and objectives. A light circle "○" represents "somewhat" feasible. CCC courses cover the UNSDGs well as most are designed to bring out the awareness of UNSDG. The 9 mechanical courses highlighted are those that are currently infused with sustainability topics. Their respective topics are shown in Table 2. Many of these topics are implemented by hands-on activities or assignments using CDIO Standard 7 (Integrated Learning Experiences and CDIO Standard 8 (Active Learning).

Table 2: Courses with sustainability topics interwoven around the 3 "pillars"

	Course	Topics for sustainability development	UN-SDG
1	Mechanical Assembly Design in CAD	Circular economy topics for design for assembly	9,12,13
2	Manufacturing Processes with Design for Manufacturing	Circular economy topics for selecting manufacturing process	7,9,11,12,13
3	Air-conditioning and Refrigeration	Touch on Green Marks in the application and ways for better energy efficiency	7,9,11,12,13
4	Renewable Energy & application	Methods for renewable energy application and design.	7,9,11,12,13
5	Building Information Modelling for MEP Services	Touch on Green Marks and energy management	7,9,11,12,13
6	Engineering Thermodynamic	Topics on energy saving	7,9
7	Engineering Material 2	Recycling of material in the various processes?	9,12
8	Fundamentals of Composite Repair	Recycling of composite of materials and new development in sustainable resin.	9,12,13
9	Quality Engineering and Management	Environmental and Sustainability Management (ISO 14000/Environmental Impact Study/Hazardous Waste Management	11, 12

THE DME CURRICULUM REVAMP APPROACH

We noticed most of the 9 mechanical courses infused with sustainability topics are either elective or specialization courses. This implies that some students from the same cohort may not have sufficient "touch points" of training in sustainability mindset development. We need to ensure at least 1 "pillar" course with CDIO Standard 5 (Design-Implement Experiences) covered in every year of study, interwoven with other courses with sustainability topics. For effectiveness in transforming behaviors and attitudes using design-implement experiences, we also need to explore relevant sustainability mindset principles and key competencies for sustainability.

Sustainability Mindset Principles

Rimanoczy (2019) conceptualized a set of 12 Sustainability Mindset Principles (SMP) which encompasses three perspectives – cognitive, behavioral, and affective. These dimensions guide the pedagogical design of learning experiences that promote sustainability beyond technical awareness. The 12 Sustainability Mindset Principles (SMP) are organized into four domains: Ecological Worldview, Systems Perspective, Emotional and Spiritual Intelligence as shown in Figure 2.

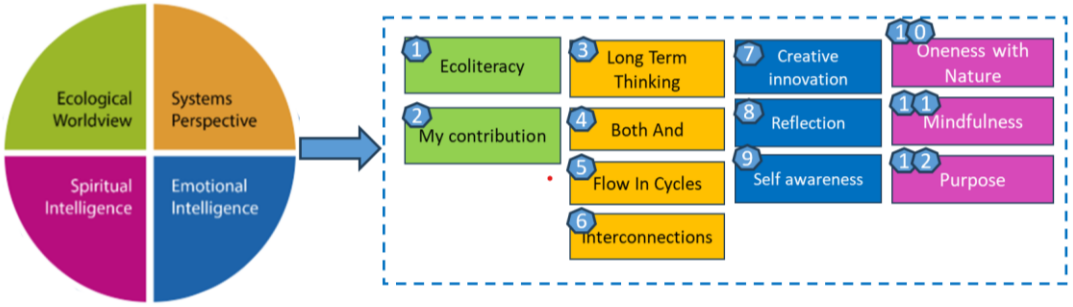


Figure 2. Sustainability Mindset Principles (SMP)

These principles explicitly define the mindset components essential for integrating sustainability into the core phases of design-Implement experiences. Key SMPs that can be actively cultivated include:

- Long-term Thinking (Principle 3): Students learn to consider that every action has consequences that are not immediately visible and that analyzing situations based on the long term has a positive impact on global sustainability.
- Both-and Thinking (Principle 4): This perspective allows students to understand paradoxes and calls for creative solutions that are inclusive of all stakeholders.
- Flow in Cycle (Principle 5): This principle encourages a mindset for reuse, reduce and recycle as early as in the design phase to reduce product design obsolescence.
- Interconnectedness (Principle 6): This principle promotes developing solutions from a system perspective especially when solving “wicked” problems.
- Creative Innovation (Principle 7): This principle emphasizes that resilience is based on constant creativity, innovation, and experimentation.
- Reflection (Principle 8): Reflective practices help students pause, ponder the situation and implications before jumping into action. This is critical for evaluating long-term consequences of design choices.
- Purpose (Principle 12): Defining one's professional purpose ensures that the skills acquired are directed toward shaping a better world.

Key Competencies for Sustainability

Retaining the United Nations Educational Scientific and Cultural Organization (UNESCO) definition of key competencies for sustainability (KCS), Cheah *et al* (2025) had reconciled the discourse on what constituted key competencies for sustainability from the extant literature and formulated a model for their integration in any program as they are transversal, multifunctional and context independent. There are altogether 8 KCS to develop students’ sustainability mindset: values thinking, intrapersonal, interpersonal, futures thinking, systems thinking, strategic thinking, implementation, integrated problem-solving. Cheah *et al* (2025) suggested that each program integrating sustainable development into its curriculum can customize the sequencing of the 8 KCS based on the program’s own pedagogical approach. In the context of DME, we identified 2 dominant KCS that run through the entire program duration: integrated problem-solving competency and systems thinking competency.

Integrated Problem-solving Competency

As the curriculum of DME is heavily dependent on projects as the backbone, Integrated Problem-Solving Competency becomes an important feature in the curriculum planning for DME, which requires students to conceive, design, implement and operate a mechanical artefact at increasing level of difficulty over the program duration. The DME curriculum made use of 3 design-implement experiences (CDIO standard 5) in each year of the 3-year program duration using 3 “pillar” courses, starting from *Introduction to Engineering* course (with design-implement experience at basic-level supporting CDIO Standard 4) in year 1, *Design & Implement* course (CDIO Standard 5, design-implement experience at intermediate-level) in year 2 and *Capstone* (Final Year Project) course in year 3 (CDIO Standard 5, design-implement experience at advanced-level). These 3 “pillar” courses formed the “project spine” for DME’s integrated curriculum (CDIO Standard 3) by partnering with other courses in the same stage to achieve larger project objectives.

Systems Thinking Competency

As project development of complex products and processes in DME consist of inter-related elements, the solution must consider the whole system and its entire life cycle. Hence, emphasis on system thinking competency is necessary. Take carbon emissions of vehicles as an example. Beyond zero-emission narratives, sustainability requires a lifecycle perspective encompassing production, usage, and end-of-life processes. Kurkin *et al* (2024) highlighted the importance of lifecycle assessment (LCA) in understanding the true environmental impact of electric and internal combustion vehicles. This comprehensive mindset extends to evaluating the social and economic impacts on environment across the entire value chain. Product design and development is an important domain in the mechanical discipline whereby systems thinking is crucial, impacting on the environment. Planned obsolescence in product development and manufacturing exacerbates environmental degradation by shortening product lifespans and increasing resource consumption, thereby underscoring the urgent need for pedagogical approaches that integrate circular economy principles and comprehensive life cycle thinking into engineering education (Guerra *et al*., 2023; Perpignan, 2021; Deng *et al*., 2021). Sierra *et al* (2023) had observed the challenges of effective strategy to reduce obsolescence which has a downstream impact on the environment. They had identified several methodological design approaches to resist or postpone obsolescence (see Figure 3). Hence, integrating real-world scenarios and hands-on projects that encourage students to analyze and optimize product lifecycles is essential for developing engineers capable of designing truly sustainable systems (Olsen *et al*., 2013). Table 2 shows some courses with sustainability topics which are currently infused into DME. Courses such as *Design for Manufacturing* and *Design for Assembly* could further contribute to students' sustainability Mindsets by including obsolescence in product design.

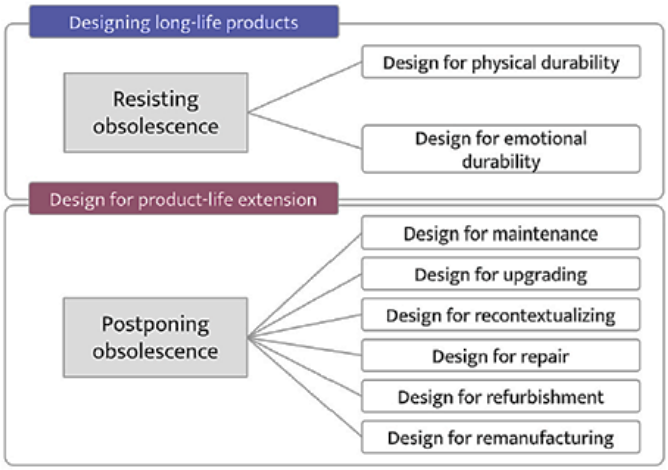


Figure 3: Resisting and postponing obsolescence in product design

DME's SUSTaiNABILITY MINDSET DEVELOPMENT MODEL

The dual focus on integrated problem-solving competency and systems thinking competency led us to formulate the double helix model as the approach for DME to develop sustainability mindset in its students.

The middle of Figure 4 shows the 3 "pillars" of the DME curriculum (i.e. the 3 courses of *Introduction to Engineering, Design & Implement,* and *Capstone*) as explained in previous section. In DME, the *Capstone* course can be in-campus industrial final year project or

internship at companies' premises. The left side of Figure 4 listed various KCS and the right side showed the 12 SMPs and UNSDGs to be infused into the courses where appropriate. Curriculum mapping was systematically carried out by analyzing existing courses, to identify opportunities for embedding SMPs and KCS.

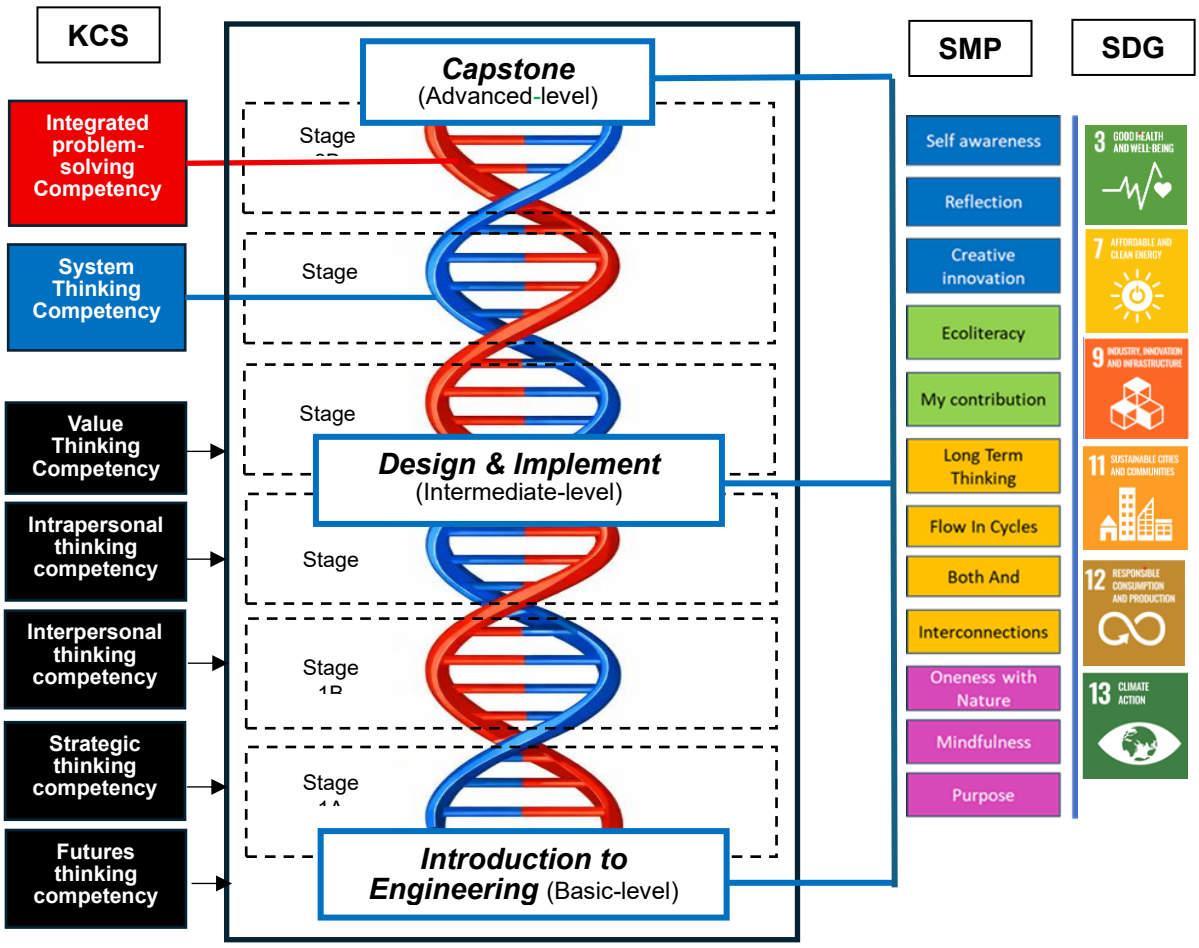


Figure 4. Double Helix as "Spine" of 2 key competencies for sustainability for DME

Values thinking will be infused during the various project activities. This is critical for students to not only comprehend environmental issues but also to develop innovative solutions and engage in reflective practices that promote long-term ecological and social well-being. Likewise other KCS will also support the development of Integrated Problem-solving and Systems Thinking Competencies.

IMPLEMENTATION PLANS FOR DME YEAR 1 AND 2

Table 3 and Table 4 showed how the 12 SMPs are mapped to the SDGs relevant to DME as explained in Table 1 and Table 2. Table 5 and Table 6 illustrate the implementation plans for the 2 "pillars" for year 1 and year 2 respectively, with activities that can be carried out in the classroom.

For year 1, the suggested learning activities are an extension of the existing cornerstone project by including an online case study, analyzing sustainability issues and proposing solutions during the fabrication of mechanical parts in the cornerstone project. The task is aimed at inculcating students' mindset and their values of reducing material and energy usage,

promoting circular economy within engineering practices and building a culture of environmental accountability. Table 5 further provides the justifications for the selected SMPs. We note that SDG 7: Affordable and Clean Energy and SDG 11: Sustainable Cities and Communities are very specific topics and would be better covered by specialization courses in the program which is beyond the scope of this paper.

Table 3. Mapping of SMP to SDG for 1st year *Introduction to Engineering* course

	SMP 1	SMP 2	SMP 3	SMP 4	SMP 5	SMP 6	SMP 7	SMP 8	SMP 9	SMP 10	SMP 11	SMP 12
SDG 3												✖
SDG 7												
SDG 9						✖						
SDG 11												
SDG 12			✖		✖							
SDG 13	✖											✖

Table 4. Mapping of SMP to SDG for 2nd year *Design & Implement* course

	SMP 1	SMP 2	SMP 3	SMP 4	SMP 5	SMP 6	SMP 7	SMP 8	SMP 9	SMP 10	SMP 11	SMP 12
SDG 3												✖
SDG 7												
SDG 9						✖	✖					✖
SDG 11												
SDG 12	✖		✖		✖			✖				
SDG 13	✖	✖	✖					✖				✖

For year 2, the task extends the current *Design & Experiment* course with elements of sustainability by:

- Uses CAD's sustainability function to estimate the carbon emission from the project
- Calculation of carbon footprint.
- To present and reflect improvements for reducing carbon footprint.

Year 3 implementation plan is not covered in this paper because Internship and Industrial projects would depend on the industry that the students are assigned to. The students are expected to develop their competencies from their learnings in Year 1 and Year 2; and able to transfer them to the projects. As part of their final year report, students are required to write an extensive account of a proposal on sustainability for the companies; based on their observation, technical work done and on-site empathy studies.

Table 5. Implementation plan for sustainability mindset on *Introduction to Engineering*

Selected SMP	Justification (Based on DME Context)	Suggested learning activity
Ecoliteracy	This principle is essential for understanding the environmental issues in metal fabrication, such as air Pollution from machining works, and high Energy Consumption. Goal 13: Climate Action requires workshops to lower their carbon footprint. Understanding environmental consequences contributes to meeting the learning objective of identifying environmental issues.	Carbon Footprint Awareness: Students estimate emissions associated with a specific workshop task or product component, promoting awareness of the role of energy-efficient motors and proper machine scheduling.
Long-term Thinking	This involves considering the entire environmental impact of decisions, supporting Goal 12: Responsible Consumption and Production. The goal specifically calls for sustainable practices throughout the lifecycle of products, from raw material to disposal. This thinking is formally applied through a Life Cycle Assessment (LCA), which measures a product's environmental impact from "cradle to grave".	Material Decision Matrix: Students compare different materials (e.g., carbon steel, brass, and aluminum) for a prototype, using recyclability and life-cycle impact as crucial factors alongside cost and strength.
Flow in Cycles	Recognizing that resources must operate in cycles rather than linear processes promotes a circular economy within engineering practice, supporting Goal 12. This is necessary to address issues like Coolant & Lubricant Waste and Material Waste.	Closed-Loop System Implementation: Students research and propose implementing Closed-loop Systems for the workshop, focusing on the recovery and recycling of coolants and metal chips to minimize environmental contamination.
Interconnected-ness	This involves ensuring that design and operational decisions contribute to the sustainability of the whole system, supporting Infrastructure Resilience under Goal 9. It requires designing facilities to reduce negative external impacts like vibration, noise, and heat waste on the surrounding environment.	Infrastructure Improvement Plan: Students propose design changes for the lab (e.g., layout optimization or machine placement) to reduce noise and vibration or improve airflow and lighting.
Purpose	Defining one's professional purpose ensures that the skills acquired are directed toward shaping a better world (Goal 3, 13). This aligns with the learning objective to propose strategies to mitigate the environmental impact of fabrication activities and use real-world examples to support decision-making in sustainable workshop practices.	Sustainable Strategy Proposal: Students apply sustainable development concepts to streamline fabrication in a mini-project, detailing their strategy using examples such as the reuse of aluminum off-cuts to reduce raw material orders

POSSIBLE FUTURE WORKS

This paper presented a roadmap with plans where sustainability mindset can be developed in DME students. At the point of writing, the plan has yet to be implemented in DME. Nevertheless, the proposed integration strategy in the roadmap provides appropriate "touch points" for cultivating sustainability mindsets by establishing a three-tier project vertical integration during the program duration: Basic-level or (Cornerstone) in Year 1, Intermediate-level Design-Implement in Year 2, and advanced-level Capstone in Year 3, interwoven with relevant specialization and core courses.

Table 6. Implementation plan for sustainability mindset for *Design Implement* course

Selected SMP	Justification (Based on DME Context)	Suggested Learning Activity
Ecoliteracy	This is the foundational principle of understanding the state of the planet and recognizing the complexity of how environmental challenges are linked. For mechanical systems focused on reducing high carbon emissions, this is crucial for establishing awareness, which directly underpins adherence to Goal 13: Climate Action and the broad objectives of sustainable production within Goal 12: Responsible Consumption and Production.	Reading Material & Videos: Students engage with materials to gain full awareness of the state of the planet and the specific environmental impacts associated with mechanical processes and carbon emission generation.
My Contribution	This principle identifies the ways an individual is unintentionally contributing to the problems. By reflecting on their design choices and engineering practices, students develop the necessary social sensitivity and consciousness to address their contribution to emissions, which is key for behavioral change required by Goal 13: Climate Action.	Project Report - Improvement: Students must analyze their design and propose specific steps to mitigate the identified negative contributions (e.g., reducing material waste or energy use), demonstrating a practical application for solving the problem.
Long-term Thinking	This involves analyzing situations and making decisions while considering the long term, recognizing that every action has consequences that are not immediately visible. Applying this ensures students design sustainable engineering solutions that minimize future consequences like prolonged carbon effects on the climate, supporting the objectives of Goal 12: Responsible Consumption and Production and Goal 13: Climate Action.	Project Report - Improvement: Documentation of design deliberation should explicitly detail how potential long-term consequences (like climate effects) encourage sustainable choices and the adoption of lasting engineering solutions.
Creative Innovation	Resilience and progress depend on constant innovation and experimentation, aligning directly with Goal 9: Industry, Innovation and Infrastructure. Mechanical engineers must promote technological upgrading and develop sustainable industries. This mindset enables the adoption of technologies such eco-design and additive manufacturing to reduce waste.	Carbon footprint analysis: Use sustainability function of CAD software to estimate the overall carbon emission of student's design.
Flow in Cycles	In mechanical design, this directly mandates the use of circular economy principles and life cycle analysis (LCA), which are the critical components of Goal 12: Responsible Consumption and Production.	Design selection: Students could use morphology charts to select alternative designs with including criterion such as material reuse and circular economy concepts, shifting away from linear, waste-generating processes.
Interconnected-ness	This involves ensuring that design and operational decisions contribute to the sustainability of the whole system, supporting Infrastructure Resilience under Goal 9. It requires designing facilities to reduce negative external impacts like vibration, noise, and heat waste on the surrounding environment.	Infrastructure Improvement Plan: Students propose design changes for the lab (e.g., layout optimization or machine placement) to reduce noise and vibration or improve airflow and lighting.

Table 6. (cont'd)

Reflection	Reflective practices help students to pause, ponder the situation and implications before jumping into action. This promotes critical thinking needed to ensure that calculations and design choices actively align with sustainability goals, enabling effective compliance and progress toward targets outlined in Goal 12: Responsible Consumption and Production and Goal 13: Climate Action.	Project Activities & Project Report: Dedicated time is spent evaluating the impact of calculated decisions against sustainability benchmarks, with the resulting critical insights documented in the project reflection.
Purpose	Defining one's purpose provides an unconscious compass that guides actions toward shaping a better world when grounded on higher values (Goal 3: Good health & Wellbeing). This principle encourages students to link their mechanical engineering education to the larger commitment required to achieve ambitious goals like contributing to sustainable industrialization (Goal 9: Industry, Innovation and Infrastructure) and securing a low-carbon future (Goal 13: Climate Action).	Project Report - Reflection: Students include a self-assessment on how their design choices and acquired knowledge align with their professional purpose of contributing to global sustainability.

Future research should focus on empirical and longitudinal investigations to validate the effectiveness of this framework. Specific areas for subsequent scholarly exploration include:

1. Assessing the longitudinal impacts of the multi-level project structure on student learning outcomes and the development of sustainability competencies.
2. Exploring the role of industry co-supervision and external partnerships to provide authentic, real-world contexts and enhance the practical relevance of sustainability education. This is important to the 3rd Pillar of the framework as students are either arranged for internship or to pursue an in campus industrial sponsored projects as their capstone program.
3. Examining the effectiveness of employing interdisciplinary teams and diverse pedagogical approaches, such as culturally responsive pedagogy, to foster a deeper, more comprehensive sustainability mindset. Notably, "Interdisciplinary collaboration has proven to be a transformative approach to sustainability education" (Alhassani *et al*., 2025, p9).

CONCLUSION

This paper successfully demonstrates a strategic and structured approach for inculcating sustainability mindsets within the Diploma in Mechanical Engineering (DME) curriculum using the CDIO (Conceive–Design–Implement–Operate) framework. The proposed revamp on DME aims to bring current sustainability education beyond the introductory and awareness level for deeper internalization through design and implement experiences.

The double helix model of having System Thinking and Integrated Problem-solving Competencies as the "Spine" is due to DME's emphasis in design-implement experiences. It enables a structure pedagogy progression utilizing 3 "pillar" courses at each year of study with a major design and implement experiences, to ensure continuous engagement with relevant Sustainability Mindset Principles (SMP), Key Competencies for Sustainability (KCS) and selected SDGs. Learning activities for the "pillar" courses are suggested. Holistic integration

with selected Sustainable Mindset principles and UN SDGs is afforded by interweaving courses with sustainability topics around these pillars.

The paper provides a comprehensive blueprint, positioning engineering education to meet the global demand for graduates capable of integrated problem-solving and systemic thinking. This framework acts as the theoretical foundation for cultivating engineers who are not only technically proficient but also possess the intrinsic values (affective dimension) and actionable skills (behavioral dimension) necessary to navigate and solve complex global sustainability challenges.

ACKNOWLEDGEMENTS

The authors received no financial support for this work. The authors also wish to thank Mr Thevaraja Kumar (Introduction to Engineering) and Mr Soon Yew Boon (Design and Implement), for developing learning activities for their respective courses, to correspond with relevant sustainability mindset principles and UNSDGs. Special thanks to Dr Ngoh Shwu Lan for mapping out MAE's courses to relevant UNSDGs.

The GenAI tool ChatGPT was used to generate the "Double Helix DNA" diagram. Gemini was also used to provide suggestions for a more coherent conclusion, which was then written by the first author using his own words. The prompts used and responses obtained can be found in the **Link**.

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EMPOWERING ICT STUDENTS AS LIFE-LONG LEARNERS THROUGH AUTHENTIC PROJECTS

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ABSTRACT

The rapid evolution of technology demands that ICT graduates become lifelong learners who continuously update their skills. This paper reflects on how theFIRMA, a student-driven ICT project office at Turku University of Applied Sciences (TUAS) empowers students to develop a lifelong learning mindset through real-world project experiences. The concept and structure of theFIRMA are described, highlighting its operation as a project-based learning environment that functions like a small company within the university (Määttä et al., 2018; Säisä et al., 2018). Students participate in authentic ICT projects for actual clients, with roles ranging from novice developer to student CEO, and with experienced peers mentoring junior students (Säisä et al., 2020; Tiura & Säisä, 2018). These real-life projects provide continuous opportunities for skills development across technical and interpersonal domains, foster adaptability through diverse project challenges, and cultivate self-directed learning habits. Evidence from previous alumni surveys and feedback indicates that theFIRMA experience has a strong long-term impact on graduates' skills, confidence, and career development (Säisä et al., 2019, 2020). The results show that the top skills gained (e.g., teamwork, communication, problem-solving) closely match those valued by industry and have significantly aided alumni in employment (Määttä et al., 2018; Säisä et al., 2019). Through a reflective analysis of these outcomes, the paper demonstrates how theFIRMA's model of authentic, student-driven projects effectively nurtures continuous learning competencies and mindsets, thereby empowering students to become lifelong learners.

KEYWORDS

Lifelong learning, project-based learning, student-driven learning environment, professional development, ICT, Standards: 6, 7, 8

INTRODUCTION

Preparing ICT students to become lifelong learners is a central challenge in modern engineering education. Rapid advances in digital technologies and artificial intelligence are reshaping jobs and skill requirements, making continuous upskilling, adaptability, and self-directed learning increasingly important. In this context, the CDIO framework is especially relevant because it combines disciplinary knowledge with personal and interpersonal capabilities, while Standards 6–8 emphasize learning workspaces, integrated learning experiences, and active learning as foundations for professional growth and lifelong learning (Cedefop, 2024; Crawley et al., 2007; World Economic Forum, 2025).

At Turku University of Applied Sciences, these principles are enacted in theFIRMA, a student-driven ICT project office that serves as an authentic project-based learning environment. By working on real projects for external clients, students apply technical knowledge in practice while also developing communication, project work, responsibility, and adaptability in a real-world setting. As such, theFIRMA provides a concrete example of how CDIO-aligned learning can support the development of lifelong learning dispositions in authentic contexts (Määttä et al., 2018; Säisä et al., 2018).

This paper examines how theFIRMA's approach supports students in becoming self-directed lifelong learners. It first describes the concept and structure of theFIRMA and then analyzes how participation in real-life ICT projects promotes continuous skill development, mentorship, adaptability, and learner autonomy. Drawing on earlier studies, including alumni surveys and feedback, the paper finally discusses lessons learned and reflects on why this project-based model is effective in cultivating lifelong learning.

THEFIRMA: A STUDENT-DRIVEN PROJECT OFFICE FOR LEARNING

TheFIRMA is a student-driven ICT project office at TUAS that operates as a project-based learning environment resembling a small company. Students work on real-world ICT projects for external clients, primarily small and medium-sized enterprises, and are responsible for delivering usable outcomes within agreed constraints (Määttä et al., 2018). The learning environment is designed to expose students to authentic professional situations while allowing them to integrate project work into their degree studies.

These projects carried out in theFIRMA cover a wide range of ICT-related activities, including but not limited to web and application development, software testing such as accessibility and usability evaluation, user interface and service design, technical documentation, and teaching-oriented activities such as workshops and training sessions. This diversity exposes students to varying technical domains and working practices, making it unlikely that previously acquired knowledge alone is sufficient for project success.

A defining feature of theFIRMA is its operational model, which differs significantly from traditional course-based education. The project office operates continuously throughout the year, rather than following a fixed academic schedule. Students may join projects at different times, participate for varying durations, and work different numbers of hours depending on their individual study plans (Määttä et al., 2018). This flexibility enables students to tailor their learning experiences but also requires them to take responsibility for managing their own learning and workload.

Over the past decade, theFIRMA has continuously expanded its operations, growing in scale and complexity year by year in response to evolving technological demands. The project office now delivers tens of real customer projects annually, engaging over 200 ICT students across different study phases each year. At any given time, multiple project teams operate in parallel, supported by faculty members and more experienced students acting as mentors rather than traditional instructors. This sustained growth and continuous development highlights that the learning model is not only scalable but also adaptable, evolving alongside the rapidly changing ICT field.

MENTORING, ROLES, AND THE DEVELOPMENT OF PROFESSIONAL SKILLS

Peer mentoring and role progression are integral elements of theFIRMA learning environment. Students typically begin their participation as project members working on specific tasks and, as they gain experience, may progress to roles with greater responsibility, such as lead or mentor roles or even student CEO, as shown in Figure 1. This progression mirrors professional ICT organizations and provides students with opportunities to develop leadership and coordination skills in an authentic context (Määttä et al., 2018).

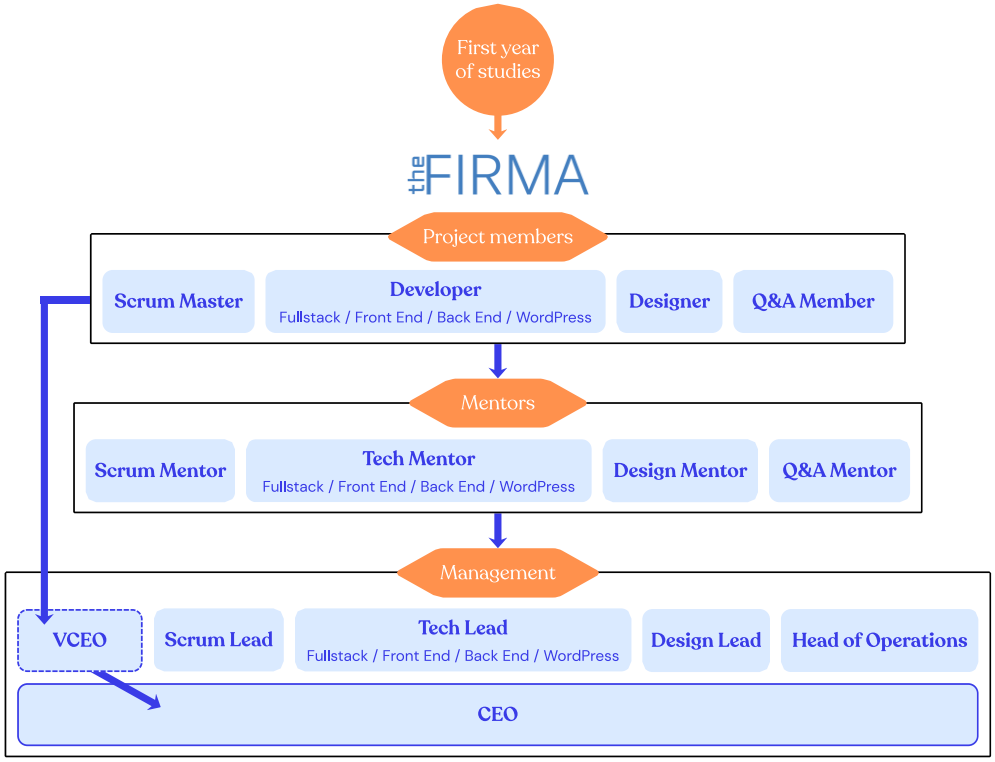


Figure 14. Progression of student roles in theFIRMA

Because projects are continuously starting and ending, onboarding and knowledge transfer are recurring activities within theFIRMA. More experienced students routinely introduce new members to tools, practices, and project contexts, while simultaneously reflecting on their own understanding. This recurring peer learning cycle reinforces the ability to explain, adapt, and evaluate knowledge, skills that are essential for continuous professional learning.

Mentoring occurs naturally through collaboration among students at different stages of their studies. More experienced students support newcomers by sharing technical knowledge,

explaining project practices, and guiding them in client communication and teamwork. This peer mentoring supports the learning of junior students while simultaneously strengthening the mentoring, communication, and leadership skills of senior students (Säisä et al., 2020). Faculty members complement this process by acting as coaches and advisors, offering guidance when needed but allowing students to retain ownership of project decisions and outcomes (Määttä et al., 2018).

For example, a senior student acting as a scrum master may guide a new project member in implementing a web application feature, while simultaneously explaining design decisions and client requirements. This interaction not only supports the junior student's technical learning but also develops the senior student's mentoring and communication skills.

Through progression from project member to leadership roles, students develop a wide range of professional skills, including teamwork, communication, problem-solving, and leadership. Previous studies conducted by surveys have shown that these skills are among the most significant learning outcomes reported by students and alumni who have worked in theFIRMA and its predecessor environments (Säisä et al., 2019). In addition to acquiring these skills, students learn how to support the learning of others, reinforcing reflective practice, and the ability to articulate knowledge, both of which are essential for continuous professional development.

FOSTERING SELF-DIRECTED LEARNING AND A LIFELONG LEARNING MINDSET

Perhaps the most distinctive aspect of theFIRMA is the degree of responsibility placed on students for directing their own learning. Unlike traditional courses with fixed schedules, predefined assignments, and teacher-led instruction, learning in theFIRMA is driven by project needs, which reinforce the idea that learning is continuous rather than episodic. Students must identify what knowledge and skills are required to complete project tasks and seek out relevant resources independently (Määttä et al., 2018).

A formal mechanism for reinforcing self-directed learning is the practice of setting project-specific learning goals. At the beginning of each project, students define learning objectives related to both technical and professional development, and they assess their achievement at the end of the project (Määttä et al., 2018). This process encourages students to reflect on their learning, evaluate their progress, and identify areas for further development. Such reflective practices align closely with the behaviors required for learning in professional contexts.

The environment also fosters a mindset of continuous improvement. Because projects differ in technologies, roles, customers, and problem contexts, students repeatedly encounter unfamiliar situations that require experimentation, collaboration, and adaptation. This orientation is strengthened by theFIRMA's continuous improvement culture: Tiura and Säisä (2018) describe a student-driven environment in which faculty members act in a coaching role and students are encouraged to participate in improving practices. Over time, this repeated exposure to new situations helps students internalize learning as an ongoing process rather than a one-time achievement.

For instance, when encountering unfamiliar technologies in a customer project, students often independently search for documentation, tutorials, or peer support to complete their tasks. This process mirrors real-world professional learning situations where formal instruction is not available.

In recent years, theFIRMA has largely adopted Scrum as its default project management approach. Scrum structures project work into short iterations with regular planning, review, and retrospective activities. From a learning perspective, these practices support continuous reflection, feedback, and adaptation, reinforcing habits that are central to lifelong learning.

These habits are further strengthened by the authentic nature of theFIRMA's customer projects. Real clients, evolving requirements, and consequences beyond course assessment mean that students cannot rely only on previously learned solutions; instead, they must continuously identify new learning needs and adjust their approach as projects develop. Research on project-based learning similarly shows that authentic contexts and real-world clients can increase engagement, strengthen collaboration, and deepen understanding. For this reason, theFIRMA does not merely provide opportunities to learn new skills; it socializes students into seeing learning itself as an ongoing, career-long responsibility. (Guo et al., 2020; Chang et al., 2024.)

OUTCOMES AND LONG-TERM IMPACT

After a decade of operation, there is tangible evidence that participation in theFIRMA has a long-term impact on students' professional development. Alumni feedback and previous survey results indicate that students perceive significant gains in both technical and interpersonal skills as a result of working in real customer projects (Säisä et al., 2019). Many alumni report that the skills developed in theFIRMA closely match those valued by industry, thereby smoothing the transition from studies to working life.

The alumni survey also sheds light on the career trajectories of former participants. Respondents report that theFIRMA experience contributed to increased confidence, improved employability, and, in some cases, accelerated progression into positions of greater responsibility (Säisä et al., 2019). These outcomes suggest that the learning environment not only supports immediate learning goals but also equips students with behaviors and attitudes that continue to benefit them throughout their careers.

For example, alumni surveys indicate that communication and teamwork were among the most frequently reported skills gained, and these were also identified as having the strongest impact on employability. These attributes are closely associated with lifelong learning and professional growth, reinforcing the idea that authentic project environments can effectively prepare students for evolving work demands.

Taken together, alumni feedback and reported career outcomes can be interpreted in light of the authentic nature of the project work. It is also noteworthy that theFIRMA's approach contributes to students' understanding of learning as a continuous process. By repeatedly engaging in reflection, self-evaluation, and skill development within real projects, students develop habits that support ongoing learning beyond formal education. In this way, theFIRMA environment can be seen as genuinely empowering students to become lifelong learners.

CONCLUSION

Empowering students to become lifelong learners requires learning environments that go beyond the transmission of disciplinary knowledge and instead engage students in authentic professional practices. This paper examined theFIRMA, a student-driven ICT project office at TUAS, as a case of how real-life project work can foster lifelong learning behaviors within ICT education. By participating in diverse customer projects, assuming increasing responsibility,

and engaging in reflective learning practices, students are repeatedly required to identify learning needs, seek new knowledge, and evaluate their own development.

From a CDIO perspective, theFIRMA demonstrates how Standards 6 (Engineering Workspaces), 7 (Integrated Learning Experiences), and 8 (Active Learning) can operate together to support professional development. TheFIRMA functions as an authentic engineering workspace in which learning is embedded in real work activities. Technical problem-solving is integrated with interpersonal and self-directed learning, and students are actively engaged in planning, implementing, and reflecting on their work rather than following predefined instructional paths. These characteristics create conditions in which lifelong learning emerges as a natural outcome of participation rather than as an explicit instructional objective.

The findings suggest that lifelong learning can be effectively cultivated through project-based learning environments that combine authenticity, responsibility, and reflection. Rather than teaching it as an abstract concept, theFIRMA requires students to practice it repeatedly in realistic contexts. This case contributes to the CDIO Implementation track by illustrating how existing project-based learning environments can support lifelong learning through embedded assessment and feedback practices. The insights from theFIRMA may be transferable to other institutions seeking to enhance student professional development and prepare graduates for continuous learning in rapidly evolving engineering fields.

While this paper is reflective in nature and does not present new empirical data, it is grounded in previous studies and long-term implementation experience of theFIRMA. The findings should therefore be interpreted within this specific educational context. Factors such as institutional support, integration into curriculum, and access to real customer projects may influence how transferable the model is to other settings.

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BRIDGING KNOWING AND DOING THROUGH HABIT FORMATION IN CDIO EDUCATION

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ABSTRACT

Oguz han Engineering and technology university of Turkmenistan, one of CDIO's youngest members, demonstrates how habit formation can ease CDIO implementation for new adopters struggling with daily framework integration. This quasi-experimental study embedded CDIO competencies as automated daily micro-habits within engineering lessons, comparing intervention and control groups through digital assessment over 13 weeks. Participants were second-year Cyber-Physical Systems students (n=25 per group). The phased intervention progressed from individual phase routines to full lifecycle integration, yielding a large effect size (d = 1.12) on the primary CDIO competency rubric. Minimal faculty training requirements and existing LMS infrastructure suggest potential for scalable adoption across disciplines, with implications for CDIO Standards 1, 2, 5, 7, 8, and 10. Cross-disciplinary and longitudinal validation remains a direction for future work.

KEYWORDS

CDIO framework, habit formation, micro-habits, engineering education, IoT education, automated assessment, Standards: 1, 2, 5, 7, 8, 10

INTRODUCTION

Oguz han Engineering and technology university has established regional CDIO leadership through five consecutive conference contributions (Orazov et al., 2025a; Mezilov et al., 2024), spanning language-integrated curricula (Orazov et al., 2025a), SUSI YWLP leadership programs (Garlyyeva et al., 2025), six-month skill frameworks (Orazov et al., 2025b), and mechatronics implementations (Mezilov et al., 2024).

Modern engineering demands integrated technical-professional competencies that traditional approaches fail to deliver. The CDIO Initiative provides a comprehensive solution (Berggren et al., 2002; Lynch et al., 2006; Edström et al., 2020), embedding engineering science within authentic lifecycle contexts—from conception through operation—enabling mastery of complex systems.

CDIO Implementation Gap

Despite its widespread adoption across more than 200 institutions worldwide and its detailed Syllabus 2.0 outlining specific learning outcomes, consistent daily integration of CDIO phases remains a persistent challenge, particularly for newer adopting institutions. Traditional implementation strategies frequently confine CDIO application to isolated project weeks or capstone experiences, resulting in superficial engagement rather than the deep, automatic competency execution that characterizes professional practice. Faculty often struggle to embed all four phases systematically into regular coursework, leading students to treat CDIO as an occasional framework rather than a habitual problem-solving approach (Woollacott, 2009). This creates a fundamental knowing-doing gap where theoretical understanding of CDIO principles fails to translate into consistent, reflexive application across diverse learning contexts. New adopters particularly face resource constraints, faculty training gaps, and curriculum integration challenges that hinder sustainable implementation beyond demonstration projects.

Habit Formation as Solution

This paper addresses CDIO implementation barriers through micro-habits—2–5-minute daily routines embedding all four phases within existing lessons (Clear, 2018). The theoretical basis for applying micro-habit automation to curriculum change rests on two complementary bodies of evidence: Lally et al.'s (2010) empirical modelling showing that small, context-specific repetitions accumulate into durable behavioral change within 18–254 days, and Bandura's (2006) self-efficacy theory, which holds that repeated successful performance in incremental tasks progressively builds the confidence and automaticity needed for complex professional practice. Together, these frameworks suggest that decomposing CDIO lifecycle competencies into minimal daily actions—triggered by environmental cues and reinforced through immediate feedback—can convert episodic engagement into habitual professional behaviour without requiring wholesale curriculum redesign. Using cueing, repetition, minimal friction, and digital reinforcement, complex competencies decompose into scalable micro-practices that leverage existing lesson structures to build automaticity. Arduino-based IoT development serves as the course subject within which micro-habits are embedded: students practice CDIO phases through smart home appliance tasks, with immediate digital progress tracking providing the reinforcement loop that bridges initial conscious effort toward unconscious competence. While the implementation is demonstrated in an IoT context, the micro-habit architecture itself is discipline-agnostic and adaptable to other engineering domains.

Research Objectives

This study pursues three objectives:

- Validate phased micro-habit framework progressing from individual CDIO phase mastery to full-cycle integration
- Test automated digital assessment infrastructure for real-time competency tracking at scale
- Compare CDIO competency and self-efficacy outcomes between a habit-based micro-habit intervention and conventional weekly CDIO instruction, using four indicators of success: CDIO rubric composite scores, habit completion rates, self-efficacy gains, and project scores.

The paper presents: Theoretical Framework (CDIO and habit science), Practical Implementation (IoT specifications), Experimental Design (standardized instruments), Results, and implications for CDIO reform. Success is defined as improvement in CDIO rubric composite scores, habit completion rates, self-efficacy, and project scores relative to conventional instruction.

THEORETICAL FRAMEWORK

CDIO Framework Foundations

The Conceive-Design-Implement-Operate (CDIO) framework establishes engineering education as a comprehensive product lifecycle process rather than fragmented technical training. Table 1: CDIO Phases and Core Competencies delineates the four core phases with their definitions, representative activities, and alignment to CDIO Syllabus 2.0:

Table 1. CDIO Phases and Core Competencies

Phase	Definition	Example Activities	Syllabus Alignment
Conceive	Define customer needs, problem scope, technical requirements	User analysis, problem statements, scoping	1.1–1.4
Design	Solution architecture, component selection, trade-off analysis	Block diagrams, solution generation, decision matrices	2.1–2.4
Implement	Build, test, verify solution functionality	Prototyping, coding, quality assurance	3.1–3.3
Operate	Deploy, maintain, continuous improvement	Testing protocols, troubleshooting, reflection	4.1–4.3

Habit Formation Mechanisms

Automaticity emerges through the cue-craving-response-reward loop, converting deliberate effort into unconscious execution (Clear, 2018). Four principles accelerate this in education: Obvious cues trigger behaviors; Attractive actions align with professional identity; Easy tasks take <2 minutes; Satisfying reinforcement strengthens neural pathways.

Meta-analyses confirm small, repeated actions compound into substantial change within 18-254 days, with engineering competencies accelerating due to contextual specificity (Lally et al., 2009). These mechanisms convert episodic CDIO awareness into reflexive daily practice.

CDIO-Habit Integration Model

The proposed integration systematically maps habit formation principles onto CDIO micro-habits, creating a scalable behavioral architecture for competency automaticity. Table 2: Habit Principles Applied to CDIO Micro-Habits illustrates this operationalization:

Table 2. Habit Principles Applied to CDIO Micro-Habits

Principle	Conceive (2 min)	Design (3 min)	Implement (5 min)	Operate (3 min)
Obvious	Lesson start prompt	Post-Conceive cue	Pre-coding checklist	Post-test reflection
Attractive	"Smart home engineer" identity	Arduino showcase	Code execution	Problem-solving mastery
Easy	Problem template	2-solution minimum	1-line pseudocode	Test scenario template
Satisfying	LMS progress bar	Peer gallery vote	Code runs successfully	Learning point recorded

Each 2–5-minute practice builds sequential mastery through temporal stacking (Conceive→Design→Implement→Operate), culminating in reflexive full-cycle execution while maintaining fidelity to CDIO Syllabus 2.0 outcomes.

PRACTICAL IMPLEMENTATION

Overview of the Phased Micro-Habit Strategy

This intervention embeds all four CDIO phases into daily 2–5-minute learning routines, enabling gradual integration without curriculum redesign. Students progress from isolated phase mastery (Weeks 1–4) to integrated full-cycle routines (Weeks 9–13), converting discrete micro-actions into reflexive professional competency.

The experimental design maintained rigorous control through two parallel groups of second-year Cyber-Physical Systems students (n = 25 per group, age M = 19.4 years, SD = 0.8; 72% male) undertaking identical IoT Arduino-based smart home appliance lessons. Both groups received comprehensive baseline CDIO instruction per established standards, including structured phase explanations, instructor-modeled examples from authentic contexts, and scaffolded practice opportunities, ensuring equivalence across content delivery, project complexity, and assessment standards.

The control group received weekly 10-minute “CDIO Spotlight” sessions (one phase per week), supplemented by instructor exemplars—replicating typical CDIO adoption patterns. Control students completed the same Google Forms instruments and CDIO Micro-Habit Rubric as the experimental group, but without LMS prompts, habit stacking cues, or real-time

dashboards.CDIO Micro-Habit Rubric was applied to all submissions, enabling direct comparison across groups.

The experimental group received identical instruction systematically augmented by daily micro-habits triggered by LMS prompts, temporally stacked onto lesson transitions, and reinforced through real-time progress dashboards. This methodological equivalence isolates habit formation as the independent variable, enabling unambiguous causal attribution of differential outcomes to the micro-habit intervention.

Week-by-Week Integration Plan for IoT Practice Lessons

The following 13-week plan embeds each CDIO phase as an automatic micro-habit within Arduino-based smart home lessons. Students progress from isolated phase mastery (Weeks 1–3) through cumulative dual- and triple-phase fluency (Weeks 4–9), to comprehensive four-phase integration (Weeks 10–12), culminating in reflexive full-cycle application to novel challenges from Week 13 onward.

Phase 1: Establishing "Conceive" Micro-Habit (Weeks 1-3).

Phase 1 establishes a 2–3-minute lesson-commencement routine: LMS prompts direct students to identify a smart home inefficiency, define an end-user profile, and record a problem statement using a standardised template (“Today’s Arduino targets X functionality for Y user need”). By Week 3, needs analysis precedes all implementation work, confirming successful habit acquisition.

Phase 2: Integrating "Design" Micro-Habit (Weeks 4-6).

Phase 2 adds a 5-minute post-acquisition session in which students write concise pseudocode (e.g., IF soilMoisture < threshold THEN digitalWrite(pumpPin, HIGH)) and justify hardware choices (e.g., capacitive over resistive sensors to reduce electrode corrosion). Structured peer review reinforces each submission. Routines extend to 7–8 minutes by Week 6 as design fluency grows.

Phase 3: Incorporating "Implement" Micro-Habit (Weeks 7-9).

Phase 3 operationalizes design specifications into verifiable IoT prototypes through 5-minute sessions translating pseudocode into functional Arduino code. Students execute hardware-software integration—sensor interfacing, pin assignments, logic implementation—under strict time constraints simulating professional sprint cycles. Compile-test-debug cycles with immediate instructor feedback reinforce automatic execution. By Week 9, routines expand to 8 minutes, enabling complex prototype assembly while preserving daily repetition essential for procedural automaticity and seamless transition to Operate phase diagnostics.

Phase 4: Completing with “Operate” Micro-Habit (Weeks 10-12).

Authentic industry deployment is infeasible academically, so 3–5-minute sessions simulate Operate thinking via structured self-diagnostic checklists. Representative prompts include: “Did the sensor maintain output across three consecutive duty cycles?” and “Identify whether the observed 15% reading drift originates in wiring, code timing, or power supply—and record the corrective step (e.g., adding a 10 µF decoupling capacitor).” Each session closes with a one-sentence LMS reflection (e.g., “Energy draw exceeded estimate by 20%—sleep-mode optimisation recommended”). Sessions reach 5–6 minutes by Week 12.

Phase 5: Full CDIO Cycle Integration (Weeks 13+).

Phase 5 synthesizes complete CDIO cycles within 10–15-minute episodes via novel micro-challenges like "automated plant hydration notification." Students execute instantaneous full-lifecycle progression: Conceive (hydroponic requirements), Design (capacitance topology), Implement (analogRead logic), Operate (stress testing). Convergent instructor prompts—"From requirements to operational protocols"—exploit cumulative habit stacking, delivering transformative identity reinforcement as holistic lifecycle practitioners.

Differentiated Support. For students unable to complete Design or Implement phases within prescribed limits, a three-tier recovery protocol was applied: (1) partial rubric credit for incomplete attempts, preserving engagement; (2) optional LMS scaffold examples (e.g., a pre-annotated DHT22 pseudocode template) released one lesson later; and (3) weekly instructor review of flagged low-completion patterns with targeted feedback. This ensured accessibility across the ability range without reducing challenge for advanced students.

EXPERIMENTAL DESIGN AND METHODOLOGY

Research Design

This investigation employed a quasi-experimental parallel-groups design to examine the impact of the phased micro-habit intervention on CDIO competency development. Two intact classes of second-year IoT/Arduino engineering students (n = 25 per group), matched on baseline demographics, prior GPA (M = 3.12 vs. 3.08, p = 0.87), and technical prerequisites, received identical core curriculum content across the 13-week term. Methodological equivalence across lecture materials, laboratory exercises, project assignments, and assessment schedules was maintained to ensure observed differences could be attributed to the experimental manipulation.

Both groups received standardized CDIO framework instruction comprising explicit phase definitions, Syllabus 2.0-aligned learning outcomes, instructor-modeled worked examples, and scaffolded practice opportunities. The experimental group's instruction was systematically augmented by the phased micro-habit architecture operationalizing CDIO competencies as automated 2–5-minute daily routines triggered by LMS-embedded behavioral cues, temporal habit stacking, and immediate digital reinforcement. The control group received equivalent CDIO exposure through conventional weekly 10-minute "CDIO Spotlight" instructional segments, replicating typical implementation patterns across adopting institutions.

Standardized Assessment Instruments

The CDIO Micro-Habit Rubric (Table 3) was constructed in three stages: criteria derived from Syllabus 2.0 descriptors and reviewed by two CDIO practitioners; pilot testing (n = 15) refining reliability from $\alpha = 0.82$ to 0.87; and bi-weekly inter-rater calibration reaching $\kappa = 0.78$. Both groups completed identical rubric submissions—experimental students via LMS prompts, control students via instructor cues at Spotlight sessions.

Primary Outcome: Daily micro-habit submissions across all four CDIO phases (Table 3) were evaluated using a standardized 0–2-point rubric yielding composite scores (Cronbach's $\alpha = 0.87$). Parallel criterion structures calibrated for IoT/Arduino contexts achieved inter-rater reliability (Cohen's $\kappa = 0.78$):

Table 3. CDIO Micro-Habit Rubric Criteria

Criterion	0 – Irrelevant/Missing	1 – Partial Definition	2 – Clear IoT Problem
Problem Clarity	Vague, off-topic, or absent	General problem stated	Specific smart home need identified
User Specification	No user identified	Vague demographic mentioned	Concrete persona with defined need

Note. Parallel rubrics assessed Design (solution diversity/feasibility), Implement (pseudocode logic/component selection), and Operate (test coverage/troubleshooting). Automated Google Forms enabled self-assessment with instructor override. Each criterion was scored 0–2; composite phase scores therefore range from 0 to 4 per phase, with the overall rubric composite aggregated across phases.

Secondary Outcome: A validated 12-item instrument (Bandura, 2006) measured phase-specific engineering self-efficacy on 5-point Likert scales, administered at baseline, Week 7, and Week 13. Four 3-item subscales demonstrated strong reliability: Conceive (α = 0.82), Design (α = 0.87), Implement (α = 0.84), Operate (α = 0.81).

Data Management Pipeline and Statistical Analysis

Student submissions flowed through an automated pipeline: Google Forms → Google Sheets → weekly dashboards. Weekly processing (approximately 30 minutes) yielded rubric scores, engagement rates, and self-efficacy trends. A mixed ANOVA tested Group × Time interaction effects on rubric scores. Cohen's d measured practical significance (α = 0.05). Statistical power was calculated at 84% for d = 0.65 using G*Power 3.1.

EXPERIMENTAL RESULTS

The following results were obtained from the 13-week intervention (n = 50; 25 per group). Pre-intervention equivalence was confirmed across all measures (all baseline p > 0.10). Table 4 presents pre- and post-intervention means, standard deviations, group differences, effect sizes, and significance levels.

Table 4. Primary Experimental Outcomes with Pre/Post Means (n=50)

Metric	Exp. Pre M (SD)	Exp. Post M (SD)	Ctrl Pre M (SD)	Ctrl Post M (SD)	Δ Post	Cohen's d	p-value
CDIO Rubric composite (0–16 total)	5.12 (1.64)	8.56 (1.20)	5.00 (2.08)	6.32 (2.40)	+2.24	1.12	<0.001
Habit Completion %	—	93% (8%)	—	77% (15%)	16%	1.35	<0.001
Self-Efficacy (1–5 scale)	2.9 (0.6)	4.3 (0.4)	2.8 (0.7)	3.5 (0.6)	+0.8	0.87	<0.01
Project Score %	—	85% (10%)	—	63% (14%)	22%	1.67	<0.001

Note. The CDIO Rubric composite is the sum of scores across all four phase rubrics (each scored 0–2 per criterion × 2 criteria = 0–4 per phase; four phases = 0–16 maximum; reported

here consistent with the 0–16 scale (experimental post-intervention mean 8.56; control 6.32). Habit Completion and Project Score were not applicable (—) at pre-intervention. Cohen's d = 1.12 corresponds to 85% vs. 63% mastery on the project score metric, representing approximately 1.5 years of equivalent traditional training gains (Sawilowsky, 2009).

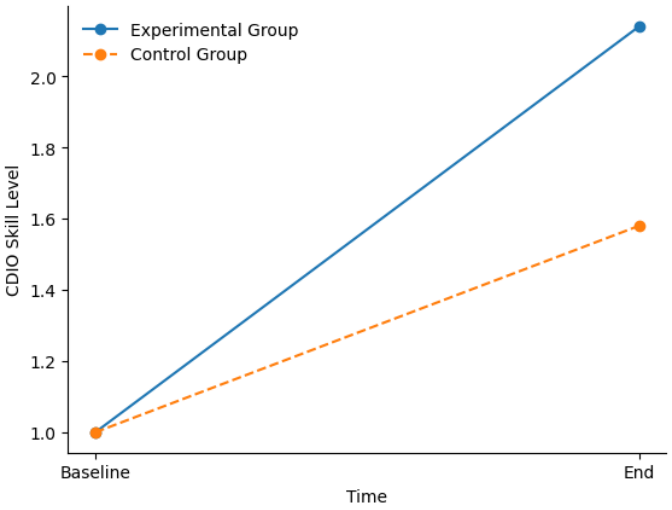


Figure 1. CDIO Skill Growth.

Figure 1 shows micro-habits accelerated mastery from equal baseline to 85% proficiency in the experimental group compared with 63% in the control group. Experimental students completed 93% of daily micro-habits and reported substantially greater confidence in solving Arduino problems (self-efficacy gain d=0.87). The large effect size (d=1.12) on the CDIO rubric likely reflects the high contextual specificity of daily practice aligned directly to assessment criteria, the intensive repetition frequency (daily vs. weekly), and the low baseline scores in both groups, all of which are known amplifiers of effect magnitude in skill-acquisition interventions. Google Forms automation demonstrated strong reliability [α=0.87, κ=0.78] and substantially reduced instructor grading time relative to manual assessment methods.

Discussion and Future Directions

Micro-habits demonstrated robust efficacy within this IoT/Arduino context (d = 1.12), with the Google Forms→Sheets pipeline reducing faculty assessment time by an estimated 95%. An important future direction is adaptation to team-based design projects, where CDIO phase execution must be coordinated across students with different roles. In such settings, micro-habit cues could be embedded at team meeting transitions—e.g., a shared "Conceive check-in" to open each session—and digital tracking adapted to assess team-level artifacts (shared design documents, sprint logs, test protocols) rather than individual submissions. These extensions are included in the future research agenda.

While pre-intervention equivalence was established [all p>0.10], the 13-week duration precludes long-term retention assessment, and IoT/Arduino specificity requires cross-disciplinary validation. Future research will address these through three extensions: a 6-month retention study tracking capstone CDIO execution [n=40]; concurrent pilots adapting micro-habit templates for Mechanical, Civil, and Chemical Engineering [n=20 each]; and industry partnerships deploying student prototypes to validate Operate phase authenticity.

These findings directly address CDIO Standards 1, 2, 5, 7, 8, and 10, offering empirically-grounded behavioral templates and digital assessment infrastructure that warrant further

validation across diverse engineering disciplines and institutional contexts within the broader CDIO community.

Limitations

This study acknowledges four key limitations:

1. Short-term Duration: The 13-week intervention captured micro-habit formation and initial automaticity but could not assess long-term retention or sustained competency transfer beyond the academic term. Full CDIO cycle execution emerged by Week 13, though longitudinal follow-up is needed to confirm permanent behavioral change.

2. Context Specificity: Implementation occurred exclusively within IoT/Arduino classes, limiting generalizability to Mechanical, Civil, Electrical, and Chemical Engineering disciplines requiring workflow-specific template adaptations.

3. Operate Phase Constraints: Laboratory prototypes could not achieve authentic industry deployment due to regulatory compliance, cybersecurity protocols, field testing, and stakeholder integration barriers absent in academic settings. Students developed comprehensive test scenarios, but actual deployment remained infeasible.

4. Year of Study and Pedagogical Adaptation: Participants were second-year students; calibration for other year groups is untested. First-year students simultaneously acquiring programming fundamentals would likely need extended scaffolding and longer phase windows before habit cues are effective. Senior students with prior CDIO exposure could compress Phases 1–2 and enter Phase 5 integration earlier. Future work should test these adaptations to establish year-group-appropriate implementation guidelines.

These pragmatic boundaries reflect classroom-based research constraints while highlighting needs for multi-disciplinary, longitudinal validation. The core methodology—phased micro-habit stacking with digital reinforcement—remains robustly generalizable despite bounded implementation conditions.

CONCLUSIONS

This study successfully implemented CDIO phases as effortless daily habits for both students and instructors, eliminating the persistent implementation barriers that challenge new adopting institutions. The 13-week intervention transformed complex lifecycle competencies into simple 2–5-minute micro-routines embedded within existing Arduino lessons, requiring only 1-hour faculty setup and 30 minutes weekly processing.

Students progressed naturally from individual phase execution (Conceive → Design → Implement → Operate) to automatic full-cycle problem-solving characteristic of professional engineering practice. Teachers shifted from framework lecturers to "habit coaches," delivering CDIO instruction through minimal-disruption behavioral cues rather than curriculum overhauls.

The approach addresses core adoption challenges—faculty training gaps, daily integration difficulties, assessment burden—while leveraging free Google infrastructure that may support scalability across engineering disciplines. Mechanical, Civil, and Chemical Engineering adaptations would require discipline-specific micro-action substitution and independent validation before scalability claims can be generalised beyond the present IoT/Arduino context.

Future research will validate long-term retention and cross-disciplinary transferability, building the evidence base needed to establish habit-based CDIO as a scalable approach to engineering education reform addressing Standards 1, 2, 5, 7, 8, and 10. The present findings suggest this methodology holds genuine promise for making CDIO implementation more consistent—a step toward the aspirational goal of fully automatic lifecycle practice.

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EMBEDDING TRANSVERSAL AND SOCIETAL SKILLS IN AEROSPACE ENGINEERING PROGRAMME: BACHELOR CURRICULUM REVISION

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ABSTRACT

The Faculty of Aerospace Engineering at TU Delft is currently reviewing its Bachelor curriculum in response to several interrelated developments. These include changes in the educational landscape, such as the growing impact of artificial intelligence (AI) and sustainability, the shifting balance between content knowledge and skills, evolving assessment practices, and an increased emphasis on student-centred learning. At the same time, the aerospace sector itself is undergoing rapid transformation, driven by the need for sustainable innovation and the growing importance of software, data, AI and sustainability. In addition, changes in the demand and capacity landscape, including skills-based educational needs, accessibility and inclusion, diversity, and rising student numbers, call for a re-evaluation of the curriculum. This paper focuses on strengthening the transversal and societal skill set of Bachelor Aerospace Engineering graduates by making these skills explicit, visible, and coherently embedded throughout the curriculum. A learning-line approach was adopted to structure the development of skills such as teamwork, ethical reasoning, learning from failure, and diversity and inclusion alongside technical content. The paper compares how these skills are addressed in the current and revised curricula and presents a concrete implementation example from the first week of the programme, called Aerospace Ground School. The paper concludes with reflections and recommendations for engineering programmes seeking to systematically embed transversal and societal skills without overloading the curriculum.

KEYWORDS

Transversal and societal skills, Bachelor Curriculum Revision, Aerospace Engineering, Standards: 2 (learning outcomes), 3 (integrated curriculum), and 5 (design-implement experiences).

INTRODUCTION

Engineering education is undergoing a significant transformation, driven by rapid technological advances, evolving societal expectations, and changes in student population. Graduates are increasingly expected to combine strong disciplinary knowledge with transversal and societal skills that enable them to work effectively in multidisciplinary teams, navigate ethical dilemmas, and contribute to sustainable innovation (Beagon et al., 2023; Fleming et al., 2024; Kimpton & Maynard, 2025; Leandro Cruz & Saunders-Smits, 2022; Passow & Passow, 2017). As a result, universities are challenged to rethink how engineering curricula are designed, taught, and assessed because the available time for the programme does not increase.

Within this context, the Faculty of Aerospace Engineering (AE) at TU Delft has initiated a comprehensive revision of its Bachelor of Science programme. Although the curriculum has been continuously adjusted through numerous small changes in response to a changing landscape, a coherent, large-scale revision has not occurred since 2009. While it has produced successful graduates and is consistently ranked among the top AE faculties in the world—13th globally in Mechanical, Aeronautical and Manufacturing Engineering (QS 2023) and 10th worldwide, 1st in Europe, in Aerospace Engineering (ShanghaiRanking, 2025)—developments in both the educational landscape and the aerospace sector necessitate a re-evaluation. These developments include the growing impact of AI and sustainability, a shifting balance between content knowledge and skills development, evolving assessment practices, and an increased emphasis on student-centred learning.

A central challenge in the curriculum revision is how to strengthen the development of transversal and societal skills without further increasing student workload or staff burden. Rather than adding standalone skills courses, the revised curriculum adopts a structured learning-line approach in which skills are explicitly articulated, aligned with programme learning objectives, and developed progressively throughout the programme.

The aim of this paper is threefold: to describe the rationale for revising the AE Bachelor curriculum, to present the learning-line framework used to embed transversal and societal skills, and to illustrate this approach through a concrete implementation example from the first week of the programme. This work builds on earlier CDIO initiatives that emphasise the development and assessment of personal and professional skills within engineering programmes (e.g., Hermon & McCartan, 2010) and extends them by applying CDIO Standards 2, 3, and 5 at faculty scale.

RATIONALE FOR CURRICULUM REVISION

Evolving educational landscape

Higher education has experienced significant changes over the past decade. Blended and online learning have become integral to many programmes (OECD, 2023), while the emergence of generative AI raises new questions about learning objectives, assessment, and academic integrity. At the same time, there is an increasing emphasis on student-centred learning, multidisciplinary teamwork, and authentic assessment (Kimpton & Maynard, 2025, Van den Broeck et al. 2024).

In the existing AE bachelor curriculum, the number and frequency of assessments place considerable pressure on both students and staff, generating high workload. Moreover, skills development is often implicit rather than explicitly addressed in course learning outcomes and

assessments. An additional challenge is the sheer size of the programme. The programme has a yearly intake of 440 freshmen students and runs with a student-to-staff-ration of roughly 22:1.

Evolving aerospace landscape

The aerospace sector itself is undergoing rapid transformation. Sustainable innovation, the integration of software, data-driven approaches, and AI (Beagon et al. 2023), and the growing importance of space-related applications are reshaping the professional profile of aerospace engineers (Gouveia et al. 2022). New topics such as sustainability, ethics, digital skills, and systems thinking need to be addressed, yet the curriculum is already densely packed. This creates a need for smarter integration rather than additional content.

Evolving demand and capacity landscape

A significant growth in student numbers since 2009, combined with increasing societal demand, growing attention to diversity and inclusion, and rising demands on facilities and staff, further challenges curriculum design. Many academic staff experience a tension between teaching and research responsibilities, making it essential to design a curriculum that is coherent, efficient, and sustainable to deliver.

These combined developments motivated a curriculum revision with several key goals: increasing programme cohesion, reducing student workload, redesigning assessment to reduce staff load, strengthening digital and sustainability-related skills, and making transversal and societal skills an explicit part of the curriculum.

TRANSVERSAL AND SOCIETAL SKILLS IN ENGINEERING EDUCATION

A substantial body of literature highlights the importance of transversal skills for engineering graduates. Systematic reviews (Passow & Passow, 2017) and empirical studies (Tuyaerts et al. 2025, Leandro Cruz & Saunders-Smits, 2022) consistently identify problem solving, communication, and teamwork as core competencies, followed by ethics and lifelong learning. Studies of engineering job advertisements (Fleming et al. 2024) similarly show a strong demand for professional skills alongside technical expertise, with digital skills such as programming increasingly valued.

Despite this recognition, research shows that these skills are often insufficiently reflected in course learning outcomes and assessments. Educators may support skills development in principle, but without explicit articulation and alignment, skills risk remaining invisible to students and staff or becoming the victim of “more important” content-driven topics. These findings underline the need for curriculum-level approaches that make skills development explicit, coherent, and assessable, rather than leaving this to individual courses or informal learning experiences.

TRANSVERSAL AND SOCIETAL SKILLS IN CURRENT AE BSC CURRCIULUM

Methodology

An analysis of the learning objectives of all BSc Aerospace Engineering courses (n = 53) in the academic year 2024–2025 was conducted to examine the explicit inclusion of transversal and societal skills. Course descriptions for the academic year 2024–2025 were collected from TU Delft's Coursebase and analysed using Atlas.ti with AI-supported coding. Identified skills were reviewed, merged where necessary, and grouped into competency categories aligned with the IDEE Future-Ready Engineering Competencies framework (TU Delft Teaching Academy, 2024).

Results

The analysis shows that most learning objectives emphasise core engineering competencies, reflecting the technically oriented nature of the programme (Figure 1). Design-related competencies—such as design thinking, problem-solving, and concept development—are particularly prominent, appearing in 23 courses across all three years. Analytical thinking is addressed in 14 courses, while critical thinking is mentioned in eight courses and is more evenly distributed. Digital literacy, including programming and software skills, appears in six courses, whereas explicit references to AI literacy are limited to a single second-year course. Systems thinking and modelling are mainly concentrated in the first year, while research-related skills, such as data analysis and knowledge acquisition, are primarily addressed in the first and second years. Project management competencies are mentioned in only three courses.

Communication and collaboration competencies are present but unevenly articulated. Collaboration is explicitly mentioned in ten courses across all programme years. Interpersonal communication skills, such as peer feedback and perspective-taking, appear in nine courses, while technical communication skills—including reporting, presenting, and visualisation—are addressed in seven courses. Although teamwork and communication are present, they do not form a clearly articulated or progressive learning trajectory.

Personal and professional competencies are less frequently represented. Seven courses include learning objectives related to self-direction and self-management, mainly in the first year. Integrity-related competencies appear in five courses, while adaptability, proactivity, and reflective practice are only sporadically mentioned.

Impact-related competencies are least represented. Environmental awareness appears in two courses and social responsibility in one first-year course. Ethical responsibility, stakeholder awareness, entrepreneurship, and business-related competencies are not explicitly addressed. Overall, the findings reveal a fragmented and largely implicit approach to transversal and societal skills development, motivating the introduction of structured learning lines in the revised curriculum (Figure 1).

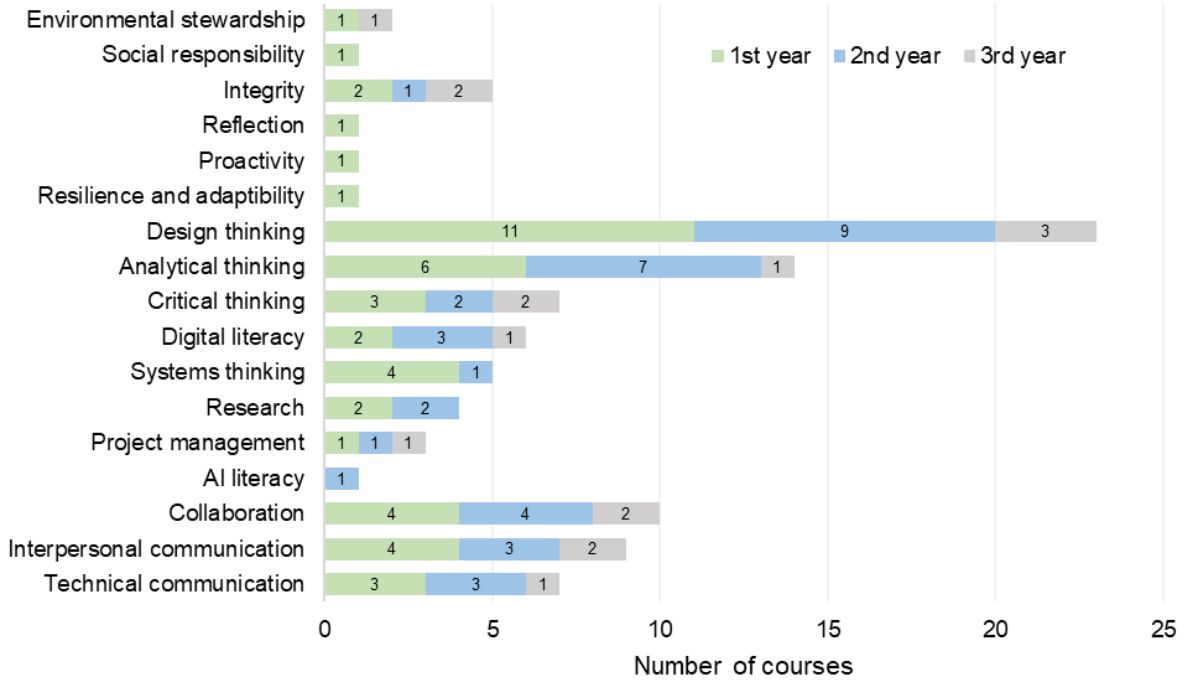


Figure 15. Distribution of transversal and societal skills across BSc courses per year.

CURRICULUM DESIGN: THE LEARNING-LINE APPROACH

To increase the visibility and coherence of skills development in the revised curriculum, four learning lines will be introduced. A learning line is defined as the progressive development of students' knowledge, skills, and attitudes in a specific area across the programme. Each learning line has clearly defined descriptors and is linked to programme-level learning objectives (APPENDIX A). The four learning lines are:

1. **Ethics and Societal Context**, focusing on ethical responsibility, sustainability, scientific integrity, and the societal impact of engineering solutions.
2. **Engineering Approach**, addressing research, design cycles, system thinking, analytical and problem solving, experimentation, and interdisciplinarity.
3. **Knowledge and Its Interconnection**, focusing on modelling, simulation, data analysis, control, and digital skills.
4. **Transversal Skills, Knowledge and Attitudes**, including teamwork, communication, continuous learning, reflective thinking, and learning how to learn.

Each learning line developed its learning objectives (APPENDIX B) through an iterative process involving faculty bodies, academic staff, and educational support staff. Concrete educational units were then aligned with these objectives, resulting in a curriculum overview (curriculum card) that visualises how skills and knowledge are distributed throughout the programme (Figure 2).

Dedicated learning-line teams with faculty-wide representation have been appointed to monitor content, alignment, and progression within each learning line in close collaboration with course teams, ensuring coherence and preventing fragmentation. Established at the outset of the curriculum development, these teams will evaluate the outcomes of the Bachelor programme implementation and remain active for at least five years after implementation to oversee ongoing adjustments and explicitly safeguard the integrity of each learning line.

Transversal and societal skills

This paper focuses on the learning lines **Ethics and Societal Context** and **Transversal Skills**, and their implementation at the start of the programme. These learning lines were selected because they address competencies that are essential for contemporary engineering practice, yet are often implicitly addressed and insufficiently visible in engineering curricula. By explicitly structuring these learning lines, the programme aims to create coherent learning paths for transversal and societal skills, enabling the design of targeted learning activities and the development of appropriate assessment approaches.

Rather than being implemented as stand-alone courses, topics from the Ethics and Societal Context and Transversal Skills learning lines are embedded within existing technical and engineering courses. The allocation of learning-line topics to specific courses is guided by a clear educational rationale: alignment with the technical content of the course, opportunities for application in projects and practicals, and the intended progression of skills across the Bachelor programme. This approach ensures that skills development is meaningfully intertwined with disciplinary learning and that students encounter these skills in increasingly complex and authentic engineering contexts over time.

Project and practical activities

In the revised curriculum, a clear distinction is made between projects (star symbol in Figure 2) and practicals (target icon in Figure 2). Projects are defined as team-based learning activities in which students work on open-ended engineering challenges with an unknown outcome, requiring integration of knowledge, collaboration, and decision-making under uncertainty. Practicals, in contrast, are also team-based activities but focus on applying specific concepts or methods to tasks with a known or expected outcome, supporting the development of technical proficiency and experimental skills.

Both projects and practicals will no longer be offered as stand-alone courses as in the current curriculum but are integrated within broader learning units. This approach preserves the hands-on character of the curriculum while strengthening the connection between theoretical content and practical application. Lectures are positioned to support labs, practicals, and projects, which are aligned with both technical content and transversal and societal skills.

IMPLEMENTATION EXAMPLE: AEROSPACE GROUND SCHOOL

To emphasise the importance of transversal and societal skills from the outset, the revised curriculum introduces the *Aerospace Ground School* in the first week of the BSc programme. This week is designed to confront students with both their incoming knowledge and the transversal and societal skills required of an engineer in training and make them excited in the program.

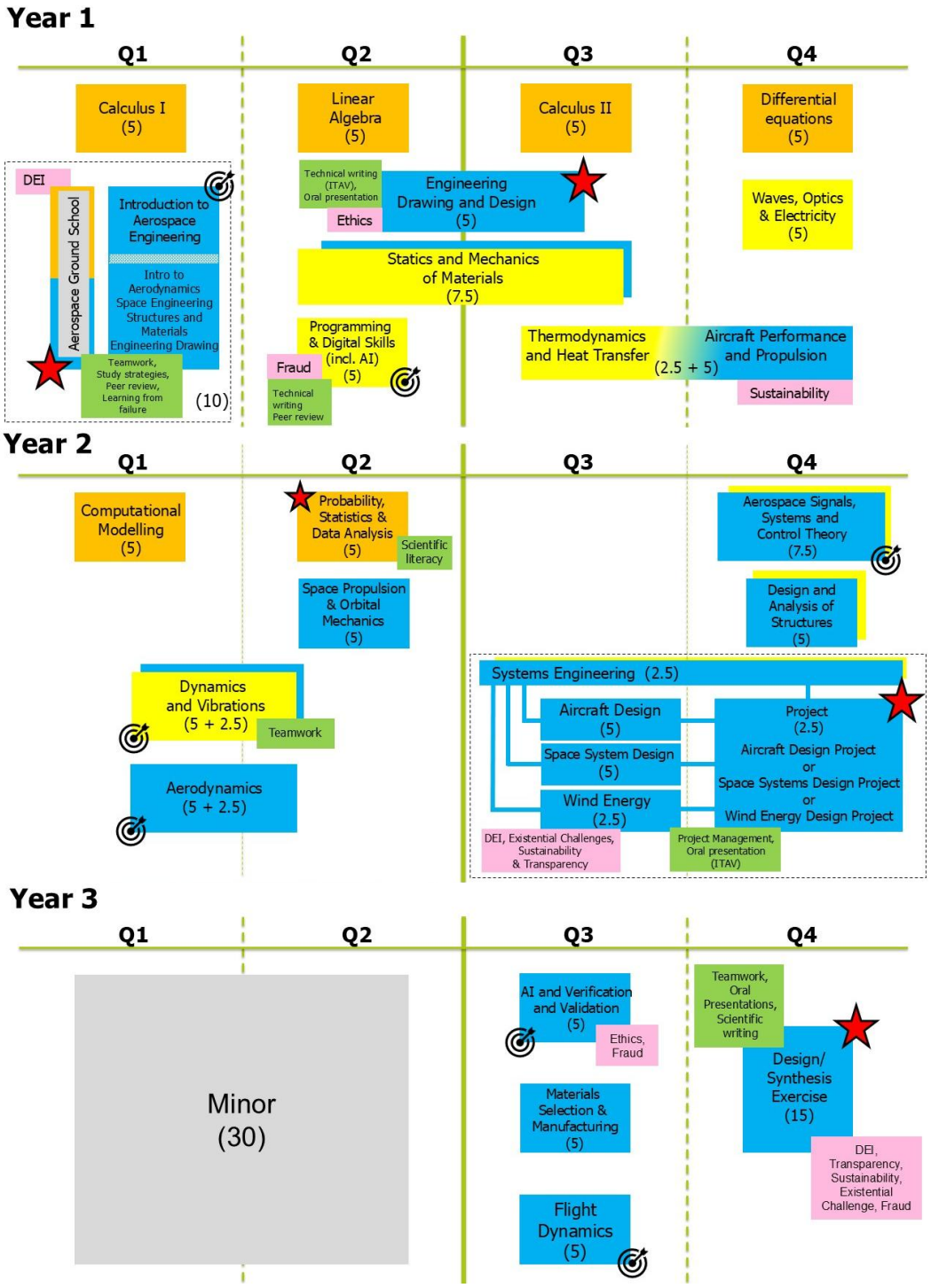


Figure 16. Overview of the curriculum card per year, showing the color-coded learning lines for each course (green: transversal skills, knowledge and attitudes; yellow: knowledge and its interconnection including mathematics in orange; blue: engineering approach; pink: ethics and societal context). Project activities are indicated with a star (teamwork with an unknown outcome), and practical activities with a target icon (teamwork with a known outcome).

The week consists of two complementary components (Figure 3):

- **Disciplinary practical sessions ("orange blocks"):** In daily practical sessions across different aerospace disciplines—such as aerodynamics and wind energy, flight performance and propulsion, space engineering, and aerospace structures and materials—in groups, students work on engineering problems that require the application of basic mathematical knowledge (e.g. integrals, derivatives) and the initial development of engineering skills. These sessions address skills such as problem formulation, basic modelling, estimation, dealing with uncertainty, and making engineering decisions.

- **Professional development sessions ("blue, green and pink blocks"):** Parallel lecture and discussion sessions focus explicitly on transversal and societal skills development. Topics include the role of the engineer, learning from failure, ethical dilemmas in engineering practice, the TU Delft code of conduct, and diversity, equity, and inclusion. These sessions also support social integration by helping students get to know each other and the faculty.

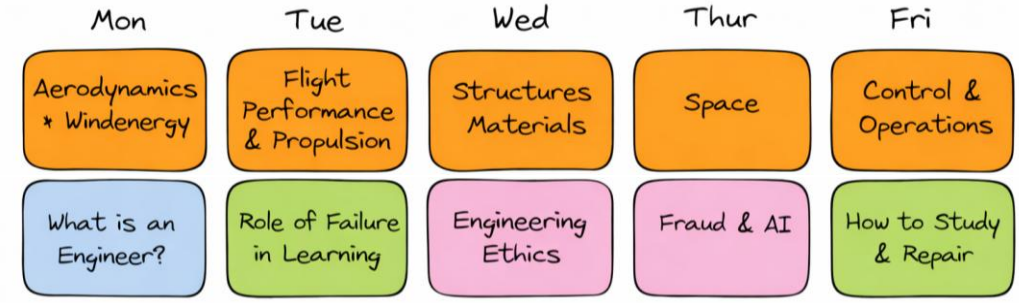


Figure 17. Components of the Aerospace Ground School per day.

The structure of the week enables large student cohorts to be divided into manageable groups of approximately 40 students within a cohort of 440 first-year Bachelor students. This group organisation combines scalability with opportunities for active and interactive learning. Although the assessment approach is still under development, the intention is to implement Aerospace Ground School as a pass–fail course. Students will be required to actively participate in all components of the week and demonstrate engagement by completing a set of required activities, which are recorded through check marks rather than graded assessments. This approach aims to emphasise participation, reflection, collaboration and skill development, while avoiding additional assessment pressure at the start of the programme.

Visibility of Transversal and Societal Skills

To enhance the visibility of transversal and societal skills, these skills are explicitly described on the course pages. This transparency allows (future) students to understand what skills they are expected to develop in each course and how these relate to the overall programme learning objectives. Making skills explicit on course pages also supports alignment across courses and provides clarity for staff and external stakeholders, such as accreditation and visitation committees.

DISCUSSION

The learning-line approach provides a structured way to embed transversal and societal skills without adding separate courses or increasing workload. By making learning objectives explicit and aligning them across courses, skills development becomes more visible to students and staff. Introducing these skills from the first week of the programme reinforces their importance and positions them as integral to engineering practice rather than as add-ons.

In the revised curriculum, transversal and societal skills are assessed within the technical and project-based courses where they are taught, using short reflections, peer feedback, and group evaluations supported by shared rubrics. These rubrics promote consistency and calibration across teaching teams while keeping assessment load manageable. To help staff integrate these skills effectively and sustainably, the faculty provides a structured implementation plan with workshops, design sessions, and feedback cycles. Learning-line team members guide these efforts to support alignment and reduce the burden on course coordinators.

Challenges remain in refining assessment methods and ensuring long-term curriculum alignment. Dedicated learning-line teams will therefore evaluate programme implementation and monitor alignment over the subsequent five years. This monitoring process will track indicators such as student progression, workload, project quality, satisfaction, and learning-objective alignment, using data from surveys, evaluations, artefact reviews, and structured reflections to provide longitudinal insight into the development of transversal and societal competencies.

CONCLUSION AND RECOMMENDATIONS

This paper set out to address the challenges facing contemporary AE education, including increasing student numbers, rapid technological developments, and growing expectations regarding transversal and societal skills. The curriculum revision presented responds to these challenges by embedding skills development in a coherent and scalable way, without further overloading the programme.

Embedding transversal and societal skills through dedicated learning lines increases their visibility, coherence, and systematic integration alongside technical knowledge. By explicitly defining learning objectives and aligning them across courses, these skills become an integral part of the overall educational design rather than implicit or fragmented elements of individual courses.

The experience gained in this work highlights the importance of establishing dedicated groups to define, monitor, and align transversal and societal skills across the curriculum. To support coherence and transparency, these skills should be explicitly articulated in learning objectives, course descriptions, and assessments, with educational advisors assisting course teams in integrating them meaningfully with disciplinary content. Ensuring that these competencies develop progressively throughout the programme is essential, as is the continuous monitoring of their implementation and impact in the years that follow. These recommendations may support other engineering programmes seeking to prepare graduates for the complex technical and societal challenges of contemporary engineering practice.

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APPENDIX A

Programme Learning Objectives

Students should be able to…

1. Synthesise fundamental theories from mathematics, physics, and engineering to analyse aerospace problems and design aerospace systems.

2. Prototype and test aerospace software, hardware and systems.

3. Critically reflect on and assess their own work and the work of others using insights from fundamental theories.

4. Identify and reflect on the needs and feedback from different stakeholders to translate these into design constraints.

5. Propose and advocate for responsible engineering solutions that meet the needs of the society, safety, social acceptance, viability and environmental impact.

6. Develop effective learning strategies both individually and collectively.

7. Demonstrate skills in communication, collaboration and team work to effectively work together in diverse teams and address different audiences.

8. Conduct research in aerospace-related sciences and technology to draw conclusions towards a research question while acknowledging their limitations.

APPENDIX B

Learning Objectives of LL: Ethics and Societal Context

Students should be able to…

LO1: Apply the principles of diversity, equity and inclusion in aerospace engineering practice and research.

LO2: Use algorithms (including AI), data and information that comply with ethical standards.

LO3: Apply principles of professional and personal ethics to aerospace engineering practice and research (including transparency).

LO4: Ensure transparency in aerospace engineering practice for inclusiveness decision making.

LO5: Evaluate the role and responsibility of aerospace engineering to tackle existential societal challenges.

LO6: Integrate the UN Sustainable Development Goals in aerospace engineering practice and research.

Learning Objectives of LL: Engineering Approach

Students should be able to…

LO1 Identify and categorize systems and subsystems in complex aerospace products.

LO2 Analyse and evaluate stakeholder requirements to enable engineering decisions.

LO3 Integrate knowledge from multiple disciplines into a coherent design framework.

LO4 Select and apply suitable theoretical, numerical and experimental models.

LO5 Generate, interpret, and use experimental data to support aerospace engineering decisions.

LO6 Verify and validate engineering models against requirements and reference data.

LO7 Compare and evaluate design alternatives using trade-offs and performance indicators.

LO8 Understand and apply system engineering principles.

LO9 Analyse a problem/system at different levels of abstraction.

LO10 Reflect on how system boundaries shape problem analysis and system interconnections.

Learning Objectives of LL: Knowledge and its Interconnection

Students should be able to…

LO1: Analyse the behaviour of aerospace systems using mathematical models (in the context of aerodynamics, thermodynamics, structural and space/flight dynamics)

LO2: Simulate the static and dynamic behaviour of aerospace systems using numerical methods.

LO3: Evaluate the strengths, limitations, and suitability of mathematical models for simulation, analysis, and design.

LO4: Implement algorithms/procedures to solve aerospace problems effectively.

LO5: Develop software and/or hardware prototypes to simulate, analyse, or optimize the behaviour of aerospace systems

LO6: Verify and validate aerospace models using data, statistical methods, and quantitative analysis.

LO7: Interpret experimental data and signals in the time and frequency domain using filtering and sampling methods.

LO8: Interact critically with AI models by relating their outputs to fundamental aerospace knowledge.

LO9: Design aerospace systems and sub-systems under various loading and environmental conditions, with analytical and numerical methods

Learning Objectives of LL: Transversal Skills

Students should be able to…

LO1: Assess and reflect on the quality of their own work and that of others.

LO2: Execute a continuous and proactive approach to learning.

LO3: Implement techniques for effective collaboration in diverse teams.

LO4: Reflect on their learning journey.

LO5: Reflect on roles and contributions (within a team).

LO6: Write clear and structured reports that communicate key findings to peers.

LO7: Deliver an effective oral presentation with visual support to diverse audiences.

PEER LEARNING AND FEEDBACK THROUGH THE CDIO FRAMEWORK IN ENGINEERING EDUCATION

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ABSTRACT

This paper examines how peer learning, knowledge sharing, and peer feedback can be systematically embedded in CDIO-based engineering education through an industry-integrated learning environment. The study presents theFIRMA, a project-based learning environment at Turku University of Applied Sciences, where student teams work on real ICT projects for internal and external industry clients. Grounded in the CDIO framework, theFIRMA integrates professional practice with academic learning through structured project processes, flexible participation, and multi-layered peer learning. The paper describes how mixed-level project teams, student-lead roles, peer-based quality assurance, and student-led Tech Clubs support active learning, integrated skill development, and continuous feedback in line with CDIO Standards 7 and 8. Particular attention is given to how peer learning and knowledge sharing are enabled across different competence levels, supporting both junior and senior students while mirroring professional engineering work practices. Lessons learned from the long-term implementation highlight the effectiveness of mixed-level teams, the importance of structured documentation for knowledge transfer, and the need for curricular integration to sustain peer-led activities. The findings suggest that combining authentic industry projects with structured peer learning and feedback mechanisms creates a learning environment that supports technical competence, professional skills, and readiness for working life. The paper contributes to a practical CDIO-aligned model that can inform the design of scalable, industry-collaborative learning environments in engineering education.

KEYWORDS

R&D learning environment, ICT, multi-layered peer learning, peer feedback, knowledge sharing, Standards: 7 and 8.

INTRODUCTION

Engineering education increasingly emphasizes the development of professional competencies alongside technical expertise. The CDIO framework supports this shift by promoting active and experiential learning environments that integrate technical work with skills such as teamwork, communication, and adaptability. CDIO Standard 7 emphasizes learning experiences in which technical knowledge and professional skills are developed simultaneously, with peer learning and knowledge sharing supporting this integration through collaboration, discussion, and shared problem-solving. Standard 8 highlights active learning approaches in which students engage directly in the learning process, and peer learning and knowledge sharing occur through interaction, joint activities, and the exchange of ideas and experiences.

Knowledge sharing is the intentional exchange of information, skills, and experiences among individuals or groups to support learning, problem-solving, and innovation. It involves not only sharing information but also interpreting and applying knowledge in meaningful contexts through both formal and informal interactions. (Ashikuzzaman, 2025). Knowledge sharing enables individuals to understand, apply, and further develop knowledge, thereby supporting effective decision-making, problem-solving, and performance in organizational and social contexts (Cummings, 2004).

Peer learning is a collaborative learning process in which individuals of comparable status or experience learn with and from one another through ongoing interaction, shared activities, and mutual support (Topping, 2005; Boud & Cohen, 2014). In engineering education and CDIO-based learning environments, peer learning takes place mainly in project and design work, where students learn together by discussing ideas, solving problems, and sharing knowledge. Through these interactions, students develop technical understanding while also practicing professional skills such as teamwork and communication.

Within project-based and CDIO-oriented learning environments, peer learning and knowledge sharing occur through collaborative tasks, shared problem-solving, and continuous interaction among students. This paper presents theFIRMA, a project-based learning environment at Turku University of Applied Sciences (TUAS), as an example of how peer learning, knowledge sharing and peer feedback can be systematically embedded into engineering education. TheFIRMA is an ICT project office in which student teams work on real industry projects, providing an authentic context for collaboration, knowledge exchange, and the development of professional competencies alongside technical skills. The paper examines how industrial collaboration within theFIRMA enhances student learning experiences and supports engineering education through authentic, industry-driven projects.

KNOWLEDGE SHARING AND PEER LEARNING IN CDIO-BASED ENGINEERING EDUCATION

Peer learning is increasingly recognized as a powerful approach within CDIO-based education, particularly when combined with knowledge sharing among students. Research shows that structured peer interaction, such as collaborative laboratory work, project-based learning, and peer feedback, supports the exchange of knowledge, experiences, and perspectives, thereby enhancing engagement, creativity, and knowledge retention. Hansson, Kolmskog, Odemark, and Högfeldt (2011) demonstrated that even small-scale peer learning interventions in laboratory exercises improved student performance and satisfaction without significant additional instructor effort, partly by encouraging students to explain concepts and

share problem-solving strategies with one another. Bienkowska and Lovén (2017) integrated peer feedback into a large CDIO leadership course and reported improvements in writing skills, assessment competence, and perspective-taking, while also highlighting challenges such as uneven feedback quality. At the program level, Hussmann et al. (2011) emphasized peer-based evaluation across universities to support organizational learning, knowledge sharing, and continuous improvement.

CDIO Standard 7 (Integrated Learning Experiences) highlights the importance of learning activities that integrate disciplinary knowledge with personal and interpersonal skills. Such experiences are intended to help students practice teamwork, communication, and collaboration while connecting technical content to professional competencies. Peer learning, knowledge sharing, and peer feedback support Standard 7 by requiring students to interact, explain concepts, negotiate solutions, review each other's work, and share expertise within teams. Through these processes, students make both explicit and tacit knowledge visible and accessible to others, while peer feedback helps students reflect on both technical and professional aspects of their work. Learning from and with peers enables students to simultaneously develop technical understanding, interpersonal competence, and feedback skills in an authentic context aligned with professional engineering practice.

CDIO Standard 8 (Active Learning) encourages student-centered approaches that promote engagement, reflection, and hands-on participation. Peer learning combined with knowledge sharing and peer feedback is inherently active, as students contribute ideas, articulate reasoning, and collaboratively construct solutions. Activities such as peer instruction, small-group discussions, collaborative problem solving, and peer feedback create opportunities for students to exchange knowledge and learn through interaction rather than passive reception. These practices align directly with Standard 8 by increasing student participation, motivation, and responsibility for learning while supporting deeper understanding through shared sense-making.

THEFIRMA: A CDIO-ALIGNED INDUSTRY-INTEGRATED LEARNING ENVIRONMENT

Operational Model and Student Participation

TheFIRMA is a student-centered learning environment that operates like a company, offering IT services and development projects for both internal and external clients. Students apply theoretical knowledge to real-world challenges, creating mutual benefits for universities, students, and industry by supporting relevant skill development and collaboration. (Säisä, Määttä & Roslöf, 2017).

Each year, about 200 students take part in theFIRMA as part of their studies. The majority of participants come from the Software Engineering and Project Management (SEPM) competence track, while additional students join from other competence tracks at TUAS. Students work in roles that match their interests, including project management, software and web development, application development, testing, and UI/UX design. This flexible arrangement supports individualized learning paths, skill development, and a smooth transition into professional engineering roles after graduation. (Säisä & Kinnari, 2025).

TheFIRMA operates year-round and does not follow the standard academic schedules of TUAS. Students may join and leave theFIRMA at any time, participate in multiple projects with varying timelines, and completely different workloads that result in varying credit amounts. As a result, theFIRMA functions with continuously changing human resources. While this flexible

structure is considered a normal and even beneficial mode of operation, it requires well-defined processes to manage effectively. (Määttä, Roslöf & Säisä, 2018).

Nevertheless, new projects are typically initiated three times per year: in September at the start of the autumn semester, in January at the start of the spring semester, and in May after the official academic year has ended, when students transition to full-time internship work at theFIRMA. If additional projects emerge mid-semester, staffing is reallocated to accommodate them.

At the start of the academic year, approximately 120–130 students participate in theFIRMA projects. The cohort is typically evenly divided between second-year SEPM students entering the competence track and theFIRMA, and fourth-year SEPM students with substantial prior project experience in the environment. In the autumn semester, second-year students are required to complete 81 hours of project work, corresponding to 3 ECTS credits within the 10 ECTS course “Introduction to ICT Projects”. Fourth-year students are required to complete 135 hours of project work, corresponding to 5 ECTS credits, i.e., half of within the 10 ECTS course “Advanced ICT Projects”. At the start of the spring semester, third-year students begin the course “ICT Projects” and complete 108 hours of project work, corresponding to 40% of the course workload (10 ECTS). (Säisä & Kinnari, 2025). Students return the completed hours on a weekly basis. If students complete the required hours before the course concludes while the project continues, they may either continue their participation to earn additional ECTS credits or be replaced to ensure appropriate resourcing.

Project Process and Learning-Oriented Quality Practices

Projects in theFIRMA follow a structured yet flexible process that supports continuity and knowledge sharing across project phases. At the start of each project, a kick-off meeting is organized to align stakeholders on goals, roles, and expectations, and the kick-off document is completed to formally initiate the project. During the first weeks of project work, the project team prepares a project plan that defines objectives, tasks, schedules, and responsibilities. When a project phase ends typically at the end of a semester, the process differs depending on whether the project continues or concludes. If the project continues into the next semester or the project team completes its allocated working hours, a handover report and a handover checklist are completed to ensure the transfer of knowledge and project status to the next team. If the project is completed, the team produces a final report and completes a project closing document to formally conclude the work and document outcomes.

The FIRMA’s project process serves a dual purpose: improving the quality of project outcomes and enhancing student learning. On one hand, it ensures that customers receive high-quality deliverables; on the other, it supports the professional growth of students. Because theFIRMA operates like a small ICT company but is fundamentally a learning environment at TUAS, its process combines both quality assurance and learning objectives. While the quality process focuses on meeting client expectations, the learning process provides students with credits and grades, reinforcing their competence development. At the start of each project, students define specific learning goals, track their working hours throughout the project, and evaluate whether these goals have been achieved at the end. (Määttä et al. 2018). In addition, at the end of the project, students complete self- and peer-assessments that contribute to their project grade, thereby encouraging reflection, responsibility, and active engagement in the learning process. These assessment practices also help make individual contributions visible within team-based work, reducing the risk of unequal participation. By combining documented work effort, self-reflection, and peer feedback, theFIRMA supports fair and transparent assessment while motivating students to actively contribute to shared project goals.

Peer Learning, Knowledge Sharing, and Feedback Practices

A distinctive feature of theFIRMA model is its multi-layered peer learning structure. Project teams are composed of students with varying levels of competence, ranging from junior to senior within the context of higher education, to mirror common practices in professional software and ICT organizations. Within these teams, junior-level students learn through participation and guided practice, while senior-level students take on more demanding tasks and support others by providing guidance and feedback. This structure supports knowledge sharing, peer learning and skill development within the team while preparing students for real-world working environments. For example, during the autumn semester, project teams often include both second- and fourth-year students from the SEPM competence track, enabling learning across different stages of study.

Each project team begins by setting shared learning goals, ensuring that professional development is a collective responsibility. Teams then produce project documentation following theFIRMA's structured process, which is assessed by a dedicated Quality Assurance (QA) team composed of peer students. The QA team provides detailed feedback, enabling project teams to refine their deliverables iteratively. At the end of each semester, students present the project they have done and what they have learned for the other project teams.

In addition to mixed-level project teams, selected advanced-level students take on lead roles in key competence areas, including front-end development, back-end development, UI and UX design, and project management. These student-leads mentor project teams, support problem-solving, and provide guidance and constructive feedback throughout the project lifecycle based on their area of expertise. Student-leads have an open session on weekly basis where students can come to ask questions as needed. They also play a central role in ensuring that teams follow theFIRMA's project processes and quality practices. Furthermore, the leads contribute to the development and continuous improvement of shared guidelines, tools, and working practices, thereby supporting consistency, knowledge sharing, and learning across projects. This mentorship fosters knowledge transfer and supports the development of leadership and coaching skills. In addition, teachers and other theFIRMA experts provide regular support to the teams, for example during bi-weekly Sprint Review meetings, offering guidance, feedback, and professional oversight.

In addition to project-based learning, theFIRMA organizes Tech Clubs as informal peer learning activities in which students share their expertise related to technologies, tools, and working methods with other students. Tech Clubs are facilitated by students and take the form of short information sessions or hands-on workshops, with durations typically ranging from 30 minutes to two hours. These sessions provide a low-threshold opportunity for students to disseminate practical knowledge, introduce new technologies, and exchange experiences across project teams. They contribute to a culture of knowledge sharing, collaboration, and continuous learning within theFIRMA. A few topics from fall 2025 were: "Using computer vision libraries for sports analysis", "Designing for the Mind: Psychology in UI/UX", and "From /brrrr to REST API with Go".

By integrating peer assessment, iterative feedback, mentoring, and peer-led skill sharing, theFIRMA creates an authentic learning environment that closely mirrors professional engineering practice. These mechanisms support active and integrated learning by combining disciplinary knowledge with personal and interpersonal skills, in line with the principles of the CDIO framework. Through continuous peer interaction and reflection, students develop competencies related to collaboration, communication, and professional responsibility while

engaging in realistic Conceive–Design–Implement–Operate activities. The multi-layered peer learning and feedback structure underlying these mechanisms is illustrated in Figure 1.

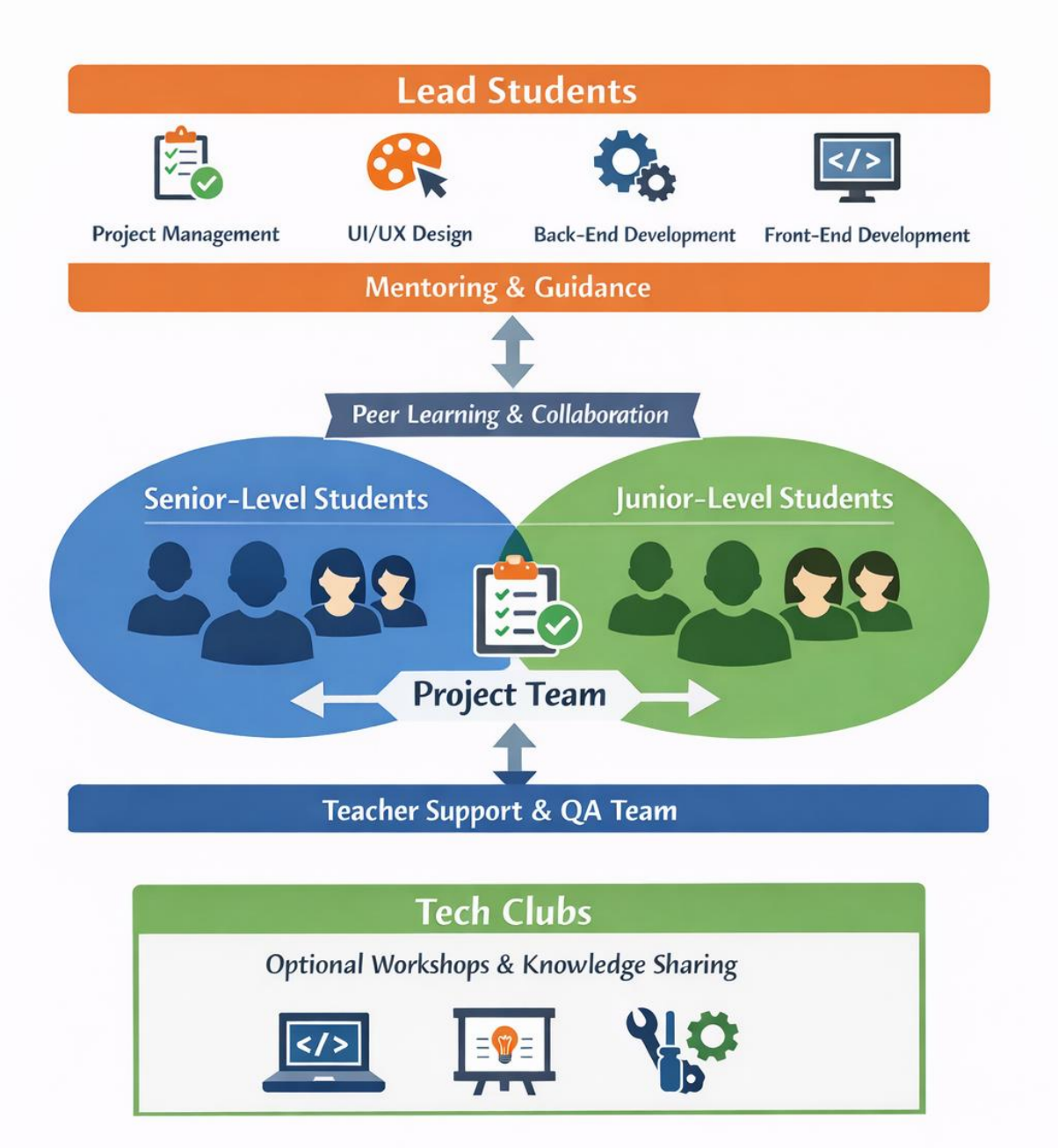


Figure 18. Multi-layered peer learning in theFIRMA

LESSONS LEARNED

TheFIRMA's project process strongly supports project implementation, communication, peer learning, and quality in line with the principles of the CDIO framework. The structured use of project documentation aligns with CDIO's emphasis on integrated and active learning by making project goals, design decisions, and implementation progress visible throughout the Conceive–Design–Implement–Operate phases. Support from the peer-based Quality Assurance team further reinforces this approach by guiding teams in producing clear and consistent documentation, thereby supporting both learning and professional quality

standards. When projects continue into the next semester and new students join the team, up-to-date and comprehensive documentation is essential for effective knowledge transfer and continuity, enabling incoming teams to engage smoothly in ongoing CDIO activities.

Mixed-level project teams generally function very well and effectively support peer learning. Senior-level students provide valuable support to junior-level students, for example by mentoring a newly appointed junior-level Scrum Master and helping them develop confidence and competence in their role. However, because multiple projects are available and students apply to three preferred projects, team composition is not always balanced. As a result, some teams may consist primarily of junior-level or senior-level students. In cases where teams are composed mainly of junior-level students, additional support from students in lead roles is often required. This support is typically initiated either once a predominantly junior team has been formed or when the team's Scrum Master signals a need for assistance during theFIRMA's weekly meeting, which is chaired by theFIRMA CEO. All Scrum Masters are required to attend this meeting and provide a brief progress update on their projects. Increased involvement from lead students has proven effective in compensating for uneven team composition and ensuring that learning and project progress are maintained.

A further lesson learned relates to the organization and sustainability of theFIRMA Tech Clubs. Initially, Tech Clubs were arranged on an ad hoc basis when motivated students volunteered to run workshops on technical topics of their choice. While student interest and attendance were consistently high, the number of students willing to act as facilitators remained limited, despite many possessing strong technical expertise. For many students, presenting to peers was perceived as challenging, which raised the threshold for leading a Tech Club and resulted in irregular scheduling. To address this, Tech Clubs have since been integrated into the SEPM competence track curriculum. Third- and fourth-year students are now required to facilitate one Tech Club per year, and all SEPM students are expected to participate in at least three Tech Clubs as attendees. This curricular integration has helped establish a more regular rhythm for Tech Clubs while maintaining strong student engagement, as participation as an audience member has not been a challenge. However, because individual sessions have typically been scheduled separately as students sign up to facilitate a Tech Club, the distribution of sessions has remained uneven. As a result, only a few Tech Clubs are offered at the beginning of the semester, whereas the second half of the semester often includes two sessions per week. To ensure a more balanced distribution, future Tech Club sessions will be scheduled on a weekly basis, for example by designating one day per week for one to two sessions.

Student feedback on the Tech Clubs has so far been collected through informal interviews, as the initiative is still under development. Overall, the feedback has been positive: students report that they find the format valuable and that facilitating a Tech Club increases their confidence in their own expertise. Students have also suggested several improvements, including a predefined schedule and more detailed session descriptions to support informed participation choices. In response, the Tech Club timetable is being redesigned to achieve a more even distribution across the semester. In addition, facilitators will be asked to provide session topics and brief content descriptions earlier, enabling students to assess relevance in advance and plan their attendance accordingly.

CONCLUSIONS AND FUTURE WORK

In summary, theFIRMA represents a CDIO-aligned, student-centered learning environment that integrates real industry projects with structured project processes, flexible participation,

and multi-layered peer learning. By operating year-round and accommodating varying student roles, workloads, and competence levels, theFIRMA mirrors professional ICT organizations while maintaining a strong educational focus. Its project processes support both quality outcomes for clients and students' professional development, while peer learning, mentoring, feedback practices, and Tech Clubs foster continuous knowledge sharing and skill development. Together, these elements create an authentic learning environment that supports technical competence, professional skills, and readiness for working life.

TheFIRMA learning environment has been in operation for more than 11 years. During its early years, participation was limited to a few dozen students (Säisä & Kinnari, 2025). As participation has increased to approximately 200 students per year, sustained emphasis has been placed on the scalability of the operating model. Key milestones in this development are reported in "Building Scalable Industry Collaboration in Engineering Education Through the CDIO Framework", presented at the 21st International CDIO Conference in Melbourne, Australia (Säisä & Kinnari, 2025), whereas the present paper focuses specifically on peer learning and peer feedback.

Peer learning and peer feedback are central to the development of future software engineering professionals because they cultivate the collaborative practices through which software is produced in contemporary organizations. Working with peers requires students to articulate technical reasoning, negotiate requirements and design decisions, and align their work with shared standards, thereby strengthening both disciplinary understanding and professional communication. Peer feedback further supports professional growth by fostering reflective practice: students learn to evaluate artefacts against explicit criteria, to justify and act on feedback, and to provide constructive, actionable input, competencies that are essential in code reviews, sprint reviews, and quality assurance processes. In addition, repeated peer interaction supports the development of professional identity and perceived competence, as students gain confidence by both receiving guidance and contributing expertise to others. Together, these mechanisms help students internalize norms of responsibility, transparency, and continuous improvement that characterize professional software engineering work.

Customer feedback is collected regularly during Sprint Review meetings and again at the final project closing meeting. In addition, customers are invited to complete a structured feedback form that includes background questions, five Likert-scale items, and an open-ended section for written comments. The five Likert-scale items assessed whether clients perceived that (1) the project met the agreed objectives, (2) the deliverables were useful to their organization, (3) the project team was motivated and worked actively, (4) the team had sufficient skills and competence to execute the project, and (5) they would recommend theFIRMA's services to other companies. Based on 40 responses, the results are consistently positive across all items, with average scores ranging from 4.43 to 4.65. Most ratings are 4 or 5, indicating high levels of satisfaction with project outcomes, team motivation, and the usefulness of the deliverables. Ratings below 4 are infrequent, suggesting that negative experiences are rare. Overall, these findings indicate that clients generally perceive the projects as successful, are willing to recommend the services, and view the project teams as motivated and capable.

The outcomes of the learning environment have also gained external recognition. In 2025, the Software Engineering and Project Management competence track and theFIRMA received the PM Academic Award from the national Finnish Project Professionals association, which acknowledged the high quality of project management education and the innovative project-office model and collaboration.

Future work will further develop learning structures that respond to the rapid learning cycles of project-based engineering education. Because students in environments such as theFIRMA acquire new competencies quickly and often transition to employment during the final stages of their studies, team composition and competence levels change continuously. This highlights the need for operating models that are both flexible and clearly structured to sustain learning continuity, support knowledge transfer, and strengthen students' readiness for professional practice in fast-changing project settings.

In addition, future development must address the ongoing transformation of software engineering work driven by advances in artificial intelligence (AI). From a CDIO perspective, AI is reshaping how engineers conceive, design, implement, and operate software systems, and therefore must be explicitly integrated into engineering education. Within the SEPM competence track, this transformation has been addressed by updating course contents to ensure that students learn to use AI tools as an integral part of their engineering workflow across the CDIO lifecycle. At the same time, emphasis is placed on developing strong foundational knowledge and professional judgment, enabling students to use AI tools effectively, critically, and responsibly. Furthermore, the curriculum update planned for students starting in autumn 2026 is in its final stages, with the aim of ensuring that future graduates are prepared for AI-augmented engineering practice. This includes strengthening competencies related to collaboration, communication, ethical awareness, and interaction with diverse stakeholders, all of which are essential in contemporary CDIO-oriented software engineering environments.

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IMPLEMENTING THE CDIO FRAMEWORK IN DATA-DRIVEN ENGINEERING CONTEXT: A COURSE-LEVEL CASE STUDY

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ABSTRACT

Engineering practice has been increasingly influenced and developed by digitalization, data availability, and advanced analytics using simulation, modelling, and Artificial Intelligence. As a result, modern engineers are expected not only to design and realize products, but also to use data to inform decisions across the entire product realization lifecycle from conception to operation and continuous improvement. This development creates new challenges and opportunities for CDIO-based engineering education. The CDIO framework aims to educate engineers capable of Conceiving, Designing, Implementing, and Operating complex systems in authentic contexts. CDIO Syllabus 3.0 reinforces this ambition by explicitly emphasizing digitalization, data-informed decision-making, sustainability, reflective learning, and systems thinking. However, many institutions still face difficulties in operationalizing these high-level learning outcomes into concrete, course-level implementations. Therefore, this paper aims to present a course-level case study of CDIO implementation through the course Data-Driven Product Realization, developed within the Chalmers initiative Tracks. The course is structured according to the Cross-Industry Standard for Process Mining model, which is an iterative and systematic approach for planning, executing, and deploying data analytics projects. It follows a project-based learning pedagogy, where diverse student teams engage in solving complex real-world industrial problems together with the companies. The paper contributes a detailed mapping between the course elements, CDIO Syllabus 3.0 outcomes, and CDIO Standards. Additionally, it proposes a reusable course design pattern that can support institutions seeking to implement CDIO Syllabus 3.0 in data-driven engineering contexts. Findings from course evaluation survey and student and teacher reflections demonstrate that the course effectively enhances integrated learning of technical and professional engineering competencies.

KEYWORDS

CDIO Implementation, CDIO Syllabus 3.0, Data-driven Engineering Course, Professional Skills Development, Project-Based Learning, Standards 1, 2, 7, 8, and11.

INTRODUCTION

Engineering practice has undergone a transformation driven by digitalization, increased data availability, and advances in simulation, modelling, and Artificial Intelligence (AI). In manufacturing industry, data-driven approaches are increasingly used to support decision-making across the entire product realization lifecycle, from early concept development to operation, maintenance, and continuous improvement (Wuest et al., 2016; Bokrantz et al., 2023). As a result, modern engineers are expected not only to design and realize products, but also to interpret, analyze, and apply data to inform engineering decisions in complex, socio-technical systems (Coskun et al., 2019; Li et al., 2021). A growing body of engineering education research emphasizes the increasing importance of interdisciplinary, digital, and professional competencies, including systems thinking and data-informed decision-making (Leles et al., 2024; Pacher et al., 2024). This aligns well with the Conceive Design Implement Operate (CDIO) framework that was developed to better align engineering education with professional engineering practice by emphasizing the integration of disciplinary knowledge with personal, interpersonal, and system-building skills in authentic contexts (Crawley, 2001; Berggren et al., 2003; Crawley et al., 2007). Since its introduction, the CDIO framework has been widely adopted internationally, with extensive implementation experiences reported in CDIO conference proceedings (Malmqvist et al., 2015).

The CDIO Syllabus 3.0 represents an evolution of the CDIO framework in response to emerging technological, societal, and industrial challenges identified by the CDIO community (Malmqvist et al., 2022). In addition to traditional engineering knowledge and skills, the updated syllabus explicitly emphasizes digitalization, data-informed decision-making, sustainability, ethics, reflective learning, interpersonal skills (e.g., teamwork and communications) and systems thinking. While the CDIO Syllabus 3.0 provides a comprehensive and future-oriented set of intended learning outcomes, it remains intentionally generic to support adaptation across disciplines and institutions, with programs expected to customize priorities based on their context and stakeholder needs (Malmqvist et al., 2022). A remaining challenge lies in translating syllabus-level ambitions into concrete, assessable, course-level elements particularly in emerging domains such as data-driven engineering, where professional practices and tools continue to evolve rapidly (Cheah & Leong, 2018). A recent review of CDIO practice also highlights persistent operational challenges in embedding CDIO principles consistently across courses (O'Connor et al., 2023). Addressing aforementioned challenges, this paper aims to present a course-level case study of CDIO implementation in the course Data-Driven Product Realization, developed within the Tracks Chalmers initiative (Enelund & Henricson Briggs, 2020).The paper contributes a detailed mapping between the course elements, CDIO Syllabus 3.0 outcomes, and selected CDIO Standards, thereby offering a practical and reusable course design pattern for implementing CDIO Syllabus 3.0 in data-driven engineering education.

BRIEF BACKGROUND

The CDIO framework conceptualizes engineering education around the full engineering lifecycle and positions this lifecycle as the authentic context for learning engineering practice (Crawley et al., 2007). Rather than prescribing specific curricula, CDIO provides a flexible educational framework that institutions adapt to disciplinary, institutional, and cultural contexts while maintaining a shared pedagogical foundation (Chuchalin, 2020). To support systematic implementation, the framework is operationalized through the CDIO Standards, which define best practices for curriculum design, teaching and learning activities, assessment, learning environments, and faculty competence (Crawley et al., 2014). The updated CDIO Standards

3.0 respond explicitly to changes in engineering practice, particularly related to sustainability and digitalization, and emphasize integrated learning experiences, active and experiential learning, and alignment between learning outcomes and assessment (Malmqvist et al., 2020). Complementing the standards, the CDIO Syllabus 3.0 provides a comprehensive and updated articulation of intended learning outcomes for engineering education in response to sustainability, digitalization, acceleration of change, and accumulated experience use in curriculum and course development (Malmqvist et al., 2022). Digitalization is treated as a cross-cutting theme, with digital and data-related competencies embedded across disciplinary knowledge, personal and professional skills, interpersonal skills, and CDIO lifecycle activities, rather than as a standalone competency area. The syllabus is intentionally formulated at a generic level to support broad applicability across engineering disciplines and institutional contexts. While this flexibility is a key strength of the CDIO framework, it also presents challenges when translating syllabus-level outcomes into concrete learning elements (e.g., teaching and learning activities and assessment tasks) at the course level, particularly in rapidly evolving domains influenced by digitalization and data-driven engineering practice (Malmqvist et al., 2022).

Within the CDIO community, this challenge is closely connected to the broader role of CDIO in engineering education research. CDIO has historically prioritized educational development, while increasingly positioning its conference and publications as spaces where usefulness for practice and scholarly rigor is jointly valued (Edström, 2020). Evidence from a systematic review of CDIO publications indicates that course-level and program-level implementation studies constitute the majority of CDIO publications and play a critical role in knowledge sharing within the community (O'Connor et al., 2023). At the same time, O'Connor et al. (2023) highlight a need for more analytically grounded studies that document not only how CDIO principles are implemented, but also how specific learning outcomes, especially those related to emerging professional practices are operationalized and assessed. Detailed course-level implementations therefore remain an important contribution to both CDIO practice and research; in this paper addressed through a course-level case study.

A COURSE-LEVEL CDIO IMPLEMENTATION

This section presents a course-level case study illustrating how CDIO Syllabus 3.0 and selected CDIO Standards are operationalized in practice within an advanced engineering course.

Context and course overview

Educational context: Tracks Chalmers

Tracks Chalmers is an educational initiative at Chalmers University of Technology aimed at providing flexible, challenge-driven, and industry-relevant learning pathways for students across engineering programs (Enelund & Henricson Briggs, 2020). The initiative emphasizes authentic engineering practice by integrating disciplinary knowledge with professional skills, interdisciplinary collaboration, and close interaction with industry partners (Bingerud et al., 2023). Courses within Tracks Chalmers are designed to address complex, real-world challenges and to prepare students for modern engineering roles characterized by digitalization, sustainability demands, and rapid technological change. An example of a course within the Tracks initiative is Data-Driven Product Realization which is offered as an elective course within the theme Sustainable Production. It brings together students from different

educational backgrounds to work collaboratively on data-driven industrial challenges provided by partner companies, thereby reflecting professional engineering practice.

Course objectives

The rapid advancement of digital technologies is currently reshaping the manufacturing industry. Above all, the recent developments in AI and Machine Learning (ML) open possibilities for improved decision-making towards sustainable manufacturing. The purpose of the course is therefore to enable data-driven and fact-based decisions in the industrial product realization process. The demand for future engineers with multi-disciplinary competencies in developing and applying AL/ML solutions in industry has been rising (Li et al., 2021: Bokrantz et al., 2023). Therefore, the course aims to provide students with fundamental knowledge about data science (including AI and ML) as well as skills in applying data science techniques for improving production systems and product development. The course is designed so students having completed the course should be able to:

- Apply data-driven methods, including analytics and modelling, to support decision-making in product development and production contexts.
- Integrate data analytics with engineering design and product realization activities across the lifecycle.
- Work effectively in multidisciplinary and culturally diverse teams.
- Experience and reflect on a full or partial CDIO lifecycle in a realistic, industry-connected project setting.

The detailed learning objectives of the course are given below:

- LO1. Critically and creatively identify and formulate data analytics problems
- LO2. Solve open-ended data analytics problems
- LO3. Lead and participate in data analytics projects
- LO4. Work in multidisciplinary analytics teams
- LO5. Work sensitively with cultural differences in analytics teams
- LO6. Assess the impact of data analytics solutions
- LO7. Identify and discuss ethical aspects of data analytics
- LO8. Present the results of data analytics project to various stakeholders

These objectives are aligned with the intended learning outcomes of CDIO Syllabus 3.0, with particular emphasis on data-informed decision-making, professional skills, and systems perspectives.

Course structure and pedagogy

The course applies project-based learning pedagogy (Thomas, 2000) and consists of a mix of teaching and learning activities as summarized below. Overall aim is to create individual, personal, and flexible study opportunities for reflection on both technical outcomes and professional skills, including teamwork, communication, and ethical considerations.

- Lecture: Theoretical knowledge, skills, and abilities needed for the project work.
- Community: Expert talks to get inspiration from real-world insights from AI/ML applications in product realization combined with paper seminars from the state-of-the-art, and self-paced learning modules on professional skills with associated group reflections.

- Project: Practical work focused on the achievement of data-driven and fact-based decisions in the industrial product realization process.
- Examination: Assessment activities that constitute the basis for the final grade.

Multidisciplinary student teams collaborate with partner companies to solve complex, open-ended industrial problems using real-world needs, requirements, and datasets provided by them. Students work under the joint guidance of an industry-connected supervisor and an academic supervisor, ensuring close collaboration that integrates practical industry insight with academic expertise throughout the project. The course structure follows the Cross-Industry Standard Process for Data Mining (CRISP-DM) (Wirth & Hipp, 2000), providing an iterative and systematic framework for planning, executing, evaluating, and deploying data analytics solutions within an engineering context. The course is organized into eight major phases with a mix of different teaching and learning activities, mapped to the CDIO lifecycle phases, as summarized in Table 1.

Table 8. Course phases mapped to the CDIO lifecycle phases

Course phase	Focus	Teaching and learning activities	CDIO phase
Phase 1 – Course & Project Introduction	Orientation and process framing	Course and project introduction (Lecture); Introduction to the CRISP-DM framework (Lecture)	Conceive
Phase 2 – Business Understanding	Problem framing and project planning	Project management (Lecture); Problem–solution mapping (Lecture); Expert talk & paper seminar #1	Conceive
Phase 3 – Data Understanding	Data exploration and contextual understanding	Data pre-processing methods (Lecture); Self-paced learning on intercultural communication	Design
Phase 4 – Data Preparation	Data readiness and quality	Data quality assessment (Lecture); Expert talk & paper seminar #2	Design
Phase 5 – Modeling	Analytics and model development	AI/ML modelling for industrial datasets (Lecture); Self-paced learning on ethics	Implement
Phase 6 – Evaluation	Performance and impact assessment	Model evaluation and assessment of business impact (Lecture)	Implement (Reflective)
Phase 7 – Deployment	Operational and lifecycle considerations	Model deployment, operation, and maintenance (Lecture); Expert talk & paper seminar #3	Operate (Reflective)
Phase 8 – Report & Presentation	Communication and reflection	Presentation seminar; Self-studies; Final project report and individual reflection submission	Operate (Reflective)

Mapping to CDIO Syllabus 3.0

This section presents how the course aligns with the CDIO Syllabus 3.0. Rather than aiming to cover all syllabus elements equally, the course focuses on a coherent subset that is particularly relevant for data-driven product realization and professional engineering practice.

Fundamental knowledge and reasoning (Syllabus section 1)

The course integrates disciplinary knowledge from product development, production systems, data analytics, and systems engineering. Students apply quantitative reasoning, data modelling, and validation techniques as central inputs to engineering decision-making. Through the CRISP-DM framework, students learn to structure and reason about complex, data-intensive engineering problems in a systematic manner.

Personal and professional skills and attributes (Syllabus section 2)

The course explicitly develops personal and professional skills relevant to data-driven engineering practice, including:

- Analytical reasoning and problem solving (2.1), through formulation and solution of open-ended analytics problems.
- Experimentation and knowledge discovery using data (2.2), supported by iterative modelling and evaluation activities.
- Ethics, equity, and other responsibilities (2.5), addressed through dedicated self-paced learning activities and reflective assignments.

Interpersonal skills: Collaboration, teamwork, and communication (Syllabus section 3)

Team-based project work is a core element of the course. Students practice:

- Teamwork and collaboration (3.1) in teams composed of students with different disciplinary backgrounds.
- Communications (3.2) through project report, presentation, and interaction with industrial partners.

Conceiving, designing, implementing, and operating systems in the enterprise, societal and environmental context – the innovation process (Syllabus section 4)

The course engages students in multiple phases of the CDIO lifecycle. Students:

- Conceive (4.3) data-informed product and production improvement concepts based on industrial needs (e.g., the students clarify the company's problem and translate a business issue into a data-driven engineering question).
- Design (4.4) solutions supported by data analysis, modelling, and systems thinking (e.g., the students decide what data to use, which models to apply, and how results will support decision and design an analytics workflow using CRISP-DM).
- Implement (4.5) analytics pipelines or decision-support tools (e.g., the students build data pipelines, AI/ML models, or dashboards).
- Operate (4.6) by reflecting on deployment including business impact and other considerations (e.g., students do not deploy the solution in the factory. Instead, they reflect on how the solution would be deployed, what maintenance, data quality, or organizational issues would arise, etc.).

This is a partial CDIO lifecycle especially in relation to Operate phase, but aligned with the CDIO intent the students still experience and reason about all phases

Alignment with CDIO standards

CDIO Standard 1: Context

The course is explicitly framed within the context of product realization across the CDIO lifecycle, with data analytics and digitalization serving as central enablers. Industrial project contexts provide authenticity and relevance, aligning learning activities with professional engineering practice.

CDIO Standard 2: Learning outcomes

Course learning objectives are derived from and mapped to the CDIO Syllabus 3.0, ensuring transparency and coherence, and the different levels of the Bloom's taxonomy (Krathwohl, 2002). Figure 1 presents a matrix illustrating the relationships between the learning objectives, teaching and learning activities, and the assessment tasks based on Constructive Alignment (Biggs, 1996). A summary mapping between the course elements, and the CDIO Syllabus 3.0 outcomes, and the CDIO Standards is provided in Table 2.

	Learning Objectives (LO)							
Teaching and Learning Activities (TLA)	**LO1**	**LO2**	**LO3**	**LO4**	**LO5**	**LO6**	**LO7**	**LO8**
CRISP-DM	X	X	X					
Project management			X	X	X			
Problem-solution mapping	X	X						
Self-paced learning (intercultural communication)					X			
Methods for pre-processing		X						
Data quality		X						
Self-paced learning (ethics)							X	
AI/ML modeling for industrial data sets			X		X			X
Model evaluation & business impact		X				X		X
Model deployment, operation, and maintenance		X				X		
Expert talks & paper seminars	X	X				X		X
Assessment Tasks (AT)								
Project report	X	X	X	X	X	X	X	X
Individual quiz	X	X						
Individual reflection			X	X	X			

Figure 19. The Constructive Alignment matrix

CDIO Standards 7 and 8: Integrated learning experiences and active learning

The course integrates disciplinary knowledge with professional skills through active, project-based learning. Students simultaneously develop technical competence, teamwork abilities, and professional judgment through continuous feedback, supervision by two main supervisors and reflection.

CDIO Standard 11: Learning assessment

Assessment is based on a combination of project presentation and report, individual quiz and reflection. These assessment tasks are aligned with the intended CDIO learning outcomes and provide both formative and summative feedback on students' technical and professional development.

DISCUSSION

This section presents evaluation and reflections from the course survey (i.e., sent out to all students that have attended the course to gather opinions about the course, which gives highly valuable input on how well it is succeeded in conveying the content of the course and how other aspects surrounding the course works) and the interviews conducted with the students to explore how students perceived and experienced the CDIO principles as intended. The course evaluation included 16 student responses from the two most recent course offerings with approximately 50% response rate. In addition, semi-structured interviews were conducted with two students.

Table 2. Mapping between the course elements, the CDIO Syllabus 3.0 outcomes, and the CDIO Standards

Course elements	Description	CDIO Syllabus 3.0 alignment	CDIO Standards alignment
Industrial project work	Multidisciplinary student teams solve real industrial product realization problems using data-driven methods in collaboration with industry partners	4.3 Conceiving systems; 4.4 Designing systems; 4.5 Implementing systems; 4.6 Operating systems; 3.1 Teamwork and collaboration	Standard 1; Standard 7; Standard 8
CRISP-DM framework	Iterative and structured process model for planning, executing, evaluating, and deploying data-driven engineering projects	1.2 Core engineering fundamental knowledge; 2.1 Analytical reasoning and problem solving; 2.2 Experimentation, investigation and knowledge discovery; 4.2 Designing systems	Standard 2; Standard 7
Use of real-industrial data sets	Analysis of real data sets provided by partner companies to support engineering decision-making	1.3 Advanced engineering fundamental knowledge, methods and tools; 2.2 Experimentation, investigation and knowledge discovery; 4.2 Designing systems	Standard 1; Standard 8
Lectures	Lectures providing theoretical foundations, methods, and tools to support project work	1.1 Knowledge of underlying mathematics and sciences; 1.2 Core engineering fundamental knowledge; 1.3 Advanced engineering fundamental knowledge, methods and tools	Standard 2
Community activities (e.g., expert talks and paper seminars)	Expert talks and paper seminars linking theory, research, and industrial practice through discussion and reflection	2.2 Experimentation, investigation and knowledge discovery; 2.4 Attitudes, thought and learning; 3.2 Communications	Standard 7; Standard 8
Self-paced learning modules	Professional learning modules addressing ethics and intercultural teamwork, combined with reflective discussion	2.5 Ethics, equity, and other responsibilities; 3.1 Teamwork and collaboration; 2.4 Attitudes, thought and learning	Standard 8
Project report	Documentation of technical results, engineering reasoning, and lifecycle considerations in a structured written format	3.2 Communications; 4.4 Designing systems; 4.5 Implementing systems; 4.6 Operating systems	Standard 2; Standard 11
Project presentation	Oral presentation of project outcomes to academic and industrial stakeholders	3.2 Communications; 2.4 Attitudes, thought and learning	Standard 8; Standard 11
Individual quiz	Assessment of foundational knowledge in data analytics, AI/ML, and product realization	1.1 Knowledge of underlying mathematics and sciences; 1.2 Core engineering fundamental knowledge	Standard 11
Individual reflection	Structured reflection on teamwork, ethics, learning process, and professional development	2.4 Attitudes, thought and learning; 2.5 Ethics, equity, and other responsibilities; 3.1 Teamwork and collaboration	Standard 11; Standard 8

To complement student perspectives, an interview was also conducted with the course examiner to reflect how the CDIO-based course design was realized in practice and how key pedagogical choices were experienced from a teaching perspective. Taking together, these multiple perspectives also allow the findings to be interpreted in relation to broader engineering education theory, particularly constructive alignment, experiential learning, and situated learning through authentic practice (Biggs, 1996; Kolb, 2014; Lave & Wenger, 1991).

Course evaluation and students' reflections

Overall course evaluation results indicate a generally positive student perception of the course structure, learning outcomes, teaching, and alignment between activities and intended learning outcomes. Students reported that learning outcomes were clearly communicated and that the course structure supported achievement of these outcomes. This perceived coherence between outcomes, activities, and assessment is consistent with constructive alignment principles, where transparent course design supports student engagement and achievement (Biggs, 1996).

Qualitative interviews provide insight into how students engaged with CDIO phases in practice. Students described the problem-framing phase as particularly influential, emphasizing how industrial partners helped shape realistic expectations and encouraged focus on learning processes rather than complete technical solutions. One student noted that early clarification that the problem was too complex to fully solve shifted the team's mindset toward iterative learning and reflection, aligning strongly with the Conceive phase of CDIO and with professional engineering practice. Such experiences also reflect experiential learning perspectives, where authentic challenges combined with reflection can deepen students' understanding of professional processes (Kolb, 2014). Students also highlighted how working with real industrial data changed their understanding of engineering practice. Challenges related to data quality, preprocessing, and contextual understanding were frequently mentioned, reinforcing the role of uncertainty and judgment in data-driven engineering. These experiences align with CDIO's emphasis on authentic contexts rather than deterministic problem-solving (Edström & Kolmos, 2014). They also resonate with situated learning theory, suggesting that professional competence develops more effectively when learning activities are embedded in realistic contexts (Lave & Wenger, 1991).

Teamwork and multidisciplinary collaboration emerged as central learning experiences. Interviewees described how differences in disciplinary background, academic level, and experience shaped role distribution and leadership within teams. Rather than formal role assignments, leadership emerged naturally, often influenced by prior experience. Students reported learning to adapt communication styles, balance technical and systems perspectives, and negotiate shared understanding and skills explicitly emphasized in CDIO Syllabus sections on teamwork and communication (Malmqvist et al., 2022).

Intercultural communication and ethics were also experienced as meaningful, though students suggested that these elements would have been even more effective if introduced earlier in the course. Reflections on data confidentiality and the potential societal impact of analytics solutions illustrate how ethical considerations were encountered as situated and practical rather than abstract. This supports the course design choice to embed ethics and professional skills within project work rather than treating them as standalone topics. This finding aligns with research indicating that professional skills are often learned more effectively when integrated into disciplinary practice rather than separated into isolated modules (Crawley et al., 2014; Malmqvist et al., 2022).

Students' reflections on CDIO lifecycle phases suggest differentiated engagement across teams and individuals. The "Conceive" and "Design" phases were most strongly experienced, while "Implement" activities were distributed unevenly within the team depending on prior technical skills.

Teacher reflections

From the teacher's perspective, students most strongly experienced the "Conceive" and "Design" phases of the CDIO lifecycle, as these are the phases that can be meaningfully addressed within the scope and timeframe of an eight-week course. Fully engaging with the "Implement" and "Operate" phases was neither expected nor feasible, given both the course duration and the practical limitations of deploying and operating solutions in real industrial settings. Instead, these later phases were addressed through application, reflection and discussion with industry stakeholders. While this was a pragmatic adaptation to the course context, it can also represent a limitation. Without full deployment and operational follow-up, students might have fewer opportunities to experience issues such as robustness, maintenance, user adoption, organizational constraints, and long-term system performance. As a result, the course may provide stronger preparation for early-stage engineering work than for later lifecycle responsibilities. This suggests that partial engagement with the CDIO lifecycle may need to be complemented elsewhere in the programme through follow-up courses, simulations, longer projects e.g., Industry-sponsored MSc thesis projects (Crawley et al., 2014; Malmqvist et al., 2022). The teacher emphasized that working with real industrial problems and data was central to the authenticity of the learning experience. Unlike curated datasets commonly used in academic settings, industrial data were described as messy, incomplete, and difficult to interpret, and these conditions that students must learn to navigate in professional practice. The teacher also noted that engagement levels were noticeably higher due to the presence of company stakeholders and the perception that student work could contribute to actual industrial improvement. This supports wider engineering education findings that authenticity, external relevance, and contact with stakeholders can strengthen motivation and perceived value of learning activities (Edström & Kolmos, 2014; Thomas, 2000).

Interdisciplinary and mixed-level student groups were described as a defining feature of the course, aligned with the broader Tracks Chalmers structure. The teacher observed clear benefits in terms of complementary competencies, role differentiation, and peer learning, with students drawing on diverse strengths in data analytics, domain knowledge, and communication. At the same time, common challenges related to workload distribution, communication styles, language barriers, and intercultural differences were acknowledged. Rather than being viewed as shortcomings, these tensions were framed as expected and educationally valuable aspects of interdisciplinary engineering practice. The use of embedded Professional Skills materials, particularly on intercultural communication and ethics, was highlighted as an important enabler of integrated learning.

The teacher reported that situating these materials within project-specific seminars helped students connect abstract concepts to their own team dynamics and project realities. Intercultural communication was perceived as especially effective, as students encountered such challenges continuously throughout the project. Ethical reasoning, while considered important, was described as more difficult for students to experience directly, given the absence of real-world consequences during the course.

Finally, the teacher reflected on the assessment tasks as they are constructively aligned with the other course elements, combining individual and group assessments to address different

cognitive levels and has worked well. It was also noted that the rapid emergence of AI assisted tools poses a major challenge for the current assessment tasks and makes them obsolete. This concern was framed not as course-specific, but as a broader systemic issue facing engineering education and requiring future research on innovation in assessment formats. More broadly, this points to a growing need for assessment approaches that capture process competence, critical judgement, teamwork, and responsible use of AI, rather than relying primarily on traditional written outputs (Pacher et al., 2024).

Recommendations

Based on the insights gained from this case study, the following recommendations are suggested for CDIO implementers seeking to integrate data-driven engineering practice and professional skills at course level.

- **Integrate professional skills modules early and through active learning:** Institution-level professional skills resources (e.g., ethics and intercultural communication) can effectively support CDIO Standard 7 and 8 when embedded as active learning activities combined with reflection and relation to students' project discussion.
- **Clarify expectations and align lectures with project work:** In project-based, CDIO-aligned courses should explicitly communicate the intended level of technical depth and ensure strong alignment between lectures and evolving project needs in open-ended, data-driven contexts.
- **Use industry-academia collaboration as a learning context, not only a setting:** Industry-connected projects naturally expose students to communication, coordination, expectation, and management challenges typical of industry-academia and research collaborations and thereby reinforcing authentic professional learning beyond technical outcomes.

CONCLUSIONS

This paper presented a course-level case study illustrating how the CDIO Syllabus 3.0 and the selected CDIO Standards can be implemented in a data-driven engineering context. The mapping between course elements, CDIO Syllabus 3.0 outcomes, and CDIO Standards shows the operationalization of CDIO principles through a constructive alignment of teaching and learning activities and assessment tasks. Industrial project work, the CRISP-DM framework, lectures, and embedded professional skills activities together support the integrated development of interdisciplinary knowledge, professional skills, teamwork, and CDIO lifecycle competencies. Findings indicate that students experienced authentic CDIO-aligned learning, with the Conceive and Design phases most strongly emphasized the course duration and the practical limitations of deploying and operating solutions in real industrial settings. The Implement phase with was addressed through building the analytics pipeline while Operate phase was mostly on reflection and interaction with industry stakeholders rather than full deployment, illustrating a pragmatic approach to lifecycle implementation. As a single course-level case, the findings are illustrative rather than generalizable, however, it provides a transparent example for institutions seeking to operationalize the CDIO Syllabus 3.0.

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IMPACTS OF CDIO FRAMEWORK IMPLEMENTATION ON OUTPUT PRODUCTIVITY AND INTERPERSONAL SKILLS DEVELOPMENT

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ABSTRACT

Universities and polytechnics under the Ministry of Higher Education, Science, and Technology in Indonesia are encouraged to generate tangible impacts for industry and society. This policy has been positively adopted by Politeknik Negeri Batam (Polibatam), which has implemented Project-Based Learning (PBL) within the Conceive–Design–Implement–Operate (CDIO) framework since 2021. Through this approach, students are actively involved in project work throughout all stages of their academic programs, from introductory to advanced levels. The implementation of PBL and the CDIO framework at Polibatam is expected to enhance both internal and external institutional impacts. Institutional records indicate that the adoption of PBL and CDIO has led to a substantial increase in output productivity, particularly in the number of registered intellectual property rights and published academic articles. In 2023, Polibatam recorded its highest outputs, with 196 intellectual property registrations and 110 academic publications. Since the initial implementation of PBL in 2018, these outputs have been expected to generate significant benefits for stakeholders and society. Several project themes directly engage external stakeholders, particularly through collaborative industry-based projects, which have produced measurable impacts for partners. Moreover, the integration of the CDIO framework with a strong emphasis on PBL has contributed to the development of students' interpersonal competencies, including communication and teamwork skills. Feedback from 52 industries employing Polibatam graduates indicates that graduates' communication and teamwork skills are predominantly rated as excellent or good, with a notable improvement observed following the implementation of PBL and CDIO.

KEYWORDS

Project-Based Learning, CDIO Framework, Tangible Impacts, Interpersonal Skills, Standards: 1-5, 7, 8, 12.

INTRODUCTION

Higher education in Indonesia, including both academic and vocational institutions, plays a crucial role in developing human resources to support national strategic goals, such as the Golden Indonesia 2045 vision (Sasrawan, 2025). Indonesian higher education institutions are mandated to fulfill three core functions—education, research, and community service—known as the Tri Dharma of Higher Education (Std.1). In line with national policy, the Ministry of Higher Education, Science, and Technology emphasized in 2025 that universities and polytechnics must generate measurable impacts for industry and society, advancing educational quality, producing competent graduates (Std.2), and delivering applied outputs that benefit external stakeholders.

Politeknik Negeri Batam (Polibatam), as a public higher education institution, actively supports government-led strategic programs while contributing to industry and community development. With four departments and 25 study programs, Polibatam has strengthened its impact through Project-Based Learning (PBL) (Std.5, 8) with the Conceive–Design–Implement–Operate (CDIO) framework. PBL is one of learning methods having been implemented at several study programs at Polibatam. Other applied learning methods are case methods, problem-based learning, and competency-based learning. Nonetheless, PBL is as a major learning method at Polibatam. PBL was first introduced in 2018 in the Robotics Engineering program with 14 projects and expanded to 10 programs with 293 projects by 2020. Since then, Polibatam has positioned itself as a “Kampus PBL,” reflecting the broad adoption of project-based initiatives across programs.

In 2020, the Robotics Engineering program formally adopted the CDIO framework to systematically guide PBL, align projects with curriculum outcomes (Std.2), and enhance learning effectiveness. By 2022, 17 study programs implemented PBL, comprising 271 internal and 87 external collaborative projects. The PBL Expo, first held in 2021 and repeated in 2022, provides a platform for students to showcase products and services developed through project activities, fostering innovation and professional skills.

Polibatam became an official CDIO member following the 2022 Asian Regional Meeting hosted by Singapore Polytechnic. The integration of PBL and CDIO has enabled more structured and effective learning processes (Std.7) (Pee & Leong, 2005), optimizing educational outcomes and generating tangible benefits for both the institution and its stakeholders. Moreover, this approach has strengthened students’ interpersonal skills (CDIO Syllabus 3), particularly teamwork and communication, through systematic engagement in collaborative, project-based learning (Säisä et al., 2017). Collectively, these initiatives demonstrate Polibatam’s commitment to producing highly competent graduates, fostering innovation, and delivering measurable impacts to industry and society.

POLIBATAM EDUCATIONAL MODEL

As a vocational higher education institution, Politeknik Negeri Batam (Polibatam) has institutional vision and mission as shown in Table 1.

Table 1. Polibatam's Vision and Mission

Vision	Mission
Become A New Generation Polytechnic That Is Excellent, Adaptive, Innovative, And Globally Competitive, With A Strong Connection to Industry and Society to Support a Progressive and Prosperous Indonesia	Active in the Process of Creating, Disseminating, and Applying Science and Technology Through High-Quality Vocational Higher Education Services and Applied Research That Is Open, Relevant, and Closely Collaborates with Society and Industry, with the Implementation of Good Institutional Governance for a Better National Life

Polibatam's educational model centers on professional training and certification, supported by an integrated curriculum (Std.3) that develops disciplinary, personal, professional, and interpersonal skills alongside product and service creation. This curriculum is built on four pillars: a business and industrial mindset, social and community engagement, sustainable development, and innovative pedagogy, the latter reinforcing Polibatam's identity as a "Kampus PBL." These pillars are guided by the institutional motto, "Double Action." Together, this model underpins Polibatam's strategic objectives of good governance, strong industry partnerships, applied research, and creative innovation (Figure 1).

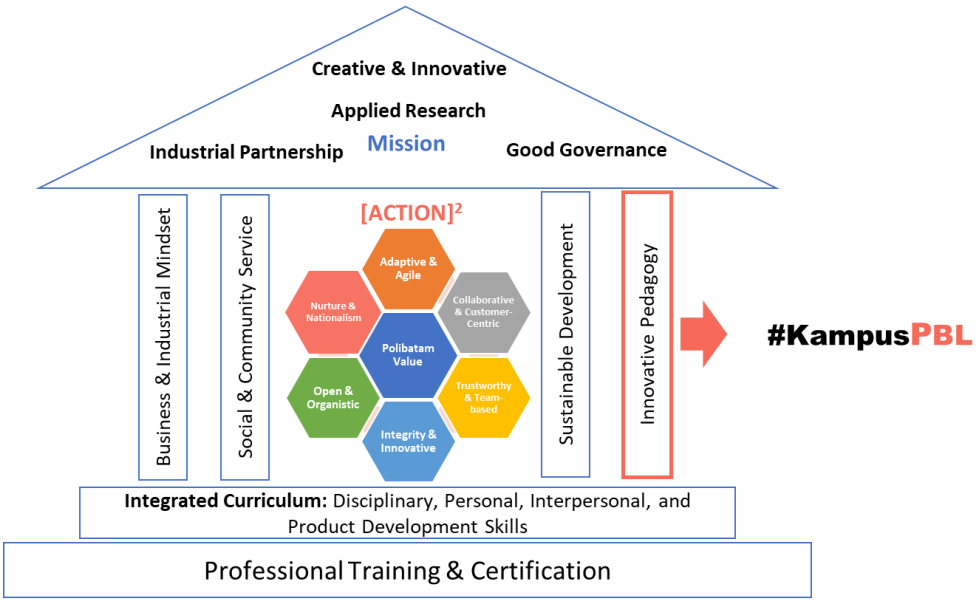


Figure 1. Polibatam Educational Model.

Politeknik Negeri Batam (Polibatam), as one of Indonesia's Institutions of Higher Learning (IHLs), fulfills three core mandates known as the Tri Dharma. These mandates are supported by established good practices at Polibatam and by key actors in PBL implementation, including lecturers, students, and industry partners. Such collaboration has fostered innovation at Polibatam, leading to the development of its identity as a "Kampus PBL." At Polibatam, PBL is interpreted not only as Project-Based Learning but also as a broader concept encompassing projects, problems, and other contextually relevant meanings. These

innovations are expected to generate substantial impacts for industry and society, as illustrated in Figure 2.

The anticipated impacts, outputs, or outcomes include tangible products and services directly beneficial to industry and the community, scholarly publications, and intellectual property outputs such as copyrights, patents, and industrial designs. Additionally, students experience direct benefits through the enhancement of interpersonal competencies, particularly teamwork and communication skills (CDIO Syllabus 3).

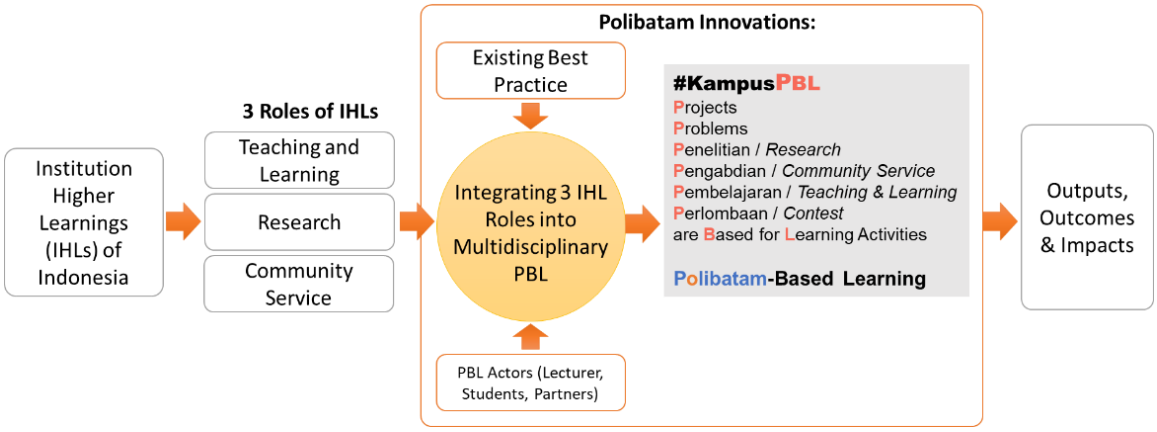


Figure 2. Integration of the Three Core Roles of Higher Education Institutions into PBL.

IMPACT ANALYSIS OF CDIO FRAMEWORK IMPLEMENTATION

Polibatam has pursued initiatives to enhance graduate quality and institutional contributions to society since its establishment in 2000. However, evaluations conducted prior to 2017 indicated that Polibatam's outputs remained limited, as many lecturers and students demonstrated low awareness of scholarly and innovation outputs, including journal publications, patents, copyrights, and industrial designs. This condition was largely attributed to the predominance of conventional, lecturer-centered teaching methods. In 2017, the Robotics Engineering study program initiated the implementation of PBL as a student-centered learning approach. Since then, learning activities across Polibatam have increasingly adopted PBL, with targeted outputs encompassing products, services, scientific publications, patents, copyrights, and industrial designs.

In the implementation of PBL, each project team is assigned responsibility for completing projects aligned with the disciplinary focus of its respective study program, with interdisciplinary collaboration applied depending on project complexity (Std.5). Project team sizes vary, typically comprising two to more than four students. Throughout the project process, students are encouraged to generate ideas and propose solutions to the assigned problems. Project topics are derived from both internal and external sources (Takemata *et al.*, 2013). Internal projects generally originate from lecturers' research activities, study programs, and Polibatam's Centers of Excellence (CoE), whereas external project topics are proposed by industry and community partners. In some cases, Polibatam teams engage directly with industry and community stakeholders to identify real-world problems, which are subsequently addressed through PBL activities. Between 2023 and 2025, approximately 16 partners participated in PBL implementation, representing industrial, governmental, academic, and technology sectors. Moreover, student projects were not limited to industry-based initiatives but also addressed internal institutional needs, competitions, student activities, lecturers'

research, community service programs, and entrepreneurial endeavors. The distribution of project topics across these categories is presented in Table 2.

Table 2. Distribution of Project Numbers by Category.

No.	Project Category	2023/2024 Academic Year		2024/2025 Academic Year	
		Fall	Spring	Fall	Spring
1	External Needs	92	65	51	90
2	Internal Needs	292	460	337	566
3	Competition	97	125	80	213
4	Student Activity	5	6	13	23
5	Research	103	110	88	147
6	Community Service	50	49	36	57
7	Entrepreneurship	13	9	13	6

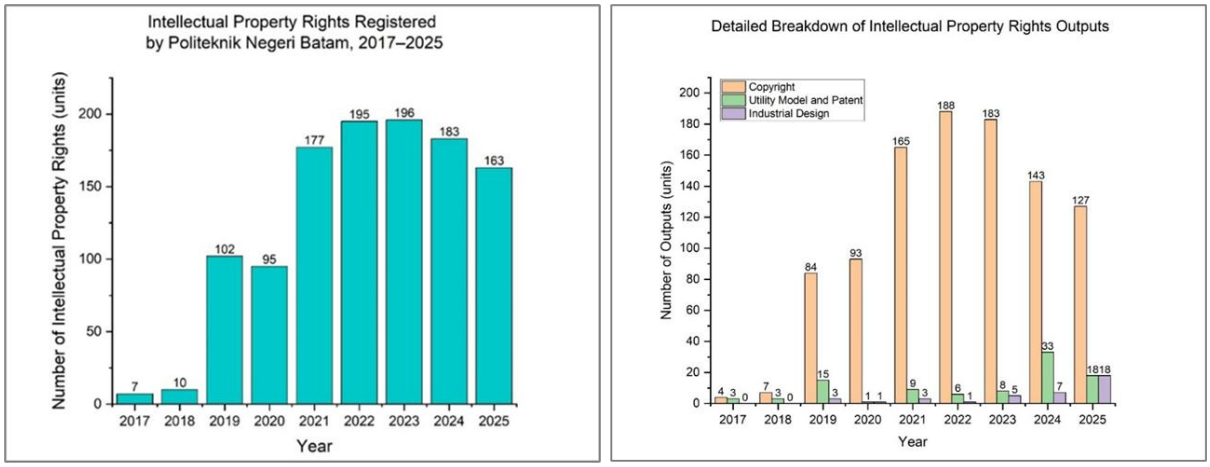
The CDIO framework provided structured guidance for study programs in managing teaching and learning processes and PBL activities. Subsequently, other study programs were encouraged to implement the CDIO framework. The integration of PBL within the CDIO framework has produced significant impacts on lecturers, students, the institution, and external partners (Std.3, 5, 7). One of the impacts is intellectual property outputs, which have been generated by Polibatam lecturers and students as illustrated in Figure 3.

Figure 3(a) shows that in 2017 and 2018, the number of registered intellectual property rights was relatively low. This condition can be attributed to several factors, including a smaller student population, lower levels of lecturer motivation, and the predominance of traditional teaching approaches that did not actively involve external stakeholders in the learning process.

However, from 2019 to 2025, the number of registered intellectual property rights increased significantly, reaching a peak in 2023 with 196 submissions. This upward trend is closely associated with the implementation and expansion of project-based learning (PBL) at Polibatam. The increase in intellectual property outputs can therefore be partially attributed to PBL activities, consistent with findings reported by Guo et al., which highlight the role of PBL in generating tangible learning outputs.

Nevertheless, the increase in intellectual property registrations cannot be attributed solely to the implementation of project-based learning (PBL). Several additional factors have likely contributed to this trend, including the expansion in the number of faculty members and students, as well as institutional incentive schemes provided by the management, particularly for those who successfully secure granted intellectual property rights. The student population at Polibatam grew substantially from approximately 4,911 in 2019 to 13,374 in 2025, accompanied by a corresponding increase in the number of lecturers. This expansion likely facilitated greater engagement in PBL activities and, consequently, a higher volume of outputs.

Furthermore, incentive mechanisms may have encouraged faculty members to more actively prepare and submit intellectual property applications. Collectively, these factors have played a significant role in the observed increase in intellectual property registrations affiliated with Polibatam. The detailed distribution of intellectual property authorship is further disaggregated into copyrights, patents (including utility patents), and industrial designs, as presented in Figure 3(b). In the Indonesian context, intellectual property rights are of considerable importance for lecturers, students, and institutions, as they support lecturers' career advancement, serve as recognized artefacts for students in specific courses, and contribute to enhancing institutional reputation.



(a) (b)

Figure 3. (a) Distribution of Intellectual Property Rights Generated by Lecturers and Students, and (2) the detailed breakdown of intellectual property rights outputs

Journal articles constitute another important output of the teaching and learning process. In this study, the total number of academic publications is treated as an artefact of problem-based learning (PBL) activities, given that PBL is integrated not only into teaching and learning but also into research. As shown in Figure 4, journal publications recorded in the SINTA database of the Ministry of Higher Education, Science, and Technology display a fluctuating trend. The number of publications peaked in 2019 with 110 articles, declined to 20 in 2022, rose again to 78 in 2023, and decreased to 34 in 2025. Despite these fluctuations, the overall average remains higher than in the pre-2018 period.

A notable decline occurred between 2020 and 2022, with publications reaching their lowest point in 2022. This decrease may be attributed to the COVID-19 pandemic, during which teaching and learning processes were significantly disrupted. Following the easing of the pandemic, publication output increased to 78 articles in 2023, although this upward trend was not sustained in the subsequent two years, with output declining to 34 articles in 2025.

Similar to the trend observed in intellectual property rights, the annual number of academic publications is influenced by multiple factors. The primary driver is the integration of PBL into the curriculum and instructional practices, which requires students to develop innovative solutions to real-world problems derived from PBL topics. Furthermore, the submission of journal manuscripts has been incorporated as a component of student assessment, encouraging students to prepare article drafts during the completion of PBL projects. In addition, institutional factors play a significant role. Polibatam, through its Center of Research and Community Service, has implemented a policy providing incentives for lecturers who publish in nationally and internationally reputable journals. This policy has encouraged

collaborative publication efforts between lecturers and students during and following PBL activities.

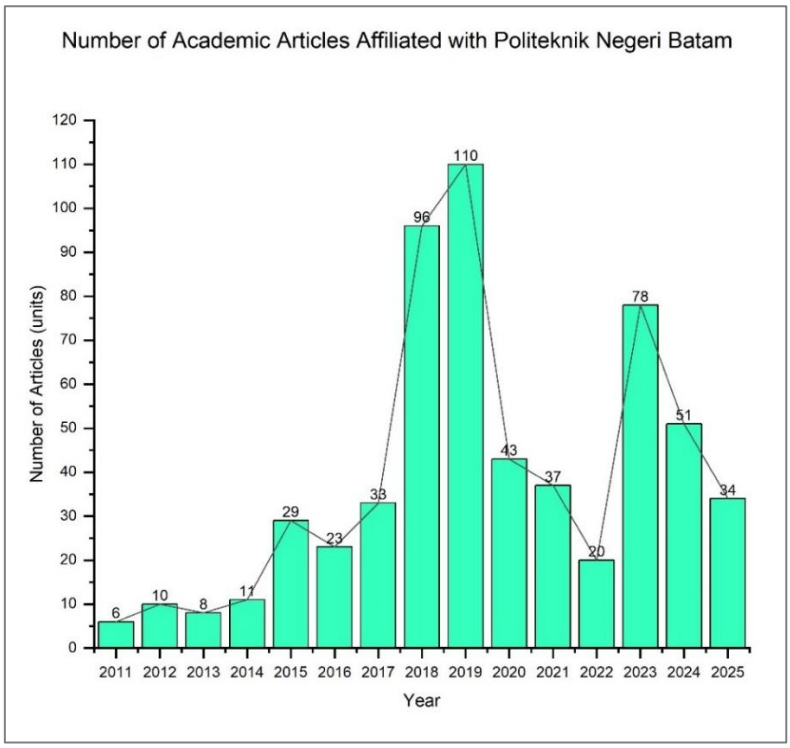


Figure 4. Total number of academic publications affiliated with Politeknik Negeri Batam.

Another observable impact of CDIO implementation is the improvement of students' interpersonal skills, particularly teamwork and communication (Deveci & Ayish, 2018). Through the widespread adoption of project-based learning within the CDIO framework, most students at Polibatam participate in project teams with assigned roles, such as team leaders and members. In addition to achieving project objectives, students implicitly develop teamwork and communication skills through continuous interaction, discussion, and collaborative problem-solving within their projects (Crespí et al., 2022).

Communication skills are developed not only through spontaneous interactions during project work but also through frequent opportunities to present project progress to peers and faculty serving as facilitators or project managers. Additionally, students are required to prepare project plans, periodic progress reports, and final reports using the "SIAP PBL" application. As students engage in projects almost every semester, these interpersonal skills are expected to be reinforced and internalized, providing lasting benefits for their future professional work.

Input and evaluations from industry stakeholders and users

Interpersonal skills, particularly teamwork and communication, are critical competencies for Polibatam graduates in the workplace. Through the implementation of project-based learning (PBL) and the Conceive–Design–Implement–Operate (CDIO) framework, Polibatam systematically fosters the development of these skills, including proficiency in both Indonesian and English. This approach is consistent with findings reported by Dampierre et al. (2024) in their review study.

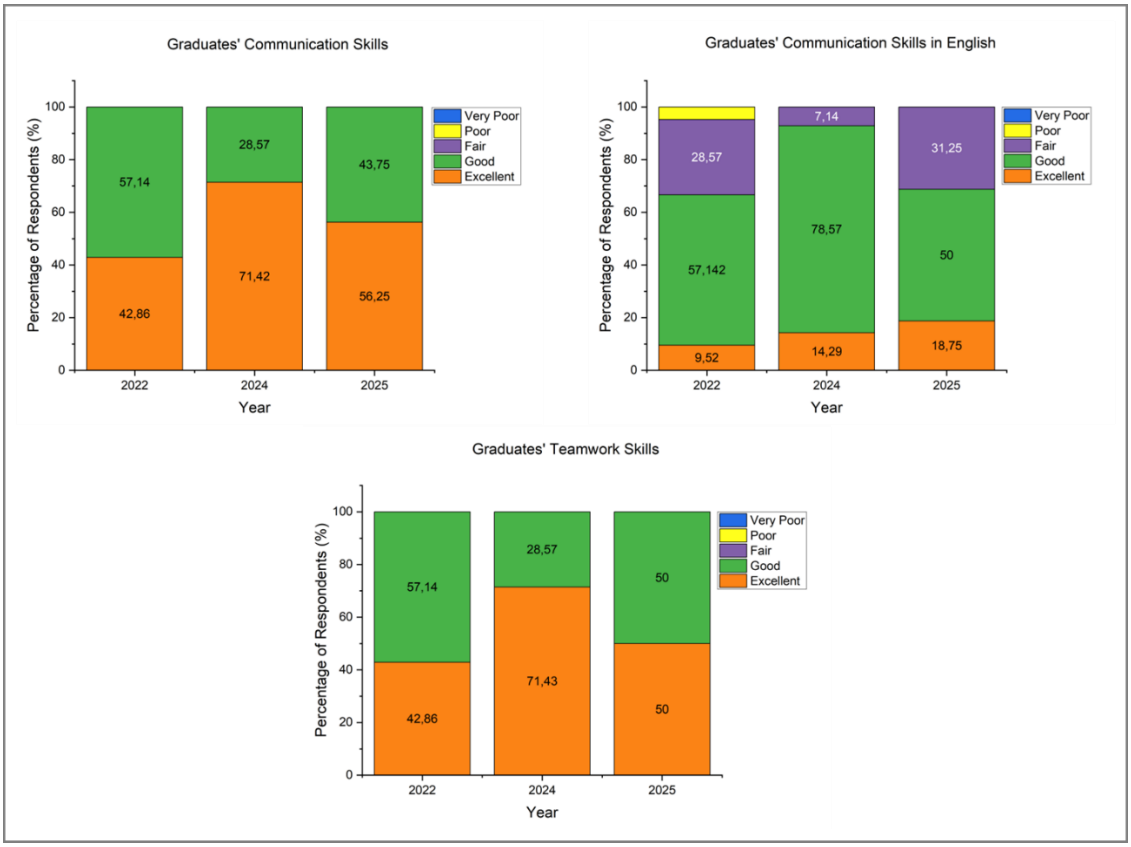


Figure 5. The communication, English communication, and teamwork skills of graduates, as evaluated through surveys conducted with industry stakeholders.

Survey data collected by the Career Development Center (CDC) in 2022, 2024, and 2025, involving approximately 52 company respondents, indicate that alumni demonstrate strong capabilities in teamwork and communication. These competencies show a consistent upward trend over the observed period, as illustrated in Figure 5. The surveyed alumni had graduated at least one year prior to participation, implying that the 2024 and 2025 data reflect graduates from 2023 and 2024, respectively. Notably, nearly all respondents had been engaged in PBL activities during their studies, particularly between 2019 and 2024.

Overall, the survey results classify alumni interpersonal skills predominantly within the “good” to “excellent” categories. These outcomes suggest that the integration of PBL into the curriculum has contributed positively to the development of interpersonal competencies prior to graduation from Polibatam.

CONCLUSION

The implementation of Project-Based Learning (PBL) in conjunction with the CDIO framework at Polibatam has had a substantial impact on both internal stakeholders and external partners, including industry and the broader community. PBL activities are integrated across nearly all study programs, beginning in the first year (Std. 4) and continuing through to final-year capstone projects (Std. 5). This approach has contributed to a notable increase in academic outputs, particularly in intellectual property (IP), including copyrights, utility models, patents, and industrial designs, as well as scholarly publications. The number of registered IP outputs at Polibatam rose significantly, reaching a peak of 196 in 2023. Although the number of academic publications also increased overall, a slight decline was observed after 2020,

followed by a recovery in 2023, potentially reflecting the impact of the COVID-19 pandemic. In addition, PBL has played a key role in enhancing students' interpersonal competencies. Feedback from industry partners indicates that Polibatam graduates exhibit strong interpersonal skills, with 71.42% rated as excellent in communication and 71.43% in teamwork in 2024.

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GPT-5.2 was employed in the review process of this paper, particularly for the Areas for Improvement section. The model was used to assist in synthesizing selected literature identified through the author's independent, manual keyword searches conducted via Google. Based on this input, the author composed the relevant sections using their own original wording and critical interpretation. The prompts submitted to the model and the corresponding responses are provided in this link: https://bit.ly/4n19hXE.

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EVALUATING A DIGITAL SIGNAL PROCESSING COURSE IN AI ERA

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ABSTRACT

A methodology for evaluating a Digital Signal Processing course in the modern Artificial Intelligence era is presented. The course is part of the Bachelor's program in Artificial Intelligence at the Federal University of Goiás, Brazil. The evaluation process contemplated a design-implement experience based on the CDIO framework for a course module whose contents evolve quickly due to a fast moving AI industry. The evaluation process was designed in cooperation with the Center of Excellence in Artificial Intelligence in Brazil. The course contents consisted of regular lectures for eleven weeks on signal processing topics, such as signal analysis, spectral analysis and synthesis and image processing. The last five weeks were dedicated to the development of a project involving state-of-the-art Artificial Intelligence methods. The learning tools provided to the students included a classroom platform to upload and share materials and a version control system to keep track of project deliverables, such as slides, project documentation and a kanban to measure teamwork. Forty-four students participated in the learning activity. Two surveys were applied to the students at the course completion in order to assess the level of achievement of the learning outcomes. As a result, the students were able to successfully conduct a project-based learning experience addressing challenging AI applications that expanded the limits of the traditional course contents in a systematic way. We designed a learning environment that allowed us to assess hard and soft skills during the learning process, which are abilities demanded by modern industries. Finally, reflections and observations and student feedback were collected to further improve the course module in further iterations.

KEYWORDS

Digital signal processing, artificial intelligence, evaluation, Design-implement experience, project-based learning, Standards: 2, 4, 5, 11.

INTRODUCTION

The availability of generative artificial intelligence resources, as educational tools, brings new challenges and opportunities to the academic community. Students now have access to powerful software able to exploit the heterogeneous online information on the internet contained in the form of text, video, audio or images, in a simple and fast way. Modern artificial intelligence (AI) systems can answer complex questions and explain the rationale behind them step by step using natural language, as if it was a conversation with an expert in the field. However, the correct use of AI requires a criterious screening of the answers in order to avoid misleading information called *hallucination* (Athaluri *et al.*, 2023). The adoption of AI tools by educators requires two key elements: adapting the course structure to support this new learning resource and the ability to cope with the rapid evolution of technological content (Holmes & Tuomi, 2022).

This work describes the process of evaluating a Digital Signal Processing course in the artificial intelligence era, a context characterized by high availability of online information and rapidly evolving subjects. A main aspect of this contribution was the switch from a traditional learning approach based on lists of exercises to project-based learning implemented as a design-build experience (see Standard 5) (Boughattas, Neji, Zladi, 2024)). An important strategy was focusing on developing the student's individual skills by allowing them to address challenging topics of their interest with the use of AI. We strongly believe that embracing AI as part of the educational process can help to design more customized and personalized learning environments. As a contribution to the CDIO community, we propose an evaluation process that can accommodate fast-paced topics in technology-aided curricula, such as Digital Signal Processing and related subjects.

We can discuss data sources as an example of customization of the learning process. Traditional course contents on signal processing, for instance, typically involve working with time series, signals, or images. Due to high availability of open data sources, datasets, code and online documentation, we were able to expand the course contents to more complex data types, such as text, audio, speech and video analysis. This, of course, implied expanding the horizon of processing techniques to deal with such signals, for example, including large language models (LLMs) for natural language processing; generative AI models (genai) for image generation; visual transformers and deep neural networks to work with style transfer in images, or; neural data compression for fast information retrieval. The role of the instructor also changes from a traditional server of information to a "*facilitator"* that promotes learning environments that allow scientific discoveries in a controlled playground.

A key challenge still remains: How to address and evaluate rapidly evolving subjects? A possible direction towards the answer is to keep our work updated with standardized methods and professional practices. The current is a follow-up on previous authors' work, in which we improve on top of related design-build experiences (Gunnarsson & Díaz-Salazar, 2023; Díaz-Salazar *et al.*, 2025). We discuss our strategy for incorporating constantly changing contents in traditional course structures in the following sections.

EVALUATION THROUGH PROJECT-BASED LEARNING

We propose a design-build experience based on team management and project-based learning. The instructor's role is assumed by the lecturer, who is responsible for validating the student's projects. During the first eleven weeks, the students received lectures on the fundamentals of the subject, such as signal and spectral analysis, time-frequency analysis,

and image processing. In the last five weeks, the students proposed a project to be worked in groups with focus on exploring artificial intelligence methods.

AI methods were presented in an introductory manner during the first weeks of the course. However, the students opted for more advanced methods since they were early exposed to practical projects conducted at the Center of Excellence in Artificial Intelligence (CEIA) during the first years of the program. The class instructor suggests the main topics of exploration, while the groups define the specific themes and validate them with the instructor. The instructor impulses the students' decision for them to benefit from the high availability of online resources, such as blogs, tutorials, and videos (*e.g.*, medium, youtube), and the access to public repositories of data and code (*e.g.,* kaggle, hugging face, github, papers with code). In such a sense, the students are free to propose the topic of their work, which becomes a potential candidate according to the description of the scope and goals.

The CDIO framework in the AI era

While the idea of integrating generative artificial intelligence into higher education offers exciting possibilities for personalized learning, training undergraduate students with the competencies required by a rapidly evolving industry is a significant challenge. One of the primary hurdles is the sheer speed of innovation. Traditional curricula often struggle to keep pace with the high availability of online resources and the constantly changing nature of technology-based education (Holmes & Tuomi, 2022). Integrating a professional-grade AI curriculum demands more than just theoretical knowledge, it requires an educational structure that can adapt as quickly as the technology itself. Without a framework that bridges the gap between theory and practice, educators face critical questions: How do we teach effectively in the age of LLMs? How do we evaluate learning outcomes when students have access to powerful generative tools?

To address these challenges, this work proposes a CDIO design-build experience that embraces AI as a core educational resource. Instructors are challenged to shift their role as providers of information to facilitators that promote learning environments with advanced and up-to-date topics (CDIO, 2026). Students' workload moves beyond theoretical exercises to more practical developments involving state-of-the-art methods and protocols. The ultimate goal is to train students who are not only technically competent, but also critical thinkers capable of managing complex AI projects safely and ethically (Mezilov *et al*., 2024).

THE CONTEXT OF THE DESIGN-IMPLEMENT EXPERIENCE

The Bachelor's Program in Artificial Intelligence

The evaluation of the course module focused on the development of software products aligned to the core program, such as deep learning, computer vision and natural language processing. The BIA is a four-year program composed of eight semesters corresponding to 3,200 hours in total. The first three years correspond to courses in Entrepreneurship, Mathematics, Computer Science, Machine Learning, and Deep Learning. The Digital Signal Processing module is given in the fourth semester, with a total of 64 hours of credits. It is the third course where students are introduced to a design-implement experience, according to the CDIO framework (other CDIO courses on the program are Computer Vision, at the fifth semester, and Robotics, at the seventh semester). The fourth year of the program includes modules on Natural Language Processing, Reinforcement Learning, Robotics and Big Data. The program concludes with a Residence Program in Artificial Intelligence in the eighth semester, in which

students work 320 hours of credits on a capstone project, as part of the requirements for graduation.

Structure of the DSP course module and learning goals

The module on Digital Signal Processing is 16-week long, which is equivalent to 3 ECTS credits (a year of full-time studies corresponds to 60 ECTS credits). The students are expected to spend 64 hours on the subject. The learning outcomes are:

- (Unsupervised) Explain the different phases of digital signal and image processing.
- (Supervised) Apply the basic algorithms of signal and image processing.
- (Following instructions) Model and implement sets of algorithms for the different phases of signal and image processing.

There are three levels of independence students must accomplish towards reaching a learning outcome. The levels of independence were designed as checkpoints for instructors to evaluate the learning process incrementally. “Unsupervised” means the students are expected to accomplish entry level goals without support from the instructor. This level was assessed through oral interventions. “Supervised” means the students act independently on intermediate level tasks, but are allowed to receive support. This was evaluated through practical laboratories. On “Following instructions”, the students are expected to execute more advanced activities. This level was assessed through a seminar implemented as a group project. In our case, the seminar was the only activity to receive a grade, while the oral tests and laboratories served to prepare the class with basic technical content.

The first eleven weeks of the module were used to present signal processing topics, such as signal and frequency analysis, spectro-temporal analysis, and image processing. The last five weeks were dedicated to the development of a group project presented as a seminar. In the following sections we explain the details of assessing the seminar process.

Evaluating software-based projects

Forty-four students took part in the course module. The evaluation consisted of preparing a capstone project for five weeks. The students were self-organized in groups of four members. From week one to eleven, the class received inductions during lectures to stimulate the proposal of projects involving modern AI applications. The topics were suggested by the instructor and refined by the students iteratively. This allowed us to expand the curriculum beyond the topics that can be explored in a period of sixteen weeks and to promote scientific discovery by working on personal projects. The learning environment simulated an immersive work experience where the participants developed a project judged by a sponsor (the instructor).

The evaluation process was performed in the following sequence:

- **Project proposal and Validation (Week 11):** In Weeks 6 and 7, the students search for project topics individually. In Weeks 8 and 9, they should identify candidate members to form teams of four people. They received a project template to be fulfilled as project documentation. In Week 11, the teams submit an abstract of the proposal to be discussed and validated with the instructor. The validation process consisted of verifying the goal and scope of the work. To validate the goal, it was checked the object of study (time series, images, text, or tabular data). To validate the scope, the proposal should fit five weeks of work. If the scope was too short, the team was asked to include

additional tasks as goals. If it was too long, the team should divide the proposal in stages to be delivered incrementally.

- **First checkpoint (Week 14):** The first checkpoint consisted of an oral examination in the form of a five-minute pitch. The deliveries were the presentation slides, a kanban of the work in progress, and a partial project documentation. The teams received feedback focused on improving soft skills (presentation) and hard skills (project management). Soft skills were improved with hints for catching up the audience's attention, keeping good posture, controlling time and speaking out loud. Hard skills were improved with hints on using up to date datasets, suitable research methods, or specialized literature.
- **Second checkpoint (Week 16):** The final checkpoint consisted of an oral examination of eight minutes with additional two minutes for practical demonstrations. The deliveries were the presentation slides, a completed kanban, and the final project documentation.

In order to successfully assess the seminar, we used a couple of online learning resources:

- **Learning platform:** We adopted Google Classroom as the classroom environment because it allowed us to communicate effectively with the class by sharing slides, practical exercises, videos, and information about the conduction of the seminar projects. The platform comes with a mobile version that is also useful for sharing instant updates and news.
- **Project deliverables:** The deliverables were submitted through GitHub in order to organize them on individual team repositories containing the slides, code, project documentation, and kanban for teamwork assessment. As version control systems, Git-based platforms also allow evaluating incremental work in progress on each submission, if required.

Teamwork was one of the hardest aspects to evaluate. A step forward towards addressing it was to require a kanban for weekly task definition. A kanban is a simple and effective way for instructors to monitor the progress of teams at a high-level of granularity. It also allows instructors to detect negative practices, such as micro management, without interfering too much into the process. Kanban is also a standard tool for project management in modern agile frameworks of software development.

Examples of project tasks and results

Twelve projects were validated in total with the following proposals:

1. Diffusion transformers for generation of manga artwork.
2. A data communication protocol through acoustic waves via 256-FSK modulation.
3. Denoising and detrending of ECG signals using AI methods to support physicians in diagnosing cardiac anomalies.
4. Reconstruction of 3D objects from multiple images using Gaussian splatting and NeRFs.
5. Comparison of Discrete Cosine Transform and autoencoders for image compression and applications in Content-Based Image Retrieval.
6. Manual feature extraction versus trained neural network embeddings for the classification of musical audio signals and Music Information Retrieval applications.
7. Extraction of embeddings with Reinforcement Learning for DeepFake analysis.
8. Spectral analysis and filter design for the detection of Bitcoin halving cycles.
9. Analysis of wildfires using deep learning segmentation in videos.

10. Super-resolution in images and videos using generative adversarial networks.
11. Automatic translator of Brazilian regionalisms.
12. Style transfer in images using diffusion models.

A common characteristic of the proposals is the complexity of the topics. Students in the AI era have access to rich online resources, such as blogs, tutorials, datasets, articles with documented code and examples, that facilitates exploring such sophisticated subjects. To keep the students confident with them, failure needed to be embraced as part of the learning process during checkpoints. An oral screening was taken during the validation of proposals in which students agreed on achieving the learning outcomes regardless of project results being positive or negative. Recognizing mistakes as a constructive outcome helps to mitigate the fear of failure.

Some of the teams used online available data, so the workload was on studying complex signals (*e.g.*, Projects 1, 3, 4, 5, 7, 8, 9, 12). Whenever data collection was necessary (*e.g.*, Projects 2, 6, 10, 11), the feasibility of the project was double checked with the students during validation to verify that the team would be able to collect the required data timely to meet the deadlines.

Two examples of the validation phase are Projects 5 and 11. The Project 5 team proposed studying image compression using a classical spectral analysis approach. As the goal was short for the proposed schedule, the project scope was extended to incorporate deep learning methods for image compression, such as embedding generation with autoencoders, in order to fulfill the five-week requirement. The proposed new methods were all well documented in literature, so the team would be able to compare classical methods with more modern ones within the timeframe. On the other hand, the Project 11 team proposed studying style transfer on voice signals using established methods and data. In such a case, the suggestion for the team was to adapt the experiment in order to build a dataset that allows translating phrases originated from a Brazilian regional dialect to a different one. The team validated the scope properly by identifying and documenting the steps required to address the new problem. Although the final result was simplified to the translation of words rather than phrases, the team managed to execute the proposed methodology to analyze such complex signals and demonstrated that phrase analysis could be performed with a larger time budget.

A survey was applied to the class by the end of the course. The questions were designed in cooperation with two students in order to collect the class' opinion about the learning experience. The survey measured the level of achievement of the three learning outcomes at the completion of the course module. It also ranked the lectures and the evaluation method, and contemplated space for general comments and suggestions.

Eleven students (N = 11) answered the survey in total, with the following results:

- I am aware that the responses to the form are ANONYMOUS? Yes (100%), No (0.0%).
- Can I explain the different phases of digital signal and image processing? Yes (45.5%), Partially (54.5%), No (0.0%).
- Can I explain the basic algorithms for signal and image processing? Yes (45.5%), Partially (45.5%), No (9.1%).
- Can I model and implement sets of algorithms for the different phases of signal and image processing? Yes (81.8%), Partially (18.2%), No (0.0%).
- Rate the DSP lectures from 1 to 5: 1 (0.0%), 2 (0.0%), 3 (27.3%), 4 (45.5%), 5 (27.3%).
- Rate the evaluation method used on a scale of 1 to 5: 1 (0.0%), 2 (0.0%), 3 (9.1%), 4 (27.3%), 5 (63.6%).

- Please provide suggestions below for changes to the lectures and/or assessment method:

  Student 1: *“I believe the evaluation was very well done. Regarding the classes, I felt they covered topics without explaining how to do them from the beginning, leaving the student to figure it out on their own. But how can you do something you've never seen anyone do before? Sometimes the challenges are too great for some students, and this can make them feel the content is too difficult. However, perhaps this could be resolved by showing how to do it the first time.”*

  Student 2: *“I think the classes were very expository, but they lacked more encouragement of practice. More than what was done in class; objective exercises on the topics covered would be a good way to do this, in my opinion.”*

  Student 3: *“I think the idea of the classes being more practical was very good, to present the content and give us a "challenge" on how to solve/implement what we saw in theory but now in practice. I only missed more "concrete" feedback on the solutions and the steps taken to arrive at them. I say this because the solutions were presented in class and the step-by-step process was followed, but if people weren't paying 100% attention and missed a step, they could get lost in the rest of the stages, and it would be difficult to recover that later because there was no material with the "answer." (...). But overall, that was it. I really liked how the subject was conducted, and the two-week evaluation method (which ended up being three by chance) was also very good because we had that initial week to do the first tests and see where we were going, and then we had more time to work on a final project. So, two weeks of evaluations was very good for that reason. In my view, if we had another week of "intermediate" progress, it could have ended up being too redundant and similar to the final results, and it wouldn't have been as interesting as it turned out to be. Otherwise, congratulations, I really enjoyed the material!”*

  Student 4: *“The classes could be more dynamic and have more weekly practical activities.”*

The university also applied a mandatory survey by the end of the semester, whose results are shown in Table 1 (SIGAA, 2026).

Table 1. Results of the evaluation of the teaching process by the class

N	Suspensions	Dimension 2		Dimension 3		Total Avg. [1]	Total Std. [1]
		Avg.	Std.	Avg.	Std.		
41	0	9.19	1.88	9.46	1.10	9.19	1.66

[1] Total Average and Total Standard Deviation are calculated from Dimension 1 - “Evaluation of the Institution by the Student” and Dimension 2 - “Evaluation of the Instructor by the Student”, which are metrics defined by UFG, of a maximum of 10.0 points. Dimension 3 - “Self-assessment by the student” follows a similar standard.

Observations and student feedback

Some lessons learned can be summarized by the end of the learning activity:

- The question, "how do we evaluate learning outcomes when students have access to powerful generative tools?", could be partially addressed. The focus on project-based learning allowed us to achieve the learning outcomes in a bottom-up approach, starting by the “Following instructions” level on project definition and validation, followed by the “Supervised” level on the development of weekly tasks, and concluding with the “Unsupervised” level at oral presentations.
- Potential factors that could limit the model’s implementation are the scalability to larger cohorts, the ability and experience of the instructor to guide the teams through managerial details, and the subjective effectiveness of the proposed software tool (git) for teamwork assessment.
- The students reported a high level of satisfaction. This was achieved by helping the teams to choose their seminar topics rather than imposing them, and to provide constructive weekly feedback that helped teams to accomplish their goals. Although this might seem unfair to the evaluation, we must remember that learning is essentially an individual process and that the transformation of mindset becomes evident over time. The focus of our approach is on providing a learning environment with proper educational resources to enable students to develop their own ideas.
- We identified a trend in our students to embrace challenging topics. The teams were able to propose and complete research topics of moderate to high technical difficulty. This statement is (partially) supported by a flexible learning process that embraces failure deliberately.
- We showed that a switch from traditional evaluation, such as lists of exercises, to more sophisticated evaluation based on addressing project management skills was necessary. This is supported by the results, which showed a positive feedback from students who enjoyed the evaluation and conduction of the seminar.
- The proposed methodology allowed us to evaluate teamwork, which is hard to address. By adopting agile methods into the classroom, we were able to recreate modern work environments in which teams grow and deliver value incrementally. The learning process also allowed us to evaluate hard and soft skills, which are complimentary abilities required in modern work environments.

CONCLUSIONS

We described the process of evaluating a subject in the artificial intelligence era, which is characterized by fast evolving contents and access to large amounts of online information. In order to address those challenges, we proposed a learning activity structured as a 3-step design-implement process: Project proposal and Validation, First checkpoint, and Second checkpoint. We used learning resources, such as Google classroom for communication and upload of materials, and GitHub for organizing the project documentation and kanban. Those platforms incorporate the necessary features to keep track of the learning process in a systematic and effective way (*e.g.*, reports, slides, code, kanban). The design-build activity was designed on top of three levels of independence towards reaching the learning outcomes incrementally: Unsupervised, Supervised and Following instructions. This structure is flexible and was implemented in a bottom-up approach in our case. The results showed that it is possible to evaluate rapidly evolving subjects, such as the Digital Signal Processing course module, by implementing an evaluation process based on project management and embracing failure as part of the learning process. As shown by the survey, the students were able to successfully complete their learning goals even when challenging situations were presented. In future, we can think of incorporating strategies to make the evaluation process

suitable for massive classes, for instance, by implementing automatic tests at intermediate steps as checkpoints, or by considering additional teaching staff to support the process.

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IF AI WRITES, WHO THINKS? STUDENT PERCEPTIONS IN CDIO EDUCATION

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ABSTRACT

This study investigates engineering students' perceptions of AI-assisted writing, thinking, and feedback within a CDIO-based curriculum. Using an open survey, the research examines how students interact with AI tools for tasks such as brainstorming, structuring reports, and improving writing quality, while exploring where cognitive engagement occurs. The study finds that AI is primarily used as a supportive tool for organization, drafting, and clarity, rather than a replacement for human reasoning. Students report that critical thinking and conceptual learning occur mainly during prompting, reviewing, and reflecting on AI-generated outputs. Feedback is most effective when it emphasizes reasoning over text quality, and students value interactive, authentic assessment methods such as oral exams, live demonstrations, and lab work. These findings align with CDIO principles, highlighting the need for competency-based learning that integrates technical knowledge, professional skills, and reflective thinking. Overall, the results underscore the importance of designing curricula that support student ownership of learning and active reflection, ensuring AI serves as a learning enhancer rather than a replacement for human thought.

KEYWORDS

Generative AI, Engineering Education Research (EER), Student Perceptions, CDIO Standard 8, CDIO Standard 11.

INTRODUCTION

This study investigates student perceptions of the relationship between writing, thinking, and learning within the context of AI-assisted academic work, emphasizing its relevance to the CDIO Standards for engineering education and building on the institutional curriculum framework documented by Atayeva, Garlyyeva, and Orazov (2023). The survey, titled “Writing vs. Thinking: The AI Dilemma,” was designed to explore how students conceptualize cognitive effort when artificial intelligence tools, such as ChatGPT, are used for coursework. The broader purpose of the survey is to inform ongoing debates in engineering education regarding academic integrity, learning authenticity, and assessment design. Given that AI tools are becoming ubiquitous in professional engineering workflows, this study specifically investigates their influence on learning experiences and their alignment with CDIO standards for continuous improvement in education and skills development (Moreno, Decker, & Leicht-Scholten, 2024).

The target population consists primarily of undergraduate and postgraduate students, with a strong representation from engineering and technology disciplines, ensuring relevance to CDIO’s focus on preparing students for both technical excellence and professional competencies (Kimpton, Maynard, & Azouz, 2024). This study also contributes to discussions on how AI can support the development of personal and professional skills as part of a comprehensive engineering education (Zéraï & Mosbeh, 2024).

Methodology

Data were collected through an online survey and exported into an Excel spreadsheet for analysis. The final dataset comprised 68 valid responses. Initial preprocessing involved screening for completeness, identifying variable types, and categorizing responses into quantitative and qualitative components. To ensure content validity, the survey instrument was reviewed by two experts in engineering education and piloted with five non-participating students to confirm the clarity of the Likert scales and open-ended questions. The survey structure employs a mix of descriptive and inferential methodologies to address student perspectives on AI-assisted writing, aligning with the CDIO framework’s focus on integrated learning and reflection.

For clarity, "coursework" was defined within the survey instructions as including various written assignments such as lab reports, problem sets, and design projects.

Likert-scale items were treated as ordinal data and summarized using descriptive statistics, consistent with CDIO’s emphasis on evidence-based decision-making (UNESCO, n.d.). Open-ended responses were analyzed using qualitative thematic analysis to identify recurring patterns in student perceptions. This analysis adheres to ethical standards for educational research, with minimal missing data handled through listwise exclusion for item-level analysis.

Given the emerging nature of Generative AI integration in engineering curricula, this research is designed as an exploratory pilot study. With a sample size of N=68, the analysis prioritizes descriptive reporting and categorical frequency over broad statistical inference, aiming to identify baseline trends within the institutional context.

Data Description

The final sample consisted of 68 respondents, with a majority identifying as engineering or technology students. The inclusion of students across various academic stages reflects the

CDIO commitment to developing competencies progressively across the academic lifecycle (Zéraï & Mosbeh, 2024), providing diverse perspectives on skills progression. Figure 1 shows the demographic breakdown of survey respondents by academic stage.

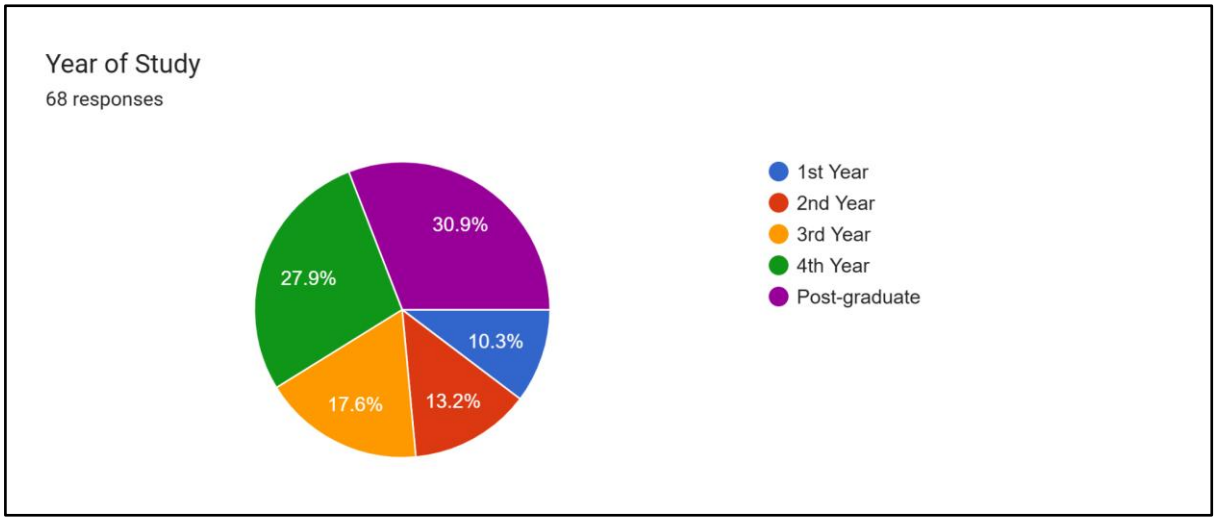


Figure 1. Demographic breakdown of survey respondents by academic stage

The survey's mixed-methods design integrated closed-ended questions, including Likert-scale items and frequency measures, alongside open-ended questions exploring students' views on where "real thinking" occurs when AI is used, and which assessment formats best demonstrate genuine understanding. Key variables measured included AI tool usage frequency, perceived cognitive engagement, ownership of ideas, and preferences for assessment formats, all central to CDIO's focus on student-centered education and professional growth (Kimpton et al., 2024).

Key Findings

Analysis of the survey data (N=68) revealed consistent patterns in AI adoption. Tool usage was widespread, with most respondents reporting occasional to frequent use of Generative AI for academic tasks, such as coding and conceptual brainstorming. As shown in Figure 2 (where 1 = Never and 5 = Daily), the majority of students (n=29; 42.6%) reported occasional use, while a smaller subset (n=10; 14.7%) reported frequent engagement. This trend reflects the integration of modern engineering tools into the academic process, aligning with CDIO Standard 7 (Integrated Learning Experiences). By utilizing AI to assist in disciplinary problem-solving, students are participating in an integrated learning environment where technical tools support the acquisition of professional skills. These findings suggest that AI engagement is transitioning from a peripheral novelty to a mainstream component of the engineering academic workflow.

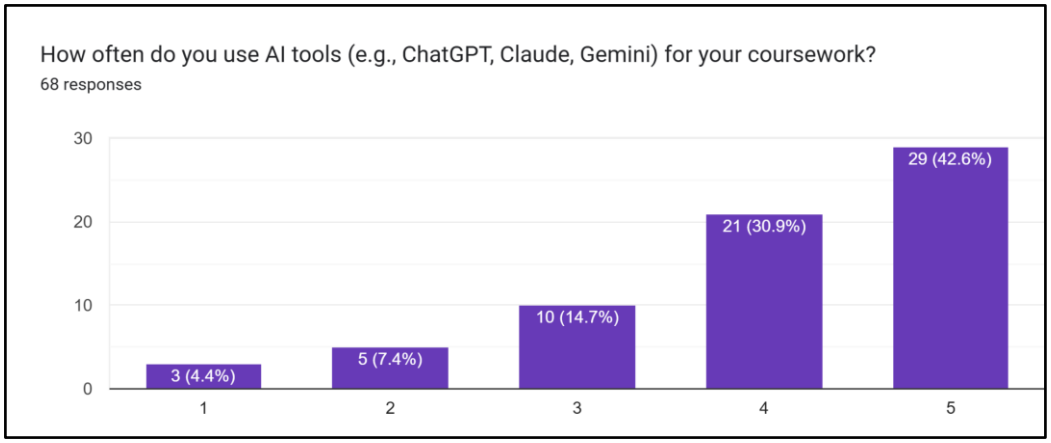
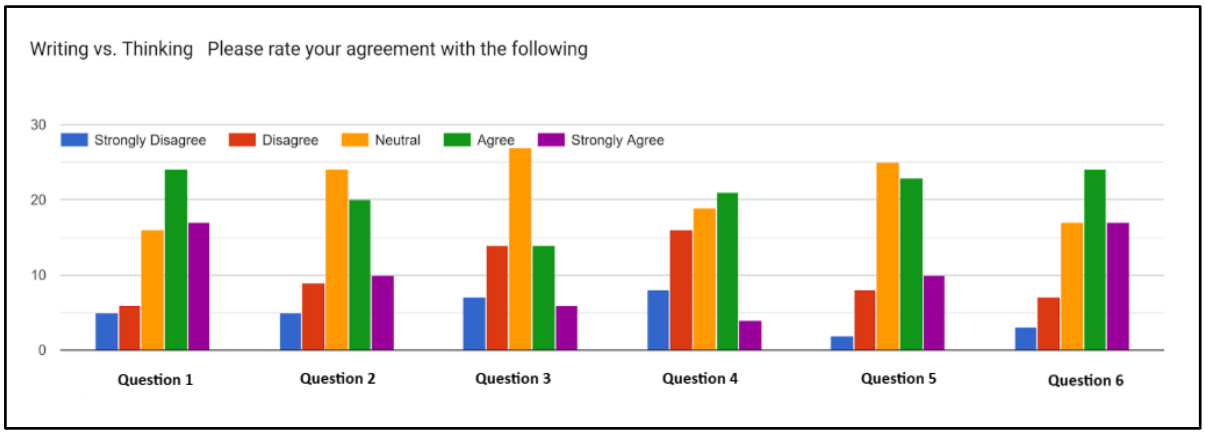


Figure 2. Frequency of AI tool usage among survey respondents

Second, students rejected the notion that AI use eliminates thinking. In line with the CDIO Syllabus for Personal and Professional Skills, students generally perceived that cognitive effort still plays a significant role in the process of using AI. Agreement levels were higher for statements suggesting that thinking continues during prompting, reviewing, and editing AI-generated outputs. Figure 3 illustrates mean agreement scores on the role of cognitive effort in AI-assisted writing. This reflects students' understanding of responsible AI use, which requires them to critically engage with AI outputs. The results also reflect a shared belief that AI tools aid, but do not replace, human intellectual effort (The Conversation, 2025a).

The following data represent the frequency of student responses (N=68). In line with the study's exploratory framework, these findings are intended to illustrate localized perceptions rather than to assert universal statistical significance.

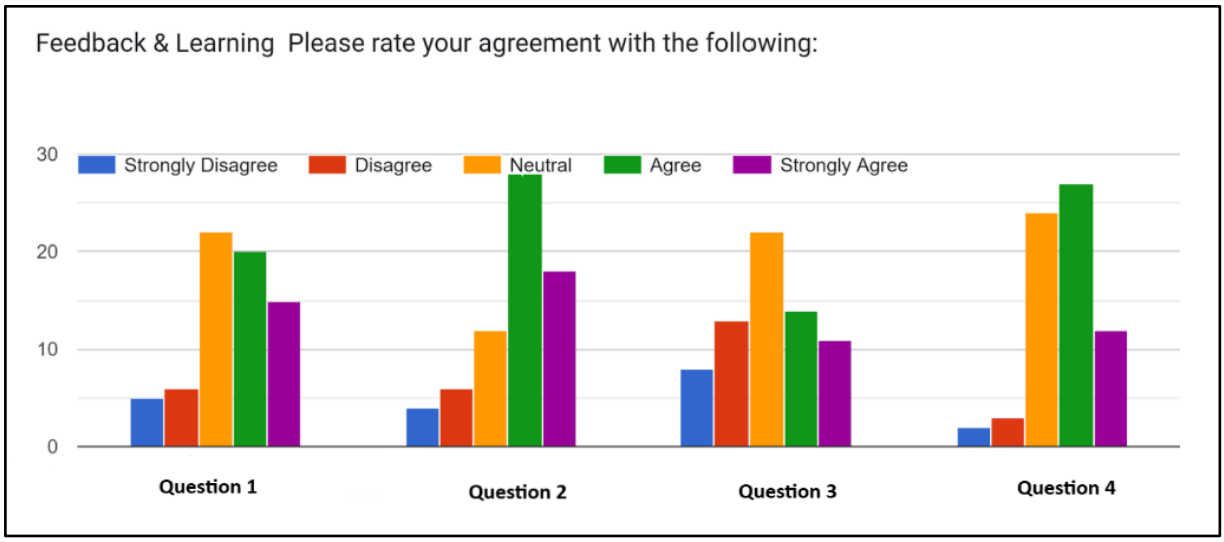


ID	Survey Question Statement
Q1	The process of writing helps me clarify my own thinking
Q2	High-quality writing is a reliable indicator of a student's understanding
Q3	AI can produce professional text without "understanding" the engineering logic

Q4	When using AI, most of my thinking happens during the "prompting" stage rather than the "writing" stage
Q5	Reviewing and editing AI-generated output requires significant mental effort
Q6	Clear writing and clear engineering thinking are two different skills.

Figure 3. Mean agreement scores on perceived cognitive effort during AI-assisted writing.

Third, students expressed skepticism toward written submissions as the sole measure of understanding. When asked which assessment types best demonstrate real comprehension, responses overwhelmingly favored practical sessions, lab work, live demonstrations, and oral examinations over traditional written reports. Figure 4 shows that students favor assessment formats emphasizing active engagement and practical application, expressing skepticism toward written submissions as the sole measure of understanding. This finding is consistent with CDIO's emphasis on active learning and performance-based assessments (Standard 11), aligning with the belief that true understanding is best demonstrated through application, analysis, and problem-solving in authentic contexts.



ID	Survey Question Statement
Q1	I carefully read instructor's feedback on my written assignments.
Q2	Feedback helps me improve my conceptual understanding, not just my grades
Q3	I feel less "ownership" of feedback if the text was largely AI-generated
Q4	Feedback is more valuable when it focuses on my reasoning rather than the final text

Figure 4. Student perceptions of assessment and feedback

STATISTICAL ANALYSIS

Descriptive analysis of the Likert-scale items related to professional engineering competence revealed moderate to high levels of agreement with statements emphasizing human responsibility and process-oriented assessment. As illustrated in Figure 5, the highest levels of agreement were observed for the statement that learning to use AI responsibly is a core skill for a modern engineer, followed by the view that engineering assessments should focus more on the design process than the final document. Agreement was more varied regarding the statement that verbally explaining a design demonstrates competence better than a written report, indicating diverse student comfort levels with oral assessments. These variations reflect CDIO Standard 1 (Contextual Learning), where learning outcomes are shaped by instructional contexts (Inside Higher Ed, 2025). The qualitative thematic analysis followed an iterative process: two independent coders reviewed 20% of the responses to develop a coding scheme. Interrater reliability was established using Cohen's Kappa ($\kappa = 0.82$), indicating substantial agreement.

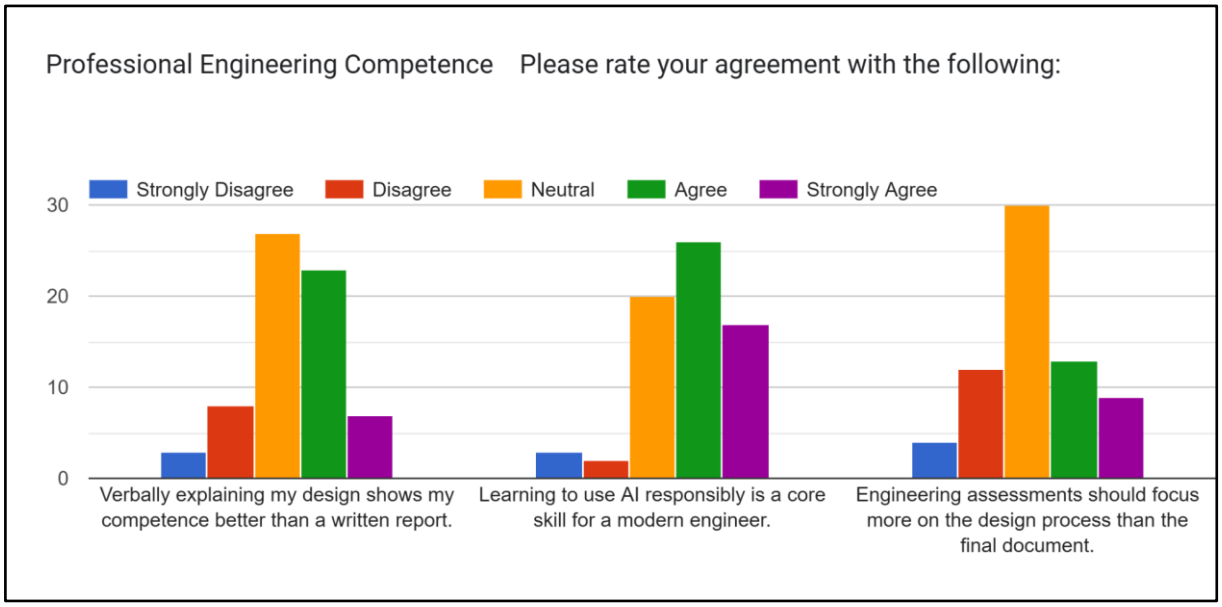


Figure 5. Student agreement with Professional Engineering Competence statements related to AI responsibility, assessment focus, and demonstration of understanding

Frequency-based and categorical analyses further reinforce these quantitative trends. Responses to the open-ended question regarding where "real thinking" occurs during AI-assisted writing clustered around several dominant themes, including **prompt formulation**, **reviewing and editing AI-generated content**, and **human judgment in evaluating accuracy, relevance, and relevance to task goals**. Very few respondents attributed genuine thinking to AI itself. Instead, students consistently framed AI as a supportive mechanism for structuring and expressing ideas, while emphasizing that ideation, decision-making, and responsibility remain human. This qualitative evidence complements the professional competence patterns shown in Figure 5, reinforcing the view that students associate engineering competence with judgment, responsibility, and process awareness rather than with textual production alone (The Conversation, 2025b).

Analysis of assessment preferences further supports this interpretation. Across responses, students overwhelmingly favored **practical and interactive assessment formats**, including laboratory work, oral examinations, and live demonstrations, as the most reliable indicators of

genuine understanding. Written reports were rarely viewed as sufficient on their own. This preference aligns with the professional competence dimensions shown in Figure 5, particularly the emphasis on process-focused evaluation and responsible engagement with tools. These findings support CDIO Standard 5 and Standard 8, which prioritize experiential learning and assessment methods that make thinking, decision-making, and application visible.

Exploratory comparisons across academic stages suggest that **senior and postgraduate students expressed more nuanced interpretations of professional competence in AI-supported contexts**, frequently emphasizing ethical responsibility, reflective judgment, and process ownership. These students were more likely to describe AI as a cognitive partner that supports—but does not replace—engineering reasoning. This developmental trend is consistent with CDIO's focus on progressive competence development across the academic lifecycle, indicating that as students advance, their understanding of professional responsibility and AI's role within engineering practice becomes more sophisticated.

While the sample size ($N=68$) limits the generalizability of the findings, as a pilot study, it provides a necessary foundation for future longitudinal research. Subsequent iterations will aim for larger, multi-institutional cohorts to validate the preliminary trends identified here.

Interpretation

The findings suggest that students do not perceive AI-assisted writing as a replacement for cognitive effort. Instead, students report that thinking occurs during prompt formulation, critical evaluation of outputs, fact-checking, and final editing. Many students explicitly framed AI as a tool rather than an author, emphasizing that responsibility for logic and coherence remains human. This aligns with CDIO's emphasis on personal and professional skills, as students must take ownership of their learning and apply knowledge responsibly (UNESCO, n.d.).

Assessment preferences further support the view that students recognize the need for authentic assessments that require critical thinking, application, and problem-solving. Students consistently expressed a preference for practical, hands-on assessments, such as oral exams, live demos, and lab-based assessments. This supports CDIO's view that competence is best demonstrated through performance and practical application, not static outputs like written reports. These preferences underscore a call for curriculum innovation that emphasizes experiential learning and performance-based assessment (Standard 5) (Zéraï & Mosbeh, 2024).

CONCLUSIONS

This survey provides empirical evidence supporting a reframing of the "AI dilemma" in higher education. Students perceive cognition as distributed across various stages of the academic process, with AI tools serving as a supplement rather than a replacement for human thinking. These findings are aligned with CDIO's vision for student-centered education, where students engage deeply with learning processes, critically reflect on their use of tools, and demonstrate their skills through performance and application (Kimpton et al., 2024).

While the sample size limits the ability to generalize findings, the consistency between quantitative trends and qualitative explanations strengthens the credibility of the results. Future research should seek to integrate performance-based data and observational analysis to validate these perceptions further. Additionally, instructional design should be re-evaluated to ensure that assessment methods align with the cognitive and professional skills needed in

a technology-rich world (The Conversation, 2025a). The study contributes to ongoing debates about AI's role in education, particularly in engineering disciplines, and supports pedagogical approaches that emphasize reflective AI use, transparent expectations, and authentic assessments aligned with the CDIO standards.

ACKNOWLEDGEMENTS

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used **Google Gemini** in order to refine the grammatical structure, improve the clarity of the research methodology descriptions, and assist in the thematic categorization of qualitative survey data. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication. This process aligns with the study's exploration of AI as an augmentative tool for human cognition rather than a replacement for critical thinking.

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A TEACHING MODEL APPLIED TO FUNCTIONAL ASSESSMENT CLASSES IN PHYSIOTHERAPY

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ABSTRACT

Understanding the musculoskeletal functional assessment process is crucial for Physiotherapy students. Although new teaching methods have emerged, an effective model for teaching Functional Assessment in Physiotherapy is still needed. The goal of this study was to describe the proposal of a teaching framework in the Functional Assessment course for Physiotherapy students. This is a design-implement experience conducted with 22 fourth-semester Physiotherapy students between March and July 2025. Students were assessed using different strategies, including role-playing, clinical cases, seminars, descriptive scripts, and presentation of scientific work. The results achieved by the course were evaluated via an electronic form. The results showed that the clinical reasoning method was favorable (90.9%), facilitating the development of the professional skills required in the course (77.3%). As negative points for the implementation of the proposal, students mainly pointed to the infrastructure and the course workload. It is concluded that the integration of the proposed framework improved essential clinical reasoning skills in Physiotherapy students. However, more research is needed to optimize the acquisition of theoretical knowledge in this area.

KEYWORDS

Physiotherapy, functional assessment, professional skills, student assessment,
Standards: 7, 8.

INTRODUCTION

CDIO, which stands for Conceive, Design, Implement, and Operate, is an initiative towards keeping high quality standards in higher education programs worldwide. The CDIO framework promotes active, project-based learning experiences that integrate theoretical and practical knowledge, overcoming traditional passive learning methods. It emphasizes the active role of students in their education, fostering creativity and initiative in a collaborative environment, while instructors act as facilitators, not as primary sources of information (Chen *et al*., 2024). The CDIO framework, originally developed for engineering fields, has been applied in various health areas, such as medicine and nursing (Dong *et al*., 2023), however, its application in Physiotherapy is not clearly detailed in the literature.

As a collaborative proposal, this work presents a design-implement experience inspired by Standards 7 and 8 about Active learning and Integrated learning for teaching and evaluation of a course module in Functional Assessment given to second-year Physiotherapy students at the Federal University of Goiás (UFG). The study introduces methodological approaches that help to overcome limitations in the traditional model of teaching in Physiotherapy, enabling the active involvement of students. More specifically, the experience describes the process of constructing the clinical reasoning model (Bachkaniwala & Ramanandi, 2023) for assessing the musculoskeletal functionality of patients with diverse health conditions, based on three stages: the first being the construction of the proposal; the second stage the development of theoretical and practical classes combined with assessments; and the final stage the results achieved in the discipline, whose model has the potential to stimulate academic thought and discussion.

Physiotherapy is part of the health field responsible for applying approaches and techniques to promote the recovery, prevention, and improvement of physical-functional function, body mobility, and quality of life of people with varying health conditions. Its actions focus on the assessment, diagnosis, prevention, and treatment of movement and functionality disorders of the human body (COFFITO, 2026). In Brazil, the expansion of undergraduate courses in recent decades reflects not only the growing demand for physiotherapists, but also the challenge of ensuring standards of excellence in teaching and qualified professional training (Gonçalves *et al*., 2017).

BACKGROUND INFORMATION

The CDIO framework

The CDIO framework consists of four main components (Crawley *et al*., 2014).:

- Characterization of the role of a professional.
- Formulation of the goals for the knowledge and skills required to act in that role. This can be done using the CDIO Syllabus.
- Formulation of what is needed from the educational program for the program to enable the students to reach their goals.
- Various methods and tools for developing the educational program.

Several healthcare courses have reported the application of the CDIO framework. In nursing education, Su et al. (2023) showed that students in the intervention group who received instruction using the CDIO framework showed significant improvements in clinical practice skills, critical thinking, autonomous learning skills, and theoretical and practical performance, as well as higher assessments of the quality of clinical teaching compared to the control group (all $p < 0.05$). Another study by Dong et al. (2023) used an online training course based on the CDIO framework for nursing students. The results demonstrated that the framework enhanced interactivity and collaboration within the course, which was crucial for improving students' learning experiences and outcomes.

THE CONTEXT OF THE DESIGN-IMPLEMENT EXPERIENCE

The Federal University of Goiás

The Federal University of Goiás (UFG) is the largest public university in the Central-West region of Brazil, located in Goiânia, Goiás. The Physiotherapy program is located at the Institute of Tropical Pathology and Public Health (IPTSP). The course has 133 students out of a total of 150, divided into five classes (17 students dropped out of the university). At the end of 2026, the course will graduate its first class of students.

The undergraduate course in Physiotherapy (Bachelor's degree)

This is a recent program, started at UFG in 2022, with a duration of 10 semesters (5 years), a total workload of 4,004 hours, and offering 30 places for students annually. The main goal of the program is to train professionals capable of working in the functional health of human beings, based on the best scientific and intellectual evidence and technological advancements, from a multi-professional and interprofessional perspective, sensitive to the health problems of society (UFG, 2022). The proposed teaching model is based on active methodologies, favoring the individual autonomy of the student and their connection with the collective, stimulating protagonism in the learning process, critical thinking and problem-solving. The Pedagogical Project of the course follows the recommendations of the National Education Council of Brazil, considering the student as the subject of learning and supported by the instructor as a facilitator and mediator of the teaching, research, and extension process (Brazilian Ministry of Education, 2022).

The quality of higher education in Physiotherapy in Brazil is a determining factor for the technical, ethical, and critical competence of professionals, which is measured by the National Student Performance Examination (ENADE). Internationally, the European Network of Physiotherapy in Higher Education (ENPHE) and guidelines from the World Confederation for Physical Therapy (WCPT) highlight the importance of developing clinical competencies, critical reasoning, and interprofessional integration from the first years of student training (ENPHE, 2022; WHO, 2010). The integration of active methodologies and evidence-based practice (EBP) in curricula is strongly recommended in Physiotherapy courses, which are associated with better clinical outcomes and greater employability of graduates. This approach, although present in Brazil, still faces structural, pedagogical, and cultural barriers that hinder its full implementation.

The Functional Assessment module

The Functional Assessment module is part of the mandatory core curriculum offered in the second year of undergraduate studies, with a workload of 64 hours, comprising 32 hours of theory and 32 hours of practice. The pedagogical principles of this module are related to the theoretical and practical teaching of methods and techniques for physical-functional assessment in Physiotherapy based on the International Classification of Functioning, Disability and Health (ICF), including the functional analysis of people with different age groups and health conditions.

Expected competencies in this course include interpersonal relationships, listening and therapeutic communication, clinical reasoning, detailed application of musculoskeletal functional assessment in patients with diverse health conditions, and the development of a kinesiological-functional diagnosis. Many teaching methodologies are strongly recommended in Physiotherapy education, such as problem-based learning (PBL), evidence-based learning (EBL), role-playing, and clinical simulation, which have demonstrated a positive impact on motivation and academic performance (Lennon *et al*., 2019). Furthermore, hands-on learning in real-world settings allows students to immerse themselves in the reality of work, developing communication, listening, and decision-making skills when dealing with patients with delicate health conditions, as well as experiencing work with a multidisciplinary team, defining the professional's role.

Although new teaching methods have emerged, especially for the development of clinical reasoning in Physiotherapy (Bachkaniwala & Ramanandi, 2023), it is necessary to develop an effective model for Functional Assessment in Physiotherapy, considering some limitations particular to the Brazilian teaching scenario, such as instructor training and infrastructure. In this sense, the CDIO framework is indicated for promoting proven active learning experiences that are used in other health areas such as nursing (Dong *et al*., 2023; Chen *et al*., 2024), but which need to be better documented in Physiotherapy. Thus, the goal of this study was to propose a design-build experience in the Functional Assessment course module for Physiotherapy students based on Standards 7 and 8 about Active learning and Integrated learning. The CDIO Syllabus was originally developed for engineering education, but the structure is very general, starting with Section 1 about subject knowledge and ending with Section 4 connected to the intended role of the graduate. Adapting the entire document to new education programs is a huge task. The learning activity described below is based on Section 4, which deals with the skills needed to perform the professional role.

METHODOLOGICAL PATH FOR TEACHING THE FUNCTIONAL ASSESSMENT MODULE IN THE PHYSIOTHERAPY COURSE AT UFG

The Functional Assessment module is based on the patient evaluation process. In it, the instructor aims to teach and evaluate the clinical reasoning of the Physiotherapy student in the face of different musculoskeletal functional conditions of patients. Clinical reasoning is defined as the cognitive process in the evaluation and treatment of the patient (Bachkaniwala & Ramanandi, 2023). Unlike the medical field, which emphasizes diagnosis, the physiotherapist performs a kinesiological-functional diagnosis, focusing on human functionality. Throughout the module, the student learns to communicate with the patient, to recognize the source of signs and symptoms, the contributing factors associated with the

symptoms (environmental, behavioral, emotional, physical, or biomechanical factors), and after receiving all the necessary information, performs a functional assessment focused on the patient's complaints.

This work, in the form of a design-build experience, describes the process of constructing a clinical reasoning model (Bachkaniwala & Ramanandi, 2023) for assessing musculoskeletal functionality in patients with diverse health conditions. The proposed model was divided into three stages: the first being the construction of the proposal; the second stage the development of theoretical and practical classes combined with assessments; and the final stage the results achieved in the module, a model with the potential to stimulate academic thought and discussion.

Scenario, teaching strategies and resources used in the module

The teaching setting consisted of 22 Physiotherapy students enrolled in the module, all in their second year. Classes were conducted in person, mediated by the instructor in charge and a physiotherapist monitor who was also a master's student. Theoretical and practical classes took place in the Physiotherapy Practice Laboratory at UFG and the Family Health Unit (USF) linked to the Brazilian Public Health System (SUS).

The course was designed to allow for a progressive method of clinical reasoning in Physiotherapy. It emphasized interpersonal relationships between therapist and patient, communication and therapeutic listening, and the construction of a musculoskeletal functional assessment protocol, which was the expected final product of the module, establishing all stages of the musculoskeletal functional assessment process. Furthermore, the theoretical-practical evaluation criteria qualified for the students' actions throughout the module.

The teaching strategies were designed for individual student activities, as well as pair work and the organization of five working groups (WGs), which were particularly important for the development of practical tasks and assessments in the subject. Theoretical classes adopted a format of interactive lectures with the instructor in charge, teaching assistant, and guest professionals, in addition to the study of scientific articles and videos, group dynamics, and seminar presentations. Practical classes consisted of supervised individual, paired, and work group scenarios, as well as problem sets and seminars.

Teaching methods

The content taught in the module was organized in an expository, dialogical, and problem-solving manner, in order to allow students to develop clinical reasoning based on the construction of a progressive musculoskeletal functional assessment protocol, built week by week, containing all the steps that should be evaluated in a patient. In relation to the content taught, different clinical cases were used, involving hypothetical and real patients of different ages and health conditions, as detailed in Table 1.

Table 1. Summary of the methodology used in the module on a weekly basis

Week	**Content**	**Teaching strategies**	
		Theoretical lessons	**Practical lessons**
Stage 1 – Proposal development			

Week 1	Presentation of the Study Plan	Lecture and discussion	Problem-based learningk and simulation between pairs of students
Stage 2 – Development of theoretical and practical lessons combined with assessments			
Week 2	Therapist-patient relationship Communication and therapeutic listening	Lecture and discussion session	Dramatization of clinical cases among five working groups
Week 3	Application of the ICF in functional assessment	Lecture and discussion session with guest speaker	Individual problem-solving exercises
Week 4	Vital signs and pain assessment	Lecture and discussion session with guest speaker	Simulation in pairs of students
Week 5		Construction of stage #1 of the musculoskeletal functional assessment protocol	Initial contact with patients Practical assessment of vital signs and pain with patients by the 5 WGs
Week 6	Spinal goniometry	Lecture and discussion session	Individual and paired simulations
Week 7	Upper and lower limb goniometry	Lecture and discussion session with monitor	Paired simulations
Week 8		Construction of stage #2 of the musculoskeletal functional assessment protocol	Practical goniometry assessment with patients by the 5 WGs
Week 9	Spinal muscle function tests	Lecture and discussion session with guest speaker	Individual and paired simulations Evidence-based learning
Week 10	Upper and lower limb muscle function tests	Construction of stage #3 of the musculoskeletal functional assessment protocol	Practical assessment of muscle function tests with patients by the 5 WGs
Week 11	Segmental osteomyoarticular assessment and functional tests	Directed study - Reading of scientific articles	Discussion of clinical cases - Problem-based learning
Week 12	Segmental osteomyoarticular assessment and functional tests	Directed study - Reading of scientific articles	Discussion of clinical cases - Problem-based learning
Week 13	Sensitivity, reflexes, and motor coordination	Presentation of theoretical-practical seminars by the 5 working groups	
Week 14	Postural assessment and gait assessment		

Week 15		Construction of stage #4 - Final product of the musculoskeletal functional assessment protocol	Practical assessment of sensitivity, reflexes, motor coordination, posture, and gait with patients by the 5 WGs
Stage 3 – Results achieved in the module			
Week 16	End of the course module	Course conclusion Application of a form for analyzing the results achieved in the module	Presentation of five papers at a scientific congress by the WGs, resulting from the development of musculoskeletal assessment protocols and patient assessments

Source: (from Authors', 2025).

RESULTS ACHIEVED BY THE CLINICAL REASONING MODEL IN THE FUNCTIONAL ASSESSMENT MODULE

Assessment

The evaluation criteria were progressively guided by different assessment experiences. The first assessment aspect (9.0 points out of a total of 10.0 points) corresponded to a set of activities carried out individually, in pairs, or collectively by the five working groups (Table 2).

Table 2. Scoring of assessments performed individually, in pairs, or in groups

Assessment activity	Student composition	Grade
Dramatization of clinical cases	WG	0.5 points
List of exercises	Individual	0.5 points
Practical simulations	Individual / Pairs	0.5 points
Clinical case with patient	WG	3.0 points
Seminar	WG	1.0 points
Musculoskeletal functional assessment protocol	Individual	3.0 points
Organization and presentation of work at a scientific congress	WG	1.5 points

Legend: WG (working group). The students enrolled in the course were divided into five WGs.
Source: (from Authors', 2025).

Course evaluation

In Week 16, students were asked to evaluate the clinical reasoning method used in the Functional Assessment module. The results were collected via an electronic form, completed by all 22 students. This activity was worth 1.0 points out of a total of 10.0 points.

The electronic form also provided a space for students to comment on what they liked most about the model implemented in the course, in addition to the positive and negative points in the teaching-learning-assessment process of the course, with some reports being presented:

What did you like most about the subject?

"Practical classes thoroughly exploring the topics covered, guest lecturers"

"Understanding how the clinical reasoning of Functional Assessment can transform rehabilitation and make patient care much more effective and individualized"

"The dynamic format of the assessments and the practical way of learning. That's why I remember almost everything. And the professor's commitment and dedication in having guest lecturers is a unique aspect. And the professor did her best to deliver all the necessary content, even if it took longer."

What did I like least about the subject:

"More practical experience outside the University would be interesting."

"The limited number of tables for practice, and I feel that if the course's workload were greater, we could take even more advantage of the content and practical experiences."

"The workload is insufficient to present the content in depth."

Some observations and lessons learned can be summarized at the end of the activity:

- Based on the Standards 7 and 8 about Active learning and Integrated learning, establishing the developmental stages of the discipline for building clinical reasoning in Physiotherapy students favored learning, as indicated by 90.9% of the students.
- The development of the expected competencies in the discipline was considered positive by 77.3% of the students; however, 9.1% disagreed and 13.6% preferred not to comment. This suggests that the model still needs to be thoroughly discussed and revised by experts in the CDIO framework.
- The assessment strategies in the module were considered adequate (81.8%).
- Students felt confident applying clinical reasoning in patient care, which also demonstrated the student's understanding of Functional Assessment as a topic studied.
- In addition to theoretical classes, practical classes are fundamental to the teaching-learning process in Physiotherapy and are highly recommended by the students who participated in the course module.

CONCLUSION AND FUTURE WORK

Given the above, this work, in the form of a design-build experience, described the process of constructing a clinical reasoning model for the functional assessment of patients with diverse health conditions. The proposed model was divided into three stages: the construction of the proposal; the development of theoretical and practical classes combined with assessments; and the results achieved in the course module, whose model has the potential to stimulate academic thought and discussion.

The results showed that students pointed to the clinical reasoning method as favorable, facilitating the development of the professional skills required in the discipline, feeling confident in conducting the method in real care scenarios. As negative points for the implementation of the proposal, students pointed to the infrastructure available in the course, the time that should be increased for the more in-depth development of the content, and the

association of theoretical and practical classes on the same day, as well as the availability of modules with similar characteristics offered in summer to complement the knowledge.

Finally, it is worth noting that the next step of the Functional Assessment course module will be to incorporate a system that will use IMU sensors and computer vision in the functional assessment process. This initiative is being developed thanks to partnerships established with researchers from the Schools of Artificial Intelligence (INF) and Medical Physics (IF), linked to interprofessional research and outreach projects.

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PROJECT-BASED LEARNING APPROACH FOR LOW COST ECG CONSTRUCTION AND CARDIOVASCULAR HEALTH OUTREACH

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ABSTRACT

Project-Based Learning (PBL) is a student-centered active learning methodology in which students acquire knowledge by addressing authentic, meaningful, real-world problems through projects. This approach fosters critical thinking, collaboration, and autonomy, as opposed to passive information reception. By investigating, researching, and creating solutions or final products, students engage in practical, motivating learning that effectively bridges the gap between theory and practice. Cardiovascular diseases represent nearly one-third of deaths in Brazil, highlighting the importance of the electrocardiogram (ECG) in assessing health. Our PBL approach encouraged students to build low-cost ECGs using an easy-to-read manual at classroom workstations. Results confirmed that students were able to engage with the social and biomedical engineering aspects of our project by gathering information about cardiology and generating the expected cardiac signals. Furthermore, the manual fulfilled its purpose by facilitating the comprehension and replication of the project by students and teachers. While initial technical challenges occurred due to low signal amplitude, they were overcome with the help of specialized amplifiers. In conclusion, the project was successfully completed through this PBL approach, significantly contributing to cardiovascular health awareness and scientific education among the students.

KEYWORDS

Medical Physics, artificial intelligence, biomedical engineering, project-based learning, CDIO Standards: 7, 8.

INTRODUCTION

A central objective of the CDIO framework is to bridge the gap between academic programs and professional practice by aligning graduate competencies with market demands (CDIO, 2025). Demonstrating the social impact of biomedical engineering through project-based learning (PBL) is essential for fostering knowledge via practical experimentation and empowering students to become lifelong learners (Fidalgo *et al*., 2025). Integrating CDIO and PBL into engineering curricula requires changes in teaching methodologies, teacher training and workspaces (Ramírez de Dampierre, M., *et al.*, 2024).The proposed educational framework is defined as a structured three-phase "Pipeline" that operationalizes the Conceive, Design, Implement, and Operate framework within the context of biomedical instrumentation. This framework is designed for transferability, offering a replicable model where specialized hardware and software tools are used to empower students to solve authentic, real-world problems. In fact, active learning leads to significant increases in examination performance and lower failure rates compared to traditional lecturing (Freeman S., 2014). This study builds upon a pioneering initiative by the authors, which introduced a CDIO design-build experience within a university extension program for the Medical Physics course at the Federal University of Goiás, Brazil. Integrating biomedical instrumentation within Medical Physics and Biomedical Engineering allows for the effective diffusion of knowledge regarding cardiovascular health (Berwanger *et al*., 2022). By fostering synergy with the medicine program, this project uses the CDIO framework to cultivate a mindset of continuous professional development through practical engagement. The core initiative involves building a functional electrocardiogram (ECG) using low-cost, accessible materials, ensuring sustainability and replicability. The project achieves a low-cost profile by replacing expensive medical grade equipment with accessible components like the Arduino Nano, breadboards, and standard analog resistors. This approach ensures sustainability and replicability (Vasan A., *et al*, 2020), allowing students to visualize cardiac waveforms using free, open-source software. Success is evaluated by the students' ability to capture clear QRS waves and clinical data despite using these affordable materials. This is vital for democratizing education and fulfilling the CDIO mission of social responsibility, as it allows sophisticated biomedical technology to be deployed in resource-limited public health settings. Furthermore, the creation of a simple and ludic assembly manual facilitates the understanding of complex biological signals for a diverse audience. This project-based learning (PBL) approach develops essential technical skills while highlighting the social impact of medical technology in promoting community awareness and excellence.

BACKGROUND INFORMATION

The CDIO framework

The CDIO (Conceive, Design, Implement, and Operate) framework represents an innovative educational methodology specifically tailored to modernize engineering education worldwide. Developed initially by MIT and Swedish universities, it provides students with a holistic view of the product, process, and system lifecycle. The "Conceive" stage involves defining customer needs and considering technology and regulations. In the "Design" phase, students create plans, drawings, and algorithms that describe what will be implemented. "Implement" refers to the transformation of the design into a product, including manufacturing and testing. Finally, the "Operate" stage focuses on using the implemented product to deliver the intended value. By integrating these four stages, the framework ensures that graduates possess not only deep technical knowledge but also the professional skills required to lead complex projects in modern industry.

The CDIO framework in Brazil

In Brazil, the adoption of the CDIO framework has gained significant momentum over the last two decades as universities seek to comply with the new National Curriculum Guidelines for Engineering courses (Díaz-Salazar *et al.*, 2023); Lourenço Jr. *et al.*, 2015). Pioneering institutions such as the Aeronautics Institute of Technology (ITA) and the University of São Paulo (USP) were among the first to join the international CDIO Initiative, setting a standard for others. The framework has proven particularly effective in the Brazilian context for fostering "hands-on" learning experiences that are often lacking in traditional theoretical programs. Many Federal and Private universities now utilize CDIO to promote interdisciplinary projects, university extension programs, and entrepreneurship. This approach is vital for addressing the local industry's demand for engineers who are capable of innovation and social problem-solving. Furthermore, Brazil hosts regional CDIO meetings, allowing for a robust exchange of pedagogical practices across different states.

DESIGN-IMPLEMENT ENVIRONMENT

Federal University of Goiás

The Federal University of Goiás (UFG) is the largest public university in the Central-West region of Brazil, located in Goiânia. The ECG project is offered annually by the Medical Physics course of the Institute of Physics.

Undergraduate education in Medical Physics (MP)

The Bachelor's program in MP at UFG has been offered since 2013. Every year, 25 new students enroll in undergraduate education. The first cohort concluded activities in February of 2017; by January 2026, there are five cohorts (128 undergraduate students in total) attending courses simultaneously. The undergraduate curriculum in MP is a 5-year program composed of ten semesters totalling 3,652 hours. The students undergo basic physics subjects in the first half (2.5 years), including calculus, physics, quantum mechanics, thermodynamics. The second half of the course (the remaining 2.5 years), students take specific subjects of MP, i.e, Physical Principles of Nuclear Medicine, Radiotherapy, Radiodiagnostics, Medical Image Processing, Introduction to Biomedical Instrumentation, Radiation Physics and Biological Effects of Ionizing Radiation. The ECG project is offered annually through the Medical Physics Academic League. This is, for now, the only opportunity for the students to be introduced to a design-implement experience according to the CDIO framework.

A framework for teaching Biomedical Instrumentation

In this project-based learning (PBL) module, students engage directly with the critical reality of cardiovascular health, investigating the high prevalence of heart diseases in Brazil to establish a meaningful, real-world context. Shifting from passive listeners to active protagonists, learners are tasked with the engineering challenge of assembling a functional ECG device on a breadboard (see table 1). Our approach relies on student autonomy and self-taught methodologies, where undergraduate tutors provide guidance while students navigate technical obstacles—such as signal noise and amplifier gain—through collaboration and troubleshooting. The basis of evaluation is a multi-dimensional rubric that weights Technical Proficiency (40%), Critical Thinking (30%), and Collaboration & Communication (30%). This assessment strategy ensures that students are not only graded on the final ECG

signal but also on their ability to articulate the correlation between cardiac anatomy and electronic signals, bridging the gap to professional market demandsThis process demands that they rapidly synthesize theoretical concepts with hands-on practice, relying on deep collaboration and critical thinking to troubleshoot complex circuitry. By navigating these technical obstacles, students not only master the physics of biomedical instrumentation but also understand the societal impact of accessible healthcare technology. Consequently, this immersive experience bridges the gap between academia and professional expectations, cultivating the autonomy and practical problem-solving skills necessary for future scientific and engineering careers (see Figure 2). The main contribution of this work to the CDIO community is the proposal of a framework for the teaching of biomedical instrumentation for students by using hardware and software tools that are embedded in the ECG device. The proposed framework includes hardware devices such as Arduino Nano, breadboard, resistors and jumper cables, alongside the Arduino IDE software. The educational framework proposed here empowers students through the practical approach to assembling an ECG device by connecting previous knowledge of basic concepts of electronics, electromagnetism and logic. For instance, not only provides knowledge about the device itself, but also about cardiovascular health through our synergy with the undergraduate medicine course.

Table 1. CDIO framework in our study.

Stage	Action	Transferable Output
Conceive	Identify medical/social problem (e.g., heart disease prevalence in Brazil).	Problem Statement & Social Context.
Design	Plan circuits, derivations, and filtering strategies.	Schematic & Algorithm Design.
Implement	Assemble prototype on a breadboard and integrate with Arduino.	Functional Prototype.
Operate	Real-time signal validation and community outreach.	Validated Device & Social Impact.

METHODOLOGY

Phase 1: Contextual Foundation & Theoretical Introduction

The initial stage of this PBL framework established the medical and social context through a comprehensive, slide-based expository lecture led by an undergraduate medical student aspiring to a Clinical Cardiology residency. This session provided a deep dive into cardiac anatomy, detailing the primary muscles, heart chambers, the circulatory system, and the physiological distinctions between venous and arterial blood. Beyond the biological mechanics, the presentation addressed the critical reality of cardiovascular health by outlining the prevalence of heart diseases in Brazil, emphasizing prevention strategies and the importance of long-term heart care. During this phase, students successfully gathered essential knowledge regarding both the biological function of the heart and the broader landscape of public health policies, including an overview of the municipality's main cardiac care centers. This theoretical grounding served as the essential prerequisite for the practical engineering challenges that followed. Aligning with CDIO Standard 4, the Design phase translates medical requirements into technical schematics, focusing on the mathematical derivation of filters and amplifier gain to capture millivolt-level cardiac signals. Students design the hardware layout on breadboards and develop software logic in the Arduino IDE to identify

specific P, QRS, and T waves. This stage also includes the creation of a didactic manual, ensuring the technical design is documented for replication and social outreach.

Phase 2: Bio-instrumentation & Hardware Assembly

Following the theoretical immersion, the pipeline advanced to the technical implementation stage, bridging the gap between medical physiology and engineering. In this phase, students shifted from observing to creating. They were introduced to the essential electronic components required for bio-signal acquisition, including instrumentation amplifiers, operational amplifiers, resistors, and capacitors.

Working in collaborative teams, students took charge of the hardware assembly, mounting the analog signal conditioning circuit onto a *breadboard*. This phase demanded the direct application of physics, anatomy, and electronics principles, as students faced the challenge of configuring the circuit to amplify the faint millivolt-level electrical signals generated by the heart while designing filters to remove significant noise. This hands-on activity transformed the abstract anatomical concepts from Phase 1 into a tangible, functional prototype, requiring students to exercise critical thinking and technical troubleshooting to ensure the device was safe and effective.

Safety and Risk assessments

To ensure the device is safe and effective, students must identify connection and logic errors to prevent electrical hazards when interfacing the Arduino Nano and breadboard circuits with human subjects. While specialized amplifiers are used to manage low signal amplitudes, proper isolation and gain adjustment are critical to protecting both the user and the sensitive electronic components. This technical troubleshooting validates the prototype's reliability before it is deployed in community health outreach campaigns.

Phase 3: Digital Integration & Clinical Correlation

In the final stage of the pipeline, students interfaced their breadboard circuits with an Arduino Nano, using its analog-to-digital converter (ADC) to read the amplified heart signals, by testing them on the group members. By connecting the Arduino to personal computers, they established a real-time monitoring station. By using the Arduino IDE, the students were able to visualize the electrical activity of their own hearts as dynamic waveforms on the screen. This was the pivotal moment where theory met reality: students had to identify the specific P, QRS, and T waves they had learned about in Phase 1 within the noisy, real-world data they captured. This activity required them to apply critical analysis to distinguish between valid biological signals and motion artifacts or electrical interference. By successfully visualizing a clean ECG trace, students not only validated their engineering prototype but also solidified their understanding of cardiac physiology, effectively demonstrating how low-cost technology can be deployed to address the health challenges discussed at the start of the project.

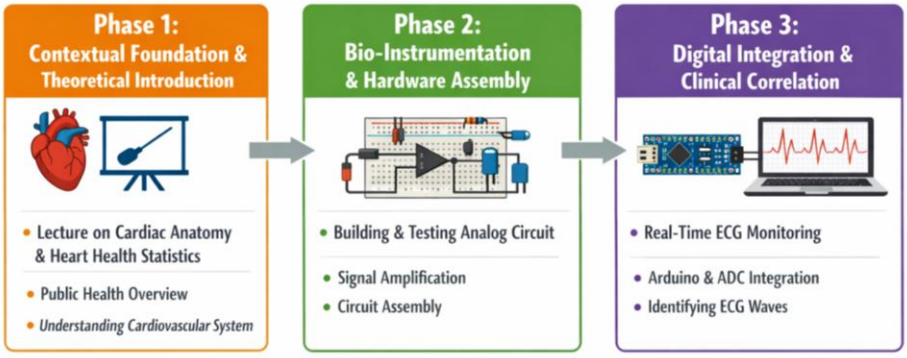


Figure 1. Diagram of the framework

Potential limitations of the framework

While highly transferable, the framework's application may be limited by the technical difficulty of acquiring low-amplitude signals without specialized instrumentation. Implementation also requires students to possess strong prerequisite knowledge in electronics and electromagnetism to succeed in the "self-taught" approach. Furthermore, its effectiveness depends on interdisciplinary synergy with medical programs to provide necessary clinical context and anatomical grounding. Finally, strict safety protocols must be maintained when testing student-built prototypes on human subjects.

Learning goals

The learning goals were to:

- Introduce how electronic devices work separately before building the ECG.
- Introduce basic concepts of how ARDUINO works on this specific task.
- Assemble the ECG device in a breadboard.
- Introduce basics of biological signals and vector derivation for signal processing.
- Introduce basics of most common cardiovascular diseases in Brazil.
- Interpret the ECG signal among peers to test the ensembled device.

Students attend an introductory session on cardiology and the most prevalent cardiovascular diseases in Brazil. During this session, they are encouraged to reflect on how their own daily routines impact their long-term health. While undergraduate tutors who have previously completed the project provide guidance, the currently enrolled students must achieve each goal through a self-taught, hands-on approach. Following the disease outreach session, students transition to the laboratory to begin the construction of the ECG.

Knowledge Dissemination and Creation of the Assembly Guide

We developed an ECG Assembly Manual using a simple, illustrative, and engaging approach, aiming to ensure accessibility for the external community (LAFISMED, 2025). This document serves as a guide for constructing the device, enabling teachers, students, and other interested parties to understand and replicate the ECG assembly; thereby it contributes to the popularization of scientific and technological knowledge related to cardiovascular health. The

manual was designed to facilitate understanding for individuals with varying levels of technical knowledge, promoting inclusive knowledge dissemination. The manual covered the following topics:

1. *Introduction*

   1.1. Cardiovascular Diseases in Brazil

   1.2. Electrocardiogram (ECG)

   1.3. ECG Applications

2. *Materials*
3. *Pin Connections*
4. *Software Setup*
5. *Conclusion*

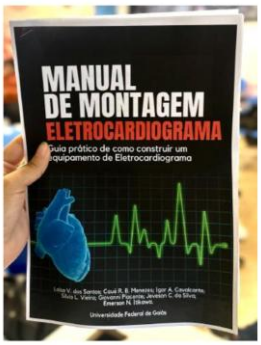


Figure 2. Assembly Guide for the students

Module conclusion & Assessment

The module concluded with a holistic review that evaluated not only the final product but also the investigative journey, reflecting the dual nature of Project-Based Learning. By integrating the medical insights from the initial lecture with the engineering challenges of the Arduino-based prototype, students demonstrated a comprehensive understanding of how biomedical instrumentation serves public health needs.

Assessment Strategy

Evaluation was conducted using a multi-dimensional rubric designed to measure both technical competency (hard skills) and behavioral development (soft skills):

- **Technical Proficiency (40%):** Students were assessed on the functionality of their protoboard circuits and the clarity of the signal visualized on the Arduino IDE Serial Plotter. High marks were awarded to teams that successfully identified the components of the low-cost ECG, demonstrated the capacity to reveal QRS waves, and accurately explained the correlation between the electronic signal and the cardiac anatomy presented in Phase 1.

- **Critical Thinking & Problem Solving (30%):** Instructors evaluated the students' autonomy in troubleshooting, logical arguments aiming solutions, conclusions and implications (CDIO Syllabus 3.0). This included their ability to diagnose connection/logic errors, adjust amplifier gain, or reduce electromagnetic interference without immediate instructor intervention. This metric specifically measured the "protagonism" of the student in overcoming the gap between theory and practice.

- **Collaboration & Communication (30%):** Instructors evaluated the students' abilities to work in teams through the CDIO Syllabus 3.0 as well: planning, leadership, handling conflicts, clarity of language, and listening carefully to each other. Through peer

reviews and a final group presentation, students were assessed on their teamwork dynamics through categorical forms of soft and hard skills, and accomplishment of the task. They were required to articulate how they divided tasks, how they synthesized the medical data with electronic assembly, and how they viewed the societal impact of their device in the context of Brazilian healthcare prevalence of cardiovascular diseases.

Ultimately, this PBL experience validated that when students are challenged to build real-world tools, they develop a durable connection between academic theory and professional application, preparing them for the complexities of modern scientific and medical careers.



Figure 3: Testing the ECG on students.

Notably, among the positive aspects of the initiative is the social impact promoted by the Medical Physics Academic League (LAFISMED). By disseminating knowledge in a simple, accessible, and engaging manner, the group contributed significantly to fostering citizens who are aware of the importance of cardiovascular health. This initiative proved especially effective among elementary and high school students, sparking interest and awareness in the young audience, aligning with the CDIO Framework. By demystifying biomedical technology, the project fulfills the CDIO mission of developing socially responsible engineers while providing tangible public health education to the Goiânia community. Moreover, this outreach action promoted science in a practical and applied manner, enriching the students' academic training and bridging the gap to the professional market. The experience gained in constructing the ECG, developing the manual, and conducting public presentations was fundamental to developing technical and communication skills, preparing students for future challenges in their academic and professional careers.

CONCLUSIONS

The implementation of the project-based learning (PBL) framework within the undergraduate education at the Federal University of Goiás successfully bridged the gap between theoretical knowledge and professional practice. By placing students at the center of the learning process, the initiative shifted the focus from simple technical execution to active problem-solving and innovation using accessible resources. While the construction of a functional, low-cost ECG served as the vehicle for learning, the primary outcome was the development of critical thinking and student autonomy in the face of complex challenges. Furthermore, the creation of a didactic manual and the engagement in community health campaigns transformed the project from an academic exercise into an act of social responsibility. Ultimately, this experience highlights the transformative power of PBL, equipping future professionals with the

essential hard and soft skills required by the modern healthcare industry while promoting true scientific citizenship.

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ORCHESTRATING CDIO-ALIGNED LEARNING TASKS THROUGH A COURSE-TYPE–DRIVEN ASSIGNMENT FRAMEWORK

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ABSTRACT

Engineering education is being increasingly challenged to equip graduates for a fast-changing technology thrust that demands implementation, systems thinking, and applied problem solving. Though the CDIO (Conceive–Design–Implement–Operate) framework provides a coherent basis for these challenges, faculty frequently report difficulty in translating these program-level principles into applicable course-level assignments. This paper addresses this gap by proposing a course-type-driven task design and orchestration framework. The framework is composed of three major contributions: a classification of nine undergraduate engineering course types; a CDIO-compliant task taxonomy of core, communication, and reflective tasks; and a logic for orchestrating student pathways under semester constraints. The tripartite task structure ensures that engineering action, communication, and judgment are interwoven in a single assignment. The framework was institutionally implemented in a third-year Mechanical Engineering course titled Design of Machine Elements (DME) as part of routine course delivery. By replacing existing numerical problem sets with an integrated design project, the framework activated prior learning and emulated professional work without transforming the curriculum. Results show that the framework increases assessment reliability, decreases faculty cognitive load in the design of assignments, and allows students to create engineering products of portfolio quality.

KEYWORDS

Engineering Education, CDIO Framework, Course-Level Implementation, Task Orchestration, Active Learning, Standards: 2, 3, 5, 7, 8 and 11.

INTRODUCTION

In the era of automation, biotechnology, cyber-physical systems, electric mobility and artificial intelligence, the engineering education sector has increasingly appreciated the significance of preparing engineering graduates for the rapidly evolving technological environment. National Academy of Engineering (2020) foresees these advances to transform the way engineering practice is performed across the globe and will compel educational institutions to rethink graduate education to prepare them for exciting yet challenging real-world engineering problems. Today's hiring managers expect graduates to be project-ready, i.e., not only having conceptual knowledge but capable of system thinking, applied problem solving, design judgment and execution. UNESCO (2021) believes society will also need engineers capable of designing ethical, socially responsible and sustainable solutions.

Undergraduate engineering programs also accommodate students whose professional paths become increasingly diverse. Placement-oriented students want to demonstrate skill profiles based on portfolio-level tasks. Research-oriented students preparing for MS or PhD study want to complete inquiry-driven tasks with significant analytical depth and modeling rigor. Entrepreneurially-oriented students want to ideate, prototype, and pitch their solutions. The diversity of these pathways highlights a core instructional challenge as to how faculty might develop course-level tasks that remain feasible within a 15-week semester while addressing unique learning intentions and future paths.

The CDIO paradigm offers a principled basis for addressing this problem by centering engineering education around the Conceive–Design–Implement–Operate life cycle (Crawley et al., 2014). CDIO promotes contextually relevant, authentic, and practice-based learning and offers a systematic perspective on how engineering work should develop throughout the curriculum. Nonetheless, while there is robust commitment to CDIO worldwide, faculty often struggle with translating the paradigm into specific day-to-day course-level assignments. CDIO adoption largely reflects changes at the curriculum level, capstone-level and design-build, multi-year reforms, and there is a lack of day-to-day Praxis-level reform.

A review of CDIO literature shows that there are rules for integrated curricula and active learning (CDIO Standards 2, 3, 5, 7, 8, and 11) (CDIO Initiative, 2020), but far less so for how to structure assignments by type of course—foundational, system-oriented, practice-oriented, design-intensive, interdisciplinary, etc.—and how to balance such tasks under normal semester limits. As a result, assignments default to theoretical problem sets, isolated coding assignments, or descriptive reports that only partially capture CDIO (Felder & Brent, 2009).

This paper fills this gap by proposing a course-type based task design and orchestration framework that aligns with CDIO principles. Our contributions are:

1. A classification of nine types of undergraduate engineering courses that can be shaped by the feasibility of learning tasks.

2. A CDIO-aligned task taxonomy, including core tasks, communication tasks and reflexive tasks for each type of courses.

3. A task orchestration logic that prepares faculty to respond to different students' pathways, industry placement, research, and entrepreneurship within the semester boundaries.

4. Course level implementation evidence, from a Design of Machine Elements course, that shows how the framework can provide the facilitation of CDIO Design-Implement learning without curriculum changes.

BACKGROUND & RELATED WORK

The CDIO Initiative was founded to meet a commonly recognized problem: engineering graduates had a solid analytical base but were not prepared for engineering practice (Crawley et al., 2014). In CDIO, engineering curricula were reorganized around real-world professional processes using the Conceive–Design–Implement–Operate lifecycle and a set of standards that drive development of the curriculum, pedagogy, and assessment (CDIO Initiative, 2020). The most relevant of these standards at the course-level task design include: Standard 2 – Learning Outcomes: describing engineering practice knowledge, skills, and attitudes, Standard 3 – Integrated Curriculum: integrating courses, Standard 5 – Design–Implement Experiences: integrating engineering design into curriculum, Standards 7 & 8 – Integrated Learning & Active Learning: promoting learning by doing, Standard 11 – Assessment: promoting linkages between learning outcomes and assessment.

A large body of the current CDIO literature has focused on active learning, systems thinking, and real-life engineering experiences (Kraft et al., 2006), demonstrating the merits of problem-based and project-based learning as effective operationalizations of CDIO (Edström & Kolmos, 2014). Other literature addresses curriculum-level changes, multidisciplinary project courses, and multidisciplinary capstone design programs that include instruction on CDIO lifecycle tasks (Malmqvist et al., 2009). Previous conference research on CDIO has also considered course-level applications, especially with regard to design-build programs, integrated projects, and disciplinary course-level approaches (Bankel et al., 2005). But none of these studies generalize a model for the purpose of designing tasks at the course level.

Much of this CDIO literature takes a program or curriculum perspective, which can be resistant and time-consuming because it involves major structural or institutional changes. There has been less focus on a course-level operationalization of CDIO, the layer where most faculty work and where most student learning activities occur. Existing research documents success for task integration and active learning, but offers little guidance on how to select and interrelate tasks and activities in accordance with course type.

Simultaneous engineering education criticism notes that 1) traditional assignments overemphasize calculations and procedures, and 2) underrepresent real-world engineering problem solving (Felder & Brent, 2009). CDIO offers a way to integrate learning experiences, but in practice faculty have few structures to guide them in selection of tasks that integrate conceptual and applied learning (i.e. design, analysis, evaluation, communication).

This paper adds to CDIO literature by focusing the CDIO operationalization on the course level, rather than the curriculum level. Rather than adding to pedagogical theory, we integrate existing CDIO standards, active learning literature, and faculty practice in a practical framework to help instructors select and structure feasible and real tasks based on course type, workload, and desired alignment to CDIO lifecycle tasks.

FRAMEWORK DEVELOPMENT OVERVIEW

The process of framework development involved a systematic approach that consisted of four phases. First, there was a review of CDIO standards. Second, an institution-wide curriculum review and faculty interviews took place. Third, the engineering courses were classified according to type. Finally, the logic of task orchestration was synthesized. All phases are illustrated in Figure 1.

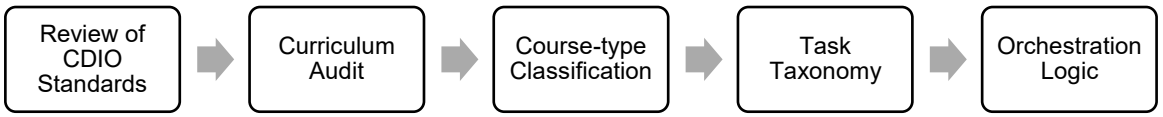


Figure 1. Framework development process

METHODOLOGY: DEVELOPING A COURSE-TYPE–DRIVEN TASK ORCHESTRATION FRAMEWORK

The development of the proposed task-orchestration framework was based on design-based research with the aim of developing a practical, course-level framework for using CDIO as an instructional model in undergraduate engineering programmes. The overarching goal was to develop a framework that allows faculty to design learning tasks that are realistic within semester-level time constraints, pedagogically coherent, and consistent with the Conceive–Design–Implement–Operate progression. The design phase included four interconnected steps: (1) a critical analysis of CDIO standards; (2) an institutional curriculum audit and faculty interviews; (3) categorization of types of engineering courses and associated task structures, and (4) synthesis of an orchestration logic that would facilitate the structured deployment of tasks within a variety of teaching contexts.

Review of CDIO Standards and Their Implications for Course-Level Learning Tasks

This step used a focused literature review of CDIO Standards and prior studies. Initial analysis involved a focused review of CDIO Standards, specifically identifying how the standards relate to learning task design. Standards 2 and 3 describe programme-level learning outcomes and integrated curricula. Standards 5, 7, 8, and 11 stress design–implementation experiences, integrated learning activities, active learning, and assessment alignment (CDIO Initiative, 2020). A central insight that emerged from this review was that CDIO has well-defined directional guidance on what students should experience. However, the standards provide relatively little direction on how designers should design learning tasks. For instance, the standards accept that rich and authentic learning tasks exist but do not provide guidance and direction on how learning tasks should be selected, structured, or sequenced with respect to credit load or learning objectives in a specific course. We used this insight as the conceptual basis for changing the focus of our enquiry from curriculum design to learning-task design as the operational definition of CDIO implementation.

Institutional Curriculum Audit and Faculty Consultation

This step used curriculum document analysis and structured faculty consultations. To investigate course-level implementation realities, an institutional curriculum audit of the undergraduate courses of the mechanical, electrical, electronics, computer science, and allied engineering programmes was carried out, assessing the course objectives, syllabi, assessment patterns, nature of existing assignments, and the constraints imposed by credit

systems and semester duration. Structured consultations and workshops with the faculty members engaged in CDIO-aligned teaching work complemented this audit; these meetings uncovered the fact that instructors tend to use intuition rather than any common criteria when making assignment choices, and thus courses of the same type differed significantly from one another.

Faculty uniformly explained their challenge in cultivating active learning while covering theory, their uncertainty in distinguishing when to use mini-projects, case studies, simulations, or applied research, and the challenge in assessing design work in limited assessment time. These findings reinforced the need for a clear framework that would guide the faculty in making the right choice of task type based on the course type, depth of learning, and the relevant CDIO stage or stages.

Identification and Classification of Engineering Course Types

This step used iterative categorization based on recurring instructional patterns. The curriculum audit and faculty consultations clarified the need to categorize engineering courses according to recurring instructional types. Based on an iterative process, nine such course types were identified as prototypical of the undergraduate engineering experience: foundational-oriented, system-oriented, practice-oriented, design-oriented, advanced theory-oriented, interdisciplinary/application-oriented, skill/tool-oriented, societal/ethics/policy-oriented, and capstone/integrative. These types were not intended to be discipline-bound — they recur across programmes.

One important rationale was that not all courses can credibly support the same kinds of active learning. Demanding complete, fully-developed projects in foundational courses, or purely theoretical projects in practice-oriented courses, results in pedagogically infeasible instruction and a burden on students. The nine-course-type classification provides an essential structural foundation for task orchestration, by specifying what makes a task pedagogically viable in a particular course type.

Development of a CDIO-Aligned Task Taxonomy

This step used synthesis from active learning and CDIO literature. The next step was to develop a taxonomy of tasks that was consistent with CDIO principles and that could link course purpose and student activity. Using research on active learning (Felder & Brent, 2009; Edström & Kolmos, 2014), we organized tasks into three functional categories: core tasks, communication tasks, and reflective tasks. Core tasks are the central learning activity that students use to process engineering concepts or problems (study project, design projects, system analysis, research with applications). Communication tasks develop students' professional engineering communication skills (technical papers, conference presentations, posters, system demonstrations, conference papers where appropriate). Reflective tasks support metacognition by having students explain their reasoning, analyze trade-offs, and explore the learning process. The three-part structure creates assignments that are balanced and intentionally linked to CDIO Standards 7, 8, and 11, as well as ensuring that tasks can be completed within the semester.

Synthesis of Task Orchestration Logic

This step used integrative mapping of course type, CDIO stage, and learning depth. The last step in the methodology was the development of a task-orchestration logic for selecting and sequencing tasks within a course. Task orchestration is defined as the intentional combination

of course type, target CDIO stage (s) within the CDIO life cycle, depth of learning (conceptual, analytical, design, implementation), time considerations and assessment feasibility. The orchestration logic obviates the need to prescribe common assignments across courses by allowing faculty to assemble combinations of tasks appropriate to the pedagogical intention of the course.

Foundational courses emphasize study and analytical tasks in the Conceive stage, design-oriented courses prioritize conceptual and detailed design tasks in Design, practice-oriented courses prioritize development and implementation tasks; and capstone courses address the whole life cycle. This logic supports constructive alignment of course objectives with CDIO intent and assessment without restructuring the curriculum, and can be implemented in the context of pre-existing academic pressures.

This orchestration approach is not rigidly defined, meaning while a course type has one dominant CDIO focus, an instructor can include additional secondary levels or alter task complexity.

Validation Through Course-Level Implementation

In order to demonstrate practical feasibility, the framework was implemented in actual courses, the most significant of which was a third-year Mechanical Engineering course titled Design of Machine Elements. The teaching staff used the orchestration logic to redesign assignments, while maintaining the existing syllabus and contact hours. The implementation demonstrated, as well as evidence that the framework is not only sound in theory but also operationally feasible and the basis for enhanced task design, clearer assessment, and improved CDIO alignment. The evidence and outcomes are reported in Section 7.

ANALYSIS AND RESULTS OF FRAMEWORK DEVELOPMENT

The analyses of the different developmental phases have led to the following outcomes: (1) the determination of nine kinds of engineering courses based on curriculum pattern analysis; (2) the identification of the orientation of key tasks that are relevant to each of the CDIO phases; (3) the creation of a three-level task taxonomy, comprising the core, communication, and reflective levels; and (4) the development of an orchestration logic.

THE TASK-ORCHESTRATION FRAMEWORK

We base the implementation of this idea on the fact that every undergraduate engineering course can be grouped into one of nine typical types which are identified in Table 1. For each of the nine course types, we define the dominant task orientation, the CDIO stages that the course naturally engenders and the typical workload for students for the course. This categorization is intended to help faculty to be clearer about what kind of engineering action this course is presumably best suited for priming and to guarantee that the CDIO stages Conceive, Design, Implement, Operate can be experienced in succession and not all at once in the same course. Table 1 presents the classification of engineering course types along with their defining characteristics, dominant task orientations, and associated CDIO stages.

Table 1. Course types and its task orientation

Course Type	Dominant Task Orientation	Primary CDIO Stage(s)	Typical Time Load
Foundational	Study and analytical tasks	Conceive	1–2 weeks
System-Oriented	System study and simulation	Conceive–Design	2–3 weeks
Practice-Oriented	Development and application	Design–Implement	3–4 weeks
Design-Oriented	Conceptual and detailed design	Design	3–4 weeks
Advanced Theory	Modeling and analysis	Conceive–Design	2–3 weeks
Interdisciplinary	Integrated projects	Conceive–Design–Implement	3–4 weeks
Skill/Tool-Oriented	Tool usage and workflows	Implement	1–2 weeks
Societal/Ethics	Case and proposal-based tasks	Conceive–Operate	2–3 weeks
Capstone	Full CDIO integration	Full lifecycle	Full semester

Each course type is defined as follows: Foundational: concept-building and analytical reasoning, System-oriented: system-level understanding and modelling, Practice-oriented: application and development tasks, Design-oriented: structured engineering design, Advanced theory: mathematical modelling and abstraction, Interdisciplinary: multi-domain integration, Skill/tool-oriented: tool proficiency and workflows, Societal/ethics: contextual and policy-driven analysis, Capstone: full lifecycle integration. Instructors can classify a course by identifying its primary learning objective (analysis, design, implementation, integration, or contextual evaluation) and aligning it with the closest dominant task orientation.

The second element of the framework is the task taxonomy, which organizes each course assignment into three mutually related elements, a core task, a communication task, and a reflective task. The purpose of this is to ensure that engineering action, engineering communication, and engineering judgment are part of the same assignment rather than being treated as discrete skill sets. The three components form a task unit, in which the core task is the center of engineering work, the communication task is the articulations of reasoning and technical clarity, and the reflective task is the meta-cognition and iterative improvement. Table 2 presents representative examples for selected course types; the framework supports extension to all nine types.

Table 2. Task Taxonomy (Representative Examples)

Course Type	Core Task Example	Communication Task	Reflective Task
Foundational	Study Project	Technical Report	Learning Reflection
System-Oriented	System Study Project	Architecture Presentation	System Reflection
Design-Oriented	Design Project	Design Review	Design Decision Reflection
Practice-Oriented	Development Project	Demo & Report	Implementation Reflection
Capstone	Integrated Project	Report, Defense & Poster	Capstone Reflection

The examples provided here are just some of the options. Several core tasks may be available for each course type, and communication and reflection aspects can also be tailored to fit the specific instructional setting.

The alignment of the course-type taxonomy and the task taxonomy results in a uniform and scalable approach to embedding CDIO into the curriculum. The key is that every course features the one integrated task unit and that the task unit always contains the same three elements, no matter the discipline. Indeed, what differs is the specifics of the core task: courses on foundational content need structured study and analytical problem framing; courses on the system need architectural reasoning; courses on practice need technical development; courses on design need structured engineering design; courses on advanced theory need modelling and interpretation; courses on interdisciplinary need integrative analysis; courses on society need contextual evaluation; courses on skills need the use of professional tools; and courses on capstone need full CDIO integration. Our framework addresses a persistent challenge in engineering education, namely that students are often bombarded by a disconnect assessment system where assignments are placed in no particular order in reference to CDIO and to each other. Now, with our framework, students see an orderly progression, where they learn to progress from conceptual analysis to system reasoning, from design exploration to design implementation and, finally, to professional reflective judgement. Further, our framework also addresses the day-to-day constraints of faculty: instead of requiring faculty to understand and design a meaningful assignment each semester, our framework provides a non-dimensional task structure for each course type. It does not require a faculty member to redesign the course or to convert each subject into some large project. Instead, the faculty member needs to assign the proper task unit for the course and this is automatically available from our framework. Thus, our framework is both rigorous and efficient and hence, scalable. Finally, our framework directly supports CDIO Standard 11 on assessment. Because every task unit contains explicit engineering, communication, and reflection elements, we can create rubrics that track consistency through analysis depth, engineering justification, communication quality, and the level of reflection maturity. We can create a clear trail for educational assessment.

COURSE-LEVEL CDIO IMPLEMENTATION AND RESULTS

In order to showcase the applicability of the proposed task-orchestration framework, it was implemented at course level in selected undergraduate engineering programs. The implementation aimed to investigate whether the framework could be embedded in a regular 15-week semester, replace traditional assignment format, and significantly operationalize CDIO concepts, without curriculum redesign. In this section, we describe the implementation context, the integration process and its instructional/learning outcomes, using the Design of Machine Elements course as a canonical implementation example.

Course Selection and Implementation Context

The choice of an appropriate course was essential to enable the demonstration that the curriculum framework is able to translate the CDIO model principles into specific, assessable learning tasks. The Design of Machine Elements (third year, fifth semester, undergraduate Mechanical Engineering Program) was chosen as this is a Design-Oriented course when applying the course-type classification that is proposed. Moreover, it was the obvious sequence for the CDIO Design stage.

The DME course requires students to integrate engineering mechanics, material behavior and failure theories for the design of mechanical elements and also to integrate knowledge from the prerequisite courses, including Matrices and Calculus, Python Programming, Engineering Mechanics and Strength of Materials. This integrative aspect made the course highly suitable to exemplify the use of a structure of tasks that activates and consolidates prior knowledge and simulates professional practice.

The chosen implementation context corresponded to a normal classroom and laboratory with no additional instructional hours or resources than what was already planned for the course. The existing assignments were restructured into one unit (CDIO-workflow) as required by the curriculum framework, but consisting of a single design task, a structured communication task and a reflective task. Hence, the implementation process represented a typical, scalable adoption process of the standards instead of a special, experimental offer.

Framework-Based Task Implementation

The task-orchestration framework was implemented in the course by redesigning an assessment strategy around a single cohesive design project, which was evaluated as a National Skills Qualifications Framework (NSQF) Level 6 design task, replacing an array of numerical, disconnected problem sets with a single, cohesive design project based on the CDIO Design and early Implement stages.

The design task required students to propose a mechanical robotic arm that could carry a given payload on defined operating conditions. For this, the students had to generate alternative design configurations, investigate material options, consider failure theories, and produce manufacturable specifications. They had to use engineering mechanics principles to compute the external loads on members and joints. They had to use strength of materials principles to compute internal stresses, deflections and factors of safety. They had to use Python programming to automate repeated calculations and investigate parameter sensitivity. The computational skills were tied to analytical thinking. They had to use CAD/CAE (Fusion 360) for modelling the assembly and to evaluate stress distribution using simulation.

Thus, the framework ensured that the technical activity is surrounded by a structure for communication and reflection. The students had to produce a comprehensive design report, in which they had to document assumptions, calculations, standards used, and the final design decisions. CAD models and simulation outputs were uploaded as evidence. The students had to give a formal design review presentation and to explain and defend engineering decisions. The students had to provide course design reflections, in which they had to evaluate trade-offs, constraints, and learning outcomes.

The new structure ensures that the course transfers from a typical topic-wise coverage towards a cohesive learning experience aligned to the CDIO domains. However, the content of the syllabus is not changed, nor have the instructional hours changed.

Implementation Outcomes and Observations

The course-level implementation was evaluated using qualitative analysis of student artefacts and structured student and instructor feedback.

Analysis of Student Artefacts

Student artefacts suggested a transition from procedural problem solving to integrated engineering reasoning. Design reports manifested the linkage of analytical calculations to design decisions, and explicit justification of assumptions and safety margins. CAD models and simulations showed proficiency in industry-standard tools and design validation approaches. Presentation artefacts indicated improved technical communication and communication of engineering reasoning to peers and faculty.

In general, the artefacts were the way a portfolio of professional engineering work would appear, rather than discrete academic exercises, suggesting successful activation of CDIO Design–Implement learning behaviors.

Faculty and Student Feedback

Faculty reported that the framework served as a clear and practical implementation structure at the course level. The separation between core, communication, and reflective tasks assisted in the design of their assignments and allowed clearer rubric development. Instructors also reported that the CDIO alignment became defensible and transparent for both instructional planning and accreditation documentation.

Students reported that the integrated project provided a clearer learning narrative for the semester. They mentioned that they better understood how their mathematical and mechanics concepts from earlier courses contributed to concrete design decisions. Students reported that the use of Python automation and CAD/CAE tools provided them with technical confidence and supported their confidence for preparation for industry placement and technical interview roles.

DISCUSSION

This section discusses the effectiveness of the proposed framework in addressing the aforementioned gap and its practical application to various instruction environments. The incorporation of the task-orchestration framework into a regular semester engineering course provides evidence that the framework can be applied in a scalable and pedagogically consistent manner. The results indicate that an organized, course-type–based task system

can have substantive impact on student learning, faculty practice, and coherence between classroom activity and CDIO's experiential mission.

One of the central insights gained from implementation is the framework's ability to operationalize CDIO which starts as a philosophy at the curriculum level and translates into activity at the course level. While CDIO emphasizes integrated curriculum design and structured design–implementation experiences, instructors often have difficulty translating the standard into semester bounded assignments that fit within existing credit structures. By standardizing task structures that explicitly link course type to authentic and assessable activity, the framework offers instructors a pedagogical scaffold that is both extensible and easy to use. This minimizes dependence on faculty intuition and the "blank-page problem" that often limits CDIO aligned course design.

The framework furthermore contributes to instructional coherence by purposefully embedding the core, communication and reflective elements into every assigned task. In embedding a tripartite structure into instructional design, learners will not simply be engaging in engineering work but will be having opportunities to communicate processes and undertake reflective learning in relation to integrated learning experiences, active learning and robust assessment.

A significant advantage of the framework is in the management of prior learning. Design of Machine Elements implementation involved the activation of prerequisites in calculus, programming, mechanics, and strength of materials, which facilitated the vertical and horizontal integration that is in accordance with CDIO Standard 3.

When viewed from the faculty perspective, the framework reduced friction in designing aligned learning experiences. Instructors reported that having an unambiguous mapping between course type and appropriate tasks helped them design assignments and lowered the cognitive load of asking the instructor to generate rubrics. The alignment of tasks to CDIO stages also increased transparency of instructional planning and accreditation reporting. Incorporating reflection and communication within the task structure also facilitated a more comprehensive assessment of learning without exceeding existing workload expectations.

However, several limitations should be noted. First, although the implementation was proven feasible in the context of the Design of Machine Elements course, additional validation in other departments and across different course types (e.g., foundational, interdisciplinary, or societal) is discussed to assess scalability. Second, the current framework only implements the course level; a program- or year-long arrangement of task-based orchestration has yet to be addressed. Third, although artefacts showed good depth of student product and quality, longitudinal information will be required to investigate whether gains lead to competence development and impact performance in internship or capstone courses.

In the absence of these limitations however, this implementation provides strong evidence that the task-driven framework offers a feasible means to promote broader implementation of CDIO in engineering education programmes. The framework enhances course design and supports structured learning, under generally uncertain conditions, within the real-world context of semester-based teaching. The results suggest that the narrative supporting CDIO that it must necessarily be implemented as a large-scale curriculum reconfiguration is unnecessary; rather, it can be leveraged at the scale of an individual assignment, incrementally, course by course. With respect to implementation, the framework entailed little modification effort as instructors had to simply (1) classify the course, (2) choose an adequate task unit format, and (3) integrate assessment to the three task elements.

CONCLUSION

This article described a structured, course-level approach to operationalizing CDIO through a differentiated task-orchestration framework. By moving away from curriculum re-design to the orchestration of coherent, semester-slice learning tasks, the framework offers a useful tool for faculty to operationalize the CDIO lifecycle within existing undergraduate engineering courses. The classification of courses into nine instructional types paired with context-appropriate core, communication and reflective tasks supports constructive alignment, limits overload and ensures tasks are realistic for the engineering study context.

Its application in a conventional third-year Design of Machine Elements course showed that the framework was useful for orienting the integration of engineering analysis, design reasoning, and computational tools together with communication and reflective judgement, all within existing instructional parameters. Artefacts collected indicated measurable gains in coherence, depth and professional credibility, and faculty reported increased clarity in framing and reduced complexity in assignment design and assessment. The results, therefore, provide evidence that it is possible to align learning to CDIO by purposefully redesigning assignments, without requiring new semester hours or a change of curriculum.

For instructors looking to use the framework, the process requires three basic steps: determining the nature of the course, picking the appropriate task unit (core–communication–reflection), and matching it with the applicable CDIO phases. The modular design of the framework easily permits its application to other course types and engineering disciplines. Its straightforwardness and flexibility make it an immediately useful tool for supporting institutional change to CDIO, accreditation readiness and the long-term strengthening of the curriculum. Application of the framework will be broadened to more courses and programmes for future evaluation and will be linked to a comprehensive competency and progression model which is planned for journal publication.

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FACULTY PROFESSIONAL DEVELOPMENT IN CDIO DURING CURRICULUM REFORM AT A CAMBODIAN UNIVERSITY

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ABSTRACT

This paper reports on the design and implement of a continuing professional development (CPD) program to assist in supporting curriculum reform based on CDIO Framework at a public university in Cambodia. As part of a wider national agenda for higher education reform to include Outcome-Based Education and International Quality Assurance, the Faculty of Engineering at the Royal University of Phnom Penh (RUPP) adopted the CDIO Framework as a central mechanism for transforming its engineering programs toward ASEAN University Network–Quality Assurance (AUN-QA) recognition. This paper outlines the multi-year partnership that RUPP has developed with Singapore Polytechnic to develop the capacity of faculty through a Train-the-Trainer program (SP-RUPP CDIO3T), to address both enhancement of faculty competence (CDIO Standard 9) and enhancement of faculty teaching competence (CDIO Standard 10). The CPD program combines the STiCC framework (School Culture, Time, Choice, and Connection to Practice) with the 70:20:10 learning model to facilitate effective transfer of learning during curriculum reform. Workshops, structured peer learning, and experiential applications are all deliberately aligned to provide coherence between training and workplace practice. Participation by senior leadership, strategic scheduling around academic cycles and mandatory application of learning to curriculum redesign will be critical to creating an organizational culture that supports CPD during periods of reform and mitigate common transfer issues associated with CPD during reform. This paper contributes to a contextualized case study of CPD in a developing higher education system, demonstrating how CDIO can be operationalized as both a curriculum framework and a quality assurance enabler aligned with AUN-QA requirements.

KEYWORDS

Curriculum reform, continual professional development, CDIO Framework, Outcome-Based Education, AUN-QA Framework

INTRODUCTION: THE NEED FOR CURRICULUM REFORM IN CAMBODIA

The Royal Government of Cambodia introduced the Pentagonal Strategy - Phase I (2023–2028) in 2023 with the goal to transform the country into a high-income nation by 2050. It focuses on five pillars: growth, employment, equity, efficiency, and sustainability (RGC, 2023). One of the key pillars is human capital development, in this response to this, the Ministry of Education, Youth and Sport (MoEYS) has established a comprehensive Education Strategic Plan 2024-28 as its reform agenda, in which Outcome-Based Education is selected to modernize higher education programs. A comprehensive OBE framework called "FutureFit Educational Framework (FEF)" was developed with 3 guidelines, namely transformative curriculum, innovative pedagogies, and holistic assessment (MoEYS, 2024) as shown in Figure 1.

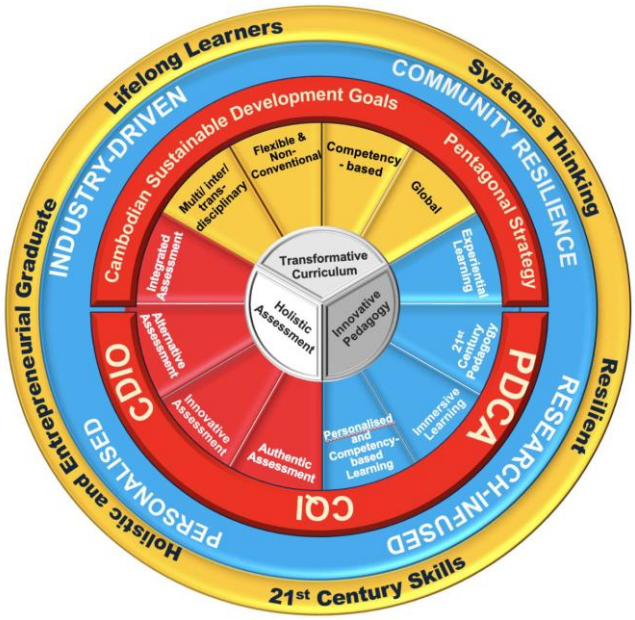


Figure 1. FutureFit Educational Framework (MoEYS, 2024)

The Royal University of Phnom Penh (RUPP) is a leading institution that worked with MoEYS to provide input into the development of FEF, most notably in the inclusion of the CDIO Framework into the FEF as can be seen in Figure 1. MoEYS under the Higher Education Improvement Project (HEIP) has selected RUPP to lead the development of engineering education reform using the CDIO Framework.

RUPP was first introduced to CDIO via a 10-day ASEAN-Republic of Korea (ASEAN-ROK) CDIO Workshop hosted by Singapore Polytechnic (SP) in 2019. From this exposure, RUPP started to reform its engineering curriculum under a project "Higher Education Improvement Project (HEIP)" with support from SP from 2021 to 2023 through a series of hybrid format workshop for CDIO faculty competency training. RUPP joined the CDIO Initiative in 2024 as a member with the stated aim of using CDIO Framework as the DNA to drive the revamp of programs from the Faculty of Engineering. Under the auspices of HEIP Phase 2 (2025–2027), RUPP has partnered with SP to train selected faculty members to be its own future CDIO trainers under the SP-RUPP CDIO Train-the-Trainer (CDIO3T) Programm, with the aim of achieving the ASEAN University Network–Quality Assurance (AUN-QA) recognition for two Faculty of Engineering programs, to drive a comprehensive, innovation-driven curriculum revamp that meets FEF requirements using the CDIO Framework.

Challenges of Processional Development at Time of Curricular Reform

Implementing the required changes to meet the requirements of FEF imposed many challenges on RUPP faculty, who are already facing heavy teaching loads. They need to learn CDIO principles during their non-teaching hours, and apply them to redesign their courses, and deliver them to the next semester. They had to juggle between current teaching commitments where interaction with students are pretty much didactic in nature, and to teach differently the next semester, and all the time trying to make sense of how the outcomes from their courses align to the needs of FEF and meet the requirements of AUN-QA.

SCOPE OF THIS PAPER

This paper documents the experience of RUPP Faculty of Engineering in executing a challenging curriculum redesign initiative using CDIO Framework within relatively short timeline. The aim is to prepare 2 programs ready for AUN-QA recognition by 2028. This paper focuses on the approach adopted in RUPP with SP support by operationalizing a faculty continual professional development (CPD) program designed using the 70:20:10 learning model, informed by the STiCC (School Culture, Time, Choice, and Connection to Practice) Framework. It provides a brief literature review of CPD with emphasis from the perspective of CDIO. An alignment between CDIO Standards ver 3.0 and AUN-QA ver 4.0 is provided, and brief explanation of how the 70:20:10 learning model is applied in context of FEF using CDIO Standards is provided. Faculty experience from this program is obtained via focus group discussion and shared. Challenges and ideas for moving forward are shared. Key takeaways useful for program owners intending on undertaking similar endeavour are presented.

BRIEF LITERATURE REVIEWS

The extant literature showed that faculty sentiments during curriculum revamp while undergoing training often reveal a mix of enthusiasm and strain. Common concerns include heavy workload, identity tensions, and skepticism toward imposed reforms (Trowler, 1998; Guskey, 2002). Faculty often feel underprepared for new pedagogical methods and worry about balancing teaching with professional development. Coping strategies typically involve reflection-in-action, experiential learning, and peer mentoring. Faculty rely on communities of practice and incremental adoption of reforms to manage the dual demands, and many validate their efforts by observing improvements in student learning (Guskey, 2002; Zellers *et al*, 2008). Institutional support that faculty value most are those that embed training into practice. Structured mentoring, workplace learning models, and recognition of teaching excellence help reduce resistance and make professional development feel integral rather than burdensome (Blackman *et al*, 2016; Steinert *et al*, 2019).

Kennedy (2005) noted that CPD can be structured and organized in several ways, and for several different reasons (p.236). She suggested that there can be a spectrum of 9 CPD models, which is shown in Figure 2. On one end of the spectrum are CPD models that are used for transmission purposes, that is, to prepare teachers for the implementation of curriculum reforms. The other end of the spectrum is one of transformative model, with accordingly to Kennedy, is “the combination of a number of processes and conditions – aspects of which are drawn from other models” and that the model “is not a clearly definable model in itself; rather it recognizes the range of different conditions required for transformative practice” (Kennedy, 2005, p.246). The series of CDIO training workshops described in this paper is our attempt to achieve the transformative outcomes of CPD, that is to prepare RUPP

faculty in using the CDIO Framework to redesign their respective courses towards an outcome-based education, aligned to the requirements of the AUN-QA Framework.

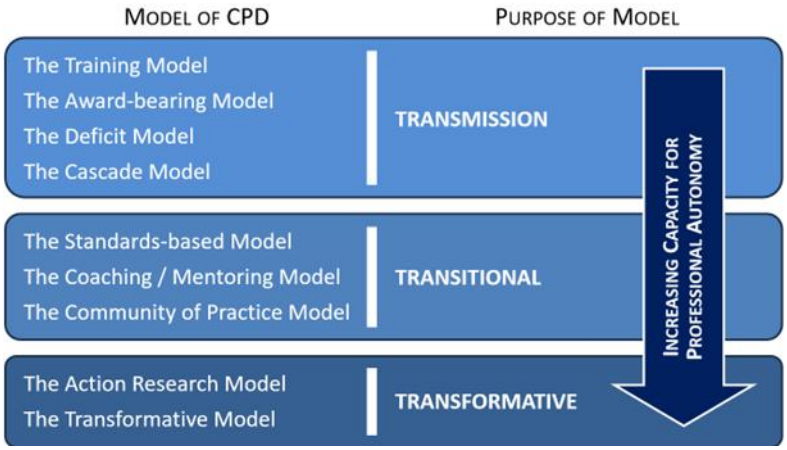


Figure 2. Spectrum of CPD Models (Kennedy, 2005)

One of the key challenges of CPD is the "transfer problem;" where positive transfer of training is defined as the degree to which trainees effectively apply the knowledge, skills, and attitudes gained in a training context to the job (Baldwin & Ford, 1988). The authors further noted that the conditions for transfer include both the generalization of learned materials to the job and the maintenance of trained skills over a period of time on the job.

CPD at a Time of Curriculum Reform

Porcenaluk *et al* (2023) noted that CPD offered during curriculum reform may look different from traditional professional development. Expecting faculty to learn and teach a new curriculum while undertaking CPD comes with challenges: one of which is the possibility that the enacted curriculum may not be quite like the intended one. The authors proposed a CPD framework to use during curriculum reform, known as the STiCC as shown in Figure 3. The framework aims to aid in creating a foundation for structuring CPD that supports teachers to shift their pedagogical approaches, learn new content knowledge, and understand theories underpinning the changes to teaching and learning, all while implementing a new curriculum (p.932).



Figure 3. STiCC Framework for CPD during Curriculum Reform (Porcenaluk *et al,* 2023)

We adopted the STiCC Framework as the basis for the training program for the SP-RUPP CDIO3T program. The program was operationalized using the 70:20:10 Framework (McCall, Lombardo & Morrison, 1988). The 70:20:10 Framework had been widely adopted by human resource development practitioners (Clardy, 2018) despite its lack of theoretical underpinnings and lack of empirical evidence to support its effectiveness. Johnson *et al* (2018) investigated how the framework is being implemented and whether it facilitates the transfer of learning. Although the outcomes were not satisfactory, the authors shared key learning points from their work that are especially useful for our present work, as will be shared in later sections.

CDIO AND FACULTY CONTINUING PROFESSIONAL DEVELOPMENT

Continuing professional development (CPD) is of paramount importance in ensuring that teaching faculty obtain to keep one's curriculum content up to date, in terms of the knowledge, skills and attitudes students needed for the workplace upon graduation. From the CDIO Framework perspective, it is also equally important that teaching faculty themselves are equipped with the appropriate teaching approaches, pedagogical know-how, design of meaningful and impactful learning experiences that engage students in learning from doing, the master the required competency to be work-ready. This is especially poignant in today's fast-changing workplace environment mediated by advances in technologies, most notable being the rapid adoption of data analytics, process automation, and artificial intelligence. New programs are introduced, and existing programs redesigned to cater for the needs of new skills demanded by employers in the workplace transformed by the adoption of digital technologies. CDIO Standard 9 and Standard 10 informed the requirements of CDP that address both the 'what" and "how" aspects of using CDIO, as shown in Table 1 below.

Table 1. Description for CDIO Standards 9 and 10

Standard 9: Enhancement of Faculty Competence	**Standard 10: Enhancement of Faculty Teaching Competence**
Actions that enhance faculty competence in personal and interpersonal skills, product, process, system, and service building skills, as well as disciplinary fundamentals.	Actions that enhance faculty competence in providing integrated learning experiences, in using active and experiential learning methods, and in assessing student learning.
CDIO programs provide support for improving the collective competence of the engineering faculty with regards to what to teach, according to the full set of intended learning outcomes of the program as described in Standard 2. Faculty competence refers to personal and interpersonal skills, product, process, system, and service building skills, including concepts and competences related to sustainable development. Faculty competence also refers to the ability to support students to achieve a deeper working understanding of the relevant disciplinary fundamentals.	CDIO programs take actions to enhance faculty teaching competence required for effectively creating, delivering, and improving courses in the curriculum. The need for faculty teaching competence includes for instance the ability to provide integrated learning experiences (Standard 7), including design-implement experiences (Standard 5) and using active and experiential learning in teaching (Standard 8), as well as assessing student learning (Standard 11) and evaluating and improving courses and programs (Standard 12).

Within the CDIO community, CPD is consistently portrayed as being delivered *concurrently with curriculum transformation:* a form of "just-in-time" training. Early comparative work showed Nordic universities experimenting with role-specific training while faculty were already

engaged in project-based teaching reforms (Malmqvist *et al*, 2008). In Sweden, Papadopoulou *et al* (2019) described a workshop designed to be explicitly "just-in-time" in that it requires participants to bring their own courses into the workshop, reflect on them, and immediately apply CDIO principles during the training. In India, Sukumaran & Gurusamy (2023) described the design and development of teaching competency development framework that addresses professional, techno-pedagogical, and organizational competencies that every faculty from their institution must possess.

At SP, CPD has been rigorously implemented for new faculty, via a systematic mentoring program which had evolved from a pilot-scale structured mentoring program by the third author (Cheah & Singh, 2011) to an institutionalized SP-wide Academic Mentor scheme that embed mentoring into ongoing curriculum redesign and concurrent support. At present the scheme is now known as the Teaching & Learning Mentor/Specialist (TLMS) scheme. Leong *et al* (2016) described a comprehensive CDP program in SP for all teaching faculty from lecturers to academic mentors to deputy director (programs). Cheah & Lee (2015) described how academic mentoring in SP is used as a professional development strategy implemented using the 70:20:10 learning model, although this term was not used in their paper at that time. The 70:20:10 model was used to embed faculty development into the act of building and delivering spiral curriculum for the chemical engineering program, making training inseparable from transformation (Cheah & Wong, 2019).

COMPARING THE CDIO STANDARDS AND THE AUN-QA REQUIREMENTS

The ASEAN University Network-Quality Assurance (AUN-QA) is a network of ASEAN higher education institutions aimed at harmonizing educational standards and promoting continuous quality improvement. Established in 1998, it provides, among others, programme-level and institutional-level assessments to enhance regional academic standards and facilitate student/faculty mobility. Nguyen *et al* (2013) suggested that under the legal, technical and social environment of Vietnam, CDIO can better prepare Vietnamese universities/colleges for international accreditation using AUN-QA as example. Phan *et al* (2020) showed that the CDIO Standards version 2.0 mapped very well to AUN-QA Criteria 3.0.

In 2023, version 4 of the AUN-QA criteria was used for assessment. It marked a significant change from earlier version where the 11 criteria have been consolidated and reduced to only 8 (Table 1.2, AUN, 2020). On the other hand, the CDIO Standards have also be upgraded to version 3.0. Table 2 below shows a mapping of the 12 CDIO Standards ver 3.0 against the 8 Criteria of AUN-QA Framework ver 4.0. It can be seen that CDIO Standards mapped well to the AUN-QA criteria related to fundamentals of good program design (learning context, integrated curriculum, outcomes, teaching and learning approaches, learning assessment). Good alignment was also achieved in program evaluation, which should not come as a surprised. However, there are several areas that the CDIO Framework did not and was not designed to cover. These are matters pertaining to student progression, offering of electives, major/minor, faculty hiring and promotions, etc. These aspects of education management rightfully be addressed by the institutions own internal policies and procedures.

RUPP FACULTY CDIO CAPABILITY DEVELOPMENT USING 70:20:10 FRAMEWORK

Preliminary discussions between SP and RUPP was initiated in early 2023 to plan for the SP-RUPP CDIO3T program with the aim of training some members of the RUPP Faculty of Engineering (FE) as master trainers. A total of 11 faculty members were eventually selected

by the RUPP management to lead the curriculum redesign effort. starting in accordance with Table 3 below.

Table 2. Mapping between CDIO Standards (ver 3.0) and AUN-QA Criteria (ver 4.0)

		AUN-QA version 4.0 Criteria							
CDIO Standards 3.0		1	2	3	4	5	6	7	8
1	The Context	1.1 1.4	2.1 2.3	3.1					
2	Learning Outcomes	1.2 1.3	2.2	3.5					
3	Integrated Curriculum	1.2	2.4 2.5		4.5		6.3		
4	Introduction to Engineering	1.1	**2**	3.1	4.2				
5	Design-Implement Experiences			3.4	4.4 4.6				
6	Engineering Learning Workspaces							**7**	
7	Integrated Learning Experiences			3.4	4.4 4.6				
8	Active Learning			3.3					
9	Enhancement of Faculty Competence				4.1 4.5	5.3			
10	Enhancement of Faculty Teaching Competence				4.1 4.5	5.7			
11	Learning Assessment	1.5			3.4 3.5	4.6			
12	Program Evaluation	1.4	2.7	3.6	4.7	5.7	6.6	7.9	**8**

Shading Explanation		Correlation with one or several sub-criteria		Correlation with whole criterion
AUN-QA 4.0 Criteria	1. Expected Learning Outcomes, 2. Program Structure & Content, 3. Teaching & Learning Approaches, 4. Student Assessment, 5. Academic Staff, 6. Student Support Services, 7. Facilities & Infrastructure, 8. Output & Outcomes			

Table 3. Program and participants for SP-RUPP CDIO3T

Program Name	Curriculum Development	Teaching & Learning	Remarks
Food Science & Engineering (FSE)	Vice dean x 1 Program manager x 1	Lecturer x 4	These 2 programs are slated to introduce new CDIO-type curriculum. All faculty members have teaching duties and experience.
Data Science & Engineering (DSE)	Vice dean x 1 Program manager x 1	Lecturer x 5	

The 3 components of the SP-RUPP CDIO3T program based on the 70:20:10 Framework are distributed as follows:

- 10% Formal – attend structured training via workshops from SP
- 20% Social – attend scheduled sharing between different programs within RUPP
- 70% Experiential – apply knowledge gained to redesign one's own program by RUPP

The entire duration for the SP-RUPP CDIO3T program took about 24 months. The program was divided into key segments in accordance with how the CDIO standards are typically used for program curriculum redesign:

- Context, Learning Outcomes
- Integrated Curriculum & Introduction to Engineering'
- Design-Implement Experiences, Integrated Learning Experiences, Active Learning
- Learning Assessment and Program Evaluation

Each segment is conducted as follows: 3 or 4 days of a workshop onsite in Phnom Penh or other city in Cambodia (i.e. the 10% formal part) followed by a break of about 2 months before the next formal workshop. During this period, faculty from both curriculum development and teaching and learning work together on their respective course(s) applying the knowledge gain from the workshop (I.e. the 70% experiential part). As for the 20% social part, we took note of the key lesson we learnt from the work of Johnson *et al* (2018) who cautioned against overlooking the role played by social learning in integrating experiential, social and formal learning in an effective CPD program. We therefore have regular sharing sessions built into the interim period for members from different program teams to meet and exchange learning experiences as well as learning from one another, e.g. what worked and what did not, etc. In addition, we also introduced an online 1-day "check-in clinic" for the 11 RUPP trainer to be in contact with SP CDIO Facilitator to share and get feedback on their work done. This is shown in Figure 4.

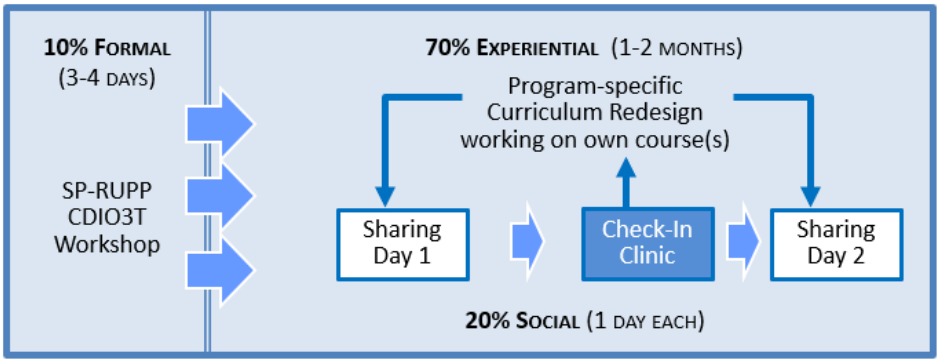


Figure 4. SP-RUPP CDIO3T Program designed using 70:20:10 Framework

Details of the SP-RUPP CDIO3T Program showing the planned dates and topics to be covered are shown in the Appendix. There are 3 main categories labelled A, B and C. Topics under Category A are foundational teaching and learning principles that formed the basis of CDIO principles, while Category B covers the use of each of the 12 CDIO Standards using 2 RUPP programs as context and referencing applicable criteria of the AUN-QA Framework, and Category C are meant to help RUPP improve its in-house quality assurance systems to continue the drive towards continual improvement using CDIO.

DESIGN OF SP-RUPP CDIO3T PROGRAM USING STiCC FRAMEWORK

The design of the program itself started with the end in mind: towards accreditation under AUN-QA Framework. In view of the fast-changing nature of today's educational landscape, especially considering technological advancements; we decided to frame the entire approach to the training to use respective CDIO standards that can demonstrate meeting the specific requirements of AUN-QA Framework. Figure 5 shows the PDCA cycle adapted for AUN-QA Framework.

We applied the STiCC model to the design of the curriculum for the SP-RUPP CDIO3T program, as briefly explained below.

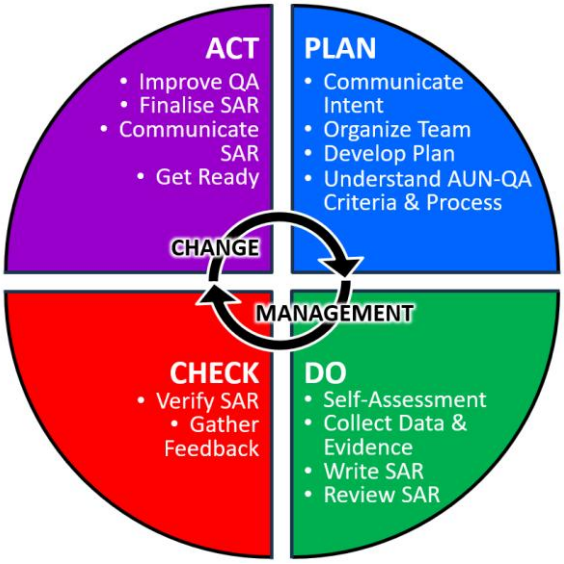


Figure 5. The PDCA Approach from AUN-QA Framework

- *School Culture*: "*Teachers should be given a supportive environment to undertake CPD*" This is the most important factor in the design of the SP-RUPP CDIO3T training program – members of the senior management team from RUPP FE took an active role in learning along with the participants in the workshop. An added benefit in the case of RUPP is that senior management themselves also have teaching duties, and their willingness to lead by example. The scheduled sharing sessions for faculty to meet up can further build a culture of sharing among faculty.
- *Time*: "*Consider when teachers will participate in CPD and what the time commitment is*" During curriculum redesign, time is especially precious given that everyone is already remarkably busy with the existing teaching commitments. SP work closely with RUPP FE senior management team to carry out advanced planning to make use of semestral breaks in the RUPP academic calendar to make time for CPD, for both the workshop (i.e. the 10% parts) as well as the sharing sessions and "check-in" clinic (i.e. the 20% parts). Careful consideration is also given to avoid peak period in a semester such as beginning of academic year, or examination period.
- *Connection to Practice*: "*Teachers must see how learning relates to teaching their students*" The training program design mandates that participants apply what they had learnt in the formal workshop to the course(s) that one is teaching. As seen from the earlier discussions, the program design provided time that allows participants to practice what they learnt.
- *Choice: "Provide teachers options in how they undertake CPD"* For the 70% experiential component, participants are encouraged to undertake action research to further deepen their knowledge of how the Framework is used to enhance teaching and learning; and attain the requirements of outcome-based education. Faculty is given a choice on which topic to do action research on.

The SP-RUPP CDIO3T program was targeted to end in June 2027. At the time of this writing, only the segment on Program Evaluation is yet to be covered. The remainder of this paper focuses on the learning points from participants on their experience from the training.

As an example of how the program works, consider the RUPP Food Science & Engineering (FSE) program. In May 2025, the FSE teaching team undergone 5 days of formal training by SP facilitators in Topics B1, B2 and B3 which cover CDIO Standards 1 (The Context), 2

(Learning Outcomes) and 3 (Integrated Curriculum). As shown in the topics in the Appendix, participants first identify key stakeholders for the FSE program and their requirements for the program's graduates in terms of job roles and responsibilities. These was mapped to RUPP's desired graduate attributes and professional identity and then unpacked to reveal the underpinning skills and attitudes needed. These requirements then cascaded into program-level learning outcomes and cascaded into appropriate courses, translated into course-level learning outcomes at the desired proficiency level and written using Bloom Taxonomy. An integrated curriculum is then designed to progressively develop the desired skills and attitudes to attain the required proficiency levels. Gaps in existing curriculum are identified as appropriate courses are identified as most appropriate to close the gaps. During this 5-day training, participants practice applying the principles learnt to their own courses and continue to do so for about a month before the "check-in" session with the same SP facilitator in June 2025. During this "check-in" session, participants presented their work done and areas of improvement identified and feedback given. Prior to the "check-in" session, RUPP management organize regular get-together for participants from FSE and the faculty from Data Science & Engineering to exchange learning points and insights, as a form of peer support in their curriculum redesign journey.

This sets the stage for applications for key elements of the FEF (Figure 1) in context of each program, namely systems thinking, lifelong learning (via self-directed learning) and Continuous Quality Improvement (CQI) using appropriate United Nations Sustainable Development Goals (UNSDGs). Topics B4, B5, B6, B7 and B8 covered these elements is a holistic manner through CDIO Standards 4 (Introduction to Engineering), 5 (Design-Implement Experiences), 7 (Integrated Learning Experiences), 8 (Active Learning), 11 (Learning Assessment) and 12 (Program Evaluation).

FACULTY REFLECTIONS ON LEARNING EXPERIENCE: FOCUS GROUP DISCUSSION

An online focus group discussion was organized by the second author from SP to learn about the experiences of participants, based on the STiCC Framework, and the 70:20:10 learning model. Questions were asked to ascertain how well the 4 dimensions of STiCC (School Culture, Time, Choice, and Connection to Practice) and different touch points of the 0:20:10 learning model facilitate participant engagement during the training. The findings are summarized into appropriate themes and discussed below.

Practice-Based Curriculum Redesign to Facilitate Transfer of Learning

Faculty valued applying CDIO concepts directly to their courses, noting stronger vertical and horizontal alignment, constructive alignment, and assessment design. Several described redesigning labs to include teamwork and peer evaluation, extending assessment beyond technical skills. Participants emphasized that the program's requirement to apply concepts immediately to curriculum work made learning "real" and sustained, addressing the common gap between training and practice.

Peer Learning and Mentoring as Support for Sense-Making at Times of Change

While workshops provided grounding, participants highlighted peer exchange as especially memorable. Sharing across departments helped them interpret CDIO, surface challenges, and validate their redesign efforts. Many expressed that these interactions built confidence and a sense of collective direction. They suggested communities of practice to sustain momentum, underscoring that peer learning is not supplementary but essential for reform.

Shifting Faculty Identity from Content Delivery to Learning Design

Reflections revealed a shift from content delivery to learning design. Faculty reported more interactive classes, with students engaging through projects and discussions. Yet they acknowledged challenges: students often preferred passive listening, and assessing teamwork or soft skills was difficult in large classes. Some suggested teaching assistants to support feedback. Participants admitted that many lecturers, trained as disciplinary experts, needed development in non-technical competencies, but also expressed excitement about designing richer learning experiences.

Accreditation as Quality Anchor

Accreditation was seen not as compliance but as a benchmark for quality and innovation. Faculty valued mock evaluations for clarifying expectations and welcomed AUN-QA as a platform to compare with established institutions. They requested ongoing training, practical examples, and the development of master teachers to guide younger colleagues. Several noted that such support would shorten learning curves and sustain capability, reinforcing the train-the-trainer approach.

Summary of Focus Group Discussion Outcomes

The program was most effective when workshops, peer exchange, and workplace application worked as an integrated system. Participants appreciated the balance of conceptual grounding, collaborative sense-making, and authentic curriculum tasks. This experiential application addressed the common gap between training and workplace practice, reinforcing the 70% experiential component of the 70:20:10 model. Sustainability, they stressed, will depend on mentoring, communities of practice, and internal master teachers as RUPP moves from redesign to enactment and continuous improvement.

CHALLENGES AND PLANS FOR MOVING FORWARD

One of the main challenges we faced is in trying to “lock in” the dates for the training. Despite the best of intentions, inevitably some changes to the dates become necessary. Because of the sequential nature of training, there will always be knock-on effects on downstream sessions. Despite the preference that the training be done face-to-face onsite and the “check-in” sessions online (to minimize cost), this arrangement is not always possible. Fortunately for the SP-RUPP CDIO3T Program, both institutions are flexible to accommodate the changes, with SP facilitators travelling and/or conducting the training during Singapore public holidays. RUPP participants also demonstrated resilience in attending workshops held during Cambodian public holiday and their vacation terms.

Heavy faculty workload continues to be challenge. Faculty were expected to redesign courses while maintaining full teaching loads. Even with careful scheduling, this dual demand risks burnout and may compromise the depth of curriculum redesign. The model assumes faculty can absorb significant additional responsibilities without reducing existing commitments. Moreover, the 70:20:10 model, though widely used in human resource development, lacks strong theoretical and empirical validation. Its effectiveness in academic CPD contexts remains contested, meaning outcomes may vary depending on institutional culture and faculty engagement. Despite widespread adoption of 70:20:10, learning transfer to the workplace was not always effective (Johnson *et al*, 2018). Faculty may struggle to sustain new practices over time, especially if institutional incentives and evaluation systems do not reinforce them.

Leadership participation in the training program can be a double-edged sword. While leadership involvement can strengthen culture, it may also unintentionally pressure faculty to conform rather than experiment. Faculty might feel less free to voice skepticism or propose alternative approaches when senior management is present in training. In the RUPP case, the 2 RUPP vice deans was actively assisting the SP facilitators during the training sessions. And it is with great respect that the 2 SP authors of this paper has noted that they successfully created a learning culture where other faculty can openly disagree and even challenge one another, including the vice deans.

Likewise, the accreditation-driven focus of training that anchors reforms to AUN-QA requirements may risk narrowing teaching and learning innovation to mere compliance instead. Faculty may prioritize meeting criteria over exploring pedagogical creativity or tailoring reforms to local student needs beyond accreditation requirements. The SP facilitators must strike a balance between over-emphasizing meeting AUN-QA criteria and focus more on innovative student-centred teaching and learning strategies using CDIO principles.

At the time of this paper, RUPP just rolled out the 2 programs redesigned using CDIO for its Year 1 students. Moving forward, RUPP will continue to work with SP in implementing the desired revamp for the remaining years of study. A longitudinal study of the impact on students learning will be introduced. RUPP and SP are in the process of discussing follow-up plans for supporting the newly minted RUPP CDIO trainers. In the near term, the focus is on supporting their action research and reflective practice using an evidence-based approach to ascertain the effectiveness of learning tasks designed using the CDIO Framework. A learning journey to SP is also being planned for 2027. The experience and learning points from this work will also be shared with other programs within RUPP, and with other institutions in Cambodia. Over the longer horizon, RUPP and SP can collaborate on joint education research on topics of mutual interest.

KEY TAKEAWAYS FOR PROGRAM OWNERS

We would like to offer the following guidance for program owners within the CDIO community who are tasked with executing a program redesign with “just-in-time” faculty CPD:

- *Embed CPD into Curriculum Reform*: Professional development is most effective when it is inseparable from the act of reform itself. Instead of treating CPD as an add-on, embed training directly into curriculum redesign cycles. This ensures faculty immediately apply new knowledge to their own courses, reducing the “transfer problem” where training remains theoretical. Embedding CPD also signals to faculty that reform and development are part of the same institutional priority, not competing demands.
- *Adopt Structured Frameworks (STiCC + 70:20:10)*: Frameworks provide coherence and balance. The STiCC model ensures faculty development is culturally supported, time-sensitive, practice-oriented, and flexible. Meanwhile, the 70:20:10 model balances formal workshops, peer learning, and experiential application. Together, they create a structured yet adaptable approach that integrates theory, collaboration, and practice, making CPD sustainable and impactful during curricular reform.
- *Secure Leadership Participation:* Leadership involvement is critical to building trust and legitimacy. When senior management participates in training alongside faculty, it demonstrates commitment and models the desired culture of learning. Leaders who also teach can bridge policy and practice, showing faculty that reform is not imposed but shared. This reduces resistance and fosters a culture of collective responsibility.

- *Plan Around Academic Cycles:* Faculty workloads are heavy, and reform adds pressure. Strategic scheduling of CPD during semester breaks or low-intensity periods prevents burnout and increases engagement. Avoiding peak times like exam seasons ensures faculty can focus on learning and application. Thoughtful timing signals respect for faculty commitments and makes CPD feel feasible rather than burdensome.
- *Mandate Application of Learning:* Training must be applied immediately to faculty's own courses to ensure transfer of learning. By requiring participants to redesign their courses during CPD, institutions guarantee that reforms are not delayed or diluted. This approach also helps faculty see the direct relevance of training, reinforcing motivation and embedding new practices into daily teaching.
- *Ensure Sustainability through Train-the-Trainer:* A train-the-trainer model builds long-term institutional capacity by creating internal champions who can cascade knowledge to others. This reduces reliance on external partners and ensures reforms continue beyond the initial project. Faculty trainers become role models and mentors, fostering peer learning and embedding CDIO principles into the institution's DNA.
- *Use Accreditation Goals as Anchors:* Anchoring CPD and curriculum reform to recognized accreditation frameworks (such as AUN-QA) provides a clear external benchmark and motivation. Faculty see the tangible value of their efforts in terms of international recognition and student mobility. Accreditation goals also help structure reforms, ensuring that training outcomes are measurable, aligned with quality assurance, and not left vague or aspirational.

CONCLUSIONS

The Royal University of Phnom Penh's (RUPP) case illustrates how faculty professional development can be embedded into curriculum reform to achieve both pedagogical transformation and international quality assurance. By aligning the CDIO Framework with Cambodia's FutureFit Educational Framework and targeting ASEAN University Network–Quality Assurance (AUN-QA) accreditation, RUPP created a reform pathway that was nationally relevant and regionally benchmarked. The SP-RUPP CDIO3T program combined the STiCC Framework and 70:20:10 Learning Model with a train-the-trainer approach, ensuring faculty development was contextualized, practice-oriented, and sustainable.

Overall, this case study demonstrates that CPD, when embedded into reform, can empower faculty and transform institutions. For program owners elsewhere, the RUPP experience offers a replicable model: anchor reforms in accreditation, embedding CPD into practice, and building sustainability through internal trainers, cultivating a culture of continual improvement that endures beyond the project cycle.

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GenAI was used in the following manner:

- To provide a concise summary of papers selected from the CDIO Knowledge Library to ascertain the content of each paper address issues of faculty development in times of curriculum change. This then formed the basis for writing literature reviews.
- To improve the abstract of the paper after the first draft was written.
- To improve conciseness of the write-up from the focus group discussion.
- To identify key takeaways from the paper, which was reviewed for validity and edited as necessary.
- To prepare the draft of the conclusion of the paper, after which it was reviewed and amended as necessary.

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APPENDIX. Details of SP-RUPP CDIO3T Program

Attached below is the listing of topics covered in the program over the duration of several months. Note that this is not the latest version of the actual program as implemented. This earlier iteration is used as illustrative only for the purpose of this paper.There are 5 topics under Category A (foundational teaching & learning principles), 8 topics under Category B (applications of core CDIO Standards) and 4 topics under Category C (quality education via continual improvement).

Date (2025)	Days	Components	Topic(s)	Type & Location
May 6 - 8	3	B1	Context of Learning via External Scanning	Training (Online)
		B2	Learning Outcomes, Proficiency Levels	
May 13 - 14	2	B3	Integrated Curriculum, Design-Implement Experiences	Training (Online)
May 30 - Jun 5	International CDIO Conference			Melbourne, AU
Jun 17 - 19	3	B1, B2, B3	As above	Checking-In @KH
Aug 4 - 7	4	A1	Manage Learning, learning theories, core principles of learning	Training @KH
		A2	Facilitating Learning (Questioning techniques, facilitation techniques, learning analytics)	
		A3	Underpinning Knowledge: Teamwork & Collaboration, Communication, Thinking	
		A4	Feedback & Assessment: Principles of Good Assessment, Types & Methods, Rubrics	
Aug 18 - 21	CDIO Asia Regional Meeting			Batam, ID
Sep 1 - 3	3	A1, A2, A3, A4	As above	Check-In (Online)
Oct 13 - 15	1	B4	Integrated Learning Experiences & Assessment	Training @KH
	1	B5	Prototyping of Basic-level (Year 1) Design Implement Experience	
	1	B6	Facilitation and Assessment of Capstone Project	
Oct 21 - 24	CDIO International Working Meeting (Oct 22-23)			Linkoping, SE
Nov 11 - 13	3	B4, B5, B6	As above	Check-In (Online)
Date (2026)	**Days**	**Components**	**Topic(s)**	**Type & Location**
Jan 12 - 14	3	B1-B3, B4-B6	Final Check before Official Roll-Out of RUPP 2 Revised Programs	Check-In @KH
Jan 15 - 16	1	B7	Special Topic: Self-Directed Learning (for Lifelong Learning)	Training @KH
	1	B8	Special Topic: Data-Enabled Flipped Classroom	
Feb 4 - 5	1	A5	Using Active Learning Methods with EduTech Tools	Training @KH
	1	A6	Using Reflective Practice to improve teaching	
Mar 11 - 12	2	A5, A6	As above	Check-In (Online)
Mar 18	1	C1	Introduction to Quality Programme and the PDCA Cycle	Training (Online)
Mar 19	1	C2	Introduction to CDIO Self-Evaluation for Continual Improvement & Quality Programme	Training (Online)
Apr 28	1	C2	Outcomes of The CDIO Self-Evaluation Process and action plans	Check-In @KH
Apr 29 - 30	1	C3	Faculty T&L Framework, Specific Job Analysis, Training Needs Analysis	Training @KH
	1	C4	Centre of Excellence for T&L, Academic Mentor Scheme	
May 20 - 22	3	C2, C4	As above (Outcomes from C3 TNA reflected in C4)	Check-In (Online)

ENGINEERING EMPATHY: USING PERSON CENTRED SIMULATION TO FOSTER INCLUSIVITY IN ENGINEERING DESIGN

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ABSTRACT

Utilised heavily within medical education, person-centred simulations have now emerged as a powerful methodological and pedagogical tool for integrating end user perspectives into engineering design processes. This is particularly important when facilitating the development of empathy within design, which is a difficult element to replicate within the classroom environment. Using a person-centred approach, an ageing simulation workshop was designed for mechanical engineering and product design engineering students, with the aim of aiding the development of empathy to enhance their ability to design devices for *all* individuals. Over the course of a three-hour workshop, students were split into groups with each group given a different scenario. Using GERT ageing suits and other devices, that mimicked mobility, hearing and visual impairments, students carried out several tasks based on their given scenario. Students were asked to identify challenges they faced while conducting the tasks within their scenario. Following a structured and evidence based debrief, each group had to isolate a specific challenge and come up with design concepts to solve that problem. This workshop brought a different dimension to both the module and the student's way of thinking. It challenged the students in their abilities as engineers while emphasising the importance of empathy in design.

KEYWORDS

Person-Centred Simulation, Empathy in Design, CDIO Standards 1, 5, 7, 8

INTRODUCTION

Utilising simulation models is customary in engineering education and practice. However, with computational simulation there is a level of detachment from the most important stakeholder – the end user. Efforts to embed empathy and stakeholder engagement within engineering education span a wide range of approaches. Some focus on immersive design activities that connect students directly with the users for whom they are creating products for. However, providing this experience in a meaningful way can be difficult to achieve, especially when the needs of the end users can vary significantly. Others take a broader view, encouraging students to reflect on empathy in the context of engineering ethics by considering the perspectives of people who are not physically present and integrating those viewpoints into their decision-making processes (Sochacka *et al*., 2020).

In medical education, person-centred rather than computational simulation has been utilised for several decades. It enables trainee health care professionals to gain experience with (simulated) patients in a simulated environment while being shielded from real-world consequences (Vage *et al.,* 2022). It has also been documented that simulated experiences of ill-health have helped health professionals demonstrate a greater empathy towards their patients (Karvelytė *et al*., 2021). This has become recognised within biomedical engineering education, and it has been documented that experiences gained through clinical immersions promote user-centred design processes in biomedical engineering students (Singh *et al.,* 2019).

Through person-centred medical simulation activities, the aim of this workshop was to nurture mechanical engineering and product design engineering students to develop empathy in design to enhance their ability to design devices for *all* individuals.

WORKSHOP DESIGN

Background

In the final year of their degree programme, MEng students in mechanical engineering and product design engineering have the option to take an elective module Advanced Materials. This is a year-long module, split into two themes, (1) Advanced Metal-Based Materials (2) Biomaterials and Medical Devices. The aim is for students to develop competence in advanced materials and their applications in engineering. This is the first opportunity for the students to explore biomedical engineering applications in depth. A variety of learning resources were utilised within the module, with different formats of tutorials and discussions used but there was no ‘hands on practical/experimental’ element.

It was important that this workshop provided a different dimension to what the students had already experienced within their degree. While empathy is one of the first stages of the design thinking process, it can be difficult to give students the opportunity to observe and consult with potential end users, particularly when it comes to product development for biomedical applications, where individual needs and abilities are personal and vary significantly. Therefore, it was key that this workshop captured that aspect.

The concept of person-centred simulation is a method that has been utilised by colleagues in Medical Health Life Sciences (MHLS) for several years. Drawing on the methods used by MHLS, this approach was adapted to suit engineering students. Trainee medical professionals are put in the position of a simulated medical emergency, and they must treat the patient. As

engineering students do not treat patients but instead design products to enhance their day-to-day living and wellbeing, it was decided the students would take on the role of the 'patient'.

Format

Employing the expertise of colleagues in the KN Cheung SK Chin InterSim Centre in the School of Medicine, a three-hour workshop was developed. Due to access to facilities, availability of facilitators and the desire to have small group sizes, the class (n=27) was split into two groups, and the workshop was delivered twice. All conditions for both workshops were the same. For ease of adaptation, the person centred simulations were based on ageing, incorporating mobility, visual and hearing impairments.

The workshop had two core themes, the first half was the ageing simulation, and the second half was the design challenge (Figure 20).

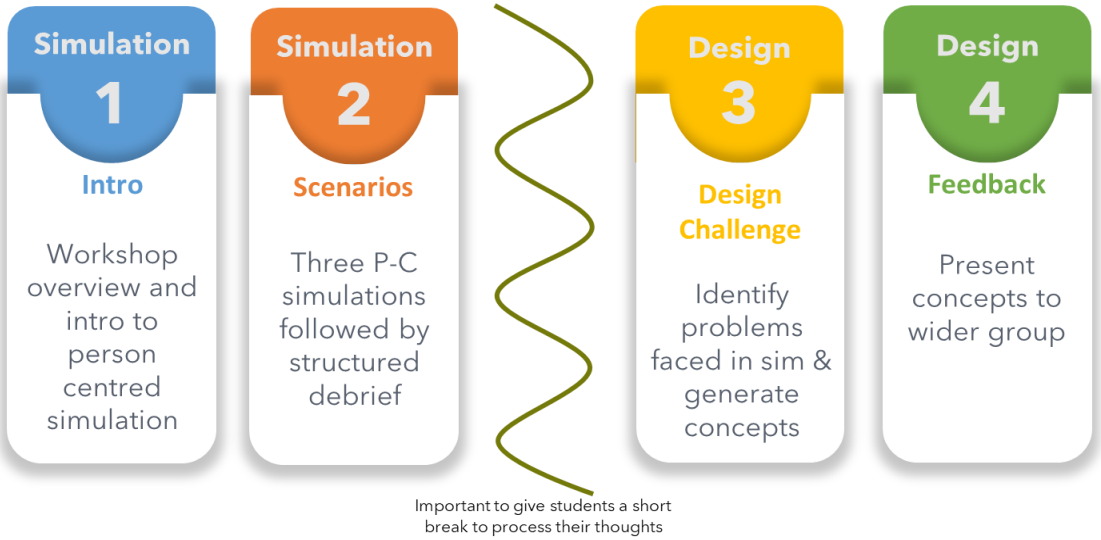


Figure 20. Person centred ageing simulation workshop format

Students were welcomed to InterSim, introduced to the format for the workshop and the concept of person-centred simulation. Time was dedicated for questions and to develop a safe participatory environment. Following this they were split into three groups. Each group had two facilitators (a GP and engineering demonstrator), and each group was given a different scenario.

1. Getting ready for the day
2. Going to meet a friend for coffee
3. Going shopping

Using GERT ageing suits and other devices, students carried out a series of small day-to-day tasks based on their given scenario. Following a structured and evidence based debrief (Bajaj *et al.,* 2017), each group had to isolate a specific challenge and use their skills as engineers to come up with design concepts to solve that problem. They had to consider how they could enhance the lives of those living with certain disabilities based on the activities they completed. Once concepts had been finalised, the groups reunited and pitched their product ideas to each other. To close the workshop the students shared their thoughts on the experience while discussing their responsibility as engineers and the importance of having empathy when designing for *all*. Students completed pre- and post-workshop perspective and exploration

questionnaires. The statements were adapted from empathy questionnaires, with the aim of capturing any change following the workshop. All students indicated on a scale from one to five how strongly they agreed with / how true the statement was / how well it described them (five being strongly agree/ very true / very well). Students also provided general feedback on the overall workshop.

Equipment & scenario environment

GERonTologic simulator (GERT) ageing suits and tremor simulation gloves were purchased from Product + Project, Wolfgang Moll (Germany). The suits provided age related impairments such as opacity of the eye lens and narrowing of the visual field, high frequency hearing loss, joint stiffness, loss of strength, reduced grip ability and reduced coordination. The suits were given to the groups and additional low-cost items such as googles, gloves, splints, patches, slings, and tape were used.

Having a mix of equipment types, i.e., equipment specially designed for this type of activity (GERT suits) and simple inexpensive pieces that are readily available provide the opportunity to expand the kit, allowing more students to experience an element of the simulation. Simulations can be achieved quite easily with everyday products for example, lab googles smeared with Vaseline were used to provide a visual impairment like cataracts. Wrist weights and taping the fingers provided an example of arthritis and problems with dexterity.

Each scenario was carefully considered and additional equipment was obtained were necessary.

1. Getting ready for the day

Using the Home-from-Home suite in InterSim, the room was set up to replicate a small studio flat, with a bed and kitchen facilities. This scenario included getting out of bed, getting dressed, making breakfast and taking medication. The medical condition for the scenario was, *the individual has left-sided weakness (hemiparesis) along with visual and hearing impairments.* Additional equipment included oversized clothing, utensils and food for making breakfast, and a basic pill box with medication (sweets) were provided.

2. Going to meet a friend for coffee

This scenario involved the group members leaving InterSim and going to the coffee shop within the medical building to purchase a hot drink and consume it on the premises. Due to ageing *the individual has problems with their right knee and ankle, arthritis in their hands and some visual/hearing impairments*.

3. Going shopping

This scenario involved the group members leaving InterSim with shopping bags, making their way to the carpark and getting into a car. *The individual has osteoarthritis. They have some minor visual and hearing impairments but are still able to drive.* Additional equipment included Zimmer frame, walking stick, shopping bags with heavy objects.

OBSERVATIONS AND OUTCOMES

In advance of the workshop students were provided with general information on InterSim, that they would be participating in an active workshop utilising the InterSim facilities, working with

medical professionals and using their skills as engineers. Therefore, it was particularly important at the start of the workshop to dedicate time to introducing the concept of person centred simulation and how they would be directly involved in these simulations. A concerted effort was made to create a safe participatory environment. It was equally important to give the students a short break after the simulation activities so they could gather their thoughts before participating in the debrief which explored their observations and feelings.



Figure 21. Images from simulations

Two participants acknowledged the relief they felt at being able to remove the equipment at the end of the simulation. While these tools provide short exposure to certain conditions, the impairment simulation cannot convey the true reality of living with such conditions, which the students recognised.

While pushing students out of their comfort zone during the simulations, this workshop also gave students the opportunity to apply their critical thinking skills as engineers as they had to identify a problem and implement an appropriate design solution to meet the needs of the individual in the scenario. Examples of design solutions generated by the students include scenario one: automatic medication dispenser, scenario two: shoe with sensors to prevent trips, scenario three: foldable walking frame with attachments for shopping bags. The primary focus was designing for the individual within their scenario however when developing their concepts it was found students didn't just consider one individual but incorporated features that would enable a variety of users to successfully use the product.

Three students (from separate groups) did not want to wear simulation equipment, due to personal reasons not disclosed, but they still participated with their group. Participation was not compulsory and it was anticipated that there may be students who may not want to undertake the simulation. Therefore, it was important there was an alternative element within the simulation to allow all students to engage. These students were given the role of 'observers. They observed the challenges faced by the individuals in simulation activities. This added a different dimension to the debrief and design section of the workshop, while giving those students the opportunity to actively participate with their group.

It is important to consider the finer details of scenarios and the environments used. For example, in scenario one the bed was pushed against the wall, meaning the individual had to get out using their left side, however this was the side of their body impacted by their condition. In scenario two students had reduced dexterity and were given cash instead of a bank card to

purchase their drinks. In scenario three the Zimmer frame was non-folding, the shopping bags had awkward handles and bulky items inserted.

Student Feedback

In an attempt to capture if their empathy towards design had changed over the course of the workshop students were asked to re-take the perspective and exploration questionnaire (Table 1) they had completed at the start of the workshop.

Evidence of a positive change was noted, however, to truly evaluate a change in empathy, students would need to be tracked for a longer period and evaluations captured from various aspects of their work.

Table 9. Pre- and Post-Workshop Perspective and Exploration Questionnaire Results

		n = 27		
	Statements	**% ↑[1]**	**=[2]**	**% ↓[3]**
1	I am confident in my ability to connect concepts and ideas that appear at first glance, to be unconnected.	33	63	4
2	I'm interested in experimenting in order to find new ideas.	26	59	15
3	Before criticising somebody, I try to imagine how I would feel if I were in their place.	59	41	0
4	I'm interested in giving a pitch or presentation to a panel about a new product or idea.	81	19	0
5	I have concerned feelings for people less fortunate than me.	37	63	0
6	If I'm sure I'm right about something, I don't waste much time listening to other people's arguments.	22	48	30
7	I am confident in my ability to generate new ideas by observing the world.	44	41	15
8	I sometimes try to understand others by imagining how things look from their perspective.	55	41	4
9	I am interested in finding resources to bring new ideas to life.	41	55	4
10	I get a strong urge to help when I see someone who is upset.	37	7	56
11	I am confident to experiment in a way to understand how things work.	33	37	30
12	I'm interested in developing plans and schedules to implement new ideas.	37	33	30
13	I sometimes find it difficult to see things from the other persons point of view.	26	33	41
14	I consider everyone's needs when it comes to designing.	59	37	4
15	I am confident in my ability to lead a team to challenge change in product development.	34	67	0
16	When I see someone being taken advantage of, I feel protective towards them.	45	55	0
17	If I see someone struggling, I am always willing to help them.	34	7	59

*__Results Key__: 1. Percentage of students whose score increased between pre- and post-workshop questionnaire, 2. Percentage of students whose score for statement remained the same, 3. Percentage of students whose score for statement decreased.

Overall, the student feedback was very positive. Key themes that came out of the workshop were, it was *interactive, enlightening, eye-opening and enjoyable*. Students enjoyed the small group format as it was '*conducive to getting involved'* and allowed for *'bouncing ideas off one another and coming towards a solution'.* One student noted that *'coming up with a new concept related to what you've done that day, helps the design process feel more grounded in reality'.*

Students stated that the simulation activities were "*good to experience*, and that it was '*eye-opening to see the difficulties people with these impairments go through on a daily basis*'. When asked how the use of ageing simulation has influenced their outlook/approach to engineering design, students said it '*really helped me think more empathetically, to take into account the needs of all types of people*', '*it has given me a fresh perspective on design, and how an optimal design can work for everyone'* and participating in the simulations '*allowed me to encounter the problems first hand rather than trying to imagine what they may be'*. Several students recommended that '*more workshops like this should be implemented for all students'*. In the final round-up, one student stated that this workshop made them think about the product they were developing as part of their final year project and how they needed to reconsider some of the features to make it more inclusive.

In terms of recommendations, the students would have liked more time to experience other simulations outside their group. While this would be ideal, it is difficult to achieve within the timeframe, and the format of the workshop would have to change. Five students suggested that it would be beneficial to experience this format of workshop earlier in their degree. However, 100% of those who completed the feedback survey (n=27) stated they enjoyed the design challenge, were very satisfied with the delivery of the workshop, and would recommend the workshop to other students.

CONCLUSIONS

This exciting inter-disciplinary, cross-faculty person-centric initiative provided a unique, innovative experience for final year mechanical and product design engineering students. Students got to briefly experience the reality of living with physical impairments, while in turn utilising their skills as engineers to develop solutions for the challenges faced within the scenarios. This also provided the opportunity for students to become more aware of the importance of empathy in the design process. Overall, the workshop has proven to be a valuable addition to the module. The format lends itself to several scenarios and could be adapted to suit other engineering disciplines.

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TAMPERING, A MAJOR CHALLENGE FOR CDIO BOOSTING

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ABSTRACT

There is a strong overlap between CDIO and Dr. Deming's System of Profound Knowledge, including his 14 points for management, except for one crucial aspect. In CDIO Standard 12 – Program Evaluation - it is a strong drive for monitoring "program's progress toward attaining its goals". Dr. Deming warns that without a clear common understanding of the difference between common cause of variation (random noise) and special cause of variation (signals) using control charts and SPC-thinking (Statistical Process Control) monitoring tend to drive over-reaction to fluctuations, that is, tampering. That in its turn according to Deming, prevents a shift from focus on individual course follow-up to an aggregated dialog on system development, that is CDIO implementation on programme and multi-program level. This study second Dr. Deming's warning. Course quality monitoring data used to trigger standard course development from 451 course evaluation surveys, from 128 courses given in four different programmes on both basic and advance level over 5 years, have been analyzed relative the definitions of common vs. special cause of variation. More than >98% of the variation in the trigger parameter stems from common cause of variation. Therefore, more than 60% of the 41 Action Plan started (9% of all courses) were done so from false alarms. The general strategi when a process is stable and predictable, that is, only varies due to common cause of variation, is to zoom-out to seek explanations to underlying patterns in the noise. In the noisy course survey data interesting patterns on course roles linked to CDIO Standards are identified. It helps shifting from individual course follow-up, driving blame game, to an aggregated dialogue on program development.

KEYWORDS

tampering, course evaluation, CDIO Standard 3.0, SPC, Common vs. Special cause of variation

INTRODUCTION

It seems to be a gap in literature on the overlap between the CDIO Standards 3.0 (CDIO Standards 3.0. 2026) and Dr. Edwards Deming's 14 Points for Management from his System of Profound Knowledge within Quality Engineering. When these two frameworks are lined up, the overlap is surprisingly strong, revealing both connections and important tensions (Table 10). The system of Profound Knowledge as a base for Quality Improvement consists of four blocks of interacting competences: understanding variation, psychology, knowledge theory and systems thinking. Deming's 14 points of management stems from his book Out of the Crisis (Deming WE. 1982[Ed1] & 2018[Ed3]) further clarified by for example Howard and Shelly Gitlow (Gitlow HS., Gitlow SJ. 1987). Recently, in March 2026, the Deming Institute republished the 14 points of management accompanied by short explanatory videos on their YouTube channel (Deming Institute. 2026) with the intention to highlight the actuality and relevance of Dr Demings almost fifty-year-old message.

Theoretical comparison of Deming's 14 points and the CDIO Standards

In Table 10, a pointwise comparison of the connection between the two frameworks is listed. They largely overlap, but there are some critical conflicts that may cause tension. A summary of the comparison reveals the following connections / tensions:

- **Strongly reinforcement**
    a. System thinking. Both frameworks insist that the unit of improvement is the system, that is, the programme, not individual courses
    b. Faculty development as central, not optional, in both frameworks. A core driver for change
    c. Integration over fragmentation. Deming: break silos. CDIO: Integrate curriculum
    d. Continuous improvement. Both rely on feedback loops
- **Crucial conflict**
    a. Measurement & evaluation
        i. CDIO encourages structured evaluation (CDIO Standard 12 – program evaluation)
        ii. Deming warns that *most variation is common cause* and that *reacting to every fluctuation* = *tampering*, that is, overreaction to variation (Deming point 5 – improving the system)

    Implication: *Overreaction to course evaluations when misinterpreting normal variation as problems*
    b. Accountability vs. system responsibility
        i. CDIO focuses on course-level accountability
        ii. Deming says that 90% of problems are system-level, not individual, and that systems cannot be improved from the inside. It requires an aggregated understanding

    Mismatch can undermine collegial trust and hinder constructive dialogue.

The bottom-line of the synthesis is that when CDIO Standards provide the structure (what to implement in education) Deming provides the philosophy of management (how to implement it effectively) and the Key insights of practical importance suggest to:

- Treat course evaluation data using variation analysis (Statistical Process Control SPC)
- Avoid blaming individual instructors
- Focus on program-level system redesign

And not:

- Rank courses or teachers based on raw scores
- React to small fluctuations in evaluation data

Tampering occurs when there is a lack of understanding the difference between common cause of variation (random noise) and special cause of variation (signal). A synthesis of Tampering understanding has recently been explored resulting definition based on Deming's original thinking: "A response to a perceived problem in the form of an action that is not directed at the fundamental" (Smeds M., 2022). Tampering leads to a deterioration of the process or the process output. It often leads to overreaction and that systems get unstable, like when a driver tries to correct a skid with overly large steering inputs. To build feedback control systems that keeps systems stable is normal engineering practice when done from the outside. However, from the inside the teaching system it is another matter. The teaching system at universities are infrastructures that consists of courses on specific topics taught different teachers in several different programmes, which are run by loosely connected teacher teams led by programme directors that interact in semi-overlapping management teams per disciplines, which in their turn are led by the headmaster's team. To aggregate the understanding of the consequences of tampering is not easy, since the normal engineering practices and tools for system control does not function equally well from the inside.

One problem when interpreting the course evaluation surveys is about understanding if the variation from year to year of the course quality monitoring numbers origin in physical changes of the course or if it stems from routine, common cause of variation. It is particularly important since variation below a certain threshold of a specific indicator in the course surveys (Q8<3) initiates a quality improvement procedure (action plan) for course development pinpointing an individual (bad?) teacher. According to Deming and others (Deming WE. (1982Ed1 & 2018Ed3), Deming WE. (2018), Wheeler DJ. (2002 & 2002). Bergman, B., Bäckström, I., Garvare, R., & Klefsjö, B. (2022), Balestracci, D. (2015). Gitlow HS., Gitlow SJ. (1987) standard operation procedure to filter out routine variation (common cause of variation to see signals in operational studies is to analyze a time series the data using control charts from SPC (Statistical Process Control). Control charts were invented 1924 by Walter Shewhart.

This study about noise level in survey responses intend to highlight the tampering phenomena and bring forward some understanding of the consequences of variation and how to handle it, when a process is stable and predictable only suffering from common cause of variation. Within Six Sigma and Design for Six Sigma (DfSS, robust engineering) a stable and predictable process containing only common cause of variation needs to be rebuilt. In Quality Engineering the standard procedure to find underlying patterns in a time series from of a stable predicable process that only contain common cause of variation is to stratify the data using describing attributes, such as technical discipline, educational level, compulsory/elective, etc.

The aim with this contribution is to illustrate the tension between CDIO Standard 12 and the Deming point 5 regarding overreaction to noise (tampering) (Table 10) and elevate the discussion about the effect of lack of common understand of how to distinguish signals from common course variation in the course quality follow-up procedure to the program development level and to help the teacher team to define concepts of mutual interest on course exceeding issues and prevent ghostbusting.

Table 10. Lineup of Demings 14 points vs. CDIO Standards 3.0

Dr Deming's 14 points		CDIO Standards 3.0
1. Constancy of Purpose 2. Adopt a new philosophy (culture change) 3. Cease dependence on inspection 4. End the practice of awarding business on price alone; instead minimize total cost by working with a single supplier (N/A) 5. Continuous improvement of the system 6. Institute training on the job 7. Adopt and Institute leadership 8. Drive out fear 9. Break down barriers between staff areas 10. Eliminate slogans, exhortations, and target for the workforce 11. Eliminate numerical quotas for the the workforce and numerical goals for management 12. Remove barriers that rob people of pride of workmanship, and eliminate the annual rating or merit system 13. Institute a vigorous program of education and self-improvement for everyone 14. Put everyone in the company to work accomplishing the transformation		1. The Context 2. Learning Outcomes 3. Integrated Curriculum 4. Introduction to Engineering 5. Design-Implement Experiences 6. Engineering Learning Workspaces 7. Integrated Learning Experience 8. Active Learning 9. Enhancement of Faculty Competence 10. Enhancement of Faculty Teaching Competence 11. Learning Assessment 12. Program Evaluation
Deming's Points	**CDIO Standard**	**Connection/Tension**
System purpose & long-term vision		
Deming Point: 1 → improve the system continuously	CDIO Standards: 1 & 2 → define what kind of engineer is educated	Both require a share, long-term purpose → without this faculty drift into *course-level thinking instead of program coherence*
Adopt a new philosophy (culture change)		
Deming point: 2 → transformation requires changing how people think about work	CDIO Standards: 1 & 8 → shift from lecturing to active, experiential learning	Both require faculty mindset change, not just new tools
Build quality into the process (not inspection)		
Deming point: 3 → quality should be built into the system	CDIO Standards: 5 & 6 → learning is embedded in authentic engineering activities, not just exams	Assessment becomes part of learning, not a separate control step
Continuous improvement of the system		
Deming Point: 5 **→Deming warns against misinterpretation of variation and tampering**	CDIO Standard: 12 →CDIO formalizes course evaluation and program reviews that often relies on r**aw metrics without SPC thinking**	Both emphasizes continuous, data-informed improvement **IMPORTANT TENSION**
Training and education of staff		
Deming Points: 6 & 13	CDIO Standards: 9 & 10	Direct match: both require systematic faculty development → No changed outcomes without investment in teach capability
Leadership vs. supervision		
Deming point: 7 → leaders improve the system, not control people	CDIO Standards: 1, 11 &12 → Program leaders must, align learning outcomes & support faculty	Weak leadership → fragmented CDIO implementation
Drive out fear (psychological safety)		
Deming point: 8	CDIO Standard: 9 - 12 + implicit across CDIO	Faculty must feel safe to discuss poor results, experiment with teaching, and critique programme design →Without this: course evaluations become **defensive tools,** not learning tools and collegial dialogue breaks down
Break down silos		
Deming point: 9 → Departments must collaborate	CDIO Standard: 3 Courses must be explicitly connected across the programme	This is one of the **strongest direct overlaps**
Avoid empty slogans and top-down mandates		
Deming Point: 10 → Deming warns: Slogans without system change create frustration	CDIO Standards: Implementation practice (not a single standard) → CDIO can fail when adopted as a 'label' without any real change	
Eliminate numerical quotas and targets		
Deming points: 11 → Deming warns that metrics can distort behavior if misunderstood	CDIO Standards: 11 & 12 → CDIO uses learning outcomes and evaluation metrics	This is a **critical contradiction** CDIO needs measurements Deming warns about misuse of measurement
Remove barriers to pride in workmanship		
Deming Point: 12	CDIO Standards: 9 & 10	Faculty need time, recognition and autonomy. Otherwise, will CDIO become bureaucratic compliance, not meaningful development
Everyone involved in transformation		
Deming Point: 14	CDIO Standards: All – system-wide implementation	CDIO is inherently a program-level transformation that requires alla faculty participation and shared ownership partial adoption = failure mode in both frameworks

PROBLEM – RISK OF TAMPERING (FALSE ACTION PLAN INITIATION)

Understanding the variation in course evaluation numbers is crucial to know when and when not to initiate quality improvement action plans on the course level. The overall course status across programs is monitored with the mean of course survey question 8 (Q8) (Figure 22). The normal procedure to monitor course quality at Chalmers starts with tabulating course survey responses for the courses completed after each study quarter (Figure 23). The numbers in column Q8 are reviewed. Green if above 3,5 and white cells below. Courses with Q8 numbers above 3,0 are left as is for next round. When Q8 numbers are below 3,0 the examiner is asked to investigate why and make appropriate changes and write an action plan report.

1. I had sufficient prior knowledge to be able to follow the course.
2. The learning outcomes clearly described what I was expected to learn in the course.
3. Learning
   - A. The course structure (division into lectures, exercises, laboratories, simulations, etc.) is appropriate for achieving the course learning outcomes.
   - B. The teaching worked well.
   - C. The course literature (including other course materials) supports learning well.
4. The examination (including all compulsory components, written exams, assignments, etc.) assessed whether I had achieved the course learning outcomes.
5. The course administration (ongoing information, course syllabus/PM, course website, etc.) worked well.
6. The course workload in relation to the number of credits was appropriate.
   - NB: scaled with $6^* = 5 - (\text{Question } 6 - 3)^2$, to obtain a max at 3, see below. Question 6 = 3 → Question $6^* = 5$.
7. Gender Equality, Diversity, and Inclusion
   - A. The course structure, teaching, and examination were designed so that I feel I was able to learn and be assessed on equal terms with other students in the course.
   - B. The course materials, such as literature, presentations, assignments, and examples, were selected and designed with the aim of including all students, i.e., not reinforcing stereotypes or being discriminatory.
8. What is your overall impression of the course?

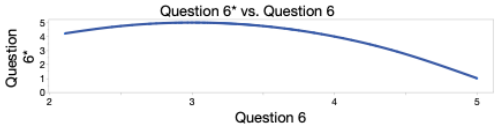
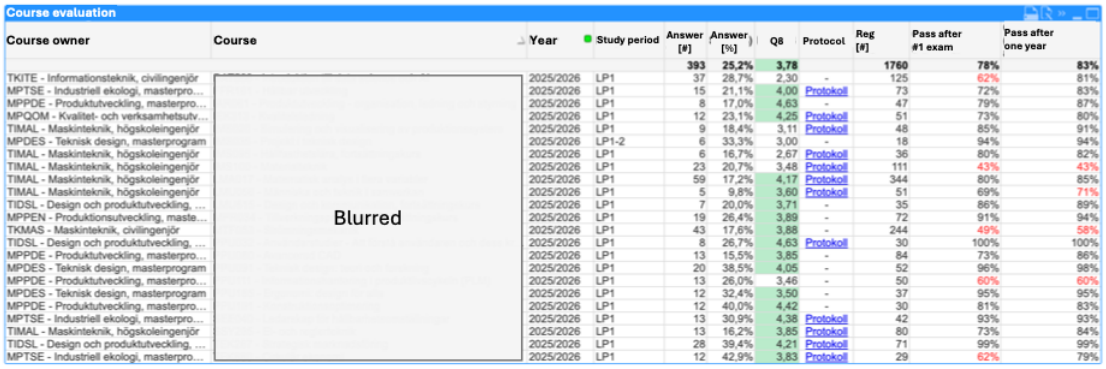


Figure 22. First eight standard questions of the course evaluation survey at Chalmers. Students classify the course they just took on a 1-5 scale for these 8 questions. The higher the better ranking, except on workload Q6 where target is 3. Q6* has been added show Q6=3 to correspond to Q6*=5



Course owner	Course	Year	Study period	Answer [#]	Answer [%]	Q8	Protocol	Reg [#]	Pass after #1 exam	Pass after one year
				393	25,2%	3,78		1760	78%	83%
TKITE - Informationsteknik, civilingenjör	Blurred	2025/2026	LP1	37	28,7%	2,30	-	125	62%	81%
MPTSE - Industriell ekologi, masterpro...		2025/2026	LP1	15	21,1%	4,00	Protokoll	73	72%	83%
MPPDE - Produktutveckling, masterpro...		2025/2026	LP1	8	17,0%	4,63	-	47	79%	87%
MPQOM - Kvalitet- och verksamhetsutv...		2025/2026	LP1	12	23,1%	4,25	Protokoll	51	73%	80%
TIMAL - Maskinteknik, högskoleingenjör		2025/2026	LP1	9	18,4%	3,11	Protokoll	48	85%	91%
MPDES - Teknisk design, masterprogram		2025/2026	LP1-2	6	33,3%	3,00	-	18	94%	94%
TIMAL - Maskinteknik, högskoleingenjör		2025/2026	LP1	6	16,7%	2,67	Protokoll	36	80%	82%
TIMAL - Maskinteknik, högskoleingenjör		2025/2026	LP1	23	20,7%	3,48	Protokoll	111	43%	43%
TIMAL - Maskinteknik, högskoleingenjör		2025/2026	LP1	59	17,2%	4,17	Protokoll	344	80%	85%
TIMAL - Maskinteknik, högskoleingenjör		2025/2026	LP1	5	9,8%	3,60	Protokoll	51	69%	71%
TIDSL - Design och produktutveckling, ...		2025/2026	LP1	7	20,0%	3,71	-	35	86%	89%
MPPEN - Produktionsutveckling, maste...		2025/2026	LP1	19	26,4%	3,89	-	72	91%	94%
TKMAS - Maskinteknik, civilingenjör		2025/2026	LP1	43	17,6%	3,88	-	244	49%	58%
TIDSL - Design och produktutveckling, ...		2025/2026	LP1	8	26,7%	4,63	Protokoll	30	100%	100%
MPPDE - Produktutveckling, masterpro...		2025/2026	LP1	13	15,5%	3,85	-	84	73%	86%
MPDES - Teknisk design, masterprogram		2025/2026	LP1	20	38,5%	4,05	-	52	96%	98%
MPPDE - Produktutveckling, masterpro...		2025/2026	LP1	13	26,0%	3,46	-	50	60%	60%
MPDES - Teknisk design, masterprogram		2025/2026	LP1	12	32,4%	3,50	-	37	95%	95%
MPPDE - Produktutveckling, masterpro...		2025/2026	LP1	12	40,0%	4,42	-	30	81%	83%
MPTSE - Industriell ekologi, masterpro...		2025/2026	LP1	13	30,9%	4,38	Protokoll	42	93%	93%
TIMAL - Maskinteknik, högskoleingenjör		2025/2026	LP1	13	16,2%	3,85	Protokoll	80	73%	84%
TIDSL - Design och produktutveckling, ...		2025/2026	LP1	28	39,4%	4,21	Protokoll	71	99%	99%
MPTSE - Industriell ekologi, masterpro...		2025/2026	LP1	12	42,9%	3,83	Protokoll	29	62%	79%

Figure 23: Sample of standard course quality monitoring for the courses in first study period academic year 2025/2026.

CONSEQUENCES OF ZOOMING-IN ON SINGLE TABULATED VALUES

Deming (and others) recommend using SPC-thinking to distinguish between common cause of variation and special cause of variation. In Figure 24, the variation of the Q8 number for one of the courses over five academic years is shown using an Individual moving Range control chart (ImR) from the Statistical Process Control (SPC) toolbox. The primary use of control

charts is to distinguish between signal and routine variation (noise) and to help avoiding two mistakes in data analysis (Wheeler Donald J. (2002)):

- Mistake One: Interpreting the routine variation of noise as if it amounted to a signal of change in the underlying process, thereby sounding a false alarm
- Mistake Two: Thinking that a signal of change in the underlying process is merely the noise of routine variation, thereby missing a signal

The ImR-chart evolved in the forties from the original control chart invented by Walter Shewhart in 1924. ImR was populated during the fifties and sixties by Dr. W. Edwards Deming and Dr. Donald Wheeler as an aid for managerial follow-up. The theories and techniques are well explored in the general quality literature, for example: 'Quality from customer needs to customer satisfaction' (Bergman, B., Bäckström, I., Garvare, R., & Klefsjö, B. (2022)), 'Understanding variation: The key to managing chaos' (Wheeler, D. J. (2000)), 'Data Sanity' (Balestracci, D. (2015)).

Figure 24 exhibit two panels, the upper shows the time sequence of Q8 over five years. The lower shows the moving range (mR) between two consecutive years in absolute numbers (positive). For this course, Q8 is stable and predictable and will most likely continue to vary with 50% chance to be over or under the average between the Upper and Lower Control Limit (UCL and LCL), respectively, for the years to come. The average moving Range mR is 0.3, which is the base for the control limits calculation using the well-established standard multiplicators 3,27 and 2,66 for mR and Individual observation panels, respectively (red lines). The control chart tells that all variation within the control limits is common cause of variation without plausible explanation. In 50% of the cases Q8 changes more than 0.3 from year to year and can be as large as 0,9 without reason.

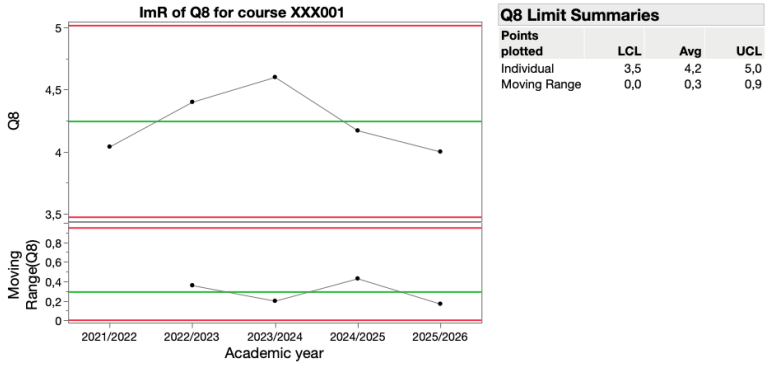


Figure 24: Individual & Moving range chart (ImR) visualizes how Q8 vary for a typical course 2021-2025. It shows no signs of signals, only common cause of variation average mR=0,3 The course quality is stable and predictable and will most likely continue to perform with Q8 on average at 4.2 but can vary from 3.5 to 5 because of common cause of variation.

In Figure 25, four different patterns of the Q8 variation have been connected to the decisions taken on action plan initiation depending on Q8<3 or not. The quarters represent the following:

- Upper left (Yes-Yes): Action plan correctly initiated when five-year average < 3.0 (left) OR single observations outside the control limits AND below 3.0 (right) (*)
- Upper right (No-Yes): Action plan is not initiated (No) even though five-year average of Q8 < 3.0. Slipped aways (▼).

- Lower left (Yes-No): Action plans initiates (Yes) because Q8 < 3, but it is inside control limits and only common cause of variation (No) (▧)
- Lower right (No-No): No action plan initiated AND Q8 & Q8 average are both >3 (•)

The intention with the classification in Figure 25 is to be able calculate the misclassification rate and the Flase-Discovery-Rate FDR as metrics of quality of this judgement procedure.

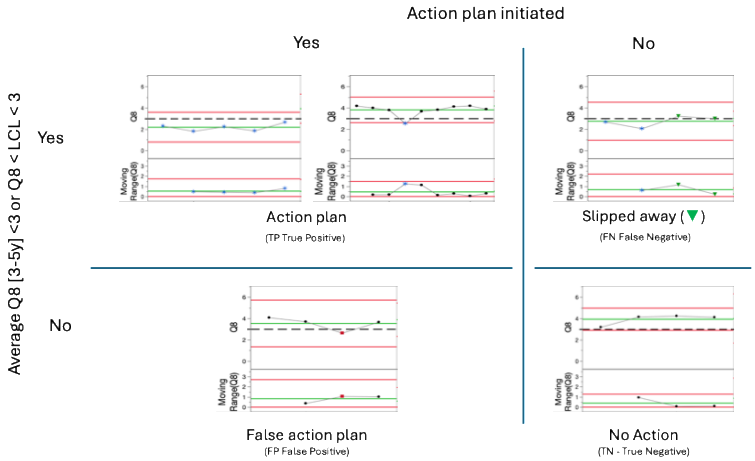


Figure 25: ImR of Q8 scores for five of the courses in relation to the trigger level of Q8=3. Yes/Yes: Action plan initiated correctly ∗, Yes/No: Action plans missed ▼, No/Yes: Action Plans on False Alarms ▧, No/No: Action plan correctly not initiated

Sample Data

Figure 26 display ImR charts of Q8 for 128 courses given in two basic (B.Sc) engineering programs, TIMAL and TIDSL, and two progammes on advance level (M.Sc), MPPDE and MPDES from Mechanical Engineering and Technical Design Engineering, respectively. Compulsory program courses are regularly run every year (five data points) and the elective courses vary between 1 and 10 depending on if students elected them and if they run two times a year (large courses). The threshold for action plan initiation (Q8 = 3,0) is marked with a horizontal black line.

- Mechanical Engineering
  - TIMAL – Mechanical Engineering 3y B.Sc.
  - MPPDE – Product Development +2y M.Sc.
- Technical Design Engineering
  - TIDSL – Design and Product Development 3y B.Sc.
  - MPDES – Technical Design +2y M.Sc.

Even if the time series are short, 6-8 data points is recommended for high precision of the control limits (Wheeler DJ. 2002), the lions' share of the 128 control charts shows a stable and predictable behaviour where most variation is common course of variation. For all courses, except three, the five-year average (green) is above 3,0. Two courses in TIMAL and one in TIDSL with correctly initiated Action Plans (∗). All together have 41 Action Plans (∗ correct + ▧ false alarm) been initiated, which is 9% of all surveys.

Figure 27, visualizes the classification of all 451 surveys according to the definitions in Figure 25. The misclassification rate is defined as the total number of misclassifications in relation to the total number of surveys, that is, 7%. In other words, 1 out of 15 surveys is misclassified,

which is 1–2 surveys per study period. Out of the 41 initiated Action Plans initiated 61% (FDR – False Detection Rate) were initiated from common cause of variation down within the noise band, when the average Q8 was > 3, that is False alarms.

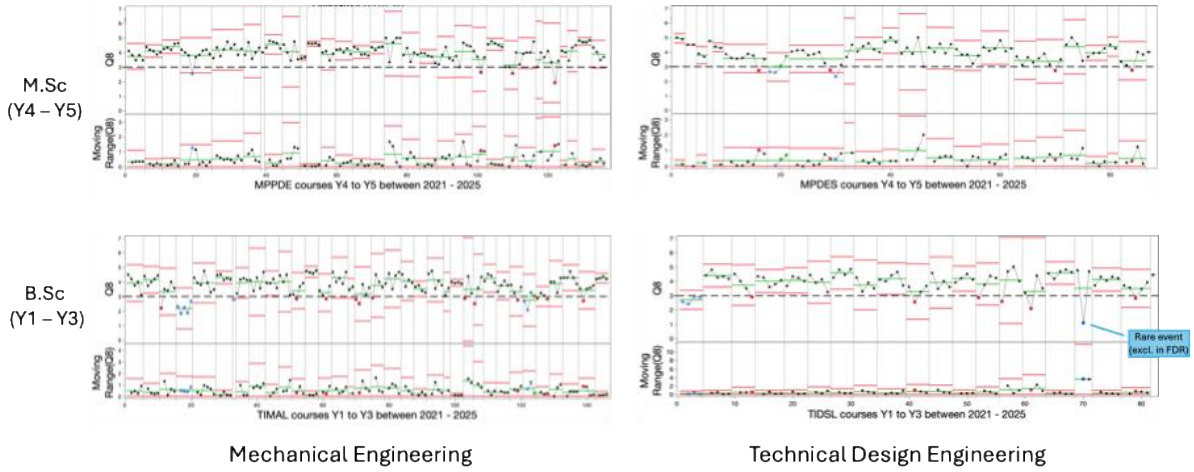


Figure 26: Variation in Q8 over five years for 128 courses in four programmes on basic (B.Sc - below) and advanced level (M.Sc - above) visualized using ImR control chart from SPC-thinking: Mechanical Engineering left and Technical Design Engineering right. Each course has a vertical segment where the upper part shows Q8 and the lower part the corresponding moving range mR. Surveys that initiated Action Plans relative Q8 <3 are coded according to Figure 25.

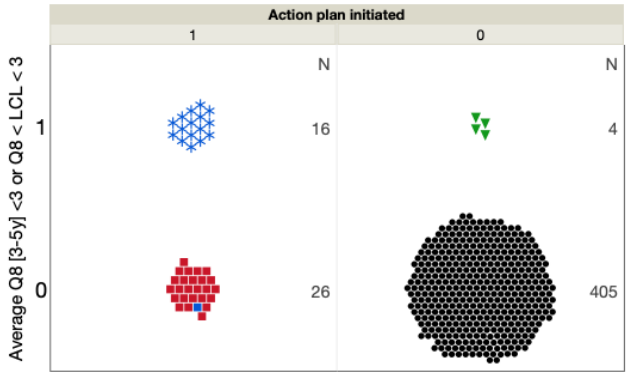


Figure 27: $Misclassification\ Rate = \frac{Number\ of\ Misclassifications}{Total\ Number\ of\ Observations} = \frac{30}{450} \rightarrow 7$ %, that is,1:15, meaning 1-2 surveys per study period are incorrectly classified as Q8<3. The precision, the ratio of false alarms, is defined as: $Precision = \frac{TP}{TP+FP} = \frac{16}{41} = 0{,}39 \rightarrow 39\%$, implying that the False Discovery Rate FDR (1-Precision) is 61%, that is, the risk to falsely initiate an action plan with Q8 < 3 is over 60%. One rare event is excluded from the calculations.

In Figure 28, the effect of the common cause of variation is visualized in the same ImR without the individual course averages. This assumes that the common course of variation in the survey process is the same based on the same level of answer frequency (Figure 29). The average mR across all courses is 0,5. The average moving range (0,5) indicates that annual changes of Q8 up to 1,5 units can be considered common cause of variation (random noise). The control limits in the upper panels +/- 1,2 units indicate the limits for random variation of Q8. More than >98% of the Q8 variation in these 452 surveys is noise.

The Answer frequency in Figure 29 is also a stable and practicable process that vary with average 28% [1,6%, 54,2%] without any reason. In the standard survey process students get a survey-link in the mail after the course is complete and exam done. There are some observations above the upper control limit with survey responses in the range of 60-80%. These results were obtained when the survey was distributed and filled in during the last lecture, that is, by another process.

The consequence of not considering the routine (random) variation in the Q8 response increase the risk starting action plans based on false alarms. This results in a tampering behaviour that overcompensate for variation, leading to unnecessary changes and frustration among teachers and programme administration.

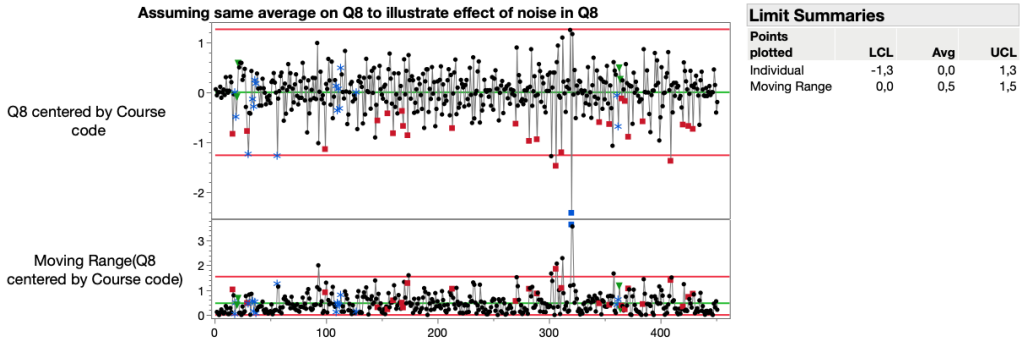


Figure 28. Almost all variation (>98%) of Q8 is within the control limits assuming a grand average moving range (mR) for all courses is 0,5 and the average Q8 level for all individual course is removed. This reflects the decision take from the table in Figure 23. This implies that Q8-scores varies +/- 1,3 without any reason.

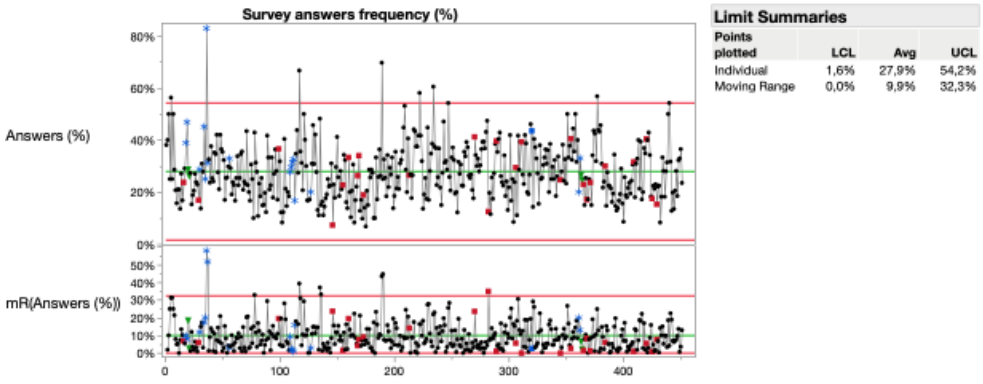


Figure 29. Answer frequency [%]. The standard process of mailing a link to the course survey results in a stable and predictable process. The points outside upper control limit, which are occasions when another survey distribution process been used, in class during final lecture.

PROBLEM ANALYSIS SUMMARY

The risk of falsely initiating action plans based on a single table value that go under a threshold is high. The False-Detection-Rate is 61%, meaning that when Q8 drops below 3.0 there is a larger chance to take the right decision when tossing a coin. The result second Dr Demings warning that managerial data of this kind mainly consist of common cause of variation driving fragmentation. Also, Davis Balestracci second this argument in his book Data Sanity (Balestracci, D. 2015) with cases from the medical field, where time series data of this kind

consists of 85% - 90% common cause of variation. Consequence is that zooming in on specific data points tend to drag programme management attention to details driving the blame game making teachers feeling guilty and frustrated since they cannot find a rout cause for the 'bad' quality, instead of shifting to an supportive overall understanding of how the programme function and on system-level. When fitting a normal distribution to Q8 data from Figure 23 it is difficult to say that the two numbers below 3 not is part of the same distribution of common cause of variation as the rest of the numbers from that Study Period $N[\bar{x}, \sigma] = N[3.8, 0.59]$.

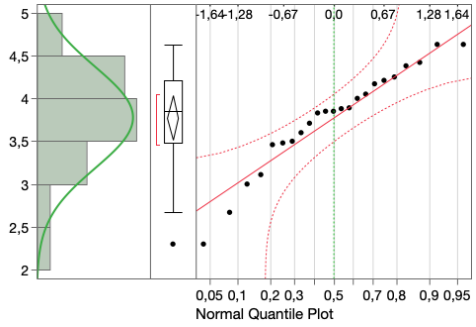


Figure 30: Fit of Normal distribution to the Q8 numbers from Study Period 1 2025 in Figure 23

BEYOND TAMPERING - DECOMPOSING COMMON CAUSE OF VARIATION

When a process only contains common cause of variation (random noise) it is said to be in statistical control and is stable and predictable. The role of control charts within statistical process control is to filter out the random noise to be able to see the signals, that is, changes in the system that has an explanation. As shown with Figure 28, there is not much information in a Q8 number, since it can vary +/- 1,3 from the year before without any reason.

However, just we cannot see any structure in the noise it does not mean there isn't any. Absence of evidence is not evidence of absence, often referred to Carl Sagan or William Wright. In radiography, the challenge is to take good decision about cancer, without increasing the general radiation dose to the society that will increase the risk of cancer. In Quality Engineering a stable and predictable process cannot be improved by fixing it, it needs to be rebuilt to understand and mitigate the influence of common cause of variation. To understand if there exist underlying patterns in the noise the strategy is to zoom-out since individual data-point won't give a clue.

However, zooming out from a single educational program is challenging for the individual PA (programme director). Challenging in several different aspects. The PA-team needs:

- a common language on common cause vs. special cause of variation, that is, signal vs. noise.
- a clear operational definition of what to monitor, how to test on aggregated level and what decisions to take, as in W. Edwards Demings point 5 (Gitlow HS., Gitlow SJ. (1987))
- a common view of the overall system and how to communicate and aggregate systematic variation and structures hidden in the noisy data

Both Deming and Einstein claim that systems cannot be understood and improved from the inside and formulated it, for example, as: "Problems that are created by our current level of thinking can't be solved by that same level of thinking".

The question is to advance the understanding of how to use the course survey results not only to initiate single course improvement (or maybe rather not to initiate action plans), to zoom-out and reinforce a structural programme development dialogue. The question is: Can the standardised course surveys be used to create a common language and structural program development on a higher hiearachical level from inside the teaching system?

REVEALING STRUCTURES IN THE UNDERLYING SYSTEM OF Q8 SCORES

Stratification using ANOVA on the natural attributes connected to the programmes Figure 31 reveal some minor effects. There is a systematic higher level of Q8 between the level of studies in Mechanical Engineering (+0,28) but not in Technical Design Engineering. Courses seem to be more appreciated in later years compared to the first (+0,45).

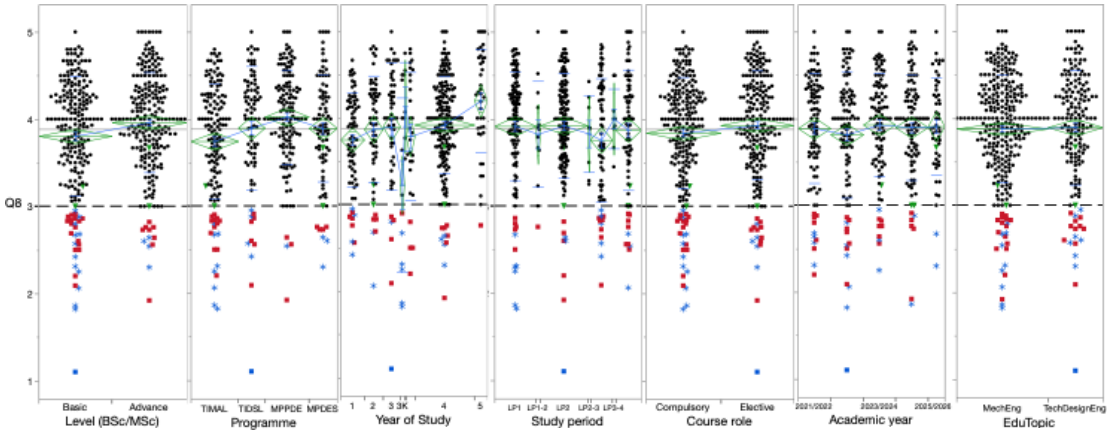


Figure 31: Some minor systematic effects explaining systematic variation in Q8 is revealed using ANOVA. The three to the left have significant shift of the means, whereas the four to right does not. From left M.Sc. programmes have systematically 0,15 higher on Q8 than B.Sc. courses, which interacts with the field of studies. No difference between levels in Technical Design Engineering, whereas in Mechanical Engineering it is. The MP is 0,28 higher on Q8. Third panel: Over time the Q8 response increase 0,45 from year 1 to year 5.

To further explore if there are any underlying patterns. The courses are classified into one of five elevated generic categories/role linked to CDIO Standards aiming to capture the course role in the programmes (Table 11). The sampled programmes all have roughly the same number of course types in each category Figure 32. A stratification on course categories and level of education Figure 33 reveals that the only notable difference is on the course category: Project and Project and applied practice (open projects - applying toolbox in profession). On advance level these courses are systematically given 0.2 more than other course categories and on basic they score 0,7 lower.

RESULT

The course evaluation response of Question Q8 (What is your general impression of the course on a scale 1-5?) vary almost only depending on common cause of variation, that is noise. It can vary +/- 1.3 units from year to year without any explanation. When Q8 drop below 3.0, the current course evaluation process requires that an Action Plan for course development is initiated. Out of 451 surveys from 128 courses in four different programs on basic and advance level, this criterion has led to the initiation of 41 Actions Plans (9%).

When considering the uncertainty in the Q8 number +/- 1.3 units, the misclassification rate is 7%. One out of fifteen surveys are incorrectly classified on the wrong side of the threshold. The FDR, the False-Detection-Rate, is large than 60%.

Decomposing the common cause of variation relative programme characteristic attribute reveal some underlying structure in the noise. Courses later in the programs get systematically ~0,5 units higher score on Q8 than courses in the first year. One underlying explanation of this is that courses with open-ended projects scores 0.9 unit lower on bachelor level compared to master programme level.

Table 11: Course characterization / role vs. CDIO Standards

Course classification/roles	CDIO Standards connection
Applied engineering courses (incl. tailored projects to train specific methods)	Standard 5 (design-implement experiences) Standard 7 (integrated learning experience)
Fundamental theory (programme spine and basic building blocks)	Standard 2 (disciplinary knowledge Standard 3 (integrated curriculum) *Conceive phase*
Methodology and tools (master the toolbox)	Standard 3 (integrated curriculum) Standard 5 (design-implement experiences)
Professional competencies and context (understand professional role, demo-projects)	Standard 2 (personal and interpersonal learning outcomes, Section 2 & 3) Standard 8 (active learning) Standard 9 (faculty competence) *Operate phase*
Project and applied practice (open projects - applying toolbox in profession)	Standard 5 (design-implement experiences) Standard 4 (introduction to engineering) Standard 12 (program evaluation)

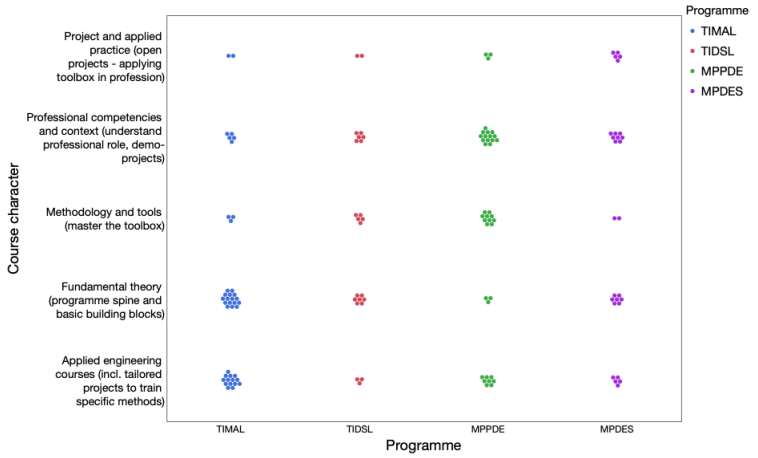


Figure 32. Classification of courses in the sampled programmes in Mechanical Engineering and Technical Design Engineering at Chalmers

DISCUSSION

Details

One plausible explanation for the different score on open-ended problem courses would be that open-ended problem solving in the beginning of the programmes are more challenging for the students where the course structure is much more unclear, in contrast to open-ended projects in the final years that address problems closer connected to their selected exit profile. Since these courses on bachelor level often fall below the Q8-threshold for Action Plan course development, it is relevant to ask if these courses should be judged by the same threshold

since they are core courses in the CDIO framework? Handling of open-ended projects with unclear solutions are at the core of the engineer profession and what we intend to educate them to handle.

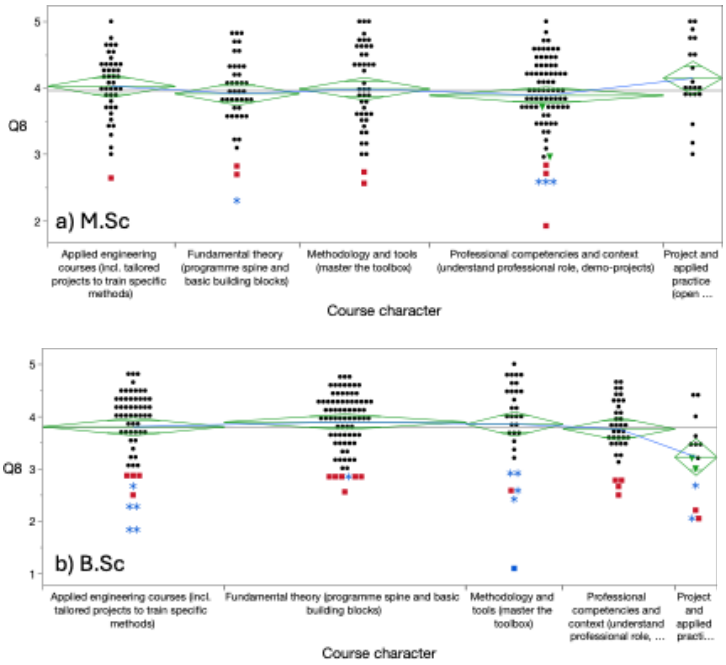


Figure 33: There are no statistically significant difference between the different course characters on advanced level, but a strong tendency that open-ended project courses overall are well accepted among students. On basic level is there a significant difference that open-ended project courses are not well received. a) 3.9 vs. 4.1, that is 0.2 systematically higher on Q8. b) 3.9 vs 3.2, that is 0,7 systematically lower. An overall difference of 0,9.

Intermediate

The high level of random noise in the survey data, visualized in Figure 28, tend to drive over-reaction on course survey response variation, which results in unnecessary initiation of action plans that raise stress levels and frustrations for nothing. In the book 'Data Sanity' (Balestracci, D. (2015)), the author claims that 85-90% of the variation seen in managerial data is common cause of variation and only a small part of the variation has assignable cause. The dilemma according to the author is that most organisations have routines for problem solving for special cause (zooming-in) but lack strategies to understand and reduce the level of common cause of variation that require zooming-out and elevated expansion of the problematic system. Problems tend to be pushed too low in organisations, too late in the chain of events in the lap of the symptom owners that only can handle them reactively instead of making it possible to identify the true root cause of the problem. There is also a built-in lurking driver for programme managers to act rather than not to. This is due to underlying cognitive that trigger tampering including mechanisms, such as fear of the consequences of not acting if not individual feel safe or there is lack of time and room for elevated discussions on system-level (Smeds, M., J. Martin, M. Elg and I. Gremyr. 2023). Avoiding tampering go hand in hand with Deming's point 8 about driving out fear.

An interesting observation of the shift in mind-set was noted during a teachers meeting for the Mechanical Engineering bachelor programme when changing from the normal follow-up visualization in Figure 23 to the aggregated multi-course control chart in Figure 26. Spontaneously, the examiner of the fourth course from the left, who struggles frustratingly with

course improvement Action Plans every year without knowing what to do to convince the students said: “Maybe this course is not the right one for this programme”. A second reflective comment from another teacher was: “if we are going to use this data for a constructive dialogue on program development, we need a better process to collect student opinions”. This spontaneous shift of mind-set from reactive to proactive when tables and bar charts are shifted to control charts visualizing signals vs. noise have been noticed before by the author and colleagues (Ericson Öberg, A., et. al. 2016).

Overall

The overlap of CDIO and Dr Deming’s System of Profound Knowledge is strong, except for one crucial point about basic data quality. This study second Dr. Deming’s warnings regarding his point 5: If there is a lack of understanding of the difference between common cause of variation and special cause of variation the shift from individual follow-up, driving blame game, to an aggregated dialog on system development hindered, that is, programme and multi-programme development and management.

CONCLUSION

There is a strong overlap between CDIO Standards 3.0 and Dr. Deming’s 14 point for management, except for the one point with tension: CDIO Standard 12 (Program Evaluation) vs Dr Deming’s point 5 (Improving the System). The former formalizes course evaluation and program reviews whereas Deming warns against misinterpretation of variation and tampering based on a lack of a common language and joint organisational strategies to differentiate between common cause and special cause of variation. This study second Dr Deming’s warning. Almost all variation in the trigger parameter for quality improvement action stems from common cause of variation that results in many actions based on False Alarms, that is, overreaction to random fluctuations – tampering. This tends to hinder a shift of joint mindset from course details to program function (system level) that needs a systematic approach to detect underlying patterns in the noisy data.

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SIMULATION-DRIVEN RESILIENCE: FROM CDIO TO CDI'S' ASSESSMENTS TO OUTSMART AI SHORTCUTS

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ABSTRACT

The Conceive–Design–Implement–Operate (CDIO) framework has played a central role in aligning engineering education with professional practice through authentic, project-based learning and outcome-oriented assessment. By embedding learning within realistic workflows, CDIO has shifted emphasis from content delivery to demonstrated competence. However, in management-oriented engineering domains such as supply chain management, operations strategy, and complex project environments, the Operate phase presents structural limitations. Real operational systems cannot be physically enacted in educational contexts due to constraints of scale, cost, risk, time, and ethical responsibility, often leading to simplified case-based or report-driven approximations that weaken experiential authenticity. At the same time, higher education faces growing challenges related to assessment integrity arising from the widespread availability of generative artificial intelligence. Traditional written assessments, including those embedded within CDIO projects, are increasingly vulnerable to AI-assisted production that obscures student reasoning and professional judgement. This paper proposes CDIS (Conceive–Design–Implement–Simulate) as an extension of the CDIO framework in which simulation replaces physical operation as the primary mechanism for experiential learning and assessment. Simulation-based environments enable complexity, uncertainty, delayed feedback, and cross-functional decision-making without the risks of real-world replication. Using The Fresh Connection supply chain simulation as an illustrative implementation, the paper argues that CDIS supports authentic, data-driven, and AI-resilient assessment. By embedding learning within dynamic systems governed by real-time KPIs and iterative decision cycles, CDIS strengthens deep learning while preserves the epistemological intent of CDIO in complex engineering and management education contexts.

KEYWORDS

Simulation-based learning, CDIO framework, Authentic assessment, Supply chain education, Assessment integrity, Standards 1–3, 5–8 and 11.

INTRODUCTION

Over the past two decades, the Conceive–Design–Implement–Operate (CDIO) framework has become one of the most influential models in engineering education. By positioning the full lifecycle of products, processes, systems, and services as the context for learning, CDIO has strengthened alignment between engineering curricula, professional practice, and outcome-based accreditation (Crawley et al., 2007, 2014). Its emphasis on experiential and active learning has shifted assessment away from passive knowledge recall towards the demonstration of integrated technical, personal, and interpersonal competences (Biggs & Tang, 2011). As a result, CDIO has addressed long-standing critiques that engineering education is overly theoretical and insufficiently connected to real-world practice (Felder & Brent, 2016).

As engineering education increasingly extends into management-oriented and system-level domains such as supply chain management, operations strategy, and complex project environments, the assumptions underlying the Operate phase warrant closer examination. In these contexts, operational performance emerges from complex interactions across networks, organisations, and time horizons rather than from a single physical artefact that can be constructed and tested within a laboratory environment. Consequently, operational learning is often approximated through case studies or report-based analysis, which can weaken the experiential authenticity central to the CDIO approach (Kolb, 1984; Prince & Felder, 2006).

At the same time, the assessment landscape in higher education is being reshaped by the rapid adoption of generative artificial intelligence tools. While these technologies offer legitimate support for learning, reflection, and ideation, they also expose structural weaknesses in traditional assessment formats. Written reports, reflective narratives, and explanatory analyses can increasingly be produced with limited cognitive engagement, making it difficult to distinguish deep understanding from surface-level reproduction (Boud & Falchikov, 2007). This challenge is particularly pronounced in management-oriented engineering education, where assessment frequently prioritises narrative justification rather than observable system behaviour and performance.

Together, these developments raise a fundamental question for contemporary engineering education: how can experiential, authentic, and outcome-based learning be sustained in domains where physical operation is infeasible and conventional assessments are vulnerable to automation? Reverting to tightly controlled or exam-based assessment would undermine the pedagogical progress achieved through CDIO and constructive alignment (Biggs & Tang, 2011). Instead, what is required is a principled evolution that preserves CDIO's core values while adapting its mechanisms to the realities of complex, data-driven systems.

This paper proposes CDIS (Conceive–Design–Implement–Simulate) as such an extension. In CDIS, simulation replaces physical operation as the final integrative phase of learning and assessment. Simulation-based environments allow students to make consequential decisions under uncertainty, observe system-level outcomes, and iteratively refine strategies without real-world risk—an approach long established in engineering, operations, and systems education (Sitzmann, 2011). By embedding assessment within measurable system performance rather than narrative output, CDIS strengthens experiential authenticity, supports interdisciplinary collaboration, and enhances assessment integrity. Using The Fresh Connection supply chain simulation as an illustrative implementation, the paper demonstrates how CDIS preserves the spirit of CDIO while extending its applicability and robustness in

contemporary engineering and management education (Kok & van Zyl-Cillié, 2024; García-Reyes, Maycotte-Felkel & Quijano-Dominguez, 2023).

BACKGROUND

CDIO, Authentic Assessment, and the Limits of Physical Operation

The Conceive–Design–Implement–Operate (CDIO) framework was developed to address critiques that engineering education is overly theoretical and insufficiently aligned with professional practice. By focusing on demonstrable competence, CDIO aligns with accreditation frameworks such as ABET and AHEP4, which emphasise applied knowledge, professional skills, and performance in complex contexts (ABET, 2025; Engineering Council, 2020). Grounded in experiential learning theory, it conceptualises learning as an active process integrating technical knowledge, teamwork, and systems thinking (Kolb, 1984b).

A key feature of CDIO is authentic assessment, where learning is evaluated through tasks resembling professional practice and requiring judgement and problem-solving under realistic constraints (Wiggins, 1998). Such approaches support deeper learning and stronger alignment with industry expectations (Kozanitis et al., 2009).

In many engineering disciplines, the Operate phase enables this through physical systems and prototypes. However, in management-oriented domains such as supply chain and operations, systems are large-scale, distributed, and socio-technical, making authentic physical operation difficult to reproduce. As a result, operational learning is often approximated through case studies or report-based assessments, which are typically static and retrospective, limiting opportunities for iteration and real-time feedback (Kozanitis et al., 2009).

These limitations are further amplified by generative artificial intelligence, which can produce coherent narratives with minimal engagement. This raises not only concerns about academic integrity but also epistemic validity, as assessments based primarily on written explanation may fail to capture genuine professional competence (Boud & Falchikov, 2007; Wiggins, 1998; Kozanitis et al., 2009).

Taken together, these considerations suggest that the purpose of the Operate phase lies in exposing students to the consequences of decisions within realistic systems rather than in physical deployment itself. In contemporary engineering practice, such consequences are often mediated through performance indicators and feedback loops. Simulation therefore provides a pedagogically robust extension, enabling realism, iteration, and measurable outcomes without the constraints of physical replication, forming the conceptual basis for CDIS. While simulation can already be integrated within CDIO implementations, CDIS should be understood not as a replacement, but as a pedagogical emphasis highlighting the central role of simulation in domains where physical operation is impractical.

Theoretical Positioning: CDIS in Relation to CDIO and Project-Based Learning

Project-Based Learning (PBL) has long been used in engineering education to promote active, contextualised problem solving. Rooted in constructivist and experiential learning theory, PBL emphasises learning through extended tasks that require inquiry, collaboration, and the production of tangible outputs (Kolb, 1984; Prince & Felder, 2006). While PBL is widely recognised for enhancing student engagement and motivation, it is often pedagogically under-specified at programme level. In particular, PBL implementations can vary substantially in

terms of curricular coherence, assessment alignment, and progression, and projects frequently culminate in reports or presentations rather than observable system performance.

The CDIO framework can be understood as a structured evolution of PBL that addresses these limitations by situating projects within a clearly articulated lifecycle of professional engineering activity (Crawley et al., 2014). By linking learning outcomes to the stages of conceiving, designing, implementing, and operating systems, CDIO strengthens curricular coherence and supports authentic assessment through engagement with real or realistic systems. However, this approach is less readily applicable in domains where physical implementation and operation are infeasible.

CDIS (Conceive–Design–Implement–Simulate) is proposed as a domain-sensitive extension of CDIO. It preserves the lifecycle logic and experiential emphasis of CDIO while replacing physical operation with simulation in contexts characterised by scale, complexity, and systemic interdependence. Simulation-based environments enable students to engage with uncertainty, trade-offs, and system feedback through measurable outcomes over time. In this way, CDIS extends CDIO's theoretical foundations to complex socio-technical systems while maintaining its focus on authenticity, integration, and assessment integrity. Table 12 summarises the distinctions between PBL, CDIO, and CDIS across key dimensions.

Table 12: Comparison of Project-Based Learning (PBL), CDIO, and CDIS

DIMENSION	PROJECT-BASED LEARNING (PBL)	CDIO	CDIS
Theoretical foundation	Constructivist and experiential learning (Kolb, 1984)	Experiential learning with outcome-based accreditation alignment (Crawley et al., 2014)	Experiential learning extended through system simulation and performance-based assessment
Curricular structure	Loosely structured; varies by course and instructor	Explicit lifecycle structure: Conceive–Design–Implement–Operate	Lifecycle structure: Conceive–Design–Implement–Simulate
Primary learning focus	Engagement through projects	Development of professional engineering competencies	Strategic and system-level decision-making in complex systems
Nature of the project	Often artefact- or report-based	Product, process, or system development	Dynamic system management within a simulation environment
Final integrative phase	Project presentation or report	Physical operation of a product or system	System simulation with evolving outcomes
Assessment approach	Often summative and narrative-based	Authentic, performance-informed assessment	Data-driven, performance-based, and iterative assessment
Feedback mechanism	Instructor-led, often periodic	Iterative feedback linked to lifecycle stages	Continuous feedback through system-generated KPIs
Handling of complexity and uncertainty	Limited; often simplified	Moderate; constrained by physical feasibility	High; uncertainty, trade-offs, and time pressure embedded
Interdisciplinary collaboration	Optional or implicit	Explicit and structured	Mandatory and role-based (e.g., sales, supply chain, operations)
Scalability to large systems	Limited	Limited in management-intensive domains	High; suitable for large-scale socio-technical systems
Vulnerability to AI-generated work	High	Moderate	Low; performance depends on real-time decisions and outcomes
Typical application domains	Design courses, capstone projects	Product design, manufacturing, laboratory systems	Supply chain management, operations strategy, project environments

From Operate to Simulate: Conceptualising CDIS

The CDIS framework (Conceive–Design–Implement–Simulate) extends the CDIO lifecycle by adapting the final integrative phase to the characteristics of complex management-oriented engineering systems. Rather than relying on physical operation, CDIS positions simulation as the environment through which students experience consequences, evaluate performance,

and demonstrate professional competence. In many contemporary engineering and managerial contexts, competence is evidenced through decision quality, system behaviour, and performance indicators rather than through direct operation of physical artefacts.

Within CDIS, the Conceive phase focuses on strategic framing, requiring students to interpret contexts, define objectives, and establish performance indicators that balance cost, service, sustainability, and resilience (Crawley et al., 2014). The Design phase translates these objectives into decision policies while considering system-wide trade-offs, consistent with principles of authentic assessment (Wiggins, 1998).During Implement, strategies are operationalised and refined through feedback, reflecting Kolb's experiential learning cycle (Kolb, 1984). Finally, the Simulate phase provides dynamic outcomes such as financial performance, service levels, and sustainability indicators that evolve over time, exposing students to uncertainty, nonlinearity, and delayed system effects.

From an assessment perspective, CDIS operationalises authentic assessment more robustly than traditional project-based approaches. Students are evaluated on their ability to interpret feedback, adapt strategies, and justify decisions in relation to observed outcomes rather than on narrative explanation alone (Kozanitis et al., 2009). Reflection remains central but is anchored in concrete performance trajectories and decision histories, significantly reducing the effectiveness of AI-generated submissions. Assessment integrity is thus achieved through pedagogical design rather than restriction.

Interdisciplinary collaboration is integral to CDIS implementations. Simulation environments such as The Fresh Connection require students to assume distinct functional roles (sales, supply chain, purchasing, and operations) each governed by competing objectives (García-Reyes, Maycotte-Felkel & Quijano-Dominguez, 2023; Akkatal, Barooti & Akkartal, 2019). System performance emerges from cross-functional coordination rather than individual optimisation, reflecting contemporary organisational practice and aligning with CDIO's emphasis on teamwork and communication (Crawley et al., 2014). Crucially, collaboration is consequential: misalignment between functions produces measurable degradation in system performance, reinforcing the necessity of integration and shared accountability.

Generative AI and the Fragility of Narrative-Based Assessment

The rapid and recent adoption of generative artificial intelligence has brought renewed attention to long-standing challenges in assessment design within higher education, particularly in disciplines that rely heavily on written explanation, reflection, and structured analysis. While generative AI tools can support learning when used transparently and ethically, their widespread availability has made visible structural vulnerabilities in assessment formats that prioritise narrative coherence over demonstrable engagement with disciplinary processes. These vulnerabilities are not new; assessment scholars have long argued that tasks focused primarily on textual articulation risk privileging presentation over performance and understanding (Boud & Falchikov, 2007; Wiggins, 1998).

In engineering and management education, this vulnerability is especially pronounced. Students are frequently assessed on their ability to justify decisions, interpret scenarios, or reflect on outcomes through textual artefacts. When such tasks are detached from observable system behaviour, acceptable submissions can be produced without sustained engagement with uncertainty, trade-offs, or decision consequences. This issue is not primarily one of academic misconduct, but of epistemic validity: as assessment scholars have long argued, evaluations that do not require students to *act within* and *respond to* a system cannot reliably

measure professional competence (Wiggins, 1998; Boud & Falchikov, 2007; Kozanitis et al., 2009).

Within experiential frameworks such as CDIO, this issue represents a misalignment between pedagogical intent and assessment practice. CDIO emphasises competence demonstrated through action, integration, and consequence rather than symbolic representation alone (Crawley et al., 2014). When the Operate phase is approximated through reports or retrospective analyses, assessment risks reverting to surface-level indicators of learning, creating conditions in which AI-generated outputs can obscure genuine understanding. These developments highlight the need for assessment designs that embed evaluation within system behaviour itself, motivating exploration of simulation-based approaches capable of sustaining authenticity and integrity under contemporary conditions.

CASE STUDY: CDIS IMPLEMENTATION AT UNIVERSITY OF HERTFORDSHIRE

Module Context and Design

The CDIS framework was implemented as a pilot within the Successful Project Delivery course (referred to as a "module" in the UK higher education system), a postgraduate module focused on foundational concepts in project and operations management. The student cohort comprised individuals from diverse academic and professional backgrounds. To promote multidisciplinary perspectives and effective collaboration, students were organised into teams of four to five members. Team composition was informed by both disciplinary background and the results of a personality assessment, with the aim of achieving a balanced mix of skills, working styles, and perspectives within each team.

Based on their background and personality profile, students were advised on functional roles that might best suit them—specifically Operations, Sales, Purchasing, Supply Chain, or Chief Executive Officer—mirroring the functional interdependence characteristic of real-world organisations. Final role allocation, however, was determined collaboratively within each team to ensure shared ownership and alignment with individual preferences. This role-based structure supported interdisciplinary collaboration and reflected CDIO principles related to teamwork, communication, and system integration (Crawley et al., 2014). The pilot cohort consisted of 26 students, forming a total of six teams. The module was deliberately designed to integrate simulation-based experiential learning as a core pedagogical and assessment mechanism rather than as a supplementary activity. This design choice aimed to align learning activities more closely with professional practice in management-oriented engineering contexts, where decision-making under uncertainty, system integration, and cross-functional coordination are central competencies.

At the outset of the module, students received structured instruction on core supply chain and operations management principles, providing the conceptual scaffolding required for informed decision-making later in the course. This initial phase ensured alignment with constructive alignment principles, enabling subsequent experiential activities to build on a shared theoretical foundation (Biggs, Tang & Kennedy, 2022). The CDIS lifecycle was then progressively embedded, with simulation serving as the primary environment through which learning and assessment were enacted.

Embedding CDIS Through Simulation-Based Learning

From the third week of the module, students were introduced to *The Fresh Connection* (TFC), a commercial supply chain simulation developed by Inchainge (Akkatal, Barooti & Akkartal, 2019; Maisiri & Hattingh, 2022; Kok & van Zyl-Cillié, 2024; García-Reyes, Maycotte-Felkel & Quijano-Dominguez, 2023). The initial exposure to TFC consisted of a guided, whole-class practice round. This activity familiarised students with the simulation interface, clarified the meaning of key performance indicators (KPIs), and illustrated how local decisions influence overall system performance. Following this shared experience, teams proceeded to formal decision rounds in which they were required to conceive strategies, design coordinated policies, implement decisions, and observe outcomes through simulation-generated feedback. In total, six decision rounds were conducted, commencing in Unit 5 and concluding in Unit 10 of the module. This iterative cycle of decision-making, feedback, and reflection became the central mechanism for operationalising the CDIS framework within the module, enabling students to engage progressively with system complexity, uncertainty, and performance trade-offs.

Throughout the semester, structured simulation time was embedded into each teaching session. New concepts such as demand forecasting, capacity planning, inventory management, and risk mitigation were introduced on a just-in-time basis, allowing teams to apply them immediately within the simulation. As the module progressed, the time available for decision-making was deliberately reduced to introduce realistic time pressure and reinforce collaborative decision-making, reflecting authentic managerial constraints (Kolb, 1984).

CDIS and Assessment Integrity in the Presence of Generative AI

The CDIS implementation also provided a practical response to emerging challenges associated with generative artificial intelligence in assessment. In engineering and management education, assessment often relies on written explanation, reflection, or structured analysis—formats that AI systems can now generate convincingly with limited cognitive engagement. While such tools may support learning when used appropriately, their availability exposes structural weaknesses in assessment designs that prioritise narrative output over observable system performance (Khodadad, 2025).

Within CDIO-aligned curricula, this challenge represents a pedagogical misalignment rather than merely a risk of misconduct. CDIO emphasises competence demonstrated through action, integration, and consequences, rather than symbolic representation alone (Crawley et al., 2014). When operational learning is approximated through reports or retrospective analyses, assessment becomes detached from system behaviour, resulting in surface learning, in which rhetorical coherence outweighs disciplinary understanding. As Wiggins (1998) argues, assessments that do not require students to “do the work of the discipline” risk measuring presentation rather than proficiency.

In the CDIS implementation, assessment was grounded in simulation-generated system behaviour rather than static outputs. Students were evaluated on their ability to interpret empirical evidence, respond to feedback, and adapt strategies across iterative decision cycles. Generic or decontextualised responses became immediately visible through misalignment with system outcomes, rendering inappropriate uses of AI pedagogically ineffective. This approach aligns with design-based perspectives on academic integrity, which emphasise assessment structures that make misconduct unproductive rather than relying on detection or prohibition (Bretag et al., 2019).

Learning Outcomes and Observed Impact

The outcomes of the pilot implementation were positive across engagement, participation, and learning performance. Attendance rates during the simulation phase ranged between 70–80%, significantly higher than the approximately 40% typically observed in modules without embedded experiential requirements. Students reported sustained engagement, attributing their participation to the interactive, consequential, and competitive nature of the simulation-based learning environment.

To further examine the impact of this engagement, correlation analysis was conducted between simulation attendance and two outcome measures, final ROI and overall performance score, as illustrated in Figure 1. Results indicate a strong positive correlation with performance score (r = 0.84) and a moderate positive correlation with ROI (r = 0.67). Student performance was systematically captured through a structured observation instrument administered at key project checkpoints. The observation form evaluated individual contribution across four dimensions: role ownership (confidence and accountability), preparedness and engagement (attendance and proactive participation), collaboration and support (team contribution and knowledge sharing), and impact on group success. Each dimension was assessed using Likert-scale measures and supplemented with qualitative observations. This enabled the integration of attendance data with observed behavioural engagement, strengthening the analysis of the relationship between engagement and performance.

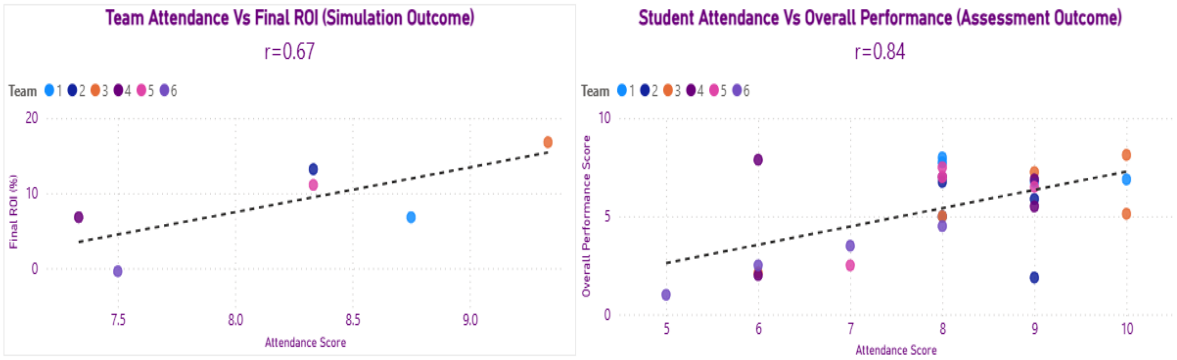


Figure 34: Relationship Between Simulation Attendance and Performance Outcomes at Team and Student Levels

While the relationship with performance score is partially influenced by the inclusion of engagement within assessment criteria, the correlation with ROI is moderate but meaningful, as ROI emerges from decision-making effectiveness within the simulation and is not directly graded. This suggests that sustained engagement contributes not only to academic performance but also the development of practical decision-making capability in complex systems.

Performance data generated by TFC simulation provided further evidence of learning progression. Most teams achieved improvements in key performance indicators, including Return on Investment (ROI), relative to their initial baseline performance, as shown in Figure 2. This upward trajectory suggests that students were not only able to understand core supply chain concepts, but also to apply them effectively within a complex, interdependent decision environment. The requirement to justify decisions in relation to observed outcomes further supported reflective learning grounded in evidence rather than abstraction (Kozanitis et al., 2009).

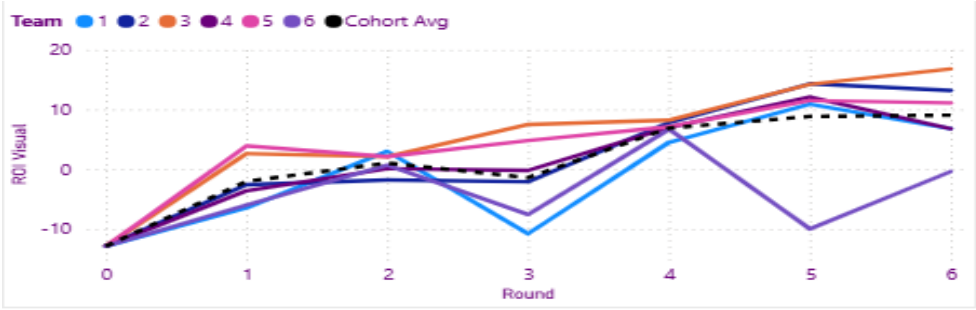


Figure 35: Return on Investment (ROI%) Performance Across Simulation Rounds

A notable pattern is observed in Team 6, whose performance fluctuated considerably across rounds. This instability is consistent with the broader trend shown in Figure 1, where lower and inconsistent attendance is associated with weaker performance. Informal observations indicated irregular participation during key decision rounds, suggesting that inconsistent engagement disrupted coordination and decision quality. This reinforces the dependence of simulation-based learning on sustained participation and effective collaboration to achieve stable system performance.

LIMITATIONS

As a conceptual paper, this work has several limitations that should be acknowledged. First, the CDIS framework is illustrated through a single institutional context and a single simulation platform, which may limit the immediate generalisability of the findings to other disciplinary domains, programme structures, or educational settings. While the case study provides rich descriptive insight into the implementation of CDIS, it does not constitute a controlled empirical evaluation. Further research is therefore required to examine learning outcomes systematically, including cognitive load, stress levels, long-term competence development, and comparative effectiveness relative to traditional CDIO or Project-Based Learning approaches.

In addition, although CDIS is positioned as resilient to AI-generated submissions through assessment-by-design, this claim remains conceptual and requires empirical verification. Future studies should investigate student behaviour, use of generative AI tools, and assessment performance under controlled or comparative conditions to substantiate this argument. These limitations do not diminish the conceptual contribution of the paper; rather, they identify clear directions for future research necessary to validate, refine, and extend the CDIS framework across contexts.

CONCLUSIONS

This paper has proposed CDIS (Conceive–Design–Implement–Simulate) as a conceptual extension of the CDIO framework for educational contexts in which physical operation is impractical. By positioning Simulation as the final integrative phase, CDIS preserves CDIO's

experiential learning principles while adapting them to complex socio-technical systems such as supply chains and project-based organisational environments.

The analysis presented across the paper indicates that CDIS addresses several interrelated challenges facing contemporary higher education. First, it provides a coherent response to the limitations of physical replication in management-oriented engineering domains, where professional competence is expressed through decision-making, coordination, and interpretation of system performance rather than artefact operation alone. Second, CDIS strengthens authentic assessment by embedding evaluation within dynamic system behaviour, requiring students to engage with uncertainty, delayed feedback, and trade-offs over time. Third, by grounding assessment in system-generated data and decision histories, CDIS reduces the effectiveness of surface learning strategies and AI-generated shortcut behaviours not through restriction, but through resilient assessment design.

From a pedagogical perspective, CDIS reinforces interdisciplinary collaboration as a consequential rather than symbolic activity. The requirement for alignment across functional roles mirrors professional practice and makes visible the systemic consequences of miscoordination. At the same time, the framework supports scalability and fairness by providing common system conditions while allowing diverse strategies and performance trajectories.

While the paper is intentionally conceptual, it opens important directions for future research, including empirical studies on learning outcomes, student engagement, cognitive load, and long-term competence development within simulation-based environments. Quantitative analysis of performance trajectories, complemented by qualitative insights into student decision-making and reflective practices, would provide a stronger evidence base to validate, refine, and extend the CDIS framework across different disciplines and institutional contexts.

Future research should investigate learning outcomes, engagement, and competence development associated with simulation-based learning environments. Empirical studies examining performance trajectories and student decision-making could further refine the CDIS framework and evaluate its applicability across different disciplines and institutional contexts.

Finally, it is acknowledged that the choice of acronym “CDIS” may evolve in time to more accurately reflect the process. Indeed, during the development of this work, the letters “CDSO” as “Conceive Design Simulate Operate” may be more appropriate and reflective of the process. The authors acknowledge the concept as being a variation and evolution of the “CDIO” approach and envisage its potential use in the context of the CDIO organisation and would thus value the CDIO community’s input on this.

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Dr. Alix Vargas is a Senior Lecturer in the School of Physics, Engineering and Computer Science at the University of Hertfordshire, United Kingdom. She holds a PhD in Engineering and postgraduate qualifications in engineering, business, and higher education pedagogy. Her work focuses on engineering education, supply chain and operations management, and project delivery, with particular emphasis on experiential and simulation-based learning. Dr Vargas has led the development of CDIO-aligned curricula and the integration of simulation environments such as The Fresh Connection to support interdisciplinary collaboration and authentic assessment. Her research interests include the evolution of CDIO-based frameworks, simulation-driven assessment, and resilient engineering education.

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ENGINEERING EDUCATION RESEARCH

CHEMICAL PRODUCT DESIGN: A CASE STUDY ON 'LEARNING FROM FAILURE'

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ABSTRACT

The purpose of this paper is to illustrate the effectiveness of learning from failure to develop resilience, creativity and innovation in students and understand the interrelatedness between creativity and innovation and conformance to norm in the Diploma in Chemical Engineering program offered by Singapore Polytechnic. The paper first provides a brief explanation of chemical product design as the context for integrating conceiving, designing, implementing and operating skills into the program when CDIO Framework was implemented in 2008. Then, it examines how the Chemical Product Design pathway offers learning opportunities for students to engage in 'learning from failure' that meet the CDIO Learning Outcomes in Section 2.4 Attitudes, Thought and Learning. In this paper, failure refers to students undertaking multiple iterations of tasks, such as refining prototypes before achieving a successful outcome. This study uses a mixed-method approach to gain a holistic understanding of students' experiences in learning from failure. It affirmed that the Chemical Product Design pathway indeed developed students' tolerance for failure and resilience. Resilient students are more likely to persist through failure or challenges and continue refining their ideas and excel. The process of coping with failure not only strengthens students' problem-solving confidence but also supports sustained creativity and innovation. However, the strong emphasis on conformity within the broader chemical engineering program may have inhibited the growth of creative thinking to a certain extent. There is a need to provide psychological safety for students to experience failure and reframe how learning from failure could bring more benefits than harm to student learning.

KEYWORDS

Chemical product design, Learning from failure, Resilience, Failure Tolerance, Confidence, CDIO Standards 2 and 5

INTRODUCTION

The purpose of this paper is to illustrate the effectiveness of learning from failure to develop resilience, creativity and innovation in students and understand the interrelatedness between creativity and innovation and conformance to norm

The paper first provides a brief explanation of chemical product design as the context. Then, it examines how the Chemical Product Design pathway offers learning opportunities for students to engage in 'learning from failure'. In this paper, failure refers to students undertaking multiple iterations of tasks, such as refining prototypes before achieving a successful outcome.

The Chemical Product Design pathway was first introduced to the diploma program in Academic Year 2008 to integrate conceiving, designing, implementing and operating skills into the program when CDIO Framework was implemented (Cheah & Sale, 2010). The Chemical Product Design pathway is rarely included in most chemical engineering programs because the professional practice in chemical engineering necessitates strict adherence to established protocols, standard operating procedures and compliance with safety regulations. These requirements constitute a core element of the discipline's professional standards and directly influence the design and delivery of chemical engineering program to ensure alignment with industry expectations and regulatory frameworks. This emphasis on conformity and operational rigour contrasts with the Chemical Product Design pathway that encourages flexibility, creativity and innovative thinking. in the Diploma in Chemical Engineering (DCHE) offered by Singapore Polytechnic (SP). Thus, the research questions are (1) how learning from failure influences the development of resilience, creativity, and innovation in students and (2) how conformance to norms interacts with students' creativity and innovation when learning from failure.

CHEMICAL PRODUCT DESIGN PATHWAY

The 3-year DCHE program consists of chemical engineering domain modules, Common Core modules that develop emerging digital and human skills, basic sciences and mathematics modules, as well as Chemical Product Design pathway that leads to Capstone Project in Year 3. In this current iteration, the Chemical Product Design pathway in the DCHE program is illustrated in Figure 1.

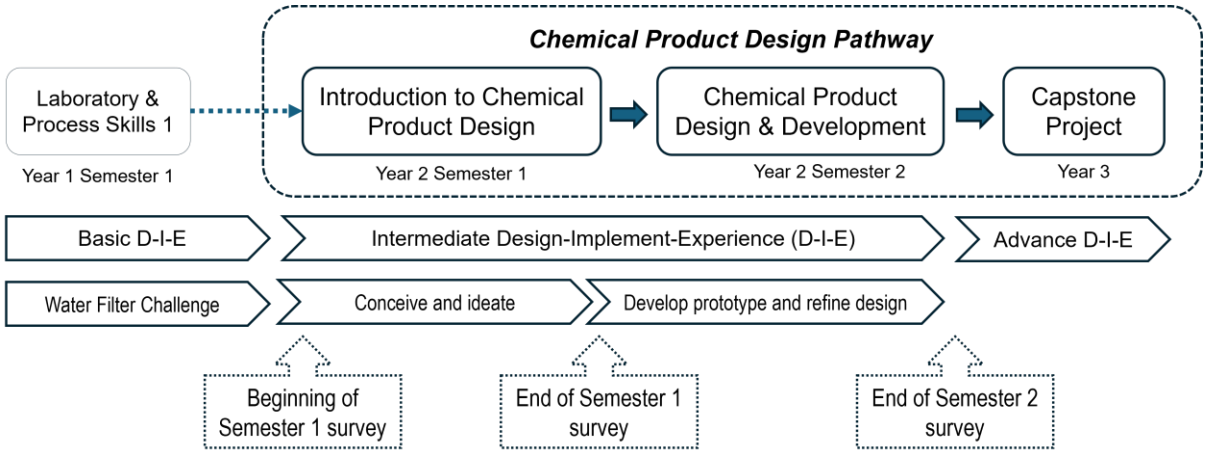


Figure 36. Chemical product design pathway in DCHE program

The integration of chemical product design provides students with learning opportunities to use chemical engineering principles to conceive and design useful products, greatly widening and enhancing DCHE graduates' competencies in 'Creativity, Innovation & Enterprise' and 'Self-Directedness & Personal Effectiveness' which are SP's graduate attributes. Hence, the Chemical Product Design pathway has gained increasing significance as means to develop creativity and design thinking competencies that graduates require to excel beyond mere conformity, preparing graduates to address complex challenges and develop innovative or novel solution for a more sustainable industry.

In addition to technical knowledge, the Chemical Product Design pathway cultivates attributes such as resilience, creativity, and innovation, which are transferable skills applicable across diverse job roles, including those outside the chemical engineering domain. To substantiate this value, the team undertook research employing a 'learning from failure' approach, collecting data to demonstrate that the pathway fosters these attributes and provides added value to students beyond a typical chemical engineering program. Hence, creativity and innovation were examined in contrast to conformance to norm because there could be a potential tension between fostering originality and adhering to established standards, which may be particularly relevant in chemical engineering that balances safety, precision and innovation.

The Chemical Product Design pathway has evolved through multiple redesigns to align with institutional priorities and industry needs. It is currently delivered mainly through two Year 2 modules: *Introduction to Chemical Product Design* module in Semester 1 and *Chemical Product Design & Development* module in Semester 2, as illustrated in Figure 1. Positioned within the framework of education for sustainable development, these modules integrate the United Nations Sustainable Development Goals as learning contexts (Cheah et al, 2022, and Oh et al, 2024). The first module develops foundational skills in product conception, evaluation, and design, incorporating advanced manufacturing and digital fabrication techniques alongside teamwork and creative problem-solving. The second module builds on this foundation by guiding students through prototype development, refinement of design specifications, and application of microcontrollers and sensors for automation, culminating in project proposals that extend into Capstone Projects. Students encounter failure during prototype development and design refinement, often due to limited experience and knowledge. In this process, they engage in reflective learning to identify what does not work and what works better. This iterative process of learning from failure fosters resilience, enabling students to recover from setbacks and develop greater tolerance for future challenges.

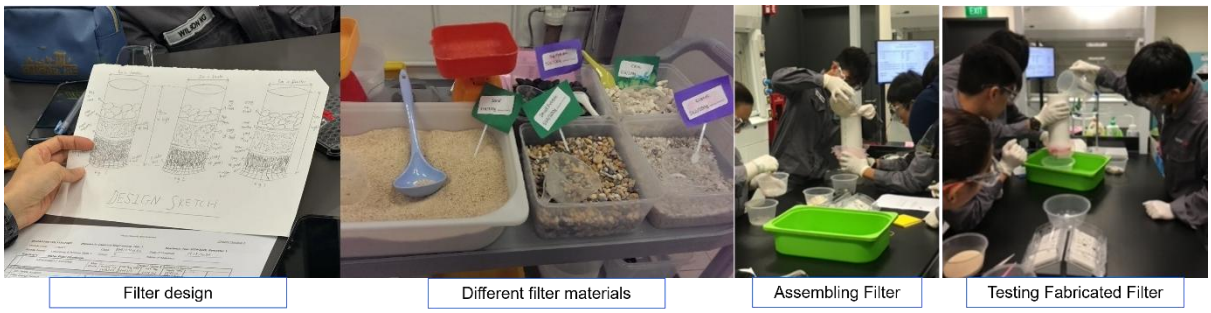


Figure 37. A Design-Implement-Experience in water filter challenge

In addition, a design-implement experience is integrated in one learning activity in the *Laboratory & Process Skills 1* module offered to first-year students in Semester 1 as a pre-

cursor to the Chemical Product Design pathway. This design-implement experience is grounded in product design principles, requiring students to construct a water filter based on a defined set of requirements and available resources, where multiple failure points were intentionally designed. Figure 2 illustrates students carrying out the Design-Implement Experience activity.

LEARNING FROM FAILURE IN CHEMICAL PRODUCT DESIGN PATHWAY AND ITS RELATIONSHIP WITH CDIO

The Chemical Product Design pathway is structured around the CDIO Innovation Process which is outlined in Section 4 of the CDIO Syllabus and 'learning from failure' enhances the development of personal and professional skills, specifically meeting the learning outcomes in Section 2.4 Attitudes, Thought and Learning of the CDIO Syllabus.

According to the Programme for International Student Assessment (PISA) 2019 survey, more than 70% of students in Singapore reported a fear of failure, a proportion that is notably higher than that observed among students in other participating countries (Teng, 2019). This finding suggests that students in Singapore experience comparatively elevated levels of fear of failure, which manifests as observable behaviours within the polytechnic context. So, the Chemical Product Design pathway presents opportunities for students to 'learn from failure' when they carry out prototype development and design refinement activities so that they become more tolerant to failure and resilient.

Resilience and tolerance to failure often develop through the experience of failure where students learn to adapt and recover from setbacks. Encountering failure challenges students' assumptions and forces students to develop coping strategies, such as reframing negative outcomes and seeking alternative solutions. Over time, these experiences strengthen emotional regulation, problem-solving skills and persistence, enabling the students to approach future challenges with greater confidence and flexibility. Learning from failure becomes a catalyst for growth and resilience, rather than negativity that should be avoided (Huang et al, 2024).

The phenomenon of failure in chemical product design differs fundamentally from failure in chemical process operation. 'Learning from failure' is generally perceived as an integral part of the creative process, fostering innovation through iterative refinement that enables students to become more resilient and tolerant to failure. Conversely, failure in chemical process operation should be avoided because it causes severe consequences, including safety hazards, environmental risks and economic losses. As a result, while design-related failure is tolerated and even used as a learning mechanism, chemical process operational failure is strictly controlled and minimised through established protocols and compliance to safety requirements.

In the Chemical Product Design pathway, students work in design teams consisting of 5 to 7 members per team to conceive and develop a prototype and refine the design to demonstrate its workability as shown in Figure 2. Failure could emerge under different scenarios depending on what students do and how they interact. The failures encountered by each design team would be different even though they are all given the same learning tasks. The level of failure tolerance for each team would depend on the willingness to make decision in the face of uncertainty (CDIO Learning Outcome 2.4.1), how much they could persevere when they face challenges would depend on their self-confidence (CDIO Learning Outcome 2.4.2) and their readiness to adapt to changes would depend on their level of resilience (CDIO Learning

Outcome 2.4.3). When students encounter failure, they will learn to reflect on their actions, embrace constructive feedback and manage their emotional responses.

In addition, students are guided to respond to setbacks ethically and with integrity (CDIO Learning Outcome 2.5.1). This has become increasingly important with the emergence of Generative Artificial Intelligence (Gen AI) where students must learn to critically evaluate the information and understand the ethical implication of AI use, including biases and misinformation. Lastly, students may become more creative and innovative to overcome the failure by reconsidering their assumptions and exploring alternative approaches in their design tasks (CDIO Learning Outcome 2.4.4).

METHODOLOGY

This study uses a mixed-method approach to gather a holistic understanding of students' experiences in learning from failure within the Chemical Product Design pathway. Quantitative and qualitative data were collected across two academic years (April 2023 to March 2025) to examine the changes in students' attitudes, resilience and creativity.

The quantitative phase employed the School Failure Tolerance (SFT) test by Clifford (1988) and the Kirton Adaptation-Innovation Inventory (Kai) by Kirton (1976). The SFT measures students' tolerance to failure, resilience and confidence while Kai measures confidence, creativity, innovation and conformance to norms. Data were collected at three points during the academic year, that is May 2023 (beginning of Semester 1), August 2023 (end of Semester 1) and February 2024 (end of Semester 2). Each measurement used a five-point Likert scale, with responses analysed using t-tests at 5% significance level to examine the developmental changes over time. The cohort size is 120 and the survey response rate ranges from 47.5% to 81.7%. Students were required to give their consent for the research team to collect data from them and they have the option of withdrawing from participating in the survey at any point.

To complement the survey data, multiple qualitative sources were triangulated to capture nuances of students' learning from failure experiences:

- **Focus Group Discussions (FGDs)** were conducted at the end of each academic year (February – March 2024 and February – March 2025) with students who participated in the survey. The FGDs explored students' emotional responses, coping strategies and perceptions of failure in design learning. These discussions revealed rich narratives about resilience, teamwork and self-reflection.
- Two structured **classroom observations** were conducted to document in-situ manifestations of failure and recovery behaviour in the learning environment. The first observation took place in January 2024 during the *Chemical Product Design and Development* module taken by students in Year 2 Semester 2. Students were observed engaging in prototyping tasks such as 3D printing the circuitry design, where instructors emphasised safety, correctness and iterative improvement. The second observation was carried out in May 2024 in the *Laboratory and Process Skills 1* module taken by students in Year 1 Semester 1. Students participated in a Water Filter Challenge, which intentionally incorporated designed failures such as blocked filters and turbidity issues, to encourage iterative redesign and reflective thinking. Both observations followed a structured template focusing on intentional failure design, student reactions to failure, instructor questioning techniques and collaborative problem-solving behaviours.

- **Student written reflections** were collected in January 2024 from the same cohort of Year 2 students. Each student responded to guided reflection questions embedded in their coursework assessment, addressing causes of failure, lessons learned and possible improvements. The reflections were analysed thematically to identify recurring themes such as recognition of failure as feedback, emotional resilience, team dynamics and safety-oriented thinking. These insights complemented the observation and FGD data, providing individual perspectives on learning from failure.

All qualitative data were coded and analysed using a thematic approach. Emerging themes from classroom observations and reflection responses were compared with focus group transcripts to ensure consistency and enhance validity through data triangulation. The combined analysis of quantitative (SFT and Kai) and qualitative findings enabled a comprehensive understanding of how students' tolerance for failure, creativity and resilience evolved over the course of the program.

RESULTS AND DISCUSSION

This section presents the data analysed from the SFT and Kai surveys and it is supported by qualitative data that were collected through the FGD with students. In the data analysis, the attributes of failure tolerance, resilience and confidence were grouped together due to their conceptual relatedness and these attributes reflect a shared dimension of personal adaptability and emotional strength. Meanwhile, creativity and innovation were examined in contrast to conformance to norm because there could be a potential tension between fostering originality and adhering to established standards, which may be particularly relevant in chemical engineering that balances safety, precision and innovation. Understanding these groupings would enable the authors to better support student growth by recognising how these traits interact and manifest within the chemical engineering program.

Failure tolerance, resilience and confidence

Data were compared at the 3-point measurements within an academic year as shown in Figure 3. Overall for the entire academic year, students' failure tolerance (1.39 to 1.57) and resilience (3.26 to 3.36) increased as expected because the chemical engineering program was designed to cultivate this attribute. The program's structure and challenges were aimed at fostering students' ability to adapt, persist, and recover from setbacks, aligning with its educational objective to build resilience and prepare its graduates for the workforce. It is worth noting that although the students' confidence remained the same when measured at start and end of the academic year, their confidence was observed to increase for the first half of the academic year and then decline to its initial level.

DCHE adopted the spiral curriculum model in 2018 (Yang et al, 2021) and its Year 1 modules primarily emphasised knowledge acquisition and comprehension-based learning outcomes, with minimal focus on application. In Year 2, the emphasis shifts toward higher-order application outcomes, supported by fewer knowledge-based learning outcomes, thereby increasing the complexity of learning. Consequently, students often find Year 1 modules relatively easy to master and they score good grades, which enhances their confidence. However, as they progress to Year 2, they encounter more challenging tasks due to advanced learning outcomes and elevated expectations. Entering Year 2 with high confidence, students face a steeper learning curve, and some challenges may have diminished their confidence as the pace and complexity exceeded their initial ability to adapt and thrive.

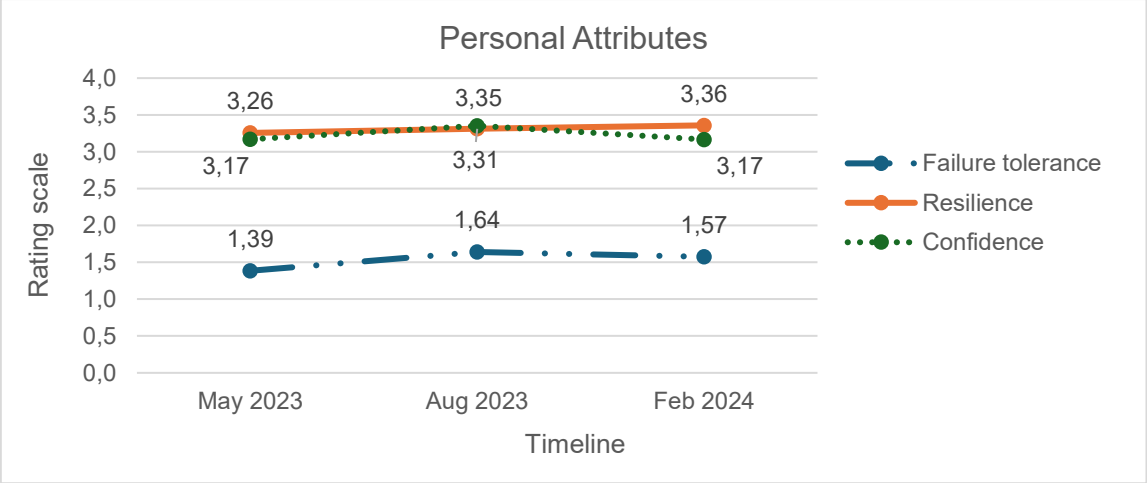


Figure 38. Rating on personal attributes

The failure tolerance (1.39 to 1.64), confidence (3.17 to 3.35) and resilience (3.26 to 3.31) followed an upward trend during the first half of the academic year. However, a notable decline in failure tolerance (1.64 to 1.57) and confidence (3.35 to 3.17) was observed in the second half, diverging from the continued growth in resilience. This pattern may be attributed to the increasing complexity of concepts and contexts introduced in Year 2 Semester 2 of the DCHE program. As students are required to engage with higher-order thinking skills and apply knowledge in real-world problem-solving, the cognitive and emotional challenges may have impacted their perceived confidence and tolerance for failure.

In general, students rated their failure tolerance (below 2.0) lower than the level of resilience and confidence (above 3.0) as shown in Figure 3. Students showed higher resilience and confidence because they seemed to have the ability to succeed and able to bounce back from setbacks but not necessarily from academic failure due to concerns of grading and peer pressure that failure leads to embarrassment. At the focus group discussion, one student shared that "*he often kept trying despite feeling frustrated and this is mainly driven by assessments and grades, having an ownership over the project and the desire to improve based on feedback*".

Another student shared that "*he does not want to fail because he is compared with his peers*." This seemed to suggest that students fear failure because it feels like a judgement rather than a learning opportunity, thus, having lower tolerance to failure.

In Year 2 Semester 1, students were introduced to the Chemical Product Design pathway for the first time within the DCHE program. This initial exposure provided a foundation for students to gradually develop their tolerance for failure, resilience and confidence, as reflected in the t-test results in Table 1 that compares the p-values for Semester 1, Semester 2 and for the entire academic year. According to constructivist learning theory (Piaget, 1976), students build knowledge through active engagement and reflection on experiences, including failures and errors. The iterative nature of design tasks in Semester 1 likely facilitated this process, allowing students to learn from failure and adjust their strategies accordingly. Repeated exposure to failure helps develop cognitive flexibility where students develop the ability to shift thinking and adapt to new information, thereby increasing the level of resilience and confidence. Within the learning environment, students were guided by their lecturers to learn from experience and see failure as part of growth. This could then support students to build

a foundation for these attributes. One student shared that "*the lecturer is the pillar of support who provide support and understand his struggle as a student*."

This dynamic was clearly demonstrated in the Laboratory and Process Skills class in May 2024 where Year 1 students were engaged in a "Water Filter Challenge". The instructors intentionally designed multiple failure points, such as incomplete water flow or unchanged turbidity, to trigger productive iteration. Instead of offering direct solutions, instructors posed probing questions like "*why 100 grams of sand?*" or "*why did the water not flow through?*". Students were prompted to reflect using a plan-do-check-act framework and document possible causes of failure as part of graded reflection. Through repeated testing and redesign, students' confidence and resilience visibly improved, embodying the "fail fast, fail early" ethos while meeting the CDIO learning outcomes.

Reflection responses revealed that many students viewed failure as a necessary but emotionally challenging part of the learning process. Several responses expressed frustration such as "*It was tiring but we learnt from mistakes.*" while others highlighted the value of iteration such as "*We improved after testing again.*" These reflections reinforced the quantitative findings that resilience increased even when confidence fluctuated.

Having gained experience from encountering and learning through failure, students entered Semester 2 with a certain level of failure tolerance, resilience and confidence. The data in Table 1 indicated that students' attitude toward failure and their resilience remained consistent throughout Semester 2 but their confidence level decreased.

Table 13. t-test outcome for failure tolerance, resilience and confidence

Data collection period	p-value (at 5% significance level)			t-test Outcome
	Failure tolerance	Resilience	Confidence	
Semester 1 (May – August 2023)	0.0000014	0.010	0.0003	Students become ***more*** tolerant to failure, resilient and confidence from start to end of Semester 1
Semester 2 (August 2023 – February 2024)	0.1318	0.122	0.0006	There is ***no change*** in students' tolerance to failure and resilience, but students become ***less*** confident from start to end of Semester 2
Full academic year (May 2023 – February 2024)	0.0014	0.015	0.4742	Students become ***more*** tolerant to failure and resilient but confidence remained the ***same*** from start to end of academic year

When the foundation is established in Semester 1 where students had accumulated prior experiences and entered Semester 2 with a more sanguine attitude toward failure. This is an indication that students become better equipped to handle failures with a consistent level of emotional strength and problem-solving capacity. This aligns with Bandura's social cognitive theory (Bandura, 1982), particularly the concept of self-efficacy, which suggests that repeated

mastery experiences, including overcoming failure, contribute to students' failure tolerance and resilience. Self-efficacy refers to an individual's belief in their ability to succeed in specific situations. So, students would be less likely to be overwhelmed by subsequent failures and more likely to approach challenges with a mindset of persistence, adaptability and self-efficacy.

When examining the attributes across the entire academic year, the findings suggest a gradual developmental trajectory: students became increasingly tolerant to failure, building resilience while maintaining the same level of confidence from beginning to the end of the academic year. This progression supports the idea that learning from failure is a critical component of active and experiential learning, where reflection on concrete experiences leads to deeper learning and personal growth. One student shared that "*the reflection journal helped him with learning and learning from mistakes helps him understand better*." Through Reflection Journals, students analysed what went wrong and they could uncover possibilities that fuel creative breakthroughs. Additionally, responses elicited from the FGDs showed that students had both intrinsic and extrinsic motivations to continue despite 'failing': they wanted to learn from the experience, they wanted to see the end product due to the time and effort spent working on it, and that their grades will be affected if the work is incomplete.

In such active and experiential learning environments, students are not passive recipients of information; rather, they engage directly with the problems and situations. They make decisions and experience the consequences of those decisions. When failure occurs, it serves as a critical learning opportunity, prompting students to analyse and reflect underlying causes, adjust their strategies and apply knowledge and skills in novel ways. This iterative process reinforces understanding through practice and fosters deeper cognitive engagement.

Creativity vs Conformance

The DCHE program effectively cultivates students' ability to conform to established norms, as evidenced by an increase in the conformity scores from the beginning to the end of the academic year as shown in Figure 4. In contrast, the Chemical Product Design pathway fostered creativity and innovation during the first semester, however, a noticeable decline in these attributes was observed in the second semester. This decline may be attributed to the increasing emphasis on conformity within the broader curriculum, which potentially suppressed the development of creative thinking.

Classroom observation during the *Chemical Product Design and Development* module in January 2024 further illustrated this tension. Students were observed meticulously following online tutorials and safety guidelines to ensure correct wiring and 3D printing connections. While such practices reinforced procedural accuracy and reduced risks, they also reflected a "single-correct-answer" mindset, leaving limited room for creative experimentation. The instructor acted primarily as a facilitator, encouraging students to self-correct through trial-and-error. This environment tended to favour adaptive over innovative problem-solving, aligning with the quantitative finding that students became more conforming rather than inventive toward Semester 2.

Analysis of students' written reflections further supported the observation that safety and correctness were dominant design priorities. Many responses emphasised avoiding errors such as "*We followed the right steps to prevent accidents*" and ensuring precision such as "*There is only one right way to make it safe*." Such language illustrates the prevalence of adaptive rather than innovative mindsets, consistent with the observed rise in conformity scores during Semester 2.



Figure 39. Rating on creativity & conformance

The t-test results shown in Table 2 further confirmed that students indeed become more conforming to norm from start to end of the academic year at 5% significance level, while creativity and innovativeness students remained stable. This could be attributed to the chemical engineering program that traditionally develops systematic problem solving, strict adherence to standard operating procedures and safety practices as well as application of established engineering principles. This structured approach cultivates analytical thinking and technical precision. One student shared that "*process operation skills training emphasised safe operation to prevent incidents and accidents because failure in a chemical plant has negative consequences*." In contrast, chemical product design requires students to engage in creative thinking, innovation and open-ended exploration, which the competencies differ significantly from those emphasised in core chemical engineering training. This contrast creates a pedagogical dichotomy within the curriculum that students must learn to navigate. Consequently, when students encounter failure in creative or design-based tasks, it may have conflicted with their dominant mindset of 'cannot fail' because failure is perceived as unacceptable in the chemical engineering workplace, leading to confusion and a decline in self-confidence as indicated in Table 1.

Table 14. t-test outcome for creativity and conformance

Data collection period	p-value (at 5% significance level)		t-test outcome
	Creativity and innovation	Conformance to norm	
Semester 1 (May – August 2023)	0.0009	0.0118	Students become ***more*** creative and innovative and conforming to norm from start to end of Semester 1
Semester 2 (August 2023 – February 2024)	0.1335	0.0713	There is ***no change*** in students' creativity and innovativeness and conformance to norm from start to end of Semester 2
Full academic year (May 2023 – February 2024)	0.0532	0.0004	There is ***no change*** in students' creativity and innovativeness but student become ***more*** conforming to norm from start to end of academic year

When failure is normalised and not punished through grades, students may become more willing to take risks. This openness to experimentation is crucial in developing creativity and innovativeness. One student shared that "*he faced many challenges during the prototyping phase and it is good learning opportunity*". The first exposure serves as a foundational phase where students begin to internalise the value of learning through trial and error. These experiences align with CDIO Standard 5 Design-Implement Experiences that enable cognitive development through assimilation and accommodation of new experiences through learning from failure.

In conclusion, when students encounter repeated failures at the different stages within their learning environment, they gradually become accustomed to the experience and develop resilience and tolerance for setbacks. This process not only strengthens their ability to cope with challenges and failures but also fosters higher levels of creativity and innovation. Equipped with these attributes, students grow in confidence while maintaining an awareness that conformity to established norms remain an essential trait within the chemical engineering industry.

LIMITATIONS AND RECOMMENDATIONS

This study has several limitations that should be considered when interpreting the findings. First, the response rate for each survey varied because participation was voluntary. This may have introduced the possibility of non-response bias, as individuals who chose to participate may differ systematically from those who did not, potentially affecting the representativeness of the results. More targeted follow-ups with students or incentives through using testimonial of participation could be employed to improve response rates.

Second, the findings presented are indicative rather than definitive. While the data provide useful insights, they should not be interpreted as conclusive evidence. Further research with larger and more diverse samples, as well as longitudinal designs, is warranted to validate and extend these observations.

Third, both the SFT and Kai instruments rely on self-reported ratings. Self-assessment measures can be influenced by cognitive biases, including the Dunning–Kruger effect, where individuals with lower ability may overestimate their competence while those with higher ability may underestimate theirs. This bias could impact the accuracy of the reported scores and, consequently, the interpretation of the results.

As students encounter and overcome failure during the first semester, they build confidence in their problem-solving abilities. However, despite developing technical competence, students may still experience emotional distress following failure because they have not fully developed the emotional tools to process failure constructively. So, the lecturer would need to play a pivotal role to shift students' focus from "what went wrong" to recognising and reflecting on "what went right". Consider striking a balance between using graded assessment and ungraded formative feedback to help the student to gain confidence through learning from mistakes. Such reframing can support the development of a stronger sense of agency and competence, fostering more confident and adaptive students.

Providing psychological safety for students to fail and learn from their mistakes would create a fail-safe environment for students to "fail fast, fail early". Such an environment not only facilitates active and experiential learning but also encourages the development of creativity and innovation by reducing the fear of failure.

Observations from both Year 1 and 2 classes reaffirm that creating psychologically safe, scaffolded environments, where students are guided on coping with failure early as observed during the Water Filter Challenge and gradually encounter structured constraints later such as those prototyping activities, can balance resilience-building with technical accuracy. Such progression may help students transit from 'fear of failure' to 'confidence through competence'.

Across the reflections collected in January 2024, three recurring themes emerged: (1) recognition of failure as feedback, (2) increased appreciation of teamwork and communication, and (3) awareness of constraints such as safety and time. These reflections demonstrate how students internalised the CDIO learning outcomes, particularly Attitudes, Thoughts and Learning (CDIO Syllabus Section 2.4), through structured reflection after experiencing failure.

A key factor that warrants deeper study is how DCHE students entertain the notion of learning from failure in product design vs non-tolerance of failure in chemical plant operations where students had to 'code switch' from product design to process operation when they attend the respective lessons. Future work could also investigate whether students could become more conforming and more creative at the same time and devise relevant teaching strategies to support students in making sense of their experiences and adopting the desired attributes referencing the approach proposed by Cheah & Willems (2025).

CONCLUSION

This study highlighted the role of chemical product design in developing students' tolerance for failure and the development of resilience. With reference to the first research question, the process of coping with failure not only strengthens students' problem-solving confidence but also supports sustained creativity and innovation. Resilient students are more likely to persist through failure or challenges and continue refining their ideas and excel. However, the strong emphasis on conformity within the broader chemical engineering program may have inhibited the growth of creative thinking and this addresses the second research question. This tension reflects prevailing industry expectations, where engineers are typically not required to exercise creativity in routine operations, particularly in the context where consistent and operational safety are of utmost importance.

In the context of the modern workplace, graduates require a more divergent set of skills and competencies. Some of these attributes such as creativity, adaptability and adherence to standards may exist in tension with one another, necessitating innovative approaches to curriculum design. Learning from failure is observed in this study to enhance active and experiential learning, enabling students to develop resilience, problem-solving abilities and creative thinking. So, the CDIO Framework can be used as a lens for program assessment, to systematically evaluate and improve educational strategies, allowing standard-by-standard analysis to identify areas for enhancement using the 'learning from failure' approach while ensuring alignment with industry needs.

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BEYOND DEMONSTRATIONS: STUDENT-LED LEARNING LABORATORIES THROUGH A CDIO LENS

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ABSTRACT

Laboratory-based learning is central to engineering education and can be a natural mechanism for implementing CDIO principles, yet traditional "follow-the-recipe" formats can limit student autonomy and engagement. In programmes where integrated CDIO design–build–test (DBT) experiences already exist, the continued use of traditional, standalone laboratories raises questions about how students perceive these, and how they might better complement the wider CDIO ethos. This study describes a workshop which explored what students currently value in traditional laboratories in a Mechanical and Aerospace Engineering undergraduate degree course, identifies perceived gaps, and maps these to the CDIO Syllabus. Students recognised the benefits of traditional laboratory formats and cited aspects that mapped across the whole CDIO syllabus, with the highest emphasis on Section 2: Personal and Professional Skills and Attributes (~40% of comments). When suggesting areas for improvement however, suggestions were concentrated in Section 4: Conceiving, Designing, Implementing and Operating (>68% of comments), with students calling for greater involvement in designing, setting up and operating experiments, more complexity, integration of design and manufacture, smaller group sizes and tighter lecture-laboratory alignment. Students also proposed concepts for multi-session, DBT laboratory activities that culminate in testing and analysis, shifting emphasis from commercial teaching laboratory equipment toward authentic, iterative projects aligned with the CDIO ethos and with Student Centred Learning (SCL) principles. These student-generated concepts were also found to be readily shaped to meet required learning outcomes. The findings from this study will drive the next phase of development and transformation of the laboratory programme at the authors' institution with planned future work to redesign laboratories with the aim of developing a student-centred structure that allows students to take ownership of their practical learning and enhances the opportunities for students to achieve and excel in CDIO-aligned learning outcomes.

KEYWORDS

Laboratory-based learning, Student-centred learning, CDIO Syllabus, Engineering education, Design–build–test, Standards: 5–8, 11–12

INTRODUCTION: LABORATORY BASED LEARNING IN ENGINEERING

Laboratory-based learning has historically been a fundamental component of engineering education, providing students with opportunities to apply theoretical concepts in practical settings and develop essential technical and transferable skills (Feisel & Rosa, 2005). However, traditional laboratory formats, which often involve following rigid, step-by-step instructions to achieve predetermined outcomes, have been criticised for limiting creativity and autonomy, leaving students feeling unchallenged and disengaged (McAfee, Armstrong, & Cunningham, 2009). In CDIO Institutions, as far back as 2008, it was argued that design-build-test projects were displacing traditional laboratories (Murphy, Surgenor, & Cunningham, 2008) and called for a review of how these were implemented.

At an early stage in development of CDIO, the focus on redesigned student workspaces was highlighted as being a key requirement in enabling the implementation of practical design-build-test experiences (Young, et al., 2005) and these purpose-built spaces highlight the kinds of environments that are needed to support authentic engineering learning. However, the same emphasis has not been placed on developing traditional engineering principles labs into active-learning activities which focus on experimentation skills. Challenges in implementing complex hands-on activity in terms of staffing, logistics, equipment and cost can often limit the opportunities for optimal delivery (Malmqvist, Hugo, & Kjellbery, 2015).

Several pedagogical strategies have been introduced to embed CDIO principles into laboratory environments. A recent study from outside engineering found that redesigning chemistry laboratories in line with CDIO principles notably improved students' experimental competence (Cao et al, 2025), while a materials course used the approach of design, manufacture and test to evaluate 3D printing materials (Zheng et al, 2025) and demonstrated improved knowledge and competencies as a result. This fits with broader work which shows that hands-on experimental work including project-based learning (PjBL), problem-based learning (PBL), inquiry-based learning (IBL), flipped classrooms, and peer teaching can improve academic performance, motivation, and engagement while fostering professional skills such as collaboration, experimental design, and project management (Friend, Woodcock, & Huang-Saad, 2021), all of which fit well within a CDIO-based curriculum.

Other strategies, such as use of digital tools and pre- and post- laboratory activities have been used to attempt to better prepare students for attending laboratory sessions, with the intention of increasing students' knowledge and understanding and enabling them to take more control of their learning experience while in the laboratory. For example, a study found that blending flipped learning with digital laboratories reduced cognitive load and improved preparedness for physical laboratory work (Portillo et al, 2024). These approaches also appear to encourage deeper learning and greater confidence among students.

However, successful implementation of CDIO principles and SCL within a laboratory setting requires careful design and support. Studies highlight that insufficient guidance can hinder learning, as seen in peer-teaching models where outcomes depended heavily on preparation and instructor support (Dosoftei & Alexa, 2024) Furthermore, while SCL offers clear benefits, questions remain about the optimal balance between independence and structure, and whether these approaches should supplement or replace traditional methods.

FORMAT OF THE CURRENT LABORATORY PROGRAMME

Although the School of Mechanical and Aerospace Engineering in the authors' institution has a strong and longstanding integrated CDIO ethos, with multiple design-build-test (DBT) experiences embedded at every programme level, a traditional engineering principles laboratory programme based on commercially available teaching equipment has also been retained for stage 1 students. Some of the typical laboratories are outlined in table 1 below.

Table 15. Typical laboratories on course

Subject area	Laboratory detail
Dynamics	Vibrations: Measuring moment of inertia of a flywheel Gyroscope: Demonstrating gyroscopic effect and measuring gyroscopic couples Static and Dynamic Balancing: Four-mass system balancing, both statically and dynamically
Fluid Mechanics	Bernoulli Demonstration: Waterflow through convergent-divergent tube Reynolds Demonstration: Laminar and turbulent flows, critical velocities, Reynolds number
Thermodynamics	Marcet Boiler: Pressure-temperature relationship of saturated steam Piston Compressor: Design and operating behaviour of compressed air generation plant
Materials	Tensile Test: Properties of different materials Hardness Test: Hardness properties of different materials
Structural Mechanics	Truss Analysis Beam Analysis

Various structures have been implemented over the years, with the programme originally running for many years with the individual laboratories aligned closely with the associated taught modules. While this was beneficial from the perspective of clearly linking theory with practice at the appropriate time, it was logistically very difficult to manage the availability and timing of the laboratories particularly as student numbers rose. A decision was made to decouple the laboratories from the modules and run dedicated laboratory weeks instead. This was much more efficient to coordinate and run but proved to be a poor learning experience for students who felt that there were too many laboratories to complete in a short time, that they did not have enough time to fully understand the principles behind each lab, and that they were not effectively learning from the laboratories. Staff marking laboratory reports at that time also reported that there was a fundamental lack of understanding by students of some of the basic theory in the laboratories, indicating a loss of integration within the curriculum. It was therefore decided in the 2023-24 academic year that the laboratory programme would be stretched over a full semester, and fewer laboratories would be undertaken by each student, but that they would spend more time in each laboratory and have more hands-on experience of each experiment. This has been an improvement in terms of student experience and learning, but further enhancements could be made.

RESEARCH OBJECTIVE

Despite extensive CDIO literature on integrated and project-based laboratory models, there is comparatively little evidence on how students themselves perceive the value of traditional, standalone laboratory experiences within otherwise CDIO-rich curricula. The focus of the present study is therefore not the laboratories per se, but an exploration of students' views on what benefits these traditional labs still offer, how they complement their DBT activities, and what enhancements students believe would make the laboratory programme more effective.

The first aim of this initial study was to understand what aspects students value in laboratory work, what they see as lacking in current provision, and the types of activities that they think they would benefit from. The second aim was then to map current provision and gaps in this provision to the CDIO syllabus areas to identify areas for improvement.

METHODOLOGY

A group of sixteen second-year students who had recently completed the laboratory programme were asked to voluntarily take part in a workshop to provide an insight into students' experiences of the laboratory programme and what they would like to see from it. They were prompted to generate some ideas for engaging laboratory structures. The workshop lasted for approximately 90 minutes. Students were arranged into four groups and provided with flipchart paper, sticky notes and markers and then asked to carry out the activities outlined in table 2. To avoid influencing the comments and ideas generated by students, the workshop made no reference to CDIO. The flipcharts produced by the students were collected and analysed. Comments on the areas that students see as valuable in the current laboratory programme, and suggested areas of improvement were tabulated, grouped into themes and then categorised into the appropriate sections of the CDIO syllabus with which they aligned. Finally, the laboratory ideas generated by the students were summarised and described, and common features across the four groups were identified.

Table 16. Workshop instructions given to students

Workshop activities and timing	**Instructions provided**
What is valuable about doing laboratory work as an engineering student? (15 minutes)	Value in laboratory-based work could include learning critical skills, knowledge and attributes that enhance student experience. Take 5 minutes individually to write down on individual post-it notes the key values that engineering students can obtain from laboratory-based learning. Then, take 10 minutes in teams to discuss these values and why they are important. Categorise similar post-it note ideas into groups.
How might we make the laboratory experience more engaging? (15 minutes)	Consider how a laboratory experience can be more effective and engaging whilst still teaching the values discussed. Take **15 minutes** in teams to brainstorm how to implement the discussed skills and attributes in an engaging way, whilst considering what specific limitations might be, and any possible solutions.
Laboratory Concept (20 minutes)	With consideration to everything discussed so far, create a concept for a laboratory-based learning experience. Each team will be given one of the following themes: Gas Laws; Material Properties; Newton's Laws of Motion Take **20 minutes** in teams to brainstorm a concept.
Reflection (5 minutes)	How does your design concept compare to any laboratory-based or hands-on learning you have experienced? Is the design concept more engaging? Does the design concept teach skills and knowledge more effectively? Take **5 minutes** to discuss this.
Presentation (30 minutes)	Present your design concept to the rest of the group! Take **10 minutes** to finalise your concept with your teams, outlining what skills, knowledge and attributes the concept teaches, how the experience is engaging for students, constraints considered with possible solutions, and how the concept may compare to previous experiences. Each team will have **5 minutes** to present.

RESULTS

On collating and analysing the data, it was noted that the students produced 67 comments on valuable aspects of the laboratory programme, and 57 on aspects that could be improved. Four separate laboratory activities were proposed.

What do Students Value in Laboratory Work?

The comments that students provided on the areas that they see as valuable in laboratory work were grouped into similar themes and these themes then mapped to the relevant areas

of the CDIO 3.0 syllabus as presented in table 3. The percentage of comments related to each CDIO syllabus section are shown in figure 1.

Table 17. Areas of laboratory work valued by students

Theme	No. of Comments	CDIO Syllabus section
Knowledge and understanding	7	1 Fundamental Knowledge and Reasoning
Data Presentation and Analysis	6	2 Personal and Professional Skills and Attributes
Learning experience	4	
Practical experimentation skills	11	
Problem solving	1	
Professional Skills	3	
Time Management	2	
Communication	12	3 Interpersonal Skills: Collaboration, Teamwork and Communication
Team working	7	
Putting theory into practice	14	4 Conceiving, Designing, Implementing and Operating Systems

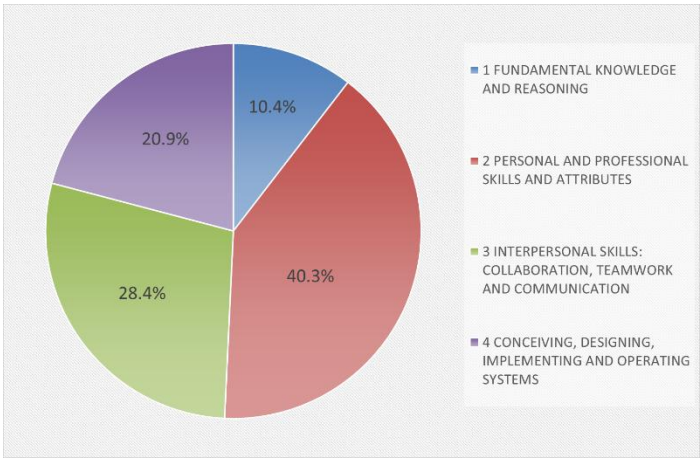


Figure 40. Distribution of comments on the perceived value of laboratory work across the areas of the CDIO syllabus

Valuable Aspects linked to CDIO Syllabus Section 1: Fundamental Knowledge and Reasoning

Just over 10% of the comments (7) from students related to a gain in knowledge, this included reinforcement and application of knowledge, and to extension of knowledge beyond that which is gained in taught lectures to allow students to stretch their learning.

Valuable Aspects linked to CDIO Syllabus section 2: Personal and Professional Skills and Attributes

The highest percentage of positive comments, approximately 40%, relate to section 2 of the syllabus, this included 11 comments about the value of practical experimental skills including learning how to follow instructions, set up experiments, gain familiarity with equipment, follow good experimental practice, and gain hands on experience. Six comments related to learning how to record, analyse and present data correctly. The benefits of active and engaging learning provided by laboratory work were also valued by students (4 comments), while students also noted skill development opportunities in time management (2 comments), professional skills such as understanding their responsibilities relating to Health and Safety and accepted industrial practices (3 comments) and one comment on problem solving skills.

Valuable Aspects linked to CDIO Syllabus section 3: Interpersonal Skills: Collaboration, Teamwork and Communication

Just over 28% of comments related to section 3 of the syllabus, with 12 relating to communication. Students highlighted report writing skills, verbal communication, presentation and listening skills as valuable aspects gained from laboratory work. The remaining comments related to this section (7) referred to improvements to skills in team working, networking, delegating, managing group work and resolving conflicts.

Valuable Aspects linked to CDIO Syllabus section 4: Conceiving, Designing, Implementing and Operating Systems

Approximately 21% of comments related to this section of the syllabus, with 8 of these comments using a close variant of the term “putting theory into practice” and the remaining 6 mentioning visualising theory in a real-world context being of great benefit.

Identified Areas for Improvement

As with the comments relating to the perceived value of laboratory work, the comments relating to suggested areas for improvement were themed and then matched to the appropriate area of the CDIO syllabus. Here the students made nine comments related to Fundamental Knowledge and Reasoning, four related to Personal and Professional Skills and Attributes, one relating to Interpersonal Skills, and, most notably, 39 relating to Conceiving, Designing, Implementing and Operating Systems. The breakdown of themes is presented in table 4, with the percentage of comments relating to each CDIO syllabus area in figure 2.

As stated above, by far the highest number of comments relating to areas of improvement were aligned with syllabus section 4, with over 68% of comments in this area. The majority of these relate to wanting more student involvement in the design, set up, and operation of the laboratories. Suggestions for reducing laboratory group sizes to provide more time for individuals to have more active involvement or changing the timing and structure of laboratories to achieve the same goal were proposed. Students also suggested that increasing the complexity of the laboratories and including other aspects into the laboratories such as design and manufacturing would be of value.

The next highest number of comments related to syllabus section 1, where students highlighted the desire to improve their understanding of concepts and stretch their learning with experience of theory and knowledge outside of that gained in taught modules. There were only a few comments about improvements required that mapped to syllabus section 2 or 3.

Table 18. Areas identified for improvement

Theme of comments	No. of comments	CDIO Syllabus Section
Improve understanding of concepts	1	1 Fundamental Knowledge and Reasoning
Provide stretch learning	2	
Link lab more closely to lectures	6	
Learning experience	2	2 Personal and Professional Skills and Attributes
Report writing	2	
Teamwork	1	3 Interpersonal Skills: Collaboration, Teamwork and Communication
Linking theory with practice	1	4 Conceiving, Designing, Implementing and Operating Systems
More manufacturing	1	
Link to industry	2	
More design based	3	
Complexity of practical tasks	5	
More hands on	27	
Other	4	Other (general comments)

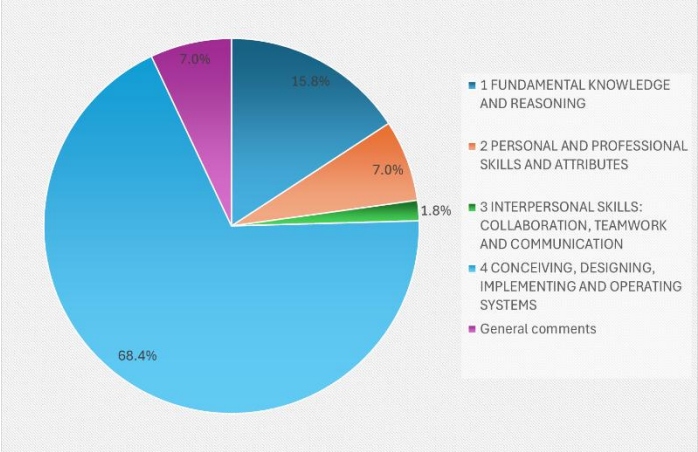


Figure 41. Distribution of comments on suggested areas for improvement in laboratory work across the areas of the CDIO syllabus

Student Proposed Laboratory Concepts

In the final phase of the workshop the students were challenged with developing laboratory concepts that they felt would be more engaging and improve their learning experience. The concepts were roughly sketched out by each group and then the students presented their ideas verbally in more detail to the room. A summary of these is given in table 5. Notably, all student-generated concepts involved a design and manufacturing aspect, followed by testing, and analysis of results. All were multi-step laboratories where students spent several sessions working on their initial concepts, learning how to use equipment, designing components and carrying out experimentation. Much less emphasis was placed on standard teaching laboratory equipment and instead focused on students learning through doing, through hands-on projects and iterative design, which resonates strongly with CDIO and SCL principles.

The current learning outcomes for the laboratory programme are drawn from the general learning outcomes for the UK Engineering Council AHEP4 standards. These are presented in table 6, along with their alignment to the CDIO syllabus sections. The same table outlines some suggested ways in which the student generated ideas could align with required learning outcomes. It can be seen that any of the proposals can be readily shaped into structured activities that meet the programme requirements, and hence further development of this process could be used to give students meaningful autonomy while remaining within the structures of accreditation requirements and the CDIO framework.

CONCLUSION

This initial study highlights both the strengths and the shortcomings students perceive in current laboratory provision and maps them to the CDIO Syllabus to inform future developments. Students value laboratories most where they develop practical experimentation and data skills (Section 2), practice communication and teamwork (Section 3), and apply theory in real-life contexts (Section 4). However, the greatest identified need for improvement is also in Section 4 with students expressing a desire for more hands-on involvement in conceiving, designing, implementing, and operating experiments. Their proposed multi-session, design-and-build concepts indicate a clear appetite for authentic, iterative work that builds ownership and confidence while better reflecting engineering practice. Student generated proposals can be readily adapted to meet required learning

outcomes, giving students autonomy and potentially higher motivation, while staying within required programme frameworks.

Actions arising from this for programme development will include restructuring selected laboratories into multi-session structured activities that support full design-build-test cycles which maximise individual hands-on time, with the aim of increasing the impact of the laboratories on student learning and skill development, aligned with CDIO and SCL principles.

Table 19. Student laboratory concepts

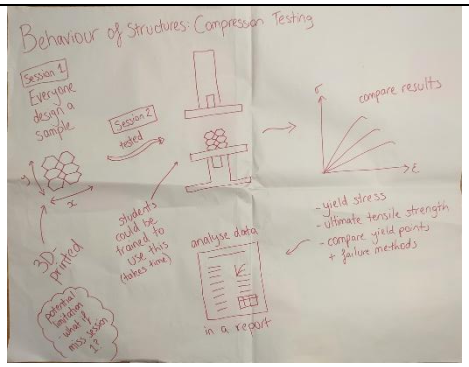
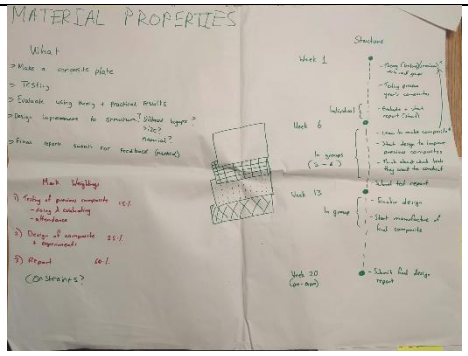
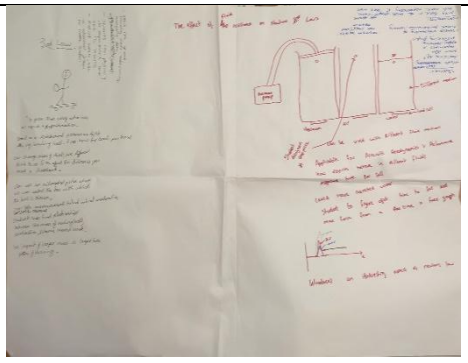
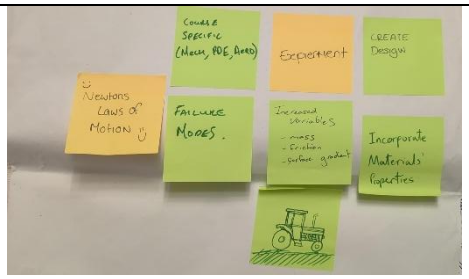
Group	Sketched Outline	Laboratory detail
1		STRUCTURES Multi-step laboratory incorporates student design of a structural component, manufacture by 3D printing, training on test equipment, testing of component, analysis of results (comparing results across group) and reporting findings.
2		MATERIALS Semester-long laboratory activity incorporates initial benchmarking and evaluation of composite panels made by students during the previous year. Students would then learn how to manufacture a composite panel, and then develop an improved design, manufacture it and test it. Finally, they would produce a technical report.
3		NEWTON'S LAWS The group had two suggestions: The first laboratory relates fluid resistance and motion of an object in different media to Newton's Laws. A student-led design element is introduced through design and manufacture of the drop piece. Students would take measurements, produce graphs and compare them with theory. Student physical interaction activity, investigating effects of mass and other variables on motion.
4		NEWTON'S LAWS Students design and manufacture a model vehicle which is course-specific e.g. for Mechanical or Aerospace. They then investigate the effect of variables on motion such as mass, friction, and surface gradient. Students suggested incorporating additional aspects such as material properties and failure mechanisms.

Table 20. Alignment of AHEP LOs with CDIO Syllabus and student proposals

Current AHEP learning outcomes on laboratory module	CDIO alignment	Group 1	Group 2	Group 3	Group 4
Apply knowledge of mathematics, statistics, natural science and engineering principles to the solution of complex problems. Some of the knowledge will be at the forefront of the particular subject of study	1.1, 1.2, 2.1, 2.4	Structures and materials theory, statistics	Composite theory, structures	Dynamics, fluid mechanics	Forces, motion, energy
Select and apply appropriate computational and analytical techniques to model complex problems, discussing the limitations of the techniques employed	2.1, 2.2, 2.3	Beam/plate models, FEA, comparison of results/theory	Use modelling tools and compare with test data	Compare experimental data to theoretical fluids models	Make predictions about motion
Select and evaluate technical literature and other sources of information to address complex problems	2.2, 2.4	Material datasets, standards, background information	Research layup strategies, failure modes	Literature search on drag, typical models	Research friction coefficients, small vehicle dynamics
Apply an integrated or systems approach to the solution of complex problems	2.3	Consider geometry, materials, printing parameters, test methods etc	Consider material, manufacturing, design, testing	Interactions between geometry, fluid medium, measurement apparatus	Consider vehicle, contact surfaces, test conditions
Use practical laboratory and workshop skills to investigate complex problems	2.2, 4.4, 4.5, 4.6	Hands-on printing and testing	Hand lay-up, cutting, testing	Manufacture of test piece, experimentation	CAD and 3D printing, assembly, testing
Select and apply appropriate materials, equipment, engineering technologies and processes, recognising their limitations	1.2, 2.1, 4.4, 4.5	Justification of material choices, printing parameters	Choose resins, fibres, moulding techniques	Choose geometry, manufacturing method, material	Choose materials, bearings, wheels
Function effectively as an individual, and as a member or leader of a team	2.4, 2.5, 3.1, 3.2	Team based	Team based	Team based	Team based
Communicate effectively on complex engineering matters with technical and non-technical audiences	3.2	Lab report, presentation	Technical report, presentation	Lab report, presentation	Technical report, presentation

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BEYOND LINEAR CDIO: PROCESS PATTERNS IN RENOVATION-ORIENTED ARCHITECTURAL ENGINEERING EDUCATION

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ABSTRACT

Architectural engineering education can adopt the Conceive-Design-Implement-Operate (CDIO) framework as a linear representation of design–engineering processes. However, renovation projects are inherently iterative and constraint-driven, challenging linear interpretations of CDIO. While iteration is acknowledged conceptually within the CDIO literature, empirical studies that make such process patterns visible in educational practice, particularly in renovation-oriented architectural engineering, remain limited. This paper addresses this gap by examining how CDIO is enacted in practice within a renovation-focused architectural engineering studio through a combined analysis of task-level process data and experiential indicators. Empirical material consists of task-sequence data from 19 students, yielding 207 CDIO-aligned transitions derived from course submissions, together with 226 task-based survey records capturing perceived Purpose, Control, Effort, Persistence, Enjoyment, and Groupmate contribution. Course-native task categories were mapped to CDIO stages, with Operate interpreted as a representational and integrative phase enacted through final posters and presentations. Process behavior was analyzed using Sankey-style visualizations and explicit identification of backward CDIO transitions as loops. Results indicate that CDIO progression is predominantly directional but explicitly non-linear. Within-stage iteration accounted for 56.5% of transitions, forward transitions for 30.4%, and backward transitions for 13.0%. Backward transitions were concentrated primarily in the Implement stage, reflecting reframing triggered by technical resolution, representational demands, and constructability constraints. Remarkably, backward transitions were also observed from Operate, indicating that final presentations occasionally prompted reconsideration of earlier design or implementation decisions rather than functioning exclusively as terminal stages. Experiential results show consistently high perceived collaboration and goal orientation across tasks, with moderate-to-high levels of Grit and Vision. Vision was strongly associated with Purpose and Enjoyment, while Grit was closely related to Effort and Persistence.

KEYWORDS

Architectural engineering, Renovation, CDIO processes, Iteration, design loops, Standards: 1, 5, 7, 8, 11.

INTRODUCTION

The Conceive-Design-Implement-Operate (CDIO) framework is a globally recognized approach to engineering education that emphasizes integrated learning, professional competencies, and engagement with real-world engineering practice across the full project lifecycle (Crawley, Malmqvist, Östlund, Brodeur, & Edström, 2014; Malmqvist, Edström, & Rosén, 2020). Developed to address persistent gaps between theoretical instruction and professional application, CDIO has been widely adopted across traditional engineering disciplines, including mechanical, electrical, and software engineering, where it has demonstrated effectiveness in fostering technical competence, teamwork, and problem-solving skills (Bankel et al., 2003; Graham, 2018; Stachura & Bar-Eli, 2024). More recently, CDIO principles have begun to inform education in architecture and the built environment. Studies in architectural engineering, sustainable design education, and studio-based learning environments indicate growing interest in CDIO as a means of integrating design, technology, and lifecycle thinking (Selim, Mayhoub, & Abuzaid, 2025; Woźniczka & Widera, 2022). These developments suggest that CDIO offers a relevant framework for architectural engineering education, particularly where project-based learning, interdisciplinarity, and sustainability considerations are central.

Although CDIO is theoretically defined as a lifecycle framework, many curricular implementations and evaluations in engineering education continue to represent CDIO as a progression through discrete phases (Rodriguez Bernal, 2017). While such representations align with new-build engineering projects, they are less suited to renovation-oriented architectural engineering, where design–engineering processes are inherently iterative and constraint-driven. Renovation projects require continuous engagement with existing structures, historical and cultural values, regulatory frameworks, and evolving technical information, frequently necessitating reconsideration of earlier decisions as new constraints emerge (Douglas, 2006; Gil-Mastalerczyk, 2020; Plevoets & Van Cleempoel, 2019).

In architectural engineering education, renovation studios typically involve repeated cycles of interpretation, spatial reframing, technical resolution, and representational synthesis rather than a single pass-through predefined phases (Schön, 2017). Iteration and backtracking are therefore not indicators of process failure but integral features of competent renovation practice. Although CDIO literature conceptually acknowledges iteration, empirical educational studies continue to prioritize phase completion, learning outcomes, or competency mapping, providing limited visibility into how iterative processes are enacted in student work. As a result, the enactment of CDIO in renovation-oriented architectural engineering education remains underexplored, particularly with respect to how iterative process patterns relate to students' experienced agency, motivation, and collaboration. Existing studies (e.g. (Lenz, Diefenbach, & Hassenzahl, 2019; Renganathan, Shanthi Priya, Kumar, Thiruvengadam, & Senthil, 2025) rarely combine task-sequence analysis with experiential data in ways that make iteration empirically visible across a cohort.

This paper addresses this gap by examining how CDIO is enacted in practice within a renovation-focused architectural engineering studio through a combined analysis of task-level process data and task-based experiential indicators. By visualizing CDIO transitions, identifying backward loops, and relating these patterns to students' perceived Purpose, Control, Effort, Persistence, Enjoyment, and collaboration, the study contributes a process-sensitive interpretation of CDIO that aligns with the realities of renovation-based architectural engineering education.

METHOD

Research Design and Analytical Framework

This study employs a quantitative, process-focused survey approach in architectural engineering education, with building renovation as the empirical case. Renovation is viewed as an iterative design-engineering process influenced by current conditions, historical constraints, and collaborative decision-making. The CDIO framework functions as the main analytical perspective, not as a measurable variable, but as a process ontology that helps interpret students' task-level experiences throughout the renovation workflow.

Educational Context and Participants

Data were collected during the autumn of 2025 from 19 second-year students enrolled in a renovation-focused architectural engineering course in Jönköping, Sweden. Students worked in pairs on a project-based renovation brief involving historical analysis, spatial design, material considerations, and architectural representation of a formal industrial building turned into a boutique hotel. Across the course, 226 task-based survey responses were recorded in direct connection with specific project activities. Participation was voluntary, and all data were anonymized.

Task Categories as Units of Analysis

Analysis was structured around empirically encoded task categories, representing distinct modes of architectural-engineering activity that could recur over time: Concept and Moodboard, Historical Analysis, Site-plan and Volume, Floorplans and Elevations, and Poster and Presentation materials. These categories formed the primary units of analysis and were interpreted through the CDIO lifecycle.

CDIO Interpretation of Tasks

Concept and Moodboard and Historical Analysis were mapped to Conceive, with the latter emphasizing constraint-driven interpretation specific to renovation practice. Site-plan and Volume corresponded to Design, while Floorplans and Elevations represented a Design–Implement transition requiring technical and representational resolution. Posters and presentations were interpreted as Operate (late-stage synthesis outputs), functioning as integrative and communicative closure rather than building use.

Measures

All constructs were measured using five-point Likert scales (1=strongly disagree, 5=strongly agree). The survey captured perceived Purpose, Control, Effort, Persistence, Enjoyment, and Groupmate contribution. Two composite indices were computed: Grit (Effort + Persistence) and Vision (Purpose + Enjoyment), calculated only when both components were present. An online tool was built for capturing students' ratings (www.designtool.se).

Analytical Strategy

Descriptive statistics and Pearson correlations were used to explore relationships among constructs, interpreted as process-sensitive associations rather than causal effects. To capture non-linearity, task entries were ordered chronologically per student and mapped to CDIO stages. A CDIO loop was recorded when a transition moved backward in the ordinal sequence (Conceive → Design → Implement → Operate). Within-stage repetition was treated as

iteration but not classified as a loop. Four loop types were identified: Design-Conceive, Implement-Design, and Implement-Conceive, and Operate-to-Earlier stage loops, reflecting cases in which late-stage synthesis and presentation activities prompted reconsideration of design or implementation decisions.

Methodological Positioning and Limitations

Loops were interpreted as meaningful indicators of constrained design reasoning characteristic of renovation practice, rather than as deviations from the CDIO framework. The study does not assess CDIO competencies or technical performance outcomes and relies on self-reported experiential data. As such, the findings should be interpreted as reflecting students' perceived engagement and process enactment rather than objective measures of design quality or learning achievement.

RESULTS

Descriptive statistics for all indicators are presented in Figure 1. Across the full dataset, mean scores for all experiential indicators exceeded the midpoint of the scale. Groupmate contribution yielded the highest mean value (M = 4.85, SD = 0.48, n = 226), indicating consistently high perceived balance of contribution within student pairs. Purpose also exhibited a high mean (M = 4.50, SD = 0.63), followed by the composite Vision index (M = 4.14, SD = 0.64). Mean Control was M = 3.98 (SD = 0.89), while Effort (M = 3.90, SD = 0.96) and Persistence (M = 3.97, SD = 0.82) demonstrated similar central tendencies. Enjoyment showed a mean of M = 3.78 (SD = 0.92), reflecting moderate to high affective engagement across tasks. The composite Grit index yielded a mean value of M = 3.93 (SD = 0.70).

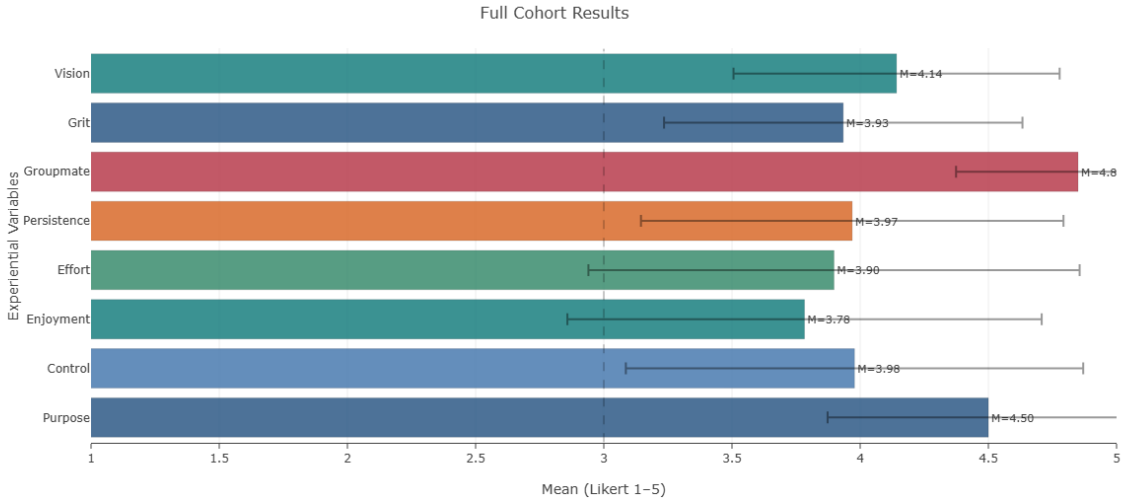


Figure 1. Full cohort descriptive statistics (N=226)

Task-Oriented Results

Considerable variation was observed across task categories (Figure 2), particularly for Purpose, Control, and Enjoyment. Mean Purpose scores ranged from M = 3.69 (SD = 0.70) during Historical Analysis tasks to M = 4.64 (SD = 0.64) during Presentation and Poster tasks. Control showed a similar pattern, with the lowest mean during Historical Analysis (M = 3.38, SD = 1.15) and the highest during Presentation and Poster (M = 4.44, SD = 0.77). Effort and Persistence demonstrated comparatively limited variation across task categories. Effort means ranged between M = 3.44 and M = 4.06, while Persistence ranged from M = 3.75 to M

= 4.08, indicating relatively stable work investment across different phases of the renovation process. Enjoyment exhibited greater task sensitivity, with lower mean values during Historical Analysis (M = 3.06, SD = 0.85) and higher values during Presentation and Poster (M = 4.44, SD = 0.77). Groupmate contribution remained consistently high across all task categories, with mean values ranging from M = 4.63 to M = 4.96 and low associated standard deviations. Composite indices reflected these task-level patterns. Vision ranged from M = 3.38 during Historical Analysis tasks to M = 4.54 during Presentation and Poster tasks. In contrast, Grit demonstrated a narrower range across task categories, varying between M = 3.70 and M = 4.00.

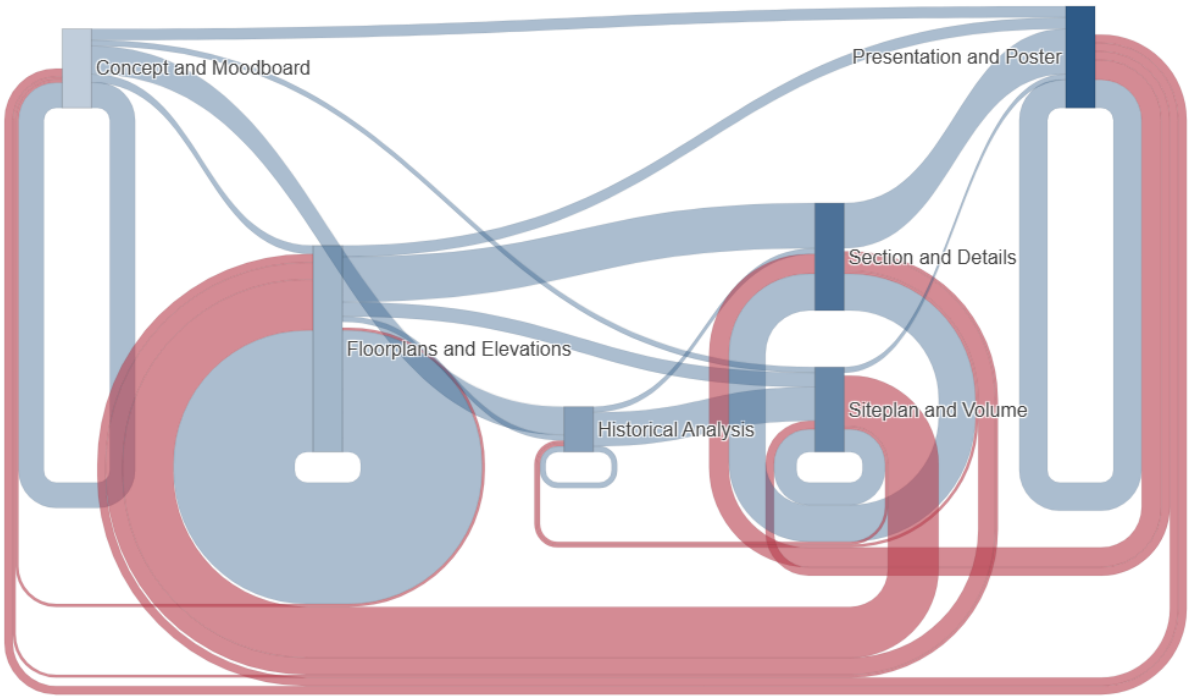


Figure 2. Static snapshot from an interactive Sankey diagram illustrating transitions between task categories; red flows indicate backward loops.

CDIO-Oriented Results

Tasks were analytically mapped to the CDIO stages (Conceive, Design, Implement, Operate), and descriptive statistics aggregated by CDIO stage are reported in Figure 3. Across all CDIO stages, mean values for all experiential indicators exceeded the midpoint of the scale, indicating generally positive perceptions of purpose, agency, effort, persistence, and collaboration throughout the renovation process. Process analysis identified 207 CDIO-aligned transitions across the cohort. Of these transitions, 117 (56.5%) occurred within the same CDIO stage, 63 (30.4%) represented forward movement to a subsequent stage, and 27 (13.0%) constituted backward transitions, indicating iterative returns to earlier stages. Backward transitions were not evenly distributed across stages. The majority originated from the Implement stage, reflecting iterative refinement triggered by technical resolution, representational demands, or constructability constraints. However, backward transitions were also observed from the Operate stage, as shown by red links returning from Operate to earlier CDIO stages. These transitions indicate that final presentations and posters occasionally prompted reconsideration of earlier design or implementation decisions, rather than functioning exclusively as terminal stages. Design-stage loops were present but less frequent, while within-stage iteration dominated the Conceive and Implement phases, suggesting

sustained exploration and refinement rather than linear progression. Despite the presence of backward transitions, Operate remained predominantly an endpoint in the process structure, with most trajectories converging toward this stage.

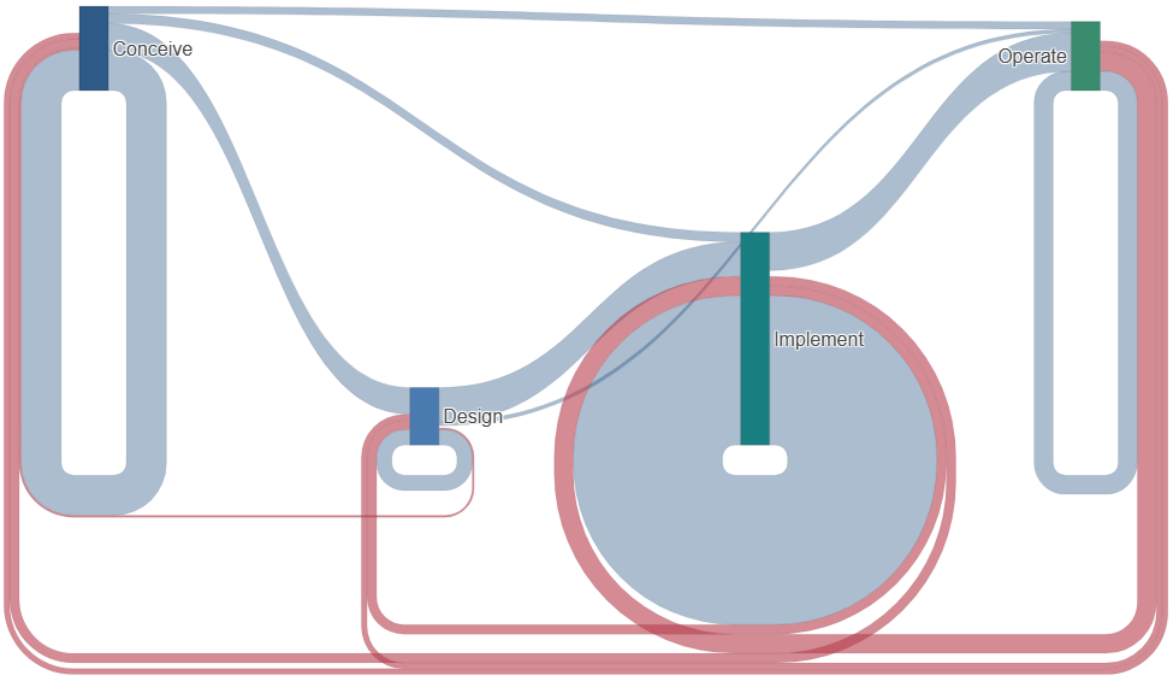


Figure 3. Static snapshot from an interactive Sankey diagram illustrating transitions between CDIO categories; red flows indicate backward loops.

Correlation Analysis

Pearson correlation coefficients among all indicators and composite indices are presented in Table 1. Vision demonstrated a strong positive correlation with Enjoyment (r=.88) and Purpose (r=.72), and a moderate positive correlation with Control (r=.44). As expected by construction, Grit showed strong positive correlations with Effort (r=.82) and Persistence (r=.74). Correlations between Groupmate contribution and other indicators were weak (|r| < .06), indicating limited association with individual experiential dimensions in this dataset.

Table 1. Correlations (r) among experiential indicators (p<.05)

	Control	**Enjoyment**	**Effort**	**Persistence**	**Grit**	**Vision**
Purpose	0.35	0.32	0.23	0.17	0.25	0.72
Control		0.38		0.15		0.45
Enjoyment				0.15		0.88
Effort				0.23	0.82	
Persistence					0.74	0.20
Groupmate						
Grit						0.17

DISCUSSION

This study aimed to examine how the CDIO framework is enacted in practice within renovation-oriented architectural engineering education, with particular attention to iterative process patterns and students' experiential responses across tasks and CDIO stages. The findings provide empirical support for interpreting CDIO as a predominantly directional yet explicitly non-linear process when applied to renovation contexts.

CDIO as a Directional but Non-Linear Process in Renovation Education

The process analysis demonstrated that while most transitions followed a forward or within-stage progression, a substantive proportion of backward transitions occurred across the cohort. The predominance of within-stage iteration and the presence of backward transitions indicate that renovation-oriented design-engineering processes involve sustained exploration and refinement rather than linear phase completion. These findings align with prior theoretical accounts of renovation practice, which emphasize constraint-driven reasoning, reinterpretation of existing conditions, and iterative negotiation between concept, design, and implementation.

Importantly, backward transitions were concentrated primarily in the Implement stage, suggesting that technical resolution and representational precision frequently trigger reframing of earlier design or conceptual decisions. This pattern supports the interpretation of loops as meaningful enactments of design reasoning rather than deviations from CDIO. The presence of backward transitions originating from Operate further challenges common educational representations of Operate as a purely end of project phase. In this study, final presentations and posters occasionally functioned as reflective and diagnostic moments that prompted reconsideration of earlier stages, reinforcing the view of Operate as an integrative and sense-making phase in educational contexts rather than a proxy for building use.

Task Sensitivity and Experiential Variation Across the Renovation Process

Task-oriented results reveal that students' experiential responses varied meaningfully across task categories, particularly for Purpose, Control, and Enjoyment. Lower scores during Historical Analysis tasks and higher scores during late-stage presentation activities suggest that interpretive and constraint-heavy phases may be experienced as more demanding and less immediately rewarding, while synthesis and communication phases provide greater clarity of purpose and perceived agency. These patterns are consistent with prior research on studio-based learning, which highlights differences in student engagement across analytical, generative, and representational tasks. In contrast, Effort and Persistence showed relatively stable mean values across tasks, indicating consistent work investment throughout the renovation process. This stability suggests that variations in enjoyment or perceived control do not necessarily translate into reduced effort, supporting the interpretation of renovation work as requiring sustained commitment regardless of task type.

Grit, Vision, and Collaboration in Renovation-Oriented CDIO Enactment

The experiential results further show moderate-to-high levels of both Grit and Vision across the cohort. The strong associations between Vision, Purpose, and Enjoyment indicate that students' future-oriented thinking and motivational alignment are closely tied to task meaningfulness and affective engagement. Similarly, the strong correlations between Grit, Effort, and Persistence confirm the internal coherence of these constructs as indicators of sustained execution capacity. Perceived Groupmate contribution remained consistently high

across tasks and showed weak associations with other experiential indicators. This pattern suggests that collaboration was experienced as stable throughout the studio, rather than varying meaningfully across task types or CDIO stages. In the context of paired renovation projects, collaborative balance may therefore reflect course organization and team formation more than task-specific experiential dynamics.

Implications for CDIO Interpretation and Architectural Engineering Education

The descriptive statistics and correlation patterns provide context for interpreting the observed process structures. The consistently high levels of Purpose, collaboration, and sustained effort indicate that students experienced the renovation project as meaningful and engaging. In this context, the iterative task and CDIO loops are unlikely to reflect confusion or disengagement. Instead, they appear within a stable motivational environment characterized by sustained effort and balanced collaboration. Vision is closely associated with Purpose and Enjoyment, while Grit reflects sustained execution through Effort and Persistence.

These findings support a process-sensitive interpretation of CDIO that is particularly relevant for renovation-oriented architectural engineering education. Rather than treating backward transitions as inefficiencies or failures to progress, the observed loops can be understood as indicators of competent design reasoning under constraint. Making such loops empirically visible allows CDIO to be interpreted as an adaptive framework capable of accommodating iterative and exploratory practices characteristic of renovation work. From an educational perspective, the results suggest that CDIO-based curricula in architectural engineering may benefit from explicitly acknowledging and supporting iteration, particularly during implementation and late-stage synthesis. This may help align pedagogical models with students' lived experiences of design–engineering processes and avoid reinforcing overly linear interpretations of professional practice.

Implications for CDIO Standards

The findings of this study have implications for several CDIO Standards. Standard 1 (CDIO as Context) is supported by the empirical demonstration that renovation-oriented architectural engineering projects naturally enact the full CDIO lifecycle, although in a non-linear manner. The observed process loops suggest that CDIO functions as a contextual framework for learning when interpreted as iterative rather than sequential.

Standard 5 (Design–Implement Experiences) is reinforced by the concentration of backward transitions within the Implement stage, indicating that design–implement activities prompt meaningful reframing and technical reflection. These loops highlight the pedagogical value of implementation tasks as sites of learning rather than endpoints of execution.

Standards 7 and 8 (Integrated Learning Experiences and Active Learning) are reflected in the stable levels of effort, persistence, and collaboration across tasks, suggesting that students engage cognitively and affectively with renovation work through continuous integration of technical, conceptual, and representational knowledge.

Finally, Standard 11 (Learning Assessment) is informed by the study's use of task-level experiential indicators and process metrics. By making iteration and looping empirically visible, the findings point toward assessment approaches that recognize iterative reasoning and process quality as integral components of learning in architectural engineering renovation education.

Limitations and Directions for Future Research

This study is limited by its reliance on self-reported experiential data and a single course context with a relatively small cohort. While the task-sequence analysis provides insights into process structure, future research could combine similar methods with observational data, design artifact analysis, or longitudinal studies across multiple courses. Further work could also explore how different instructional strategies or assessment formats influence the frequency and character of CDIO loops. Despite these limitations, the present study demonstrates the value of integrating task-level process analysis with experiential indicators to advance empirical understanding of CDIO enactment in architectural engineering education.

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USING LARGE LANGUAGE MODELS AS TOOLS IN INTRODUCTORY PROGRAMMING COURSES

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ABSTRACT

This paper explores the utilization of large language models (LLMs) in introductory programming courses in higher education. The primary objective is to examine how LLMs can support the creation of programming-related teaching materials. In addition, the aim is to reflect their potential impact on the learning objectives of these courses. The study is conducted as a literature review. The findings indicate that LLMs can be employed to generate a variety of programming tasks, such as small programming exercises and multiple-choice questions, with the quality of these tasks often comparable to those created by humans. Furthermore, LLMs enable the development of novel assignment types. In terms of learning objectives, the increasing prevalence of LLMs highlights the potential to introduce more advanced course content earlier. If LLMs are used to generate code, instructional emphasis may shift from code writing to reading, analyzing, and modifying code. Nevertheless, teaching fundamental programming concepts seems to remain essential, necessitating a balanced approach between leveraging LLMs and maintaining traditional programming practices.

KEYWORDS

Large language model, ChatGPT, Generative artificial intelligence, Programming education, Engineering education, Standards: 2, 8, 11

INTRODUCTION

Generative artificial intelligence (GAI) is transforming both working life and education. Many widely used tools, such as GitHub Copilot and Openai's ChatGPT, are freely available to students (Openai, n.d.), and their adoption among learners is increasing. Since its launch in November 2022, the number of active users of ChatGPT has continually increased from less than 100 million in 2023 to more than 700 million in 2025 (Chatterji et al., 2025). The development of AI tools has raised concerns among teaching staff. In a study conducted by Lau and Guo (2023), every interviewee mentioned the possibility of cheating, even though the interview questions did not explicitly address it. Many were also worried that students who rely heavily on AI might fail to understand course content. Consequently, several respondents emphasized the importance of supervised exams in assessment. Increasing the number of exams, however, was seen as only a short-term reaction to the growing use of AI tools.

Large language models also present opportunities. Lau and Guo (2023) identify capabilities that can be leveraged in teaching, such as code generation and explanation. AI could also assist in generating test cases and fixing errors. Modern LLMs are powerful enough to create programming exercises. Rytilahti, Weerakoon, and Kaila (2024) utilized ChatGPT to generate programming exercise descriptions using various strategies. While many exercises required slight manual adjustments, students were unable to distinguish between human-made and AI-generated versions of exercises. GAI can also be used to support students by creating personalized learning plans based on the students' needs (Chin & Ming, 2024). Utilizing generative AI can ease the workload for both students and instructors. However, a study conducted by Prather et al. (2025) found that fewer than half of programming course instructors include generative AI in their courses, but three-quarters believe that LLMs have changed the skills needed in software development. The most common reason for not adopting it was a lack of resources, be it skills or time, to do so.

This paper explores the utilization of LLMs in introductory programming courses in higher education. The primary objective is to examine how LLMs can support the creation of programming-related teaching materials. In addition, the aim is to study their potential impact on the learning objectives of these courses. This study is an extended version of the Bachelors' Thesis of the first author (Roslöf, 2024).

RESEARCH QUESTIONS AND METHODS

The goal of this study is to identify situations in which LLMs could be utilized for creating teaching materials for introductory programming courses. If the creation of various materials with the help of GAI is feasible, it could reduce the workload of teaching staff and enable a more personalized learning experience for students. In addition, this study aims to reflect the impact of LLMs on the learning objectives of these courses. LLMs may render many of the current course assignments trivial. Therefore, combining instructors' views with the opportunities offered by LLMs may provide insights into potential changes in course design. Thus, the following research questions have been defined for this work:

RQ1: In what types of programming-related teaching material creation for introductory programming courses can large language models be utilized?

RQ2: How is the increasing prevalence of large language models expected to affect the learning objectives of introductory programming courses?

RQ1 serves as the primary research question while RQ2 functions as a secondary, supporting question. Introductory programming courses refer to courses designed for first-year university students. Teaching materials, in this context, denote resources provided by course staff for student learning focusing on programming-related assignments.

Other teaching resources such as code examples, explanations describing code functionality or error messages, are excluded from this study. In addition, lecture videos or audio recordings, as well as support provided by course assistants, are excluded. The study also does not cover automated assessment of assignments or related feedback mechanisms. The discussion of RQ1 emphasizes positive opportunities and does not address ethical issues related to the use of GAI. RQ2 considers potential future changes. Furthermore, the study examines only changes related to individual courses, not broader institutional or degree program-level structures or policies.

This study was conducted as a literature review. Given the rapid development of LLMs, only references published after 2020 were included. The initial search for research articles was conducted in February 2024, and a supplementary search in December 2025. Consequently, this study reflects the state of LLM-related research as of December 2025. However, it should be noted that a large amount of research is being done on the topic. Google Scholar finds more than 3000 results published in 2025 matching the search terms "*Generative AI",* and *"computing education".* As such, the goal of this study is not to provide a systematic review of all existing literature. Instead, we aim at providing an overview into the field. To ensure access to the most recent findings, preprints from arXiv were also utilized, which may result in minor discrepancies. Most of the material consisted of peer-reviewed research articles and conference papers. Sources used to address RQ2 primarily comprised interview-based studies. Literature searches were conducted mainly through the Scopus and ACM databases using keywords such as *"programming education," "generative AI," "ChatGPT,"* and *"LLM evolution".* In addition to database searches, sources were identified through reference lists of other publications. Microsoft Copilot was utilized exclusively to assist with the initial translation of the original report (Roslöf, 2024) from Finnish to English. All other components of this study were conducted without the use of AI tools or software.

RESULTS

Modern tools that utilize GAI are the result of research spanning over a hundred years. The term "generative artificial intelligence" covers all computational techniques that enable the creation of material based on training data. The generated material can be almost anything, such as text or photographs. The content produced by GAI is meaningful and appears new—it does not simply reproduce the training data as-is. Generative AI is based on generative modeling, which is often combined with machine learning. This makes it possible to create new material based on learned information (Feuerriegel et al., 2024). Language models belong to the field of natural language processing (NLP) that combines computer science, AI, and linguistics. NLP is applied in tasks such as translation and text generation. Modern NLP uses deep learning to train language models (Li, 2022). Due to the rapid development of large language models, forming an up-to-date assessment of their capabilities is challenging. Prather et al. (2023) note that the abilities of the latest models may be underestimated in studies, and many commonly used performance evaluation methods are unsuitable when assessing LLMs from an educational perspective.

Programming-Related Assignments

A large part of the content in many introductory programming courses consists of various exercises. However, creating exercises is often a time-consuming process, and course staff may overlook aspects that are important for student learning. First, we discuss creating small programming exercises with the help of LLMs. After that, a new type of exercise where AI supports learning is introduced and, finally, the use of LLMs in creating multiple-choice questions that support the learning objectives is addressed.

Learner-Centered Exercises and Automatic Exercise Generation

Creating programming exercises is a laborious process, and considering the interests and skills of individual students in large courses is difficult. Students can also participate in creating exercises, but they seem not always to be very motivated to do so, and the quality of the questions produced varies. Small, automatically graded programming exercises are a common exercise type in introductory programming courses. Due to their small size, these exercises can help students practice specific skills, and completing multiple exercises promotes regular practice. In addition to the exercise description, a model solution and tests must be created. The difficulty level must also be carefully adjusted, as exercises that are too difficult or too easy affect student motivation and provide little learning benefit. Students in introductory courses often represent different skill levels and backgrounds. For this reason, Sarsa et al. (2022) point out that personalizing programming exercises based on student interests and skill levels can be beneficial for learning. Sharing solutions to programming exercises among students online is also unfortunately common.

According to Denny et al. (2022), attempts have been made to create practice exercises automatically using different approaches. Exercise creation often uses parameterized questions or question templates. However, they note that both generating questions based on templates and creating new, high-quality templates for different topics is labor-intensive. Thus, large numbers of programming exercises can be created by leveraging students. This results in a large exercise pool that can cover topics instructors might not include but that are important to students. However, learner-sourced exercises have two major problems in practice. First, even if students want to use exercises created by others, they are often not motivated to create them. Second, the quality of many student-created questions is generally low, limiting their usefulness for learning (Denny et al, 2022).

LLMs may be a key to creating large pools of personalized exercises. Sarsa et al. (2022) discuss this possibility and evaluate a set of exercises generated by Openai's Codex language model. The exercise set was created by providing the LLM with an example exercise that included the task description, a model solution, and automated tests. In addition, it was given a list of programming concepts and general themes, such as fishing, that should appear in the generated exercises. Only a small portion of the generated exercises were ready to use as-is. Sarsa et al. (2022) evaluated the generated exercises based on four criteria. The first criterion, meaningfulness, addresses whether the exercise description is reasonable and solvable by students. Three-quarters of the 120 evaluated exercises were classified as meaningful. The occurrence rate of the given programming concepts and themes ranged between 75% and 80%. The research team also assessed usability. Only 21% included both a model solution and automated tests that the solution passed. Of the exercises with both, one-third of the solutions passed the tests. Although the proportion of ready-to-use exercises was small, Sarsa et al. (2022) see potential in LLM-generated exercises. Modifying existing exercises and tests is easier than creating new ones, so even flawed outputs can be useful. Additionally, they suggested that students could create targeted and meaningful questions using keywords and

instructor-provided examples. Denny et al. (2022) also proposed a new type of exercise that uses LLMs to address problems in learner-sourced exercise creation. In robot-sourced exercise creation, the student creates an example exercise and keywords as described above. The LLM then generates multiple exercises based on the prompt.

A more complex exercise generation model is advantageous to creating high-quality exercises. Instead of using a single prompt, Jacobs et al. (2025) created a pipeline containing several prompts, each of which creating a part of the exercise. In addition to the exercise-generating prompts, it contained a reflection module with initiated up to five iterations of the generation process, if the created model solution could not pass the generated unit tests. As its input, the pipeline only required a context and a programming context which should be included in the exercise. They generated 200 exercises for different contexts, each requested to contain between one and three different introductory programming concepts. Based on expert evaluation, Jacobs et al. (2025) found that most exercises had correct syntax and were solvable based on the task description. All exercises incorporated the requested context. Out of the exercises deemed solvable, 80% had unit tests and 85% had a correct model solution. This is a significant improvement from the earlier work of Sarsa et al. (2022). However, the share of exercises that included the requested programming concepts decreased from 94% to 40% when the number of concepts was changed from one to three (Jacobs et al., 2025).

Jacobs et al. (2025) also demonstrated the potential of LLMs as a part of learner-sourcing. Using the exercise generation methodology described above, 26 introductory programming students participated in generating, solving, and evaluating exercises for which they could request contexts and concepts. The students rated the exercises similarly to the experts. Additionally, they found the process of generating personalized exercises interesting and useful for learning. They further recognized the usefulness of being able to generate and solve unlimited amounts of customized exercises (Jacobs et al., 2025). As students seem motivated to generate exercises and the generated exercises are mostly of high quality, the weaknesses of learner-sourcing noted by Denny et al. (2022) could be mitigated with LLMs.

Using LLMs for programming exercise creation is an attractive possibility that can increase the number of exercises available to students and reduce instructors' workload. Combining LLM use with learner-sourced exercise creation can address its problems and help students develop code evaluation skills.

Prompt Problems

The use of LLMs can also be taught and integrated into instruction. Prompt problems are a new exercise type developed by Denny et al. (2024), where students work with a LLM to solve a programming task. The exercise description is presented to the student visually rather than as a traditional text-based description so that the student cannot copy it directly into the LLM. Based on the description, the student develops a prompt, which is sent to the LLM. The LLM generates code, which is checked by an automated validator. The student sees both the code and the test results. If all tests are not passed, the student can generate a new prompt to try to get a better response from the LLM (Denny et al., 2024).

The main learning objective of prompt problems is teaching students how to create good code generation prompts. In a pilot study conducted by Denny et al. (2024), participants noted that prompt problems helped them practice computational thinking and problem-solving, as well as introduced them to previously unknown programming conventions. While most feedback was positive, some students were hesitant to use LLMs in programming. Additionally, prompt problems have been explored as a potential method for easing the learning process of non-

native English speakers. In a study by Prather, Reeves, et al. (2025), Arabic, Chinese, and Portuguese students solved prompt problems using their native languages. Most students were able to correctly solve the problems and found that using their native languages allowed for better expression of their thoughts. However, ChatGPT – the LLM used, had difficulties in understanding the participants' prompts, likely due to only a small number of its training materials being other than English. Programming languages and programming as a field being highly English-centric could also play a role (Prather, Reeves, et al., 2025). As the linguistic capabilities of LLMs improve, it's likely that the usefulness of prompt problems increases.

Although the previously mentioned studies had limited participation, prompt problems have been studied on a larger scale. Pădurean et al. (2025) expanded on the initial idea, adding more complex exercises, a chat interface allowing for iterative refinement of code, and making code execution available on request instead of happening automatically. Each of three different problem sets were attempted by over 900 students from an introductory programming course. In all cases more than 95% of students were able to complete the exercise. However, in two of the more complex problem sets, completion of the exercise did not require correct answers to all exercises. In addition to the high success rate, they found that students saw prompting to be easier than coding but did not seem overtly reliant on the LLM. Participants were more likely to request the execution of correct code rather than incorrect and thought that when solving difficult problems, a combination of prompting and code editing would be ideal (Pădurean et al., 2025).

Multiple-Choice Questions

There is a high demand for new, high-quality multiple-choice questions. This is influenced by growing interest in programming education and the sharing of answers to old exercises among students. Creating high-quality multiple-choice questions requires considerable expertise. If GAI could be used to create high-quality multiple-choice questions that support learning objectives, the workload of teaching staff would be significantly reduced (Doughty et al., 2024). Doughty et al. (2024) analyzed the ability of GPT-4 to create multiple-choice questions based on learning objectives and course descriptions: Approximately 250 learning objectives were collected from six different courses covering Python or data science fundamentals. As comparison material, 449 human-created multiple-choice questions were collected from these courses. Questions were classified according to the learning objective that were categorized into six levels based on the revised version of Bloom's taxonomy (Krathwohl, 2022). A system was created for generating multiple-choice questions that uses user input and static materials. Static materials include guidelines for creating multiple-choice questions, descriptions of Bloom's taxonomy levels and different question types, a small set of example questions, and instructions for returning results. Several questions were created for each learning objective—one for each question type defined for the objective's Bloom's taxonomy level.

The quality of the generated multiple-choice questions was comparable to human-created ones. Generated questions generally contained sufficient information, diverse options, and few errors in code. A larger proportion of these questions contained multiple correct options or revealed the correct answer in the question compared to human-created questions. However, the error rate was low, and compared to human-created questions, GPT-4 questions were better aligned with the learning objectives. Doughty et al. (2024) suggest that teaching staff focus more on aligning questions with the topic of the module rather than the learning objective. They also note that alignment of human-created questions with learning objectives was done manually, which may have influenced results (Doughty et al., 2024). The results

were promising and suggest that LLMs could be used to create better multiple-choice questions more quickly and with less effort.

Shu et al. (2025) expanded on the idea of utilizing learning objectives in multiple-choice question generation. Instead of learning objectives and course information, they used the name of the relevant module and a file containing the lecture notes as inputs. Additionally, the LLM received static materials similar to those of Doughty et al. (2024), but they did not include any example questions. Prior to generating the questions, the LLM was instructed to extract learning objectives aligning to Bloom's revised taxonomy from the lecture notes to use as a basis for the questions. They generated 66 questions based on four engineering courses' lecture notes, one of which was software engineering. Most of the questions were appropriate to the extracted learning objective and contained a well-constructed question stem. The answer option marked as correct was correct in 85% of cases, and in 72% of the questions the distractors were of high quality. Notably, all the cases with incorrect answers being marked as correct involved computations. Overall, Shu et al. (2025) noted that approximately 60% of the questions would be usable as-is, and approximately 30% could be modified to be usable. Additionally, they tested three of the generated questions on students, with the questions being mixed between human-generated questions. Approximately half of the students found the questions to be difficult, and the majority thought they were helpful in testing their understanding (Shu et al., 2025). As such, LLMs are capable of generating meaningful and non-trivial multiple-choice questions, although some human oversight is still needed.

Learning objectives

LLMs are likely to change what is taught in introductory programming courses. Research on this topic has described LLMs as a calculator-like tool that can reduce students' workload (Zastudil, 2023). The faculty opinions regarding the use of LLMs will influence what is taught in these courses in the future. If language models are utilized for code generation, introductory programming courses could cover topics traditionally reserved for advanced courses.

Denny et al. (2023) present several pedagogical approaches enabled by LLMs. If students do not need to focus on learning syntax, algorithmic concepts could be introduced earlier. They also suggest that assignments could shift from implementation to specification creation. Tasks might focus on designing prompts for LLMs rather than writing code. Moreover, language models can generate code that helps students start an assignment or project, targeting the focus on code modification, refactoring, and debugging skills. Emphasizing testing and performing it multiple times during an assignment could also help students understand both their own code and the code generated by LLMs (Denny et al., 2023).

The attitudes of programming course instructors toward changes brought by LLMs have been studied in several papers. Prather et al. (2023) interviewed 22 course instructors about LLMs' impact on their teaching. One topic discussed was the effect of LLMs on course learning objectives. Lau & Guo (2023) interviewed 20 members of introductory programming course staff, asking them to consider changes they would make if students had access to a perfect, invisible AI tool capable of generating and explaining code. Although the description was hypothetical, they note that many interviewees referred to existing tools such as ChatGPT. Both studies revealed concerns about student learning when using LLMs in introductory courses. The interviewees emphasized that understanding fundamental programming principles remains essential, even if language models perform part of the work (Lau & Guo, 2023; Prather et al., 2023). Some respondents did not want to change the learning objectives, as these topics form the foundation of programming knowledge (Prather et al., 2023). Lau & Guo (2023) report that some instructors critical of LLMs aimed to restrict their use, for example,

by adding more paper-based exams. Their interviewees noted that leveraging LLMs would allow complex topics, such as software design, to be introduced earlier. Courses could focus more on reading, modifying, and critically analyzing code rather than writing it.

Some instructors have already altered their courses as a result of the emergence of LLMs. As a part of a larger study, Prather, Leinonen, et al. (2025) conducted a survey on 76 persons involved in computing education, most of whom teach at universities, and interviewed 12 educators using or researching generative AI. More than three quarters of the respondents felt that the skills needed in software development have changed due to LLMs. However, only a third of them had included GAI in their courses. A minority had taken action to prevent LLM usage, with techniques focusing on examining student-written code and changing existing assignments. The respondents who had changed their courses reported focusing more on reading and editing code as well using LLMs effectively. This higher level of abstraction was deemed to be more important than learning syntax, which echoes the ideas presented by Denny et al. (2023). Additionally, Prather, Leinonen, et al. (2025) found that instructors had increased proctoring of assignments and exams.

Across the studies reviewed, two contrasting perspectives emerged. On one hand, LLMs could enable earlier coverage of complex topics, such as algorithms, in introductory courses. Many also believe teaching should increasingly emphasize code analysis and modification. On the other hand, some argue that core programming concepts must still be taught in introductory courses, so learning objectives should remain unchanged. Among educators from other disciplines and educational levels, there was interest in teaching LLM usage, and only a small minority would ban them entirely. Most studies addressed anticipated future changes, as educators have not yet fully adapted to the rapid development of LLMs. The changes that have already been made are quite similar to the expected changes. Actions are being taken to both include LLMs into learning objectives and ensure assessment results reflect student skills instead of the answering capabilities of LLMs. Institutional policies, such as those of universities, may also influence how LLMs are incorporated into course objectives.

DISCUSSION

This study has provided an overview of several types of programming-related teaching materials generated by LLMs that could be utilized in programming courses. The creation of these materials supports the presented learning objectives. For example, the prompt-based tasks help students develop skills in reading and analyzing code while also teaching effective use of language models. However, it should be noted that the practical use of LLMs for creating teaching materials is still developing rapidly, making it difficult to assess their future potential or the extent to which their adoption will become widespread. Furthermore, many material types—such as prompt problems– have only been examined by limited number of researchers. Future research should therefore incorporate data from multiple research teams. It is also important to recognize that the quality of LLM outputs depends heavily on the prompts; if they are incomplete, the results may be worse than the model's actual capabilities.

LLMs could also enable the creation of content types not addressed in this study. For example, generating general text-based course materials based on the learning objectives could be possible. LLMs could also be used for more complex tasks, such as creating specifications for programming projects. Furthermore, many introductory programming courses include tasks where students complete partially written code. LLMs could generate these code fragments. They could also create UML diagrams that students would use for implementing programs. LLMs could also enable the creation of interactive tasks like prompt problems. For instance,

coding style practices could be taught by having students submit their code to an LLM, which would provide feedback on aspects such as variable naming.

Learner-generated tasks have traditionally suffered from low student motivation. Assistance from LLMs could enable the creation of larger pools of tasks and help improve motivation. Learner-centered approaches could also be applied to refining LLM-generated materials through identifying mistakes in them. Assignments focused on error correction would help instructors produce high-quality AI-based materials with minimal effort while training students to identify and fix mistakes. Similarly, refactoring could be taught more effectively if prompts instruct the LLM to generate poorly structured code. The ability of LLMs to personalize materials also allows for more individualized and engaging learning experiences. Personalization could also account for differences in students' backgrounds and provide varying levels of support based on individual needs. However, the accessibility of LLMs means that students must take greater responsibility for their own learning. They can use these tools to solve a large portion of assignments, often without instructors noticing. Therefore, students themselves bear responsibility for how they use LLMs. If a student relies on an LLM to produce all answers without engaging with the material, meaningful learning is unlikely to occur. Students should also recognize that LLMs can be used productively in learning—for example, to generate new tasks at different difficulty levels, or explain programming concepts repeatedly until they are understood.

Although not within the scope of this paper, the use of LLMs in automated assessment should be considered. Nagakalyani et al. (2025) found that an LLM-based grading assistant could speed up the process of manually grading assignments in an introductory programming course by almost a quarter on average. While LLMs can create feedback for programming exercise, Er et al. (2025) found that human-generated feedback was perceived as more useful by students, and its usage led to greater improvements in assignment scores compared to LLM-generated feedback. Regardless of the technical capabilities of LLMs in grading or creating feedback for assignments, human oversight is needed. Furthermore, the ethical implications of using LLMs in assesses should be considered before implementation.

CONCLUSIONS

This study aimed to identify ways in which LLMs can be utilized in creating teaching materials for introductory programming courses. Based on the findings, LLMs can be applied to the generation of both programming tasks and multiple-choice questions. The created materials are of high quality, and a portion is ready for use in teaching. LLMs can also be used to create prompt-based exercises, where the generated code helps students practice writing prompts and analyzing code. Language models can further support the creation of other types of materials not discussed in this study. For example, LLMs can produce entirely new code examples and explanations (Sarsa et al., 2022; MacNeil et al., 2023; Jury et al., 2024). In addition, LLMs can be used for explaining error messages that are typically challenging for many students (Leinonen et al., 2023).

It was also explored how LLMs may influence learning objectives in programming courses. With the help of language models, it could be possible to incorporate topics such as algorithms and software design into introductory courses. Teaching could also place greater emphasis on code analysis and modification rather than solely on code writing. Nevertheless, teaching the fundamentals of programming is still considered essential, and not all stakeholders view changes to learning objectives as justified.

The rapid advancement of LLMs and other AI tools is likely to have significant practical implications for the development of engineering education in general, including the CDIO framework and its associated practices. For example, although the current version of the CDIO Syllabus (Malmqvist et al., 2022) identifies digitalization as a key enabling technology that supports engineers in addressing emerging and existing challenges more effectively, the accelerating evolution of AI tools—and their impact on the competencies expected of graduating engineers—will need to be addressed in future revisions.

This study could be expanded in several ways, such as by including empirical studies, evaluating practical classroom implementations, or exploring ethical and pedagogical implications of LLM use in programming education. Beyond learning objectives, future research could also explore the potential of LLMs to act as course assistants.

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PRIVACY-ADAPTIVE GENERATIVE AI: FROM UNSTRUCTURED REPORTS TO COMPETENCY-BASED LEARNING ANALYTICS

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ABSTRACT

Background: Challenge-Based Learning (CBL) courses generate a wealth of unstructured student artifacts (e.g., reports, prototypes) that contain rich evidence of professional competencies (CDIO Standard 11). However, extracting these process variables for longitudinal analysis has historically required prohibitive manual effort, leaving valuable curriculum insights inaccessible. As a result, assessment practices often rely on coarse indicators (e.g., grades), limiting evidence-based feedback on innovation and professional skills. **Challenge:** While Generative AI offers a scalable solution to automate this extraction, institutions face a dilemma: utilizing frontier cloud models risks violating data sovereignty regulations, while privacy-preserving local models have historically lacked the reasoning capability required for complex assessment. **Methodology:** This paper presents a Privacy-Adaptive Dual-Pipeline framework to resolve this tension. We analyze a subset of 15-year archive of engineering capstone projects ($N = 63$ validated samples) by benchmarking a local, offline Large Language Model (LLM) against a frontier Cloud model. **Results:** We identify a distinct *Inference Gap*: while local models successfully extract explicit identity metadata (Title: 78.2% match), they struggle with semantic reasoning tasks (e.g., Value Proposition: 0.0% match) compared to the cloud benchmark. **Contribution:** We propose a tiered implementation strategy that allows educators to select the appropriate privacy tier based on data sensitivity. This methodology provides the CDIO community with a validated workflow to transform unstructured repositories into structured datasets, enabling scalable, evidence-based assessment and feedback without compromising student privacy.

KEYWORDS

Generative AI, Learning Analytics, Challenge-Based Learning, Data Extraction, CDIO Standards: 2, 5, 11

INTRODUCTION

Challenge-Based Learning (CBL) is a primary vehicle for implementing CDIO Standard 5 (Design-Implement Experiences) (Kohn Rådberg et al., 2020; Malmqvist et al., 2015). By engaging students in open-ended, real-world problems, these courses foster both technical competence and professional skills. However, systematically assessing such multifaceted experiences remains challenging for engineering educators (CDIO Standard 11).

Although quantitative indicators such as grades are readily available, they fail to capture the process-level variables that shape student outcomes. Information related to team organization, prototype fidelity, or technical decision-making is typically embedded in unstructured artifacts such as project reports. In long-running courses, this results in substantial dark data.

Since the widespread availability of generative AI, about two years ago, the methodology for evaluating project-based and challenge-based subjects is moving towards observing the process rather than observing the results. However, having information on various indicators in a semi-automatic way to evaluate projects can be very useful. In addition, being able to obtain information on the characteristics of challenges that generate better learning outcomes can be very useful for the institution's Learning Analytics.

Generative AI offers a pathway to unlock this archive but introduces a tension between capability and privacy. While frontier cloud models offer the reasoning depth to analyze complex documents, transmitting student data to third parties raises sovereignty concerns. Conversely, local models ensure privacy but often lack the inference capability for high-level assessment tasks. To resolve this, we propose a Privacy-Adaptive Dual-Pipeline Framework benchmarking local extraction against a cloud baseline.

The study is situated in the Advanced Engineering Project (PAE) and Challenge-Based Innovation (CBI) courses at the Universitat Politècnica de Catalunya (UPC) (Bragós Bardia et al., 2022; Garcia-Huertes et al., 2024). Since 2011, these programs have collectively generated over 200 projects involving 1,900+ students. Using this dataset, we address the following research question: *To what extent can privacy-preserving local Large Language Models (LLMs) replicate the extraction capabilities of frontier cloud models when analyzing unstructured engineering project artifacts, and across which dimensions does their performance diverge?*

The contribution of this paper is methodological. We present a validated, replicable approach that allows institutions to quantify trade-offs between local and cloud-based extraction, enabling tiered assessment without compromising data sovereignty. Although situated within a CDIO-aligned program, the proposed methodology is designed to be transferable to similar courses across higher education institutions that rely on unstructured student artifacts for assessment.

LITERATURE REVIEW

To position the methodological contribution of this paper, this literature review is structured around three themes: assessment challenges in CDIO-aligned CBL environments; the resulting data gap in quantifying project-based competencies; and the emerging role of Generative AI in addressing this gap.

Challenge-Based Learning and the CDIO Assessment Challenge

CBL and Project-Based Learning (PBL) are foundational to the CDIO Syllabus, particularly in fostering competencies in Conceiving, Designing, Implementing, and Operating (Standards 5 and 6). The Advanced Engineering Project course aligns with these principles by requiring students to manage the full lifecycle of a solution from ideation to pitch. Research in engineering entrepreneurship education indicates that such courses enhance entrepreneurial intentions and skills, although measuring their long-term impact remains challenging (Cobb et al., 2016).

Despite their educational value, the rigorous assessment of non-technical skills such as teamwork, communication, and business model viability remains difficult (Standard 11). The CDIO initiative has long acknowledged the tension between usefulness in improving educational practice and scholarliness in generating generalizable knowledge (Edström, 2016). Addressing both requires assessment approaches that move beyond subjective faculty impressions toward robust, evidence-based data.

The Data Gap in Assessing Project-Based Competencies

Engineering Education Research (EER) on project-based courses has traditionally relied on subjective data (surveys, interviews) or aggregated metrics like final grades. Recent bibliographic analyses within the CDIO community show that while interest in outcome measurement is increasing, most studies remain survey-based and focus on constructs like entrepreneurial mindset or intention rather than observable behaviors (Garcia-Huertes & Bragós, 2023).

Deeper quantitative analyses face a data resolution problem, since key explanatory variables including challenge type, team structure, and prototype fidelity are embedded in unstructured artifacts such as reports and presentations. Extracting these process-level variables typically requires time-intensive manual content analysis, constraining study scale (Berdanier et al., 2018; Borrego et al., 2014). This methodological bottleneck limits large-scale synthesis and hinders the identification of high-impact instructional practices.

The Emerging Role of Generative AI in Educational Research Methodology

The maturation of Generative AI and Large Language Models (LLMs) represents a significant shift in educational research methodology. Systematic reviews report rapid adoption of LLMs across engineering disciplines, though primarily for instructional support rather than assessment-focused analysis (Filippi & Motyl, 2024). Emerging work, however, demonstrates that LLMs can function as *zero-shot* data annotators, offering scalable alternatives to manual coding in computational social science (Ziems et al., 2024).

Empirical studies have begun to validate this approach in educational contexts. For example, Ding et al. (2024) showed that LLMs such as LLaMA and BERT can outperform traditional machine learning in analyzing qualitative student survey responses. Similarly, Tai et al. (2024) proposed a systematic methodology for using LLMs to support deductive coding of interview transcripts, highlighting the role of recursive analysis in improving reliability.

Despite this promise, adoption is constrained by data sovereignty: while frontier cloud models offer superior reasoning, transmitting student artifacts to third parties introduces significant privacy risks (Bahrini et al., 2023; Hingle et al., 2023). Furthermore, empirical evidence on the

viability of privacy-preserving local models for complex extraction remains limited. This paper bridges this gap by benchmarking local versus cloud performance, validating a privacy-aware methodology for extracting assessment variables from unstructured artifacts at scale.

METHODOLOGICAL FRAMEWORK

To extract structured data from the unstructured historical archive of the PAE and CBI courses, we designed a privacy-first, scalable data processing pipeline. The methodology employs a Privacy-Adaptive Dual-Pipeline approach that leverages recent advances in multimodal LLMs while adhering to strict data protection standards.

Data Corpus and Execution Environment

Although the complete PAE and CBI archive spans more than 15 years (200+ projects), this study focuses on a stratified sample of 63 final project reports from recent academic periods (2019–2024). This subset was selected to validate the extraction methodology against contemporary technical vocabularies and report formats. The corpus consists of unstructured PDF files averaging 50–60 pages.

All experiments were conducted in a Google Colab environment with Institutional Account of Google Drive used for secure file storage. This setup supports reproducibility and reflects the capabilities of standard commercial laptops (e.g., NVIDIA T4 GPU), making the methodology accessible without dedicated HPC infrastructure. In addition, Google's enterprise Data Privacy Terms & Conditions (T&C) ensure compliance with GDPR requirements for educational data.

Privacy Pre-processing Layer

A core element of the framework is a common Privacy Pre-processing Layer (Figure 1). All PDF artifacts undergo automated sanitization implemented in Python. *PyMuPDF* is used for document parsing, combined with *spaCy* models and Regular Expressions to redact Personally Identifiable Information (PII) such as names and email addresses. OpenCV with Haar Cascade classifiers is additionally used to detect and obfuscate human faces in project images.

Dual-Pipeline Architecture

Sanitized documents are processed through two parallel pipelines for benchmarking purposes, enabling systematic comparison of offline local extraction against a cloud benchmark and evaluation of trade-offs between assessment depth, infrastructure, and data sovereignty:

1. **Pipeline A (Cloud Benchmark):** Redacted text is transmitted to Google's *Gemini 2.5 Flash-Lite*. This frontier model was selected for its large context window ($>$1 million tokens) and strong multimodal reasoning capabilities. Document structure analysis (e.g., table parsing, header and footer exclusion) is performed in a single inference pass, trading data locality for high-precision extraction.
2. **Pipeline B (Local/Private):** Redacted text is processed locally using *DeepSeek-R1-Distill-Llama-8B*, optimized with the *Unsloth* framework. This pipeline demonstrates fully offline execution on consumer hardware. Owing to the model's limited context window

(8k tokens), a multi-step strategy is required:

- **Context Windowing:** The first 8,000 characters and final 4,000 characters of each report are concatenated, capturing sections with high metadata density.
- **Two-Pass Extraction:** Extraction is divided into two sequential passes, with Pass 1 targeting Project Identity variables (Title, Tech Stack) and Pass 2 focusing on Business Metrics (Revenue, TRL).
- **Retry Logic:** A temperature-scaling retry mechanism is applied when malformed JSON is produced, automatically increasing temperature ($T = 0.1 \rightarrow T = 0.4$) to recover valid output.

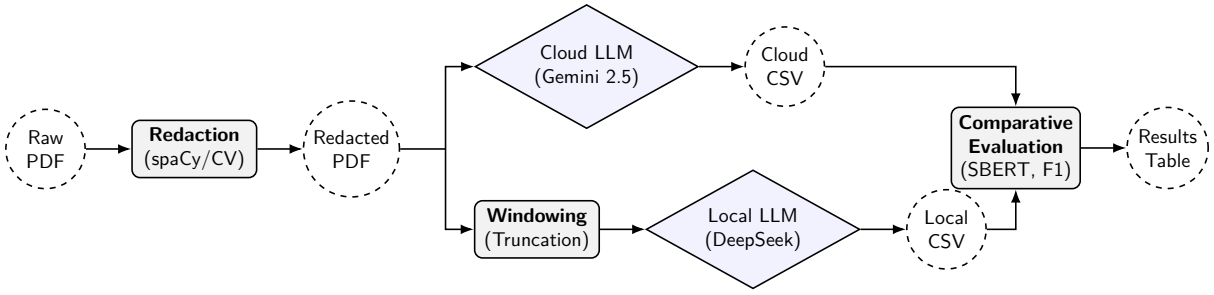


Figure 1. The methodological pipeline for assessment-oriented data extraction. Redacted reports follow two paths: a Cloud Benchmark (Gemini) or a Local Pipeline (DeepSeek) requiring windowing and truncation prior to inference.

Target Variables

To represent the multi-dimensional nature of the projects, we defined a strict schema using *Pydantic* objects to enforce structured JSON output. Variables were grouped as follows:

- **Identity Variables:** *Project Title*, *Company Name*, and *Domain*.
- **Narrative Variables:** *Problem Statement*, *Solution*, and *Value Proposition*.
- **Technical Variables:** *Tech Stack*, *Tools*, and *Data Sources*.
- **Strategic Variables:** *SDG Goals*, *TRL (Technology Readiness Level)*, and *Team Size*.

Evaluation Framework

To compare Local and Cloud extraction performance, three Natural Language Processing (NLP) metrics were employed, selected according to variable type:

1. **Semantic Similarity (SBERT):** Narrative fields (e.g., Problem Description) were evaluated using *all-MiniLM-L6-v2* embeddings and cosine similarity.
2. **F1-Score (Set Overlap):** List-based fields (e.g., Tech Stack, SDGs) were evaluated using F1-score based on entity overlap.
3. **ROUGE-L & BLEU:** Short text fields (e.g., Titles) were evaluated using standard n-gram overlap metrics to measure exact reproduction.

Table 1. Performance of privacy-preserving local extraction against cloud benchmark: variable-level assessment feasibility

Data	Variable	Description	Metric	Match
Project	Title	Official project name.	Semantic	78.2%
	Company	External partner or stakeholder.	Semantic	72.0%
	Domain	Industry sector (e.g., Bio-Tech).	Semantic	35.3%
Narrative	Problem	Summary of the user need or pain point.	Semantic	56.1%
	Solution	Summary of the proposed solution.	Semantic	56.1%
	Value Prop.	Core benefit provided to the user.	Semantic	0.0%
Technical	Tech Stack	Core technologies used (e.g., Python).	F1-Score	17.0%
	Tools	Specific hardware/software (e.g., RPi).	F1-Score	13.6%
	Data Sources	Inputs used (e.g., APIs, datasets).	F1-Score	5.6%
Strategic	SDGs	UN Sustainable Development Goals.	F1-Score	10.0%
	TRL	Technology Readiness Level (1–9).	Numeric	18.3%
	Team Size	Number of students involved.	Numeric	20.0%

METHODOLOGY VALIDATION AND RESULTS FOR ASSESSMENT

To validate the proposed Dual-Pipeline framework, we processed a stratified sample of 63 final project reports from Academic Years 2019–2024. The primary contribution is a comparative performance analysis between the Privacy-Preserving (Local) and High-Capability (Cloud) approaches, assessing the viability of offline AI for educational assessment.

Comparative Performance Analysis

Table 1 reports the quantitative agreement between the Local (DeepSeek-8B) and Cloud (Gemini 2.5) pipelines. The results reveal a distinct *Inference Gap*, characterized by increasing divergence with the abstraction level of the target variable.

Analysis of the Enriched Dataset

Given the higher semantic accuracy of the Cloud pipeline (Table 1), we synthesized extraction outputs to explore preliminary trends that were previously inaccessible in static PDF archives. Treating the Cloud outputs as a benchmark and using local data for corroboration, we examined project evolution over the five-year period.

The analysis suggests a clear technological shift in project focus. In 2019, approximately 33% of projects centered on Hardware/IoT solutions, whereas by 2024, AI-native projects had become dominant, with nearly 45% incorporating Machine Learning components. This marks a departure from earlier emphasis on web and mobile development.

In parallel, semantic extraction of strategic variables indicates a strong alignment with UN Sustainable Development Goals. SDG 9 (Industry, Innovation, and Infrastructure) emerged as the most prevalent focus ($N = 38$), followed by SDG 11 (Sustainable Cities) and SDG 3 (Good Health). This distribution suggests that the course's PDP model naturally steers student projects toward infrastructure and urban health challenges.

DISCUSSION

The quantitative divergence between the two pipelines highlights key boundary conditions for deploying LLM-based extraction in educational data mining.

First, the high agreement scores for *Project Identity* variables (Title: 78.2%, Company: 72.0%) indicate that Local LLMs function effectively as *Librarians*. Even with truncated contexts, these models accurately identify *what* a document is and *who* it relates to. This suggests that institutions can reliably build privacy-preserving, searchable indexes of historical archives using offline models, supporting low-risk assessment tasks such as project classification and curriculum mapping while minimizing exposure.

A distinct Inference Gap emerges when extraction requires semantic abstraction. Although the Local model could summarize explicit sections such as the Problem Statement (56.1%), it struggled to infer the *Value Proposition* (0.0%) or classify the *Domain* (35.3%) unless these elements were explicitly labeled. This indicates that current offline models are effective for Retrieval Augmented Generation (RAG) tasks when answers are directly stated, but lack the *Analyst* capability needed for higher-level semantic categorization.

Low F1-scores for Technical Variables (Tech Stack: 17.0%) further reveal a methodological pitfall we term the *Boilerplate Trap*. A manual audit showed that the Local model, constrained by its 8k token window, often failed to distinguish assignment instructions (e.g., "Students must use Python or Java") from actual implementation choices. In contrast, the Cloud model, leveraging its large context window ($>$1M tokens), consistently differentiated instructional boilerplate from student-generated content.

Taken together, these findings support a tiered implementation strategy. For tasks requiring strict data sovereignty, such as indexing and metadata extraction, Local models provide a viable privacy-first solution for foundational assessment activities. However, for deeper curriculum analysis that depends on disentangling instructional scaffolding from student work, the reasoning depth and context capacity of frontier Cloud models remain necessary. Importantly, the framework does not assume concurrent deployment of both pipelines in practice; rather, it provides empirical evidence to support informed selection of a single pipeline aligned with institutional regulatory, infrastructural, and assessment requirements.

LIMITATIONS AND FUTURE WORK

The primary limitation of the Local pipeline stems from hardware constraints typical of consumer environments. The model's 8k token limit required a strict windowing strategy that concatenated the introduction and conclusion sections, likely excluding technical details embedded in middle appendices and contributing to lower recall for technical variables. In addition, while the automated comparison across 63 reports provides sufficient statistical support for methodological validation, the manual human-in-the-loop verification was limited to targeted spot-checks rather than a comprehensive audit of all extracted data points.

Current work focuses on scaling the analysis from the validation sample to the complete historical archive (200+ projects), enabling robust longitudinal insights to inform course design and preparation. In parallel, we are conducting human validation of the identified project features.

The enriched dataset will also be integrated with institutional academic records, such as grades, to statistically model relationships between extracted project complexity indicators (e.g., TRL level) and academic performance. In parallel, and aligned with emerging cost-efficient AI practices, we plan to explore fine-tuning local LLMs on the structural patterns of PAE reports. This approach has the potential to reduce the observed Inference Gap, allowing local models to achieve higher accuracy while preserving data sovereignty.

CONCLUSION

This paper presents a scalable, privacy-adaptive methodology for educational data mining in engineering education. We demonstrate that unstructured student reports can be transformed into structured curriculum data using Generative AI while explicitly prioritizing data privacy through local execution.

The findings support a tiered implementation strategy. Local models are well suited for privacy-safe project indexing and discovery, whereas redacted cloud models remain necessary for deeper curriculum auditing and high-stakes competency assessment. This framework enables informed, context-sensitive decisions by combining cost-effective local extraction with targeted use of secure cloud capabilities. By adopting this tiered strategy, institutions can unlock insights from digital educational archives while maintaining strong data governance. From a CDIO perspective, the proposed methodology provides a practical decision framework for transparent, repeatable, and evidence-based learning analytics.

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Declaration of Generative AI Usage

Generative AI was used to refine data extraction code and improve linguistic clarity. All outputs were validated as described in the Methodological Framework. The authors assume full responsibility.

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REFRAMING PROFESSIONAL LEARNING ASSESSMENT IN THE AI ERA

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ABSTRACT

The rapid adoption of generative artificial intelligence (AI) in higher education has prompted educators to reconsider how professional learning and assessment are designed and justified. While AI can improve feedback quality and efficiency, it also raised concerns about academic integrity and learner agency, i.e., the transition of students from passive recipients of information to active participants in their own learning. Traditional assessment practices are increasingly misaligned with contemporary digital competencies. This study examines AI integration in engineering education, with a focus on assessment design and educator reasoning. Using a qualitative approach, the study analysed open-ended survey responses from engineering educators at an Australian university. Participants reflected on their use of large language models for teaching, assessment and professional judgement. The results show that educators value AI for idea generation, but remain concerned about over-reliance, reduced learner accountability, and misalignment between AI use and intended learning outcomes. Educators emphasised the need for deliberately designed assessments that require learners to evaluate AI outputs, justify their decisions using evidence and disciplinary reasoning. The findings show that the educational value of AI depends on pedagogical intentions rather than the technology itself. When aligned with frameworks such as CDIO (Conceive-Design-Implement-Operate), AI-supported assessment can shift the focus from simple task completion toward the development of professional judgement and ethical awareness, positioning AI as a supplement for, rather than a replacement for, professional thinking.

KEYWORDS

Generative AI, assessment design, Large Language Models (LLMs), higher education pedagogy, engineering, Standards: 2, 7, 8, 11.

INTRODUCTION

The rapid advancement of artificial intelligence (AI) and digital technologies has reshaped how individuals access, produce and evaluate information in professional and academic contexts (aiello, 2024; Hohenstein et al., 2023; Taeihagh, 2025). As AI-enabled tools increasingly facilitate personal learning and work (OECD, 2025; Pallant et al., 2025), the capacity to critically evaluate the accuracy, reliability and source of information generated by both humans and machines has become an essential professional capability (Hattingh et al., 2020). Higher education, therefore, faces growing expectations to prepare graduates who can engage with AI technologies in informed, ethical and reflective ways.

Education systems play a central role in developing these capabilities. In response to the pace and complexity of technological change, the Council of Europe's Committee of Ministers recommended adopting digital citizenship education, with explicit attention to the implications of AI for learning and teaching (Council of Europe, 2019). Holmes et al. (2022) also argued that educators must understand both the affordances and limitations of AI to retain pedagogical agency and ensure that technology supports rather than displaces educational intent. These perspectives position educators as key mediators between AI technologies, institutional policies and student learning experiences.

Within educational contexts, AI applications most commonly draw on machine learning and natural language processing (NLP) techniques (Holmes et al., 2022; Lund & Wang, 2023; Norouzi et al., 2020; Shaik et al., 2022; Sullivan & Keith, 2019). NLP-powered systems frequently employ conversational interfaces to support dialogue, feedback and supported learning (Litman, 2016; Sullivan & Keith, 2019). The public release of ChatGPT, a large language model (LLM)-based chatbot developed by Openai, in November 2022 intensified institutional and scholarly attention to these technologies (Erwin, 2023; Zamfiroiu et al., 2023). While ChatGPT and other AI-based academic tools have demonstrated the capacity to generate fluent academic-style text, their use has raised concerns about authorship, assessment validity and academic integrity (Cotton et al., 2024; Evangelista, 2024; Yeo, 2023).

Recent studies suggest that LLMs are already influencing teaching practices, feedback processes, and assessment design in higher education (Liang et al., 2025; Shi et al., 2026). Researchers report both opportunities (e.g., personalised feedback, richer assessment tasks, support for lesson planning) and risks (e.g., over-reliance, validity threats, equity concerns) that are driving changes in how courses and assessments are designed (Agostini & Picasso, 2024; Anson, 2024). Interviews with academics across European universities further emphasised the importance of supporting students in understanding how LLMs operate, verifying AI-generated outputs, and acknowledging AI use transparently (Symeou et al., 2025). This body of work suggests that the educational value of AI tools does not lie solely in their outputs, but in how they are pedagogically framed, regulated, and embedded in assessment and learning activities.

Despite growing interest, limited research examines how educators interpret institutional AI policies, translate them into assessment design decisions, and balance opportunities for learning support with concerns about academic integrity. This gap is particularly relevant in engineering education, where assessment plays a central role in developing transferable competencies such as critical thinking, ethical judgement, communication and lifelong learning, consistent with professional accreditation expectations.

Pedagogical theories such as constructivist and experiential learning approaches provide a valuable lens for examining these issues. Such approaches emphasise active engagement, reflection, and the co-construction of knowledge, positioning educators as facilitators who guide learners through complex problem spaces rather than transmit predefined solutions (Brandon & All, 2010; Kolb, 2015; Moosavi & Bush, 2021). These approaches align with lifelong learning models that link education, professional development and future workforce needs (Figure 1) (Griffin & Care, 2015). However, the emergence of generative AI can disrupt this traditional learning cycle by altering how professional skills are acquired and verified.

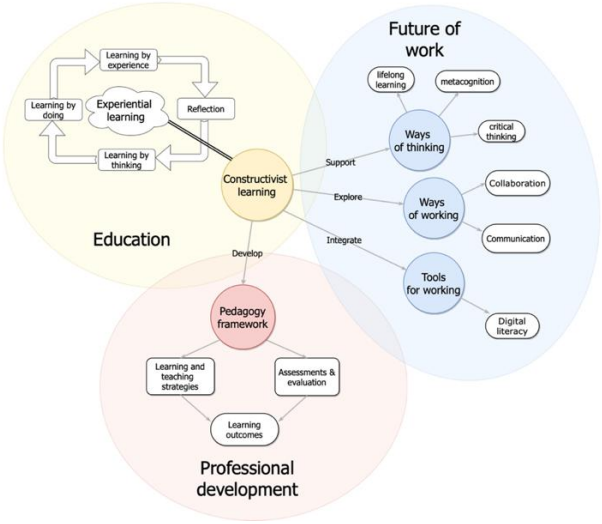


Figure 1. A lifelong learning process that uses constructivist and experiential learning approaches to cultivate professional development and prepare the future workforce

As AI technologies, particularly those leveraging NLP and LLMs, become increasingly prevalent in educational contexts, educators face critical decisions about their adoption and use. Exploring how educators make sense of these tools within their teaching practice and assessment design is essential for identifying effective strategies, addressing challenges, and ensuring that technology supports meaningful learning experiences and professional skill development while upholding academic standards and integrity. Therefore, the study is guided by the following research questions:

- RQ1: How do educators conceptualise the role of NLP/LLM tools in supporting students' research, writing and professional skill development in higher education?
- RQ2: What pedagogical and assessment design strategies do educators employ when integrating NLP/LLM tools into existing curricula?
- RQ3: What challenges, risks and trade-offs do educators identify when incorporating LLM tools into assessment and feedback practices?
- RQ4: How do educators adapt assessment structures and expectations to maintain academic integrity while enabling student engagement with AI tools?

METHODOLOGY

Research Design

This study adopted qualitative research to examine how academic staff engage with AI-powered natural language processing (NLP) tools, such as ChatGPT, in teaching and research contexts. The study was designed as an initial scoping and pilot investigation, with an

emphasis on reflective practice, professional judgement, and evidence-informed innovation in assessment and feedback, particularly in relation to the use of AI in engineering education.

Participants and context

Academic staff were invited to participate via email, which included an information statement outlining the study's purpose, the voluntary nature of participation, and data-handling procedures. Participants accessed a Microsoft Forms questionnaire and responded anonymously. The survey was open for two weeks and distributed to staff across four engineering disciplines: Aerospace and Aviation, Electrical and Biomedical Engineering, Manufacturing, Materials and Mechatronics, and Mechanical and Automotive Engineering. These disciplines were selected to capture a range of teaching contexts, class sizes, and assessment practices commonly found in engineering degrees. Two reminder emails were sent to improve response rates and reduce non-response bias.

Data collection and analysis

Data were collected using four open-ended questions that invited participants to describe their experiences, decision-making processes, and reflections on the use of AI-based NLP tools in their teaching and research. Open-ended questioning enabled participants to articulate their perspectives in their own words, supporting the identification of unanticipated practices and concerns, particularly around feedback, academic judgement, and the evolving role of the educator.

Data analysis followed established qualitative analysis procedures informed by (Braun & Clarke, 2006) and (Thomas & Harden, 2008). The process involved three stages: 1. Open coding, where responses were examined line-by-line to identify meaningful units of text related to AI use, pedagogical intent, and perceived impact on teaching and feedback. 2. Axial coding, where codes were compared, refined, and grouped into broader categories through iterative discussion among the research team, and 3. Selective coding, where core themes were finalised by examining alignment between the data, emerging interpretations and the study aim. A constant comparative approach was applied throughout the analysis to identify consistencies and contrasts across participants and disciplines. To enhance analytic rigour, themes were repeatedly cross-checked against the raw data, and divergent or minority views were retained to avoid over-simplification. Appendix A outlines the analysis workflow, including the mind mapping and keyword synthesis used in this study.

RESULTS

Eleven academic staff from four engineering disciplines completed the open-ended survey. Participants reported varied levels of experience with NLP/LLM tools, ranging from exploratory awareness to active classroom use. To address the research questions, findings are organised into four themes. Each theme corresponds directly to one research question and represents a synthesis of staff perspectives on the role, integration, risks and assessment implications of NLP/LLM tools in higher education.

Educators' Perception of NLP/LLM Tools as Learning and Professional Skill Supports

Participants have considered AI tools, especially ChatGPT, as supportive learning aids rather than authoritative sources of knowledge. They emphasised that its educational value depends on how it is positioned within disciplinary practices and how students are guided to exercise judgement when using it.

Several educators stressed the importance of educators first understanding the tool themselves, including its limits within specific disciplines:

Staff need to become familiar with ChatGPT themselves to determine the limitations of AI within their own discipline... Place the AI within the context of a broad range of tools used to gain information: eg databases, search engines. (Anonymous #6)

In relation to professional skill development, educators highlighted its potential to support communication, comprehension and language clarity, particularly for students with diverse linguistic backgrounds:

I believe it can be a useful tool to assist diverse student populations - providing extra help to students by facilitating discussions among them and also could offer as a language translation service for non-native speakers. (Anonymous #8)

Pedagogical and Curriculum Design Strategies for Integrating NLP/LLM Tools

Participants described a range of deliberate pedagogical strategies for integrating ChatGPT into existing curricula. Rather than embedding the tool implicitly, educators emphasised explicit instruction, modelling and scaffolding, which focus on cultivating students' critical use of tools (e.g., prompting, checking, refining outputs) rather than letting them rely on AI as an unexamined answer machine.

One commonly reported approach involved teaching students how to ask effective questions and interrogate AI-generated responses:

To ensure students make the most of their interactions with ChatGPT, educators should teach them to ask follow-up questions, request justifications for its answers, and challenge its responses with "why" and "what-if" questions. This approach encourages critical thinking and helps students develop effective questioning skills. (Anonymous #4)

In terms of practical classroom use, staff reported applications in formative feedback and discussion facilitation:

[1] Using the tool to provide personalized feedback - student submit their work on ChatGPT which checks and provide feedback on grammar, syntax and I believe style. 2. Facilitating discussions among students on a particular topic - students engage in dialogue and explore different perspectives on particular issues arising. (Anonymous #8)

Challenges, Risks and Pedagogical Trade-offs

Educators identified several challenges in incorporating ChatGPT into teaching, particularly regarding accuracy and governance.

Concerns about misleading outputs were prominent:

I think the most important advice is to understand the limitation of the AI. A nicely written definitive answer can be very wrong! (Anonymous #7)

Participants also highlighted the difficulty of establishing consistent guidelines in a rapidly evolving landscape:

Once the tool is better established, a conversation is needed to better manage its use by the students. Currently the tool, and its use by the students is evolving and it is difficult to frame a guideline. (Anonymous #3)

Several educators reflected on broader pedagogical trade-offs, including a shift away from content coverage towards skill development:

Had to think deeply about what skills I really want the students to learn & develop and reassure myself that it's o.k to potentially deliver less content if the students learn more. (Anonymous #6)

Assessment Adaptation and Academic Integrity in AI-Enabled Learning

Rather than prohibiting ChatGPT, participants described assessment redesign as the primary mechanism for maintaining academic integrity while enabling meaningful engagement with AI tools.

Educators reframed integrity as an ethical and reflective practice:

It's important to recognize that using ChatGPT should not be considered cheating. Instead, it's like having a "wise friend" who can answer questions and provide guidance. The real concern lies in ethical issues, such as whether someone is using ChatGPT's ideas without proper credit or not taking the time to verify its answers in different contexts and conditions. (Anonymous #4)

Several staff reported shifting assessment emphasis towards justification, critique and validation:

The emphasis of assessments has shifted away from content to the presentation and validation of data. In addition, assessments now include a self-critique from the students of how the data was found. (Anonymous #6)

A proactive approach to assessment testing was also reported:

I have modified my assessments to avoid students pasting the questions onto AI platforms and getting instant answers. Before handing out assessments to students, I test my questions using available AI tools to see what responses the AI tools are giving. I adjust the question until I get to a point where it is apparent the students would need more than just AI tools to resolve the problem at hand. (Anonymous #11)

DISCUSSION

This study examined how engineering educators conceptualise, integrate and regulate the use of NLP/LLM tools within teaching, assessment and feedback practices. Given the small scale of the study, the findings represent emerging patterns in educator reasoning rather than generalisable outcomes about effectiveness.

The findings suggest that educators do not perceive AI as a replacement for human judgement; instead, they position it as a critical tool for enhancing disciplinary communication and idea development. By framing AI in this way, the study connects technological integration with CDIO-aligned competencies, emphasising that reflection and professional reasoning are essential components of engineering practice.

Rather than describing ad hoc adoption, participants reported deliberate pedagogical strategies for integrating AI tools. These included explicit instruction on questioning techniques, modelling appropriate use, and embedding AI within inquiry-based and formative learning activities. Such practices reflect CDIO principles that prioritise learning processes over tools and position students as active participants in knowledge construction. However, the variability in these reported practices suggests that AI integration remains uneven and highly dependent on individual educator judgement, necessitating further case-based research to examine how these strategies function in practice.

Despite the benefits, educators identified risks involving inaccurate outputs, accessibility gaps, and the ambiguity of 'acceptable use' in a constantly evolving technological landscape. These issues were characterised as ongoing assessment (re-)design constraints rather than temporary obstacles, requiring continuous instructional adjustment. Notably, the study reveals a trade-off between traditional content delivery and deeper skill development; thus, AI acts as a catalyst for educators to more explicitly define and justify their learning objectives.

In response to these challenges, participants reported a strategic shift toward redesigning assessment tasks to emphasise justification, critique and reflection. This approach seeks to mitigate AI misuse 'by design' by making the student's reasoning process visible. Within this framework, academic integrity is redefined as a structural alignment between learning outcomes, assessment expectations and procedural transparency, moving away from a reactive reliance on computational detection tools toward a culture of student accountability.

To implement the findings of this study within a CDIO context, engineering educators should shift from a focus on technological policing to intentional assessment design that prioritises professional reasoning. Practical application involves integrating AI as a supervised assistant throughout the CDIO lifecycle, particularly in the Conceive and Design phases. Students can use AI to simulate project constraints or explore ideas, provided they maintain a "justification log" that explains why they chose or rejected specific AI suggestions. This approach shifts the student from a passive recipient of AI outputs to an active participant who must critically evaluate, verify and justify the machine's technical reasoning against disciplinary standards. Ultimately, by embedding evaluative judgement and transparency into the curriculum, educators can balance the trade-off between covering course content and developing great professional skills. This ensures that academic integrity is built into the assignment's structure rather than relying on detection tools.

CONCLUSIONS

This study demonstrates that engineering educators do not regard generative AI as a replacement for professional expertise, but as a supervised assistant that requires active oversight. Rather than providing a solution to structural assessment challenges, AI tools are perceived as offering a controlled aid for idea development, feedback drafting and reflective prompting. These benefits must be interpreted within the qualitative scope and institutional context of this research.

The findings indicate that the primary challenge associated with AI in higher education is pedagogical rather than technical. Educators emphasised the need for clear assessment intent and explicit design decisions to mitigate risks related to over-reliance and reduced learner agency. By shifting students from passive recipients of information to active participants in their learning, educators can maintain academic integrity. From a CDIO

perspective, AI supports professional skill development when assessment tasks prioritise justification, evaluative judgement and disciplinary reasoning.

In conclusion, maintaining integrity in AI-rich environments depends less on detection mechanisms and more on redesigning assessments that promote transparency and critical engagement. Future research should examine the long-term impact on learner outcomes and equity across broader engineering contexts to ensure AI remains a supplement to, rather than a substitute for, professional thinking.

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BIOGRAPHICAL INFORMATION

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APPENDIX

This appendix presents the mind-mapping and word-cloud techniques the research team used to visually organise the specific data for each theme. This involved looking at the language and phrases used by the participants in relation to the research questions and in the context of a pedagogical model that could provide insight into the meaning of the data collected.

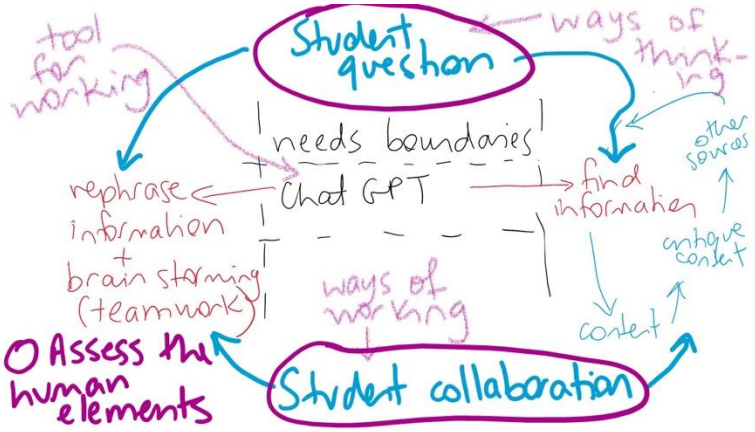


Figure A1: A mind map was created to visually organise themes that emerged from the data related to the future of work and pedagogy for the context of the study.

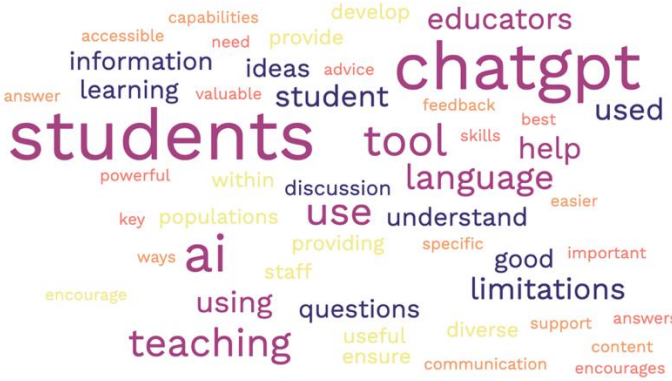


Figure A2: A word cloud used to quickly identify the most common words or phrases that emerged from the collected data, which helped the research team to identify key themes.

AI-SUPPORTED LEARNING: SELF-ASSESSMENT OF ENGINEERING STUDENTS

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ABSTRACT

Assessment and feedback are foundational components of CDIO-based engineering education, and an expanding body of research has investigated the role of artificial intelligence (AI) in enhancing teaching and learning processes. As AI tools become increasingly embedded in academic and professional environments, it is necessary to examine how their use influences students' learning experiences, particularly within engineering programs that emphasize problem-solving, active learning, and continuous improvement. This study investigates AI-supported learning through engineering students' self-assessment of their learning experiences when using Google Gemini as a learning tool. Drawing on existing research on AI in education and technology acceptance, the study examines changes in students' perceptions across twelve dimensions, including intrinsic motivation, learning readiness, self-efficacy, anxiety, interaction, perceived usefulness, and learning achievement. The study sample comprised 136 students from the University of Engineering and Technology, of whom 78 engineering students participated in AI-supported instruction, while the remaining 58 received traditional instruction without AI support. The analysis focuses on how AI influences students' motivation, confidence, engagement, and perceived learning success, which are directly related to CDIO Standard 8 (Active Learning) and CDIO Standard 11 (Learning Assessment). The results indicate that students experience both benefits and challenges when using AI-based learning tools; however, strong patterns of positive engagement, high self-efficacy, and low anxiety were observed. The findings provide empirical insight into how AI can support professional competence development and learning effectiveness in CDIO-oriented engineering education based on self-assessment data from engineering students in Mongolia.

KEYWORDS

Self-assessment, AI-supported learning, engineering education, student perspectives, CDIO Standards: 8, 11

INTRODUCTION

The rapid expansion of artificial intelligence (AI) across all sectors in Mongolia has produced significant transformations in educational systems, particularly in the ways learning content is delivered, accessed, assessed, and managed. In higher education, AI technologies are reshaping conventional pedagogical methods by supporting personalized and adaptive instruction, enhancing interactive learning experiences, and enabling data-driven approaches to teaching and learning (Sharples, M. 2025; Ash, A. M., 2026; Burns et al., 2026). International organizations and policymakers increasingly recognize AI as a strategic driver of educational innovation (Krstić, Aleksić, & Krstić, 2022). According to UNESCO's Guidance for Generative AI in Education and Research (2023), AI can contribute to learning effectiveness when it supports three core competencies: cognitive competence, reflective thinking, and learning competence. These competencies provide a conceptual foundation for integrating AI into teaching and learning in a way that promotes deeper understanding, self-regulation, and continuous improvement.

AI tools such as Google Gemini and Microsoft Copilot now provide learners and educators with advanced capabilities for content generation, problem-solving, adaptive feedback, and instructional design. These tools support engineering education by enabling learners to explore complex problems, receive immediate feedback, and engage in iterative learning cycles that reflect professional engineering practice. In Mongolia, the integration of digital and AI-based learning is supported by a national legal and policy framework, including the Electronic Signature Law (2021), Personal Data Protection Law (2021), Cybersecurity Law (2021), and Intellectual Property Law (2020), as well as the Mongolian Education Sector Digital Transition Implementation Plan (2023). Together, these regulations establish a secure and ethically grounded environment for digital transformation in education.

In practice, AI has been applied to enhance distance learning, personalized instruction, automated assessment, teacher support, and student engagement. Platforms such as Khan Academy and other intelligent tutoring systems demonstrate how AI can provide individualized feedback, scaffold learning, and promote learner autonomy. UNESCO (2023) emphasizes that generative AI should function as a complement to human teaching rather than a replacement, reinforcing the role of educators as facilitators of learning. This perspective aligns closely with the CDIO framework, particularly Standard 8 (Active Learning), which emphasizes student engagement and experiential learning, and Standard 11 (Learning Assessment), which focuses on meaningful feedback and continuous improvement. Through these standards, CDIO encourages learning environments that are interactive, reflective, and aligned with real-world engineering practice.

Within this context, the present study examines how engineering students experience AI-supported learning through the use of Google Gemini. Specifically, it investigates how students' learning-related perceptions change across twelve dimensions: intrinsic motivation, learning readiness, self-efficacy, anxiety, user interface, content, interaction, perceived usefulness, perceived ease of use, attitude, behavioral intention, and learning achievement. By analyzing students' self-assessments, this study contributes empirical evidence on how AI can support CDIO-aligned engineering education.

BACKGROUND AND THEORY

Student learning is influenced by a complex interaction of individual and environmental factors, and these factors were selected because they align with the constructs measured in this study.

Individual factors include cognitive ability, motivation, effort, self-confidence, learning strategies, and physical and psychological well-being, while external factors include family support, teacher guidance, institutional environment, socioeconomic conditions, and cultural context. A holistic understanding of these factors is essential for supporting academic success, as learners must be able to recognize their strengths, limitations, and learning opportunities. AI-based instructional systems are designed to address these complexities by integrating multiple learner attributes into adaptive and personalized learning environments.

AI-supported personalized learning systems can assess learners' cognitive abilities and provide content that matches their proficiency levels. This allows advanced students to engage with more challenging material while offering additional support to those who struggle, thereby reducing learning disparities and promoting equitable learning outcomes (Luckin et al., 2018). By continuously analyzing learner performance, AI systems can adapt instructional pathways and recommend targeted resources that enhance understanding and retention.

Motivation and persistence are strongly associated with academic achievement. AI-based environments that include interactive features, conversational agents, and gamified elements can stimulate learners' intrinsic motivation and increase engagement. However, some research cautions that excessive reliance on reward-based AI systems may weaken intrinsic motivation by shifting learners toward extrinsic incentives (Zawacki-Richter et al., 2019). AI can also support persistence by monitoring engagement patterns and delivering motivational feedback or adaptive challenges (Roll & Wylie, 2016).

Self-confidence and assessment accuracy play a crucial role in effective learning. AI can provide rapid and individualized feedback that helps learners evaluate their knowledge and skills, potentially increasing self-confidence and metacognitive awareness. At the same time, poorly designed systems or excessive automation may lead to overconfidence or inaccurate self-evaluation (Chen et al., 2020). Therefore, AI systems must be carefully aligned with pedagogical goals to ensure that feedback supports authentic learning.

Learning strategies and metacognitive skills directly affect how students process information and regulate their learning. AI can detect learning patterns and suggest strategies for planning, monitoring, and evaluating progress, thereby strengthening metacognitive development (Holmes et al., 2021). Additionally, AI-based systems can monitor attention and workload to support learners' well-being, although excessive dependence on digital tools may introduce risks related to stress or digital fatigue.

AI also influences the broader learning environment. In families, AI can provide insights into learners' progress, while in classrooms, teachers increasingly take on the role of facilitators who guide students' interaction with intelligent systems. These shifts highlight the importance of aligning AI integration with educational frameworks such as CDIO, which emphasize experiential learning, reflection, and continuous assessment.

METHODS

This study employed an experimental design involving an experimental group and a control group. Both groups completed pre-test and post-test assessments to measure changes in learning performance. Prior to instruction, all participants completed a pre-test to establish baseline levels. Following instruction, a post-test was administered to evaluate learning outcomes.

A total of 136 students from the University of Engineering and Technology participated in the study. Of these, 78 engineering students were assigned to the experimental group and engaged in 32 hours of instruction supported by Google Gemini. The remaining 58 students formed the control group and received traditional instruction without AI support. The experimental group used Google Gemini as a learning assistant during course activities, including problem-solving, information retrieval, and concept clarification.

The study employed a validated survey instrument to measure twelve dimensions related to AI acceptance and learning outcomes. All items were rated on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). The measurement instrument encompassed 12 variables, each grounded in the literature reviewed in this paper.

RESULTS AND ANALYSIS

To ensure that the results were not influenced by initial differences in student ability or motivation, Baseline Equivalence of groups was established using pre-test measures. An independent samples t-test indicated no statistically significant differences ($p>.05$) between the experimental ($n=78$) and control ($n=58$) groups across all twelve dimensions at the outset of the study. This ensures a level playing field for the intervention.

Table 1. Pre-Test Baseline Equivalence (Experimental vs. Control)

№	VARIABLE	EXP. (M)	CTRL. (M)
1	Internal Motivation	3.78	3.80
2	Readiness	3.45	3.48
3	Confidence	3.52	3.55
4	Anxiety	2.95	2.92
5	User Interface	3.10	3.12
6	Content	3.25	3.28
7	Interactivity	3.40	3.38
8	Perceived Usefulness	3.60	3.62
9	Perceived Ease of Use	3.55	3.58
10	Attitude	3.65	3.68
11	Behavioral Intention	3.70	3.72
12	Academic Performance	69.91	69.93

The primary objective of the study was to assess the impact of AI-supported instruction on academic performance. Post-test results indicate a statistically significant difference between the two groups:

- Experimental Group Mean: 86.92 (SD=6.5)
- Control Group Mean: 82.34 (SD=7.0)

- Statistical Significance: t=5.78, p<.001

The observed mean difference of 4.58 points reflects a meaningful academic performance for students in the experimental group in AI-supported instruction (M = 86.92) over the control group (M = 82.34), which hasn't received AI-supported instruction. Although both groups demonstrated improvement from the baseline, the experimental group's higher "minimum" score (72.00 vs. 61.00) suggests that AI-supported scaffolding may have contributed to reducing performance variability by supporting lower-achieving students and effectively raising the performance floor.

In addition to overall academic performance, the experimental group demonstrated statistically significant advantages in several key dimensions, including Internal Motivation (p=.003), Interactivity (p=.003), and Perceived Usefulness (p<.001).

Further analysis was conducted within the experimental group to better understand students' perceptions of the AI-supported learning environment, revealing consistently high mean scores across most variables, ranging between 4.0 and 4.5. Behavioral intention (M = 4.53), self-efficacy (M = 4.51), and interaction (M = 4.49) were particularly high, suggesting that students were confident in using AI and intended to continue doing so.

Standard deviations ranged from 0.45 to 0.78, indicating low variability and high agreement among students. Anxiety had a low mean (M = 1.62) and low standard deviation (SD = 0.35), demonstrating that most students experienced minimal anxiety when using AI. Learning achievement averaged 82.60, indicating strong academic performance.

These results provide evidence that AI-supported learning positively influenced motivation, confidence, interaction, and perceived learning effectiveness while maintaining low psychological stress.

DISCUSSION

This study examined how engineering students perceive AI-supported learning across multiple cognitive, motivational, and technological dimensions. Rather than viewing these constructs in isolation, the findings reveal a coherent learning ecosystem in which motivation, readiness, self-efficacy, and technological affordances interact to shape students' engagement and achievement in an AI-mediated learning environment.

Intrinsic Motivation and Learning Engagement

A strong level of intrinsic motivation was evident across the sample. Specifically, 66.67% of students rated their intrinsic motivation at the highest level (5), while an additional 26.92% rated it as 4, meaning that over 93% of students reported high or very high intrinsic motivation when learning with Google Gemini. Only 1.28% of students reported a neutral level of motivation, and none reported low motivation. This distribution indicates that the AI-supported learning environment effectively stimulated students' internal interest, curiosity, and willingness to engage with learning tasks.

Readiness to Engage in AI-Supported Learning

Students also demonstrated a high level of readiness to learn in an AI-supported environment. 44.88% of students rated their readiness as 5, and 21.79% rated it as 4, meaning that approximately 67% of students perceived themselves as highly prepared to use AI for learning.

Only 3.84% of students rated their readiness at the neutral level, indicating that lack of preparedness was rare.

Self-Efficacy in Using AI for Learning

Students' self-efficacy was particularly strong. A total of 59.0% of students rated their self-efficacy at the highest level (5), while more than 40% rated it as 4, meaning that nearly 100% of students expressed high confidence in their ability to use AI effectively for learning. Very few students reported lower levels of self-efficacy. This pattern indicates that the AI-based learning environment not only provided functional support but also strengthened students' beliefs in their own competence. High self-efficacy is known to promote persistence, problem-solving, and resilience—qualities that are essential for engineering education and professional practice.

Anxiety and Psychological Comfort

An important finding is the relatively low level of anxiety associated with AI use. 62.82% of students reported low to moderate anxiety, while only 17.66% fell into the high-anxiety category. This suggests that most students felt psychologically comfortable interacting with the AI system. Given that new technologies often introduce uncertainty and cognitive stress, this result indicates that Google Gemini functioned as a supportive learning tool rather than a source of intimidation.

User Interface and Learning Environment Design

The quality of the AI system's interface also influenced students' experiences. 42.31% of students rated the interface at levels 4–5, indicating that nearly half of the students perceived it as easy to use, well structured, and visually supportive of learning. However, approximately 20% of students rated the interface at 3 or below, suggesting that some learners encountered usability challenges. While the overall perception was positive, these results indicate that improvements in interface clarity, navigation, and responsiveness could further enhance learning efficiency and user satisfaction.

Content Quality

The instructional content delivered through the AI tool was evaluated positively by most students. More than 60% rated content quality at 4–5, indicating that the material was generally perceived as clear, relevant, and aligned with learning objectives. Approximately 15% rated the content at 3, suggesting that some students found it insufficiently detailed or in need of deeper explanation. These results suggest that while AI-generated or AI-mediated content is broadly effective, its pedagogical value can be further enhanced through improved contextualization and alignment with course objectives.

Interaction and Active Learning

Learning interaction received some of the strongest evaluations. The predominance of high ratings indicates that the AI-supported environment successfully facilitated student–AI, student–content, and student–teacher interaction. This confirms that the AI tool enabled real-time feedback, continuous questioning, and iterative learning processes, thereby supporting the active learning principles of CDIO Standard 8. The interactive structure encouraged students to engage cognitively rather than passively consume information.

Perceived Usefulness

Students overwhelmingly perceived the AI tool as beneficial. More than 75% of students rated usefulness at 4 or 5, with 34.62% assigning the highest rating. Only 2.56% rated usefulness at levels 2 or 3. This indicates that students strongly believed that AI improved their learning efficiency, academic performance, and engagement. These results align with the technology acceptance model, confirming that perceived usefulness is a major driver of adoption and sustained use.

Perceived Ease of Use

Ease of use was also rated highly. Approximately 60% of students rated ease of use as 5, and an additional group rated it as 4, meaning that the vast majority experienced the system as intuitive and user-friendly. Only a very small percentage (1.28–2.56%) reported moderate difficulty. This reinforces the conclusion that the technical accessibility of the AI system played a key role in enabling learning rather than obstructing it.

Attitude and Behavioral Intention

Students' attitudes toward AI were more moderate than their functional evaluations. About 28% of students reported relatively low attitudes (level 2), while most clustered around levels 3–4, and only 6–10% reported very strong positive attitudes (level 5). Despite this, behavioral intention was high, indicating that students planned to continue using AI even if emotional acceptance was still developing. This suggests that functional benefits currently outweigh affective reservations, and that attitudes may improve with more refined pedagogical integration.

Learning Achievement

Learning achievement showed moderate to high performance overall, with some students demonstrating particularly strong results. These differences suggest that achievement depends not only on the availability of AI but also on individual readiness, engagement, and learning strategies. However, the overall performance supports the conclusion that AI-supported instruction can enhance academic outcomes when properly implemented.

CONCLUSION

The primary aim of this study was to systematically examine the educational potential of an AI-supported learning environment using Google Gemini within an engineering education context. A total of 136 students were divided into experimental and control groups, and instruction was organized according to a structured pre-class, in-class, and post-class learning model. This design enabled a direct comparison of learning processes and outcomes between AI-supported and traditional instructional approaches.

The empirical results demonstrate that students in the experimental group consistently outperformed the control group across key learning dimensions, including intrinsic motivation, self-efficacy, learning readiness, technological understanding, learning attitude, and academic achievement. These findings provide strong evidence that AI-supported learning environments can meaningfully enhance both effective and cognitive components of learning, which are essential for effective engineering education.

During the intervention, students actively used Google Gemini, which supported the development of logical reasoning, analytical thinking, and independent learning skills, which are core outcomes emphasized by the CDIO framework.

CDIO Standard 8 (Active learning) focused on student engagement in the learning process, which this study utilized through AI-supported instruction. This promotes active learning by asking questions, filtering and analyzing information, interpreting results, and engaging in discussion with both peers and instructors. Rather than passively receiving information, students engaged in iterative inquiry and problem-solving, reflecting authentic engineering learning processes.

CDIO Standard 11 (Learning Assessment) focused on measuring the achievement of intended outcomes, which shows that the student performances were evaluated through pre- and post-test aligned with course learning outcomes.

In addition to personal learning factors, environmental characteristics, including content quality, interface design, and interactive functionality, were shown to have both direct and indirect effects on students' technology acceptance, learning engagement, and academic performance. This confirms that effective AI integration depends not only on the tool itself but also on how it is embedded within instructional design and learning activities.

Overall, the findings indicate that an AI-based learning environment using Google Gemini:

- Enhances cognitive engagement, analytical thinking, and logical reasoning
- Strengthens intrinsic motivation, learning readiness, and self-confidence
- Demonstrates the importance of interface design, content quality, and interaction in technology-supported learning
- Provides a reliable and theoretically grounded foundation for digital and AI-supported engineering education

Consequently, this study confirms that AI-supported learning, when aligned with CDIO principles, offers a student-centered, interactive, and analytically rich educational model that effectively supports both learning quality and professional skill development in modern engineering education.

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DISCOVERING ASSESSMENT CATEGORIES FOR LEARNING DIARIES: AI-ASSISTED FORMATIVE FEEDBACK IN ENGINEERING EDUCATION

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ABSTRACT

This paper reports a method for discerning formative assessment categories and criteria from tacit expert practice for the evaluation of reflective learning diaries with AI, and a taxonomy that covers the main dimensions, analytical frames, and criteria discovered by using the method. The approach is rooted in over two decades of practice in the context of reflective education in design and engineering. The reported category structure surfaced in one instructor's practice across 2023-2025 through a hermeneutic procedure, where the AI-based assessment tooling was constantly improved by comparing the instructor's and AI's assessments of 1346 individual diary entries from in total 164 students across three project-course instances. The evolution of the instruction for the AI happened mainly through disagreements where the instructor was not satisfied with the AI's assessment, which led into a rewrite of the instructions in the AI's system prompt. This process made visible and shareable a formerly tacitly operating set of frames and criteria that the instructor utilised in their work. The approach shows a path to enabling a formative assessment practice of students reflective learning diaries that can result in more elaborate, relevant, and consistent assessments than those provided by human evaluators without AI.

KEYWORDS

AI-assisted assessment, Formative feedback, Learning diaries, Reflective learning, Practice-led research, Standards: 2, 8, 11

INTRODUCTION

Engineering education faces a challenge to meet the demands of the increasingly rapidly developing networked world which calls for the cultivation of self-regulated learning and transversal competencies (Chen et al., 2021; Devika et al., 2020). These are skills and competencies making students "*capable of adapting according to the needs and changing demands in different situations and conditions*" (Devika et al., 2020, p. 350). These skills are also included in the CDIO syllabus 3.0 under labels, such as "life-long learning," "self-directed learning," and "creative thinking" (Malmqvist et al., 2022). While the development of these capabilities can be supported through challenge-based learning approaches, such as problem- and project-based methods (Gaskins et al., 2015), the *assessment* in challenge-based learning is underdeveloped, varied, and widely struggled with (Doulougeri et al., 2024; Valencia et al., 2020).

Reflective learning diaries are proven to be a promising means to support the cultivation of self-regulated learning and transversal skills as they provide instructors with visibility to the individual student's learning process in a manner that examinations, surveys, quizzes, and technical deliverables do not produce (Wallin et al., 2016; Wallin & Adawi, 2018). However, reflection-based methods remain among the least used methods in engineering, because of their labour intensity and time demand of the assessor (Cruz et al., 2020). As the review depends heavily on the reflective judgment capabilities of the assessor, the statements across different reviewers may vary a lot depending on their personal sensitivities alike conference paper review do. Competent review also requires domain knowledge, whereby, assessment is not easily delegated to teaching assistants with limited experience in the domain and in reflection assessment. Assessing reflective writing at scale, thereafter, still presents engineering educators with a persistent difficulty.

We, nevertheless, see reflective learning diaries as a potential scalable solution for the formative assessment of reflection given that the diary assignments are designed to be *constrained* and *supported by AI*, more specifically, systems that use specifically instructed large language models (LLMs). The viability of the approach is based on two premises: Firstly, the instruction for weekly reflective learning diary writing can be designed to aim for rather short entries with required ingredients, such as project photos, that are not easily generated by AI by the students. Secondly, as reflective learning diaries are essentially text, they are readily available to an LLM for review. LLMs matured in their reflective analysis capabilities significantly between 2023-2025 reaching performance comparable to, or even outperforming, that of an expert evaluator of reflection, based on our experience.

The success of the approach, nevertheless, relies on students actually reading the feedback. Diefes-Dux and Cruz Castro (2022) report that even where instructor feedback is generated, students may not view it at all, especially, when the perceived authenticity of the exchange is low. When the students are informed that the feedback is based on AI, they are thus less likely to read it and learn from it. However, based on our experience, it is possible to design an AI-based approach in a way that encourages students to actually read the feedback and develop their learning outcomes accordingly.

This paper reports on our practice-led study of developing AI-assisted formative feedback for reflective learning diaries. The focus is on the development of the AI-based assessment approach grounded in decades of work with reflective education in the context of engineering and design. We first describe the approach for discovering and operationalising reflective writing assessment dimensions, frames, and criteria with AI, and then expose an overview of the identified dimensions, frames, and criteria for the assessment. As such, the study

contributes to identifying analytical categories of reflection and reflexivity and their markers in student learning diaries. The development process, in turn, provides an example of the codifying tacit knowledge from course instructors into grading criteria with the help of LLM-assisted grading processes.

METHOD – HERMENEUTIC PROCEDURE FOR ARTICULATING TACIT JUDGMENT

Origins and trajectory of the inquiry

The inquiry reported here is based on approach the first author has developed during over two decades of teaching in design and engineering education, grounded theoretically in the pragmatist and interactionist traditions (Ylirisku, 2013). The work was originally inspired by a visit to Jacob Buur's group at the University of Southern Denmark in 2003, where Buur presented a three-level schema for identifying different levels of reflective articulation, i.e., 1) chronological reporting, 2) thematic description, and 3) conceptually unified presentation. This schema underlay an aspiration similar to Moon's (2004) idea of the *depth of reflection*, where the assessment and grading of reflection is based on specific qualitative differences in text.

Hermeneutic inquiry and the prompt as research artefact

The inquiry reported here is hermeneutic in the specific sense of proceeding through iterative interpretation where successive encounters with material revise the interpretive frame that is brought to the next encounter. The procedure followed the practice-led research tradition as characterised by Candy (2006), producing knowledge that has operational significance for the practice from which it emerges. In terms of academic knowledge production, or research discovery, of the dimensions, frames and criteria for the formative assessment the AI system functioned as a dialogical partner. The researcher instructed the AI, submitted a diary for review, judged the output, and either agreed or disagreed with the AI's review based on their own reading of the diary. In case of a disagreement, the instructor explained to the AI what was wrong in its assessment and developed a more accurate version of the AI's instruction, i.e., the *system prompt*. The editing of the prompt continued until the instructor was satisfied with the newly prompted AI's review. The system prompt thus is a knowledge artefact that contains traces of all the agreements and disagreements through the review of over 1000 diaries. It is a shareable and operational expression of the originally tacit categories that the experienced instructor implicitly used in the assessment of the reflective learning diaries.

The first attempt to operationalise this and related distinctions through AI was made already on the 26th of April 2023 when the first author drafted a prompt for GPT-4, based on the above-mentioned three-fold schema by Jacob Buur. The early test, however, resulted in a failure, as the AI invented its own categories while it was analysing the essays, and the results were very inconsistent. After several unsuccessful attempts, the development was set aside. The AI models were clearly not yet mature enough for the task. The inquiry was resumed in autumn 2024 with Claude Sonnet 3.5 and again in autumn 2025 using Claude Opus 4.1 and 4.5 as the primary assessment tools. ChatGPT-4o, 5.1 and 5.2 models were also used, but they were later abandoned as they, most of the time, refused to process the long prompt.

Course contexts and the weekly assessment cycle

The primary site for the study was the Design Thinking and Electronic Prototyping course (DTEP), a 12-week first-year project-based course at Aalto University (in autumn 2025, n=58, piloted in in autumn 2024, n=50). In it, student teams conceive design ideas, build functional

IoT demonstrators, and submit weekly learning diaries integrating course literature, lecture content, and project experience. The grading of the diaries was originally completely based on technical criteria: 600+ words, images labelled and referred to, citations in APA or IEEE format, evidence of weekly activities, and bibliography. In 2025, we added progressive weighting between technical and content dimensions across the 12 weeks, (weeks 1-4 100%/0%, weeks 5-8 50%/50%, and weeks 8-12 30%70% technical/content). We also tested the AI-based assessment in a master's-level course Networked Partnering and Product Innovation (NEPPI, 6 weeks, n=56) with similar technical requirements to gain understanding about the scalability of the approach across courses. The instructor of the courses was the same (the first author).

The assessment process followed a seven-step cycle:

1. Download a diary submission from learning management system (LMS).
2. Anonymise the entry (remove student names, remove images).
3. Submit the anonymised text to AI review.
4. Read the full diary entry while the AI is working and form independent judgment.
5. Compare your and AI assessments. If the reviews do not align, edit the prompt, update the AI system, and redo steps 3-5.
6. Decide on the grade.
7. Edit a statement based on the AI-generated feedback to the LMS.

The methodological commitment by the authors is to form independent assessment *before* AI consultation. This preserves the instructor judgment as the reference point against which AI output is evaluated. Examples of statements are exhibited in Appendices 2-4.

Emergence of distinctions in the system prompt

The system prompt revisions were not scheduled. Each revision was triggered by specific occasions where the instructor's and AI's assessments diverged. This could mean that the frames and criteria written into the system prompt could not accommodate a diary fairly, or that the instructor had been implicitly assuming a distinction that had not yet been explicitly expressed in the system prompt. Each revision was made at the prompt level rather than by editing the AI's output for a single student so that the distinction could be repeatedly applied to the review of subsequent diaries. The instructional prompt grew from approximately 500 lines in late 2024 to approximately 7,500 lines by late 2025 as the distinctions accumulated.

One early event illustrates the mechanism concretely. The autumn 2024 deployment began with a minimal set of distinctions, including only reflection as the singular main dimension. On the 9th of September 2024, a first-year student's opening diary entry presented a case the single-category structure could not assess fairly. The diary displayed a thematic organisation that the prompt was instructed to consider as an intermediate level of reflection based on the original idea from Buur. However, the diary also presented a candid story on how the student was experiencing what they were encountering in the course, i.e., "*I must admit I wasn't too excited when I learned about the course book … but my opinion changed after starting it"*. It revealed thinking in progress, explained the reasons for their own structural choices, connected current experience to prior decisions about their major, and identified knowledge gaps with a plan to address them. Assessing the entry as intermediate would have misrepresented what the student was doing and assessing it as strong would have muddied what "strong reflection" meant. The instructor's diary entry that day recorded the resolution: *"Strong reflexivity <> Strong reflection."* After some contemplation, reflexivity was added as a co-equal category to reflection, i.e., as a core dimension of the assessment. This event

represents an instance of the mechanism that would operate throughout the inquiry. Both reflection and reflexivity dimensions were further differentiated into five frames during September-October 2025.

FINDINGS: TYPES OF REFLECTION AND REFLEXIVITY

As the result of the hermeneutic process, we distinguished 5 analytical frames in both reflection and reflexivity. In terms of the 'depth' or 'strength' or reflection, the prompt was elaborated with the signs of weak, intermediate, and strong reflection/reflexivity. A diary entry that would be considered strong would need to feature multiple strong reviews from the point of view of the different frames. Below we explain the analytical frames discovered in the study.

Five frames of reflection

Conceptual understanding concerns the grasp of theoretical foundations and principles that explain how and why phenomena occur. For example, a student who adopts the concept of root cause analysis from Norman (2013) and uses it to explain a phenomenon in their own words: "*…if there is another technical or system design flaw that was actually the root cause for the human error [..] During the summer I worked as a customer service agent. [..] The exhausting part for me was to constantly switch between the chats to see if other customers have answered yet. But by doing so my thoughts were constantly interrupted and sometimes that lead me to making silly mistakes like answering a specific question to the wrong customer or opening the wrong information in our system."* Here the student transferred Norman's concept of root cause analysis to their own domain and, by doing so, showed how the concept could be operationalised in and applied to practical day-to-day design work rather than simply cited and repeated the source.

Theory-practice integration concerns bidirectional flow between theoretical knowledge and lived experience. In a diary text that displays theory-practice integration, a student uses personal experiences to investigate theoretical concepts. In one diary entry, a student explored Norman's concept of mapping: "*I don't think my mistake [using a wrong dial] happened because the mapping on the stove is not logical (the course book does have better mapping design examples that I agree with seem more logical), but rather I was so used to my old stove, that I didn't think twice when turning the switches.*" Key difference from conceptual understanding is that here the student may, in addition to exploring the meaning of experiences in the light of theoretical concepts, also critically investigate the meaning and validity of theoretical concepts in the light of everyday experiences.

Critical analysis concerns systematic evaluation of experiences and claims through evidence-based argumentation. Students may use explicit criteria, context-dependent perceptions, and reasoned argumentation to form views and judgments of what is happening. Critical analysis does not necessarily utilise academic concepts in the way 'conceptual understanding' and 'theory-practice integration' does. A diary excerpt: "*There was a safety device that used motion sensors to detect if an object went through [..] The exhibitor explained that this sensor had a light transmitter and a receptor, and if the receptor was not getting signals from the transmitter (object blocking the way) the safety precautions would activate. [..] In hindsight I wondered why they would use a slightly more complex sensor instead of just the simple ultrasonic sensor we're using in our project. Why make it more complicated?*" This passage also displays signs of intellectual inquiry, which is triggered by a puzzling experience, thus illustrating that the use of multiple analytical frames on single text passages may reveal a more nuanced understanding of the text than singular ones do.

Knowledge synthesis concerns integration across sources and domains into coherent understanding, building arguments that cross disparate experiences. The following excerpt shows an interrogation of a student's earlier experiences in the light of the in-class feedback exercise: "*Designing the casing has also taught me to appreciate the precision involved in translating a digital design into a physical object. Small dimension changes can affect how components fit or how the final prototype looks, which reminded me of Norman's (2013) idea that "good design is in the details." I've learned that prototypes communicate ideas not only through function but also through their physical form, which relates back to lecture notes about articulation. The prototype itself becomes a way to express and refine our concept.*" While this excerpt resembles theory-practice integration, the key difference is in how the student connects multiple sources (experience of precision, Norman's point on details, lecture notes on articulation) into a new unified conceptual understanding (prototype as host of expression and refinement).

Intellectual inquiry concerns self-directed questioning beyond assignment requirements, i.e., generating explanations, pursuing tangential implications, engaging in speculative reasoning. A vivid example of intellectual inquiry is a diary entry that explored the concept of 'girl shopping' triggered by Norman's explanation of how people might want different things than what they actually buy. "*I have personally also experienced this in my own buying behavior [..] For me personally, I think my "girl shopping" behavior is due to either not actually affording the item or appreciating some specific design elements in it but knowing I don't need it and therefore leaving it behind."* The student proceeded to investigate the relation between desires and needs.

Five frames of reflexivity

Personal learning identity concerns self-knowledge as a learner, recognising how one approaches learning situations, articulating, not merely what they learned, but who one is when learning. An example from a diary entry: "*In the beginning of the course, this would have caused me stress because at the time I felt the need to control the process and teamwork. However, seeing that my team was able to successfully finalize the prototype and video without me was a moment of pride.*" Here, the student recognised a pattern in how they perceived themself, as a person needing to have control over the teamwork, and how this tendency shaped collaborative learning. The passage suggests that the person is becoming aware of a tension between different feelings, that of being in control and that of not.

Self-investigation for pattern recognition involves systematic examination of one's own behaviours to uncover underlying patterns. This kind of text moves beyond surface observations to ask why, identifying recurring tendencies, and developing causal explanations. An example: *"The aforementioned style of questioning [from the course book] seemed to properly display the issue of our idea [..] and likely revealed a similar reasoning our unconsciousness had robustly performed during the lecture."* The student applied methodology from the course book to interrogate their own design thinking that was a major learning goal in the course, tracing surface failure to root cause, and recognising that conscious analysis revealed what unconscious processing had already detected.

Transformative self-awareness involves recognising how one is changing through learning in terms of not merely acquiring skills but undergoing shifts in perspective or identity. Students demonstrated this through explicit before-after contrasts and articulating how past selves differ from present understanding: "*I used to think the lectures were some pretentious theory, but I came to see that there are some valuable insights to be gained once you look closer. I used to brush off the diary feedback as the professor simply being nitpicky and not appreciating my*

writing style, I now see that was never the point. I've been subconsciously internalizing the feedback and that's been changing the way I approach things." The student articulated two distinct perspective shifts, identified the mechanism of transformation ("subconsciously internalizing"), and recognised that change extends into behaviour ("changing the way I approach things"). The honesty about earlier dismissiveness makes the transformation credible. This passage also displays support for the effectiveness of the repeated and consistent diary feedback.

Learning challenge navigation concerns how students work with personal barriers. It involves honest acknowledgment of struggles, identifying obstacles, and developing strategic responses: *"For me it was hard to 'let loose' and doodle on the paper since I was overthinking my ideas too much. I think I also felt the time pressure as a constraint on my creativeness... After the second exercise I was able to go back to the circle exercise and draw more things. I think it helped me to have a bit more time and not feel too pressured to be more creative. I want to take this into the group project as well, to allow myself to think in peace."* The displayed learning challenge navigation here is forward loaded: the diary entry itself is part of the strategic response, since articulating the pattern is what makes it transferable to the group project rather than remaining a one-off observation.

Emotional and personal significance concerns how emotions connect to learning and treats emotions as learning data rather than noise, exploring also what feelings reveal about engagement: *"I also tried to worry about the proximity sensor reader for the prototype that isn't actually even necessary for our project to work... Which in essence is great, but if it leads me to stress this much, I should probably take some breaks and focus on one thing at a time... Maybe all worry isn't needless."* The student initially identified stress as problematic but arrived at a revaluation, "maybe all worry isn't needless." Rather than dismissing the emotion, they interrogated what it reveals, transforming anxiety from obstacle into signal.

Competent fluency and the challenge of detecting it

Initial versions of the AI prompt featured a bias towards the detection of explicit signs of specified aspects, for example, specific wordings or phrasings. The earlier AI models were also less capable in making interpretations on text, which required the prompt to point out to the AI very clearly what should be assessed and how. However, when students internalise concepts, they may display the understanding as an embodied and tacit quality in what they do and write, similarly to how a trained professional does their practice. The action and its presentation in text *show* what happens rather than explains the rationale behind or explicates the assumptions that underlie it. They use concepts as cognitive infrastructure, not as if they had just learned those and needed to explain their behaviour: "*I noted that I had made the assumption that she [user] would most definitely approve of it without question. That's not exactly the ideal mindset of a developer towards user feedback, but I'll cut myself some slack for it being a friend whom I already knew really well.*" This passage contained no citations, theoretical vocabulary, or explicit reference to user-centred design principles. Yet the student was performing user-centred thinking: recognizing their own confirmation bias, critiquing their methodology, demonstrating awareness that user feedback requires genuine openness rather than validation-seeking. The theory had become invisible as it had been internalized, similar to a native speaker constructing complex sentences without reciting grammatical rules. We identified this kind of cases in approximately 1-5% of submissions, where category boundaries and even dimensional categories between reflection and reflexivity dissolved.

Detecting this kind of fluency in text requires the LLM to have knowledge of the practice that the students are learning, here design thinking. The prompt needed to recognize that a student

reflexively catching themselves in a methodological error demonstrates deeper integration than a student who correctly defines “user-centred design” but applies it mechanically. For the prompt, we included a separate review step for ***performative integration***, which stands for a case where a student seems to have internalised the concepts and theory intended to be learned, and then display their understanding and capability by explaining how they act while having integrated these into their practice. Here, theory operates as natural voice rather than being cited through authoritative references. A single paragraph may simultaneously demonstrate reflection and reflexivity, each insight enabling the next.

In terms of the review, such fluent text presents a challenge, since it may appear poor from the point of view of an individual narrow analytical frame, but yet display the highest form of educational outcome in the given practice. Based on our experiment, recognising performative integration required several mechanisms. The most fundamental was adding a screening stage posing inverse questions: rather than only asking “Does the student cite theory?”, the prompt also asks: “Does the student use theoretical concepts as natural thinking tools WITHOUT formal citation markers?” This reframes absence as potential evidence of fluency. This, however, required the prompt to feature domain-specific key learning outcomes.

The final prompt included explicit recognition rules interrupting default assessment logic. Before classifying conceptual understanding as weak, the system must check for implicit mastery through application: “*Novices EXPLaiN concepts. Experts USE concepts as thinking tools. The second form is HIGHER competence, not lower.*” We developed named patterns with concrete textual markers. For example, the “*Concept-as-Cognitive-Infrastructure Pattern*” sensitises the system to self-correction mid-thought, evaluative language implying unstated criteria, and real-world application without explicit framing. The phrase “*that's not exactly the ideal mindset*” becomes legible as theoretical and practice-relevant engagement rather than as casual statement. The prompt also specifies what performative integration is not, e.g., explicitly excluding forced connections (“*This relates to what Norman said about...*”) and performative academic tone (“*Upon reflection, I realized...*”) from excellence indicators of performative integration. When multiple performative integration indicators converge on high level of performance, the prompt instructs to elevate the content review to the highest grade.

We also noted that the role of explicit reflexivity in the diaries seemed to reduce after a couple of weeks when the students were actively involved in the project activities. It was strongest in the early phases of the course, especially, as the design thinking approach was completely new to most of the students and they were writing about how they felt about it. This seems similar to performative integration in that the students, once familiar with the course and the domain, do not anymore feel the need to explicate how they perceive their experience, but instead, focus on working towards practical outcomes in the project-based course.

PRACTICAL CONSIDERATIONS FOR IMPLEMENTING AI-ASSISTED FEEDBACK

To our surprise, AI assistance increased rather than decreased instructor workload. Before the use of the AI system, in 2023, the students got feedback almost solely on the superficial technical aspects of their diaries, such as “*Otherwise good diary, reflections on reading missing.*” Generating feedback on content quality is demanding and time consuming, but the AI-based assessment enabled, for the first time, the students to receive verbose feedback tailored on the basis of their own work reviewing their text from multiple points of view. However, the instructor had to work now on an independent judgment, compare it to the AI’s review, edit a statement, and sometimes rewrite parts of the system prompt. We could process comfortably around 50-60 diaries per week when dedicating between one to two full days for the review.

This experience suggests that AI-assisted assessment does not support the easy scaling up of the learning diary assessment practice. What the AI-system does, however, provide is a mechanism to create draft assessments in a consistent and, based on our experience, highly reliable manner. The amount of edits the instructor had to do for individual learning diary assessment statements kept reducing meanwhile the system prompt grow more detailed. However, blind spots are still expected to be in the system, and the review of the next diary might reveal a new one. The system is not yet reliable enough to be trusted on assessment without human supervision.

Perceived effect on student performance

The students in the DTEP course were mostly bachelor's students on their very first semester in the university. Based on our reading of the diaries, the students were very responsive to the feedback, even to the extent that surprised us when we saw some of them gaining the fluency we call in this paper *performative integration*. We had not perceived this kind of fluency in learning diaries from the previous years during this course, whereby, the appreciation of it and the explicit categorisation of it in the prompt emerged together with the students improving in their project performance and writing in connection with getting better feedback. The master's students appeared less responsive to the feedback and adjusted their project work or writing less. This may stem having already learned a particular way of writing and sticking to it as there was no penalty for low quality reflection in the grading in the NEPPI course. As such, the experience highlights the need to consider the level of students, type of feedback format as well as grading emphases when designing AI-assisted grading.

We also noticed that the format of the feedback seemed to influence how students perceived it. The original format with explicit category-based structure with headings ("Reflection" and "Reflexivity") was dismissed by some students as too AI-like. Especially the master's students complained about this after the first diary feedback in the NEPPI course (personal communication). We then changed the prompt to output the feedback in a 'hamburger' structure (praise-gap-encouragement) and made it shorter, focusing on only the aspects that got lowest reviews. We then got feedback from students in both the DTEP and NEPPI courses that they started to follow the feedback more closely after this change in the statement format.

As such, the experience suggests that when students feel that no humans are reading their diary, they may start to seek ways of generating the text with AI and not invest personal effort in reflective learning anymore. Some students already expressed their concerns in their diaries that they expected the teacher not to even read their diaries. We think that teacher involvement important, not only in terms of ensuring the quality of the feedback, but also in retaining human connection with the students, so that they can feel been heard and seen by the senior members of the community.

DISCUSSION

In this paper we have reported a hermeneutic process, following Candy (2006), to discover dimensions, frames, and criteria for developing an AI-based mechanism for giving formative feedback on reflective learning diaries to students in project-based courses. The most recent updates to the CDIO syllabus (Malmqvist et al., 2022) suggest that we should focus on cultivating skills also named as self-regulated learning (Wallin & Adawi, 2018) and transversal competencies (Devika et al., 2020). A key means identified by scholars to cultivate such skills is the use of challenge-based approaches, such as problem- and project-based methods (Gaskins et al., 2015). Our here-reported research journey has covered 1346 individual diary

entries from in total 164 students across three project-course instances. The development resulted in an AI system prompt that embodies distinctions in operational format that an expert learning diary reviewer originally held tacitly. We presented the emergence and qualities of the two main dimensions, reflection and reflexivity, as well as five analytical frames within these dimensions. We also elaborated "*performative integration*," which appears as the silence of explicit elaboration of rationale behind fluent domain-specific practice, which is an intended learning outcome in the project-based courses we covered.

Noteworthily, AI had a role in the naming of the new analytical frames and assessment criteria. This is interesting as naming is amongst the three main activities of naming, framing, and moving, in reflective practice as outlined by Schön (1983). The names for many of the identified patterns were suggested by the AI. The most important may be the naming of the frame "performative integration" which was suggested by the AI during a debate triggered by the instruction about a single diary entry. The name stuck. It has been since used as the name of the explicit frame and part of the assessment process that all subsequent diary analyses have followed. Such frames, for which we do not yet have established vocabulary, are likely to still emerge from further investigations into the realm of AI-supported educational practices.

The hereby described process was developed by one instructor working on a limited set of courses and while using an evolving set of AI models. The practice-led approach lacks independent validation: categories emerged from one instructor's interpretive engagement in their own courses and have not been tested through inter-rater reliability or across different instructors. The learning goals of the courses reported here included learning to empathise, to interpret, to reflect on personal experiences, on self and on personal thinking, to articulate thoughts and ideas, and to focus on what matters; courses with other learning goals might be less aligned with reflexive and reflective performance, but could also result in distinct reflective and reflexive patterns not surfaced in our exploration Future work will need to examine feedback across cohorts, transferability of the frames across courses and contexts, instructor dependency, and AI model requirements.

Furthermore, further development is required in considering safeguards and countermeasures in AI-assisted grading. In the current experiment, one teacher manually reviewed all the learning diaries and kept grading consistent and fair across different students and student cohorts despite the evolving AI prompt. Fully automating this process would need more research. We also observed some students embedding hidden instructions for AI in their diary text to influence the AI's assessment. We implemented technical counter measures (enclosing anonymised text in clearly marked tags, instructing the model to treat content between the tags as text rather than as instructions) to address the most obvious cases. We also designed the diary assignment in a way that made it difficult for students to generate their diary entry with AI, i.e., required project photographs, lecture and exercise reflections, personal learning goals and explanation of how the students worked to achieve these, which would require significant effort to generate with AI. As technology evolves, the need to recognize and prevent misuse also presents evolving challenges to teachers interested in leveraging AI-assisted grading to support the development and assessment of transversal skills within the CDIO framework.

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APPENDIX 1:

Final assessment categories and main prompt contents in year 2025

```
Assessment Categories
|
├── REFLECTION (Sense-Making Skills) [1-5]
|   |
|   ├── 1. Conceptual Understanding
|   |   ├── Core: Grasping theories, mechanisms, and principles
|   |   ├── Signs: "I realized...", "basically...", mechanism explanations
|   |   ├── Characteristics: Principle extraction, meta-cognition, paradox recognition
|   |   ├── Patterns: Theory-validation cycle, dialectical pattern, progressive depth
|   |   └── Excellence: "Theory Demonstration" pattern, "Retrospective Understanding" pattern
|   |
|   ├── 2. Theory-Practice Integration
|   |   ├── Core: Bidirectional flow between theory and practice
|   |   ├── Signs: "This matters because...", "[Author] showed me...", "With those
|   |   |   guidelines..."
|   |   ├── Characteristics: Multi-layered significance, theory-practice dialogue
|   |   ├── Patterns: Learning arc, problem-solving sequence, discovery narrative
|   |   └── Excellence: "Personal Anthropology", "Lecture Framework Application", "Living
|   |       Theory"
|   |
|   ├── 3. Critical Analysis
|   |   ├── Core: Systematic evaluation with evidence-based argumentation
|   |   ├── Signs: "This worked well...", "what didn't work...", comparison language
|   |   ├── Characteristics: Criteria articulation, context-dependent judgment
|   |   ├── Patterns: Evidence-building, scaffolded evaluation, comparative analysis
|   |   └── Excellence: Systematic evaluation using explicit frameworks
|   |
|   ├── 4. Knowledge Synthesis
|   |   ├── Core: Integration across sources, contexts, and domains
|   |   ├── Signs: Argument building, cross-domain connections, integration markers
|   |   ├── Characteristics: Pattern recognition, thematic organization
|   |   ├── Patterns: "Lecture + Literature Convergence", "Theory as Lens", "Natural
|   |   |   Integration Flow"
|   |   └── Excellence: Connects 3+ different sources/domains meaningfully
|   |
|   └── 5. Intellectual Inquiry
|       ├── Core: Self-directed questioning and exploration beyond requirements
|       ├── Signs: "I want to talk about...", "What if...", "I started wondering..."
|       ├── Characteristics: Philosophical questioning, comfort with uncertainty
|       ├── Patterns: "Wondering Cascade", "Living Inquiry"
|       └── Excellence: Question generation, sustained inquiry cascade
|
├── REFLEXIVITY (Personal Development) [1-5]
|   |
|   ├── 1. Personal Learning Identity
|   |   ├── Core: "Who am I as a learner?"
|   |   ├── Signs: "I'm the kind of person who...", "I tend to...", learning preference
|   |   |   language
|   |   ├── Characteristics: Metacognitive awareness, personal authority in learning
|   |   ├── Patterns: "Informed Stance", "Cognitive Process Awareness", "Progressive Self-
|   |   |   Assembly"
|   |   └── Excellence: Self as researcher of own learning experience
|   |
|   ├── 2. Self-Investigation & Pattern Recognition
|   |   ├── Core: "How do I investigate my own behaviors?"
|   |   ├── Signs: "I learned that I...", "my issue has been...", behavioral discovery
|   |   |   language
```

```
|   |   ├── Characteristics: Investigative stance, root cause analysis, dual-track awareness
|   |   └── Excellence: Behavioral forensics capability
|   |
|   ├── 3. Transformative Self-Awareness
|   |   ├── Core: "How am I changing through this learning?"
|   |   ├── Signs: "I've changed...", before/after comparisons, breakthrough moments
|   |   ├── Characteristics: Growth acknowledgment, perspective shift recognition
|   |   └── Excellence: Identity-level transformation awareness
|   |
|   ├── 4. Learning Challenge Navigation
|   |   ├── Core: "How do I work with my personal barriers?"
|   |   ├── Signs: "Even if it's difficult...", struggle acknowledgment with strategy
|   |   ├── Characteristics: Vulnerability with objectivity, strategic weakness approach
|   |   ├── Patterns: "Even If Commitment", "Psychological Architecture"
|   |   └── Excellence: Behavioral intervention design for challenges
|   |
|   └── 5. Emotional & Personal Significance
|       ├── Core: "How do my emotions connect to learning?"
|       ├── Signs: Emotions as learning data, connection to values/goals
|       ├── Characteristics: Personal meaning-making, affective investment
|       └── Excellence: Value formation from experience
|
├── TECHNICAL (Superficial Requirements) [0-5]
|   ├── Word count (600+)
|   ├── Image usage and labeling
|   ├── Literature usage (Norman or other relevant source)
|   ├── Citation format (APA/IEEE)
|   └── Weekly activities evidence
|
├── COURSE-SPECIFIC CRITERIA
|   |
|   ├── Engineering Excellence Recognition
|       ├── Conciseness Excellence Rule: "Brief but complete = valued"
|       ├── Design Thinking Excellence: Comparing alternatives, user-centered reasoning
|       └── Project Work Recognition Rule: Team contribution OR enabling others required
|
└── INTEGRATION SCREENING (Stage 2)
    |
    ├── Performative Integration Detection
    |   └── "Learning so internalized that dimensional boundaries dissolve"
    |
    ├── 5 Screening Questions
    |   ├── 1. Theory-as-Voice Check: Concepts used without citation markers?
    |   ├── 2. Unified Performance Check: Single paragraph shows all dimensions?
    |   ├── 3. Generative Flow Check: Insights naturally birth new insights?
    |   ├── 4. Learning-as-Becoming Check: Student becoming, not just learning?
    |   └── 5. Naturalness Test: Could this be someone thinking aloud?
    |
    └── Professional Writing Recognition
        ├── "Students writing like professionals hide excellence through:"
        |   ├── Not explicitly stating contributions (because professionals don't)
        |   ├── Using "we" without detailing personal role (team-first mindset)
        |   └── Analyzing team dynamics without hero narrative
        └── "This understated style should trigger HIGHER grades, not lower"

Assessment Stages: 4 (9 steps)
├── Stage 1: Dimensional Analysis (steps 1-5)
|   └── WRITE OUT complete analyses in prose before any calculations
├── Stage 2: Performative Integration Screening (step 6)
|   └── Check for hidden excellence in natural writing
├── Stage 3: Contextual Grading (steps 7-8)
|   └── Apply week-based weights and course-specific criteria
└── Stage 4: Statement Authoring (step 9)
    └── Create evaluation ONLY after all analyses complete
```

Grading Weights by Period:
├— Weeks 1-4: 100% Technical (Content for feedback only)
├— Weeks 5-8: 50% Technical + 50% Content
└— Weeks 9-12: 30% Technical + 70% Content

APPENDIX 2: EXAMPLE OF WRITTEN ASSESSMENT FROM WEEK11 / DTEP 2025

This was clearly a demanding week, and you navigated it with real determination. What stands out most is how thoughtfully you examined your own response to pressure—your analysis of why you fall silent under stress and how your coping habits work against you shows genuine self-awareness that many students never develop.

The one area that could strengthen your diary is deeper engagement with course theory. You cited Norman's point about business constraints, which was relevant, but the connection to your own experience remained fairly brief. When you mention that "making calculated decisions at an effective pace requires skill and practice," this is exactly the kind of insight that could be developed further—how did Norman's framework actually shape your team's decisions this week? What did your prototyping struggles reveal about the theory? Pushing yourself to use the literature as a lens for understanding your specific challenges, rather than as supporting evidence added afterward, would elevate your reflection considerably.

Your resilience through circuit failures, stepping in to learn soldering when your teammate couldn't, and delivering a complete prototype under serious time pressure demonstrates exactly the kind of professional attitude that will serve you well. The fact that you're already thinking about refinements for the final presentation shows admirable commitment to quality.

Content grade: 4/5

Reflection 4/5, Reflexivity 4.5/5

Technical grade: 5/5

Final grade: 5/5 (30% technical/70% content)

Dr. Salu Ylirisku

APPENDIX 3: EXAMPLE OF WRITTEN ASSESSMENT FROM WEEK 11 / DTEP 2024

Dear [blinded],

Your reflection demonstrates strong depth as you extensively detail the technical challenges faced during the prototype development. You provide clear reasoning for your decisions, such as choosing a single box design over separated boxes to prevent instability. The narrative shows excellent problem-solving progression, particularly in how you systematically approached the LED strip freezing issue through research and testing.

Your writing displays strong reflexivity throughout. You openly share your emotional journey from feeling "devastated" to taking decisive action. Your text reveals deep personal agency in how you handled the absence of your teammate and technical obstacles. You show clear self-awareness in recognizing the value of testing before permanent assembly and in acknowledging your feelings about the rehearsal performance while maintaining hope for improvement.

Regarding the superficial grading elements:

1. Text exceeds 600 words ✓
2. Images are used ✓
3. Images are integrated with references (Picture 1, 2, 3) ✓
4. External sources are referenced ✓
5. Citations follow academic format ✓

In sum, the grade will be 5/5.

Best regards,

Dr. Salu Ylirisku

APPENDIX 4: EXAMPLE OF WRITTEN ASSESSMENT FROM WEEK 11 / DTEP 2022

Otherwise good diary, reflections on reading missing.

AI-SUPPORTED SOCRATIC TUTORING CHATBOT IN MANUFACTURING EDUCATION: A THEORY-INFORMED CDIO IMPLEMENTATION

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ABSTRACT

This paper describes theory-informed AI-powered chatbots as Socratic tutors in a first-year Manufacturing Technology course (Productietechniek 1) at The Hague University of Applied Sciences. The chatbots combine large language models (ChatGPT and Gemini) with Retrieval-Augmented Generation (RAG), drawing on curriculum-specific resources including lecture materials and worked examples. Unlike much AI-in-education research, the implementation is grounded in established learning theories: Cognitive Load Theory, Explicit Instruction, Self-Regulated Learning, Formative Assessment, Self-Determination Theory, and Sociocultural Learning Theory. Students used the chatbot collaboratively in small groups to analyse products and design production processes. Across five weeks of structured teacher observation in four parallel class groups, the two observers noted patterns consistent with the theoretical predictions: sustained on-task behaviour, more explicit technical reasoning in group dialogue, engagement with AI fallibility as a learning moment, and emerging articulation of what a professional product requires. These observations are offered as candidate design hypotheses rather than evaluated outcomes. In the subset of chatbot exchanges directly observed, incorrect AI output was frequently traceable to incomplete or imprecise student input, and these moments appeared to function productively within group discussion. This work contributes to the CDIO initiative by demonstrating how AI can enhance formative feedback, student agency, and professional competence development as a theory-informed conversational learning partner.

KEYWORDS

AI-supported learning, Socratic tutoring, formative assessment, manufacturing education, Cognitive Load Theory, Self-Regulated Learning, Standards: 2, 7, 8, 11

INTRODUCTION

The rapid development of generative AI tools such as ChatGPT and Gemini presents opportunities and risks for engineering education. Recent meta-analyses demonstrate positive effects of AI chatbots on student learning outcomes (Wu & Yu, 2024; Wang & Fan, 2025). However, the same research highlights significant risks: AI systems may produce inaccurate information through hallucination, encourage superficial learning through over-reliance, or undermine student agency when used as substitutes for thinking rather than supports for it (Danyaro et al., 2025; Hon, 2025).

The educational research literature reveals a concerning pattern: many studies of AI-based learning environments report student satisfaction and perceived learning benefits, but lack explicit grounding in established learning theories or critical discussion of pedagogical design (Ofosu-Ampong, 2024; Memarian & Doleck, 2024). This theoretical gap limits the capacity to understand why certain AI implementations succeed while others fail, and hampers the transfer of design principles across educational contexts.

Within the CDIO framework, AI introduces a clear educational challenge and opportunity. The CDIO Syllabus 3.0 emphasises that engineering graduates must develop capacities for critical thinking, professional reasoning, and collaborative problem-solving (Malmqvist et al., 2022). Professional engineering practice increasingly involves working with AI-driven tools across design, analysis, and manufacturing domains. Engineering programmes therefore bear responsibility to help students critically and responsibly engage with AI, while simultaneously strengthening key CDIO outcomes including reflective practice, feedback-rich learning, professional judgement, and collaborative reasoning.

This paper reports on AI-supported Socratic tutoring in the first-year course Productietechniek 1 (Manufacturing Technology 1) in the Mechanical Engineering programme at The Hague University of Applied Sciences. Approximately 150 students enrol annually, comprising diverse entrants from MBO, HAVO, VWO, and university transfer routes. This heterogeneity creates substantial variation in prior knowledge and learning approaches, which the AI tutoring system was designed to accommodate.

The course introduces fundamental manufacturing processes and requires students to design justified production process plans for real-world components. Two key design intentions guided the intervention. First, AI should function as a formative feedback instrument rather than a replacement for student reasoning. Second, AI use should strengthen peer learning, agency, and reflection rather than isolate students from collaborative learning dynamics.

The guiding research question is: *How can AI chatbots be deployed in manufacturing education such that they add didactic and pedagogical value while stimulating peer interaction and professional learning?* The paper presents the theoretical foundations, instructional design, technical configuration, and the learning dynamics the two observers noticed during this first implementation cycle, contributing to the growing body of CDIO scholarship on technology-enhanced active learning.

THEORETICAL FRAMEWORK

Although AI-in-education research has expanded rapidly since 2023, integration of established learning theories remains limited. Systematic reviews consistently identify this weakness (Batista et al., 2024; Liang et al., 2025). This implementation explicitly embeds chatbot design within six complementary learning theories, responding to CDIO community calls for evidence-based innovation (Edström et al., 2020).

Cognitive Load Theory

Cognitive Load Theory (CLT) explains how instructional design affects learning (Sweller, 1988, 1994). The theory distinguishes intrinsic load (element interactivity), extraneous load (suboptimal design), and germane load (schema construction). Effective instruction should manage intrinsic load through sequencing, minimise extraneous load, and promote germane load (Sweller et al., 1998, 2019). The AI tutoring system supports CLT-aligned design by providing short instructional turns, using structured questioning that reduces ambiguity, breaking complex tasks into smaller steps, and encouraging visual and procedural reasoning before process selection. Research on intelligent tutoring systems shows effect sizes of approximately d = 0.76 compared to conventional instruction (VanLehn, 2011; Ma et al., 2014; Kulik & Fletcher, 2016).

Explicit Instruction

Explicit Instruction is characterized by clear learning objectives, systematic presentation, modelling of cognitive processes, guided practice with feedback, and gradual release of responsibility (Rosenshine & Stevens, 1986; Rosenshine, 2012; Archer & Hughes, 2011). The approach benefits novice learners lacking schema structures for discovery-based instruction (Hughes et al., 2017). The chatbot incorporates these elements by articulating learning goals, modelling expert reasoning, offering guided practice through worked examples, and checking understanding through targeted questions. Students construct reasoning pathways themselves rather than receiving direct solutions—balancing explicit guidance with productive struggle.

Formative Assessment

Formative assessment powerfully influences student learning. Sadler (1989) established that effective formative assessment requires students to understand learning goals, perceive performance gaps, and take action to close them. Black and Wiliam's (1998) landmark review demonstrated effect sizes of 0.4 to 0.7 standard deviations, while Hattie (2009) found d = 0.73 for feedback interventions. The chatbot operationalizes these principles by eliciting current understanding before offering guidance, identifying misconceptions through probing, providing feedback through hinge questions rather than declarative judgement, and periodically revisiting learning goals.

Self-Regulated Learning

Self-Regulated Learning (SRL) theory describes how learners manage their cognitive processes, motivation, and behaviour (Zimmerman, 1989, 2000). Zimmerman's model identifies three cyclical phases: forethought, performance, and self-reflection. Pintrich and De Groot (1990) demonstrated that SRL components predict academic performance beyond cognitive ability alone, while Panadero (2017) highlighted the need for interventions that explicitly develop self-regulatory skills. The chatbot

stimulates SRL by requiring students to plan before receiving guidance, monitor their understanding, adjust their prompts based on responses, and evaluate AI-generated proposals critically. Students observe a direct relationship between their input quality and AI output quality, reinforcing metacognitive control and countering over-reliance risks.

Self-Determination Theory

Self-Determination Theory (SDT) identifies three psychological needs: autonomy, competence, and relatedness (Deci & Ryan, 1985, 2000; Ryan & Deci, 2000). When supported, these needs foster autonomous motivation characterized by interest and integrated self-regulation. Autonomy-supportive practices predict greater engagement and deeper learning (Ryan, 2023). The chatbot addresses all three pillars. Autonomy is supported by student control of questioning pace and direction. Competence is supported through mastery-focused feedback rather than comparative evaluation. Relatedness is maintained through collaborative use in small groups.

Sociocultural Learning Theory

Sociocultural learning theory emphasizes that learning is a social process mediated by cultural tools and more capable others (Vygotsky, 1978). Wood, Bruner, and Ross (1976) operationalized Vygotsky's Zone of Proximal Development through their analysis of scaffolding. Lave and Wenger (1991) extended this through situated learning and legitimate peripheral participation. Because students use the chatbot collaboratively in small groups, learning becomes dialogic and socially mediated. The chatbot functions as a neutral third conversational partner that stimulates negotiation of meaning, joint decision-making, and justification of design choices.

Theoretical Integration

By integrating CLT, Explicit Instruction, Formative Assessment, SRL, SDT, and Sociocultural Theory, this paper responds to a significant gap in AI-based educational research where theoretical grounding is often limited or implicit. Each theory contributes distinct insights: CLT addresses cognitive architecture, Explicit Instruction provides sequencing principles, Formative Assessment guides feedback design, SRL emphasises metacognitive development, SDT addresses motivation, and Sociocultural Theory frames the social learning context. This theoretical triangulation provides a robust foundation for both design decisions and interpretation of observed effects.

This work builds on prior CDIO community emphasis on active learning (Edström & Kolmos, 2014), formative assessment (Hansen & Sindre, 2023), and student agency (Crawley et al., 2014), extending these themes into AI-supported learning. The framework aligns with CDIO Standards 8, 11, and 2.

COURSE CONTEXT AND CDIO ALIGNMENT

The scientific calculator reshaped engineering education in the 1970s not by giving students answers, but by shifting the locus of cognitive effort: away from manual computation and toward problem formulation, estimation, and interpretation (Ruthven, 2013). GenAI in the manufacturing classroom warrants the same framing. It is a cognitive tool embedded within the learning activity — not a substitute for

instruction, and not a peripheral technology encountered only outside class. This framing matters because it determines how the tool should be aligned with educational standards. The Mechanical Engineering programme at The Hague University of Applied Sciences prepares students for applied professional engineering practice in the Dutch and international manufacturing industry, and follows CDIO principles with particular emphasis on the integration of disciplinary knowledge with professional skills development throughout the curriculum. The remainder of this section situates the course within that CDIO framework and, in the final subsection, maps the intervention explicitly to the CDIO Standards.

Course Description and Learning Outcomes

Productietechniek 1 (Manufacturing Technology 1) introduces fundamental manufacturing processes: forming (casting, forging, sheet metal forming), separating (machining, cutting), joining (welding, adhesive bonding, mechanical fastening), and relationships between material properties, process selection, and product quality. Learning outcomes align with CDIO Syllabus 3.0 competencies in disciplinary knowledge (Section 1), engineering reasoning and problem solving (Section 2.1), and conceiving and designing engineering processes (Section 4.3). Students are expected to analyze products to identify manufacturing considerations, select and justify processes based on technical and economic criteria, develop logically sequenced production process plans, and evaluate choices against quality, cost, and sustainability criteria.

Student Population Characteristics

The student population is heterogeneous, comprising entrants from MBO (practical technical experience), HAVO (limited technical background), VWO (strong theoretical but limited practical experience), and university transfer routes. This creates instructional challenges: substantially different prior knowledge, varied learning approaches, limited individual feedback opportunities in traditional instruction, and the need to bridge theoretical and practical knowledge. The AI tutoring system was designed specifically to address this heterogeneity by providing adaptive, individualized support within a structured learning framework.

Professional Assessment Structure

Professional assessment requires students to produce a production process plan demonstrating ability to apply manufacturing knowledge to realistic engineering problems. Students analyze a component's geometry, material, function, and quality requirements; select and justify manufacturing processes with explicit reasoning; sequence operations coherently; and evaluate choices against professional criteria. The AI chatbots support analysis, reasoning, and reflection during the formative learning phase—not for summative assessment. This distinction is important: the chatbot functions as a practice and feedback tool in a low-stakes environment, encouraging experimentation and learning from errors.

Alignment with CDIO Standards

Situating the chatbot-supported activity explicitly within the CDIO Standards (CDIO Initiative, 2020; Malmqvist et al., 2019, 2020) clarifies how the classroom pedagogy

aligns with the framework and, equally importantly, how it responds to external signals from industry and society.

Standard 2 (Learning Outcomes).

The learning outcomes of Productietechniek 1 are deliberately aligned not only with CDIO Syllabus 3.0 Section 1 (disciplinary fundamentals) and Section 4.3 (conceiving and designing engineering processes), but also with Section 2.1 (engineering reasoning and problem solving), Section 2.4 (attitudes, thought, and learning), Section 2.5 (ethics, equity, and other responsibilities), and Sections 3.1–3.2 (teamwork and communication), precisely the competencies that external stakeholders now flag as decisive for employability. The World Economic Forum's Future of Jobs Report 2025 identifies AI and big data as the fastest-growing skill categories worldwide, with 86% of surveyed employers expecting AI and data analytics to drive business transformation and 39% of core skills projected to change by 2030 (World Economic Forum, 2025). In the Dutch manufacturing context specifically, FME, Smart Industry and Koninklijke Metaalunie's joint market research reports that 83% of Dutch SME manufacturers lack insight into which parts of their production process are suitable for AI-supported automation, and the FME Smart Industry Productiviteitsagenda 2026–2028 names AI literacy and workplace innovation as preconditions for restoring Dutch manufacturing productivity (FME, 2025). The Sociaal-Economische Raad (SER), in its advice “AI en werk” to the Dutch government, argues that the workforce needs critical thinking, digital skills, and domain-specific problem-solving capacity to work alongside AI systems responsibly rather than defer to them uncritically (SER, 2025), echoing earlier Rathenau Instituut framing of responsible AI adoption (Rathenau Instituut, 2023). The EU AI Act, effective February 2025, reinforces this through its AI literacy obligation for organisations developing or deploying AI. Read together, these industry and societal voices align closely with CDIO Syllabus 3.0 Section 2.4 and 2.5: graduates of a Dutch mechanical engineering programme must be able not only to apply manufacturing knowledge, but to reason critically about AI-generated proposals, judge their validity against disciplinary criteria, and work ethically with AI tools in a team setting. The learning outcomes of this course should be updated to reflect this industry rationale, and the chatbot-supported activity is the primary mechanism through which these updated outcomes are enacted in class.

Standard 7 (Integrated Learning Experiences).

Standard 7 requires that disciplinary knowledge be learned alongside professional skills in integrated activities that mirror engineering practice. The chatbot-supported design task directly mirrors a growing category of contemporary engineering work: a production engineer at a Dutch manufacturer using GenAI to triage design-for-manufacturing (DFM) issues, iteratively evaluating both process choices (which manufacturing route, at what cost and quality) and design choices (whether to modify geometry, tolerances, or material selection to improve manufacturability), with the AI tool as a first-pass conversational partner whose suggestions must then be critically verified against standards, supplier data, and the engineer's own judgement. Students in Productietechniek 1 are not simulating this workflow at a distance; they are performing a legitimate peripheral version of it (Lave & Wenger, 1991), integrating material science, process knowledge, professional reasoning, communication, and responsible AI use within a single activity.

Standard 8 (Active Learning).

The intervention operationalises Standard 8 through four concrete mechanisms observable in the classroom: (i) chatbot questions trigger peer discussion within the small group before a response is composed, making student-student dialogue a structural feature rather than an optional extra; (ii) prompt construction becomes a joint analytical task, in which students negotiate what to tell the chatbot and why; (iii) every chatbot output is treated as a proposal to be evaluated, not an answer to be copied, shifting cognitive work toward critique and justification; and (iv) the lecturer circulates between groups to deepen reasoning at moments where the chatbot alone would under-challenge the students. Active learning in this design is therefore produced by the interaction between chatbot, peers, and lecturer, not by any single agent.

Standard 11 (Learning Assessment).

Standard 11 is operationalised through a clear separation between formative and summative functions. The chatbot is used formatively only: students use it during class to test reasoning, identify gaps, and rehearse justifications. Formative feedback is sourced primarily from the lecturer and from peers within the group, with the chatbot playing a secondary role by prompting students to self-assess or to check their group's shared understanding. Because the chatbot's knowledge base includes worked examples of professional production process plans from previous cohorts, students who become stuck can request and interrogate concrete exemplars of the target artefact, consistent with Explicit Instruction principles on the role of worked examples for novice learners (Hughes et al., 2017). The chatbot does not generate the summative deliverable, but it makes the standard of a high-quality plan more visible during the learning phase. The summative assessment, the production process plan, is completed independently of the chatbot and assessed against a professional rubric by the lecturer. This separation preserves assessment validity while allowing the chatbot to extend formative feedback capacity beyond what a single lecturer can provide to approximately 150 students individually.

The intervention aligns with multiple CDIO Standards (CDIO Initiative, 2020; Malmqvist et al., 2019, 2020). Standard 2 (Learning Outcomes) is addressed through focus on engineering reasoning, problem-solving, and system thinking competencies, requiring students to integrate knowledge across materials, processes, and quality systems. Standard 7 (Integrated Learning Experiences) is supported as the activity integrates disciplinary knowledge with professional skills, mirroring workplace practices where engineers increasingly use AI tools. Standard 8 (Active Learning) is central to the design. The Socratic questioning approach requires students to engage deeply rather than passively receive information. Standard 11 (Learning Assessment) is operationalised through continuous formative assessment embedded in chatbot interactions, providing immediate feedback enabling real-time adjustment of understanding.

METHODOLOGY

Research Design

This study employs a qualitative, practice-based case study design within a design-based research (DBR) tradition (Anderson & Shattuck, 2012; McKenney & Reeves, 2018), appropriate for investigating pedagogical innovations in their authentic classroom context. DBR is well-suited to the iterative development of theory-informed

educational interventions, where the researcher is simultaneously designer, practitioner, and investigator, and where the goal is to generate both usable knowledge for practice and transferable design principles for the wider community (Bakker, 2018). The case is bounded by a single course, Productietechniek 1, taught in the Mechanical Engineering programme at The Hague University of Applied Sciences during the 2025-2026 academic year, with approximately 150 first-year students distributed across parallel class groups. Within this case, the unit of analysis is the small student group (2–3 students) engaging collaboratively with the AI chatbot during in-class design sessions. The primary data source is structured teacher-researcher observation of these group interactions, supplemented by a secondary analysis of anonymised chatbot conversation logs. The study does not employ survey or interview methods; claims in this paper are therefore grounded in observational and log data only, with formal survey-based evaluation and inter-cohort comparison planned for a subsequent iteration of the design cycle. The author served as both lecturer and researcher, which offered privileged access to classroom dynamics but introduces a risk of observer bias that is explicitly addressed in the Limitations section. The study was conducted as part of routine educational practice; no identifying student data are reported, and we had no access to chatbot log excerpts, except for the numbers of chats conducted by the student groups.

Observation Method

Classroom observation was conducted jointly by the lecturer-researcher (the author) and a second lecturer teaching parallel class groups, providing two independent observer perspectives on the same intervention. Observations took place across five consecutive weekly sessions, distributed over four parallel class groups, yielding a total of approximately twenty observed session-hours. During each session, the two observers focused on two readily accessible layers of classroom interaction: (1) student–student dialogue within the small groups, which was easily observable at a distance and captured peer negotiation of meaning, disagreement, and joint decision-making; and (2) student–chatbot dialogue, observed opportunistically when students raised a question, requested lecturer input, or were prompted by the lecturer to share and justify their current chatbot exchange. Direct observation of chatbot dialogue was therefore partial rather than systematic, and biased toward moments where students themselves surfaced the interaction. Data were recorded in two complementary forms: brief contemporaneous field notes taken during the sessions, and more reflective post-session memos written by each observer shortly after class, capturing salient patterns, notable student utterances, and emerging questions. The analytic approach was deliberately light-touch and interpretive rather than formally systematic: observations were not coded against a predefined framework, and no thematic analysis in the Braun and Clarke (2006) sense was undertaken. Instead, the two observers compared field notes and memos informally across the five-week period, identifying recurrent patterns and moments that "stood out" with respect to engagement, reasoning quality, and student handling of AI fallibility. This pragmatic approach is consistent with first-cycle design-based research, where the aim is to surface candidate design hypotheses for subsequent, more rigorous evaluation (McKenney & Reeves, 2018), but it clearly limits the strength of inferential claims, as discussed in the Limitations section.

Chatbot conversation logs at the message level were not available to the research team; the learning platform recorded only session-level metadata. Across the five-week intervention, approximately 300 chatbot sessions were initiated by student

groups. Each session typically contained multiple message exchanges, but the number of exchanges per session was not captured and varied substantially by group. The figure of 300 should therefore be read as an indicator of adoption intensity rather than as a measure of dialogue depth.

Because no chat content, audio, or video was recorded, and no personally identifiable student data were collected or analysed, the THUAS ethics committee confirmed that formal ethical review was not required for this study. The observations were conducted as part of the author's regular teaching practice, and all observed examples reported in this paper are paraphrased rather than quoted verbatim to further protect student anonymity.

TECHNICAL AND INSTRUCTIONAL DESIGN

The technical and instructional design reflects the theoretical framework above, with decisions driven by learning theory rather than technological capabilities alone (Labadze, Grigolia & Machaidze, 2023; Liu et al., 2025).

Retrieval-Augmented Generation Architecture

Each chatbot uses a commercial large language model (ChatGPT-4 or Gemini Pro) connected to a course-specific knowledge base through Retrieval-Augmented Generation (RAG). RAG architectures allow language models to ground responses in authoritative source materials while maintaining conversational flexibility (Liu et al., 2025). The knowledge base includes lecture PowerPoints based on Basisboek Productietechniek (the course textbook), structured guidance documents for production process design, worked example professional products from previous cohorts, and assessment formats, templates, and rubric criteria. This design limits irrelevant information and maintains curricular alignment. The system retrieves relevant content and incorporates it into responses, reducing hallucination likelihood while ensuring guidance aligns with process selection approaches taught in the course.

Didactic Prompt Design and Behavioral Rules

The chatbot's pedagogical behavior is shaped through carefully engineered instructions. Explicit behavioral instructions affect learning outcomes (Zhang, Z., et al., 2024). The chatbot is framed as a Socratic tutor that guides through questioning rather than telling, a formative assessor that identifies gaps and provides developmental feedback, and a metacognitive coach that prompts reflection on learning processes.

Core behavioral rules include the following. The chatbot should scaffold understanding through progressive questioning rather than providing full answers immediately. It should begin by clarifying student intent and current knowledge level. It should ask probing questions that reveal thinking and identify misconceptions. Explanations should be short and structured, addressing specific gaps rather than comprehensive lectures. It should adapt language level and technical depth to student responses, providing more scaffolding for struggling students and more challenge for advanced students.

Additional rules address AI-specific considerations. The chatbot warns students that hallucinations may occur and responses should be verified against course materials. It requires students to justify their reasoning rather than accepting suggestions

uncritically, and promotes reflection on both the task and the learning process. Research on Socratic chatbots suggests this questioning approach enhances critical thinking and deeper learning compared to information-delivery approaches (Favero et al., 2024; Zhang, L., et al (2024)).

Learning Task Structure and Sequencing

The learning task follows a structured sequence developing systematic product analysis and process reasoning skills. Students first analyze their product in terms of material (type, properties, processing behavior), geometry (dimensions, tolerances, surface requirements), functional requirements (load bearing, wear resistance, corrosion resistance), context of use (environment, maintenance, lifecycle), and expected production quantities (prototype, batch, mass production). This structure reflects professional manufacturing process selection, ensuring students consider relevant factors before jumping to process choices. Students upload product images with their initial analysis, grounding conversation in concrete artefacts.

Following product analysis, the chatbot guides students through iterative design reasoning. It identifies missing information by questioning gaps, requests additional analysis where students have overlooked factors, proposes provisional process routes with reasoning, and asks students to critique and refine decisions by identifying potential problems or alternatives. This cycle continues until students develop a complete, justified production process plan. The chatbot's role is to guide and question rather than provide definitive answers, maintaining student ownership of design decisions.

Collaborative Learning Implementation

Students work with the chatbot in small groups of 2-3, sharing a single session. This design was driven by sociocultural learning theory and SDT considerations: collaborative use maintains social learning dynamics, supports relatedness needs that might be undermined by isolated AI interaction, enables peer evaluation of AI responses before acting on them, and distributes cognitive load across multiple students. The collaborative structure transforms the chatbot into a shared resource stimulating group discussion. When the chatbot asks a question or makes a suggestion, students discuss before responding, creating opportunities for peer learning and mutual explanation. Across implementation, students engaged in over 300 chatbot interactions. The collaborative structure also safeguards against over-reliance: multiple students evaluating responses reduces uncritical acceptance of incorrect information.

LIMITATIONS

Several limitations should be acknowledged, spanning both the evidence base and the methodological choices made in this first design-based research cycle. Framing these explicitly against established qualitative case study methodology (Creswell & Poth, 2018; Yin, 2018) helps clarify what this study can and cannot legitimately claim.

Evidence base

First, the absence of completed survey-based evaluation and inter-cohort comparison of assessment outcomes limits the evidence to observational and session-level log data. While observations provide valuable qualitative insights, they cannot establish

causal relationships or quantify learning effects. A validated student survey and comparative analysis of assessment outcomes is planned for the next iteration. Second, the absence of message-level chatbot logs meant that dialogue depth, prompt quality evolution over time, and the precise point at which student groups shifted from answer-seeking to reasoning-seeking could not be quantified. The figure of approximately 300 chatbot sessions therefore indicates adoption intensity rather than dialogue depth, and reviewer-relevant questions about the number of exchanges required for critical evaluation to emerge cannot be answered from the current data.

Observer bias.

The dual role of the author as teacher, designer, and researcher introduces a substantial and unavoidable risk of observer bias (Yin, 2018). Both observers — the author and a second lecturer teaching parallel class groups — were personally invested in the pedagogical intervention and in the broader project of responsible AI integration at THUAS. Neither was blind to the design intent, the theoretical framework, or the desired learning behaviours. It is therefore plausible that the observers' attention was disproportionately drawn to confirmatory evidence (for example, instances of productive Socratic dialogue or critical evaluation of AI output) and less attuned to disconfirming evidence (for example, groups that used the chatbot superficially or disengaged). The absence of inter-rater reliability checks between the two observers, and the interpretive rather than formally coded analytic approach, compounds this limitation. Future cycles of the research will mitigate this through independent observation by a researcher not involved in course delivery, structured observation protocols, and formal consensus coding of field notes.

Partial observation of chatbot dialogue.

As noted in the Observation Method section, direct observation of student–chatbot exchanges was opportunistic rather than systematic: the observers captured dialogue primarily when students surfaced it through questions to the lecturer or when the lecturer prompted them to share their exchange. Student–student discussion was readily observable at a distance, but the content of chatbot conversations within groups that worked autonomously throughout a session was not accessible to the observers. Claims about the nature of student–chatbot dialogue in this paper are therefore based on a non-random subset of interactions and should be read as illustrative rather than representative.

Hawthorne and novelty effects.

Although students were not formally aware of being observed as research subjects (no chats, audio, or video were recorded, and formal ethical review was not required), they were explicitly aware that the lecturers were interested in how the new AI chatbot supported their learning. This creates conditions for both a Hawthorne effect — behavioural change in response to the perceived interest of authority figures — and a novelty effect associated with the introduction of an unfamiliar tool. While the sustained engagement observed across five weeks argues against pure novelty as the sole driver, neither effect can be ruled out on the basis of observational data alone. Longitudinal comparison across multiple cohorts, once the intervention is no longer novel, will be necessary to disentangle these confounds.

Single-site generalisability and transferability.

The study is situated in a single course at a single Dutch university of applied sciences, which constrains statistical generalisability in the conventional sense (Yin, 2018). However, following Creswell and Poth's (2018) notion of transferability in qualitative inquiry, the theoretical foundations that guided this design — Cognitive Load Theory, Explicit Instruction, Formative Assessment, Self-Regulated Learning, Self-Determination Theory, and Sociocultural Learning Theory — are broadly supported across disciplines and contexts in the educational research literature. The classroom observations reported here are consistent with the predictions of this literature, lending cautious support to the expectation that the underlying design principles would transfer to other engineering education contexts. What will vary substantially, however, is the implementation: the specific curricular knowledge base, the nature of the professional artefact students design, the balance of lecturer facilitation and chatbot scaffolding, and the disciplinary norms governing what counts as a justified design decision. The contribution of this paper is therefore best read as a set of transferable design principles rather than a replicable classroom recipe.

Long-term transfer.

Finally, the study does not track whether the observed learning effects persist beyond the course or transfer to professional engineering practice, where AI-mediated reasoning is increasingly expected. Ultimate educational value therefore remains partially unknown and will require longitudinal follow-up with graduates, which is beyond the scope of a first-cycle design-based study.

Taken together, these limitations are consistent with the exploratory, practice-oriented nature of first-cycle design-based research (McKenney & Reeves, 2018) and with Yin's (2018) view that single-case studies generate analytic rather than statistical generalisation. The findings presented here are offered as candidate design hypotheses to be tested, refined, and challenged in subsequent cycles and in replication by the wider CDIO community.

OBSERVED PATTERNS AND CANDIDATE DESIGN HYPOTHESES

The two observers identified recurrent patterns across the five-week period, surfaced through informal comparison of post-session memos rather than through formal coding. These patterns are reported here as candidate design hypotheses to be tested in subsequent DBR cycles through survey, inter-cohort comparison, and message-level log analysis. They are not offered as evidence that the design caused particular learning outcomes, and language of increase, improvement, or effectiveness should be read accordingly.

Engagement and On-Task Behaviour

Both observers recorded an impression of sustained engagement with the manufacturing process design activity across the five-week period. Because no systematic comparison against prior cohorts was undertaken, this impression should be read as hypothesis-generating rather than comparative. Novelty plausibly contributed to initial engagement. Whether the observed sustained attention reflects the pedagogical design, the collaborative format, the chatbot specifically, or residual novelty cannot be determined from the present data; this is a question for the planned inter-cohort comparison. The collaborative structure amplified engagement. The observers noted animated within-group discussion and debate about process choices,

consistent with the sociocultural rationale for collaborative chatbot use. The comparison to 'individual work typically observed' is impressionistic; no matched comparison was performed. The chatbot functioned as a conversation starter and maintained momentum when group discussion flagged. These observations align with meta-analytic findings on AI chatbots and engagement (Wang & Fan, 2025) and SDT predictions about autonomy-supportive learning environments.

Reasoning Quality and Technical Analysis

In the subset of student–chatbot and student–student exchanges that the observers directly witnessed or that students surfaced during lecturer interaction, a recurrent pattern appeared: questions framed as 'what is the correct process?' earlier in the five weeks were, in later sessions, more often accompanied by 'why is this appropriate?' reasoning within the group. Because chatbot dialogue was observed opportunistically rather than systematically, and no message-level logs were analysed, the timing and prevalence of this shift cannot be quantified. The pattern is offered as a candidate hypothesis for the planned log-based analysis. In observed group discussions, technical analysis appeared more explicit and structured later in the five-week period than earlier, and students more frequently referenced the characteristics of a high-quality professional product when justifying process choices. Whether this reflects the chatbot, the lecturer's facilitation, peer discussion, or the combination remains an open question for subsequent analysis. The observers noted instances of students challenging their own assumptions and chatbot suggestions, asking follow-up questions, requesting clarification of AI reasoning, and cross-checking against course materials. The claim that such behaviours increased over time is based on the observers' collective impression across the five weeks, not on coded frequency data, and should be treated as hypothesis-generating. This critical stance is particularly valuable given concerns about over-reliance on AI systems.

Productive Engagement with AI Fallibility

Most significant was student engagement with AI errors. The observers repeatedly noticed instances of chatbot output that the student group themselves, or the lecturer on circulation, identified as inappropriate for the product under analysis. In the observed cases, these errors were frequently traceable to incomplete or imprecise student input – missing material specification, omitted tolerance or quantity information, or ambiguous geometric description – rather than to failures of the retrieval base. No systematic error audit was conducted, and no rate of incorrect output is claimed. When students provided vague descriptions or omitted technical details, suggestions were more likely to be inappropriate. In the observed cases, this input–output relationship appeared to function as a learning moment: students discussed what information the chatbot had been given and what had been omitted, and revised their input accordingly. Whether this generalises across groups, or to professional practice, is an open question. In the observed cases where errors were identified, students were seen to refine problem framing, improve prompt precision, verify reasoning against course materials, and cross-check with peers. The 'productive failure' and 'desirable difficulties' literatures offer a plausible theoretical reading of this pattern, but the present data do not establish that students 'developed' critical evaluation skills in a measured sense.

Understanding of Professional Quality Standards

In group discussions observed later in the five-week period, students more frequently articulated what a high-quality professional product (beroepsproduct) should contain. Without pre/post measurement or a comparison cohort, the claim that understanding itself became clearer cannot be substantiated here. The chatbot's consistent requests for justification and evidence plausibly contributed to making these quality expectations salient during group work, alongside lecturer facilitation and peer discussion. Disentangling the contribution of each is beyond what observational data support. Students were repeatedly observed articulating that professional engineering work requires explicit reasoning, not only correct answers. Whether this represents internalisation or situational performance cannot be determined from the present data. The worked examples in the knowledge base provided concrete models of professional quality, and the chatbot's questioning helped students understand what made those examples successful. This aligns with Explicit Instruction principles regarding the importance of models and worked examples for novice learners.

DISCUSSION

The patterns the observers noticed are broadly consistent with the directions the guiding theories would predict. This consistency should not be read as confirmation of any single theory, nor as evidence that the theoretical framework caused the observed patterns; observational alignment with theory is a weak test, particularly when six complementary theories are in play and the observers were not blind to the design intent.

Theoretical Interpretation of Observations

From a CLT perspective, the structured questioning approach was designed to manage cognitive load, and the observers did not notice signs of overwhelm during group work. Cognitive load was not directly measured. The Explicit Instruction elements functioned as intended: students received scaffolding and models without replacement of their own reasoning. The Socratic approach ensured students constructed understanding rather than passively receiving it. Formative Assessment principles were operationalised through continuous AI-mediated questioning that created feedback loops throughout the learning process, enabling real-time adjustment. The input–output relationship between student analysis quality and AI response quality was designed to surface metacognitive control, and the observers noted instances of students monitoring and adjusting their prompts in response to chatbot output. The claim that SRL as a capacity developed is not one the present data can support; it is a candidate hypothesis for longitudinal follow-up. SDT needs appeared well-supported: autonomy through student control of interaction pace, competence through mastery-focused feedback, and relatedness through the collaborative learning structure. Sociocultural Theory helps explain how the chatbot functioned as a stabilising conversational partner, stimulating discussion and providing a shared reference point for negotiation of meaning.

The Instructional Ecology: Chatbot, Peers, and Lecturer

A candid interpretation of the observed shifts requires disentangling the chatbot's contribution from that of the broader instructional ecology in which it was embedded. The shift from answer-seeking to reasoning-seeking, and the growing critical evaluation of AI output over the five-week period, cannot be attributed to the chatbot

alone. Three agents were at work simultaneously, and the design depended on their interaction.

The lecturer's role remained active throughout. The two lecturers circulated between groups, questioned students on their reasoning, prompted groups to share and justify their current chatbot exchange, and reminded students of their own responsibility to arrive at a defensible design decision rather than outsourcing the judgement to the system. Crucially, the chatbot's structured Socratic design also allowed the lecturers to hand off tasks that would otherwise have required direct instruction, particularly the patient, repeated questioning that surfaces missing product analysis, which no single lecturer can sustain across approximately 150 students in parallel. The instructional ecology therefore redistributed lecturer effort rather than reducing it: more time on deep reasoning with individual groups, less time on first-pass diagnostic questioning.

The peer group contributed through three concrete behaviours observed repeatedly across the five weeks: negotiation of prompts before they were submitted to the chatbot, joint evaluation of chatbot output before any of it was acted upon, and mutual explanation when one group member understood a process decision that another did not. These peer behaviours are themselves predicted by sociocultural learning theory (Vygotsky, 1978; Lave & Wenger, 1991), and the collaborative chatbot design was specifically intended to elicit them, but the peers, not the chatbot, are the ones doing this work.

The chatbot's specific contribution was to sustain a particular kind of questioning pressure that is difficult to maintain through lecturer or peer interaction alone: consistently asking for justification, surfacing missing information, and refusing to provide a finished answer. Students were not told explicitly that the chatbot was designed as a Socratic tutor; they were told only that it was not an answer machine, but a system intended to stimulate their learning. The shift toward reasoning-seeking behaviour therefore emerged from students' direct experience of the chatbot's behaviour in interaction with lecturer facilitation and peer discussion, rather than from instructional framing of the tool's purpose.

This ecological reading has two consequences for how the findings should be read. First, the observed effects should be understood as properties of a designed learning environment in which chatbot, peers, and lecturer each play a distinct role, rather than as properties of the chatbot itself. Transferring the intervention to another context therefore requires transferring all three elements, not only the technical artefact. Second, the lecturer's role in this design is not diminished by the introduction of AI – it is repositioned. Pedagogical expertise becomes more visible, not less, precisely because the chatbot takes over the repetitive scaffolding work and frees the lecturer to intervene where disciplinary judgement is most needed.

Central Insight: AI as Feedback Instrument

AI is educationally valuable when designed as a structured feedback instrument rather than an answer engine. AI tools that provide direct answers may satisfy immediate student needs but undermine learning by removing productive struggle. AI tools designed as feedback instruments—that question, probe, and guide rather than tell—maintain cognitive engagement and support deeper learning. This has implications for the broader AI-in-education field. The theoretical framework here provides principles for distinguishing educationally valuable AI applications from potentially harmful ones.

Implications for the CDIO Community

This work has several implications for the CDIO community. First, it demonstrates that AI can be integrated into CDIO programmes in ways that strengthen rather than undermine core educational values through thoughtful design grounded in learning theory. Second, it provides a model for how AI tools can support formative feedback and active learning emphasised in CDIO Standards 8 and 11, extending feedback opportunities beyond what instructors can provide individually. Third, preparing students for professional AI use can be integrated with core disciplinary learning. Students simultaneously learn manufacturing process design and develop critical AI evaluation skills. Recent CDIO work supports these findings. Nikolic et al. (2025) developed a CDIO-based framework for AI integration, Lei et al. (2025) demonstrated positive effects of generative AI-enabled CDIO teaching on computational thinking, and Karoui and Bettaieb (2024) presented strategies for AI-supported active learning in engineering education.

CONCLUSIONS

This study has described a theory-informed Socratic chatbot intervention in a first-year manufacturing course, grounded in six complementary learning theories and enacted through an instructional ecology in which chatbot, peers, and lecturer each play a distinct role. Observational evidence across five weeks and four class groups is consistent with the theoretical predictions: students shifted from answer-seeking to reasoning-seeking, engaged productively with AI fallibility, and developed a clearer sense of what a high-quality professional artefact demands. These claims are offered cautiously, as candidate design hypotheses to be tested in subsequent DBR cycles through the survey and inter-cohort analysis now in preparation.

The contribution to CDIO Standards 2 and 7 is where the pedagogical development lands most concretely. Standard 2 is strengthened by aligning the course's learning outcomes with the AI-literacy signals now converging from industry and society — the World Economic Forum, FME, Koninklijke Metaalunie, the SER, and the EU AI Act — and mapping these onto CDIO Syllabus 3.0 Sections 2.4, 2.5, and 3.1–3.2, alongside the disciplinary core. Standard 7 is strengthened by designing an activity that mirrors a recognisable category of contemporary engineering work: the production engineer using GenAI to triage design-for-manufacturing issues, integrating process choices, design choices, and responsible AI use within a single task. Students perform a legitimate peripheral version of this workflow rather than simulating it at a distance.

A broader design principle follows: the general-purpose large language models supplied by commercial AI providers are not, by themselves, learning companions. They become learning partners only when augmented with pedagogy and disciplinary knowledge — through curriculum-grounded retrieval, behavioural instructions derived from learning theory, and embedding within a classroom ecology of peers and lecturers. Transferring this intervention therefore means transferring the ecology, not only the artefact. Future work will extend the evidence base through systematic student evaluation, inter-cohort comparison, and longitudinal follow-up, and the CDIO community is invited to replicate and challenge these design principles in other disciplinary contexts.

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AI usage declaration

AI tools (ChatGPT, Claude and Gemini) were used both as part of the educational intervention described in this paper and for language editing and drafting support in preparing this manuscript. All conceptual, theoretical, and pedagogical design decisions were made by the author. The author takes full responsibility for the content and any errors or omissions.

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INTEGRITY BY DESIGN FOR ETHICAL AI USE IN CDIO ASSESSMENT

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ABSTRACT

Generative artificial intelligence (AI) has created uncertainty in higher education assessment because students can use AI productively for ideation, explanation and technical support, but can also use it to bypass learning. This paper presents the AI Reflection Coefficient Model, an integrity-by-design assessment approach developed within a CDIO-aligned Year 4 Precision Engineering module at Technological University of the Shannon (TUS) Midwest. The model requires students to complete a technical design assignment and submit a structured audio reflection on their use of AI. Reflection quality, assessed using a rubric informed by Gibbs' Reflective Cycle and the Traffic Light System for AI use, acts as a coefficient influencing the final assignment grade. The study used an exploratory practitioner-inquiry design, combining thematic analysis of student reflections with descriptive analysis of rubric scores. Fifteen students participated in the survey and reflection activity. Findings suggest that structured reflection helped make AI use more visible, encouraged students to recognise AI limitations and supported discussion of ethical boundaries. However, students required further scaffolding to move from procedural description towards deeper ethical reasoning. The paper contributes a practical model for embedding reflective academic integrity practices within AI-supported CDIO assessment.

KEYWORDS

Academic integrity, generative AI, CDIO, reflective assessment, engineering education, Standards: 2, 3, 7, 8, 11

INTRODUCTION

Generative artificial intelligence (AI) is now embedded within the academic practices of many students. AI tools can assist with brainstorming, explanation, coding support, literature searching, structuring and design ideation. In engineering education, these affordances are potentially valuable because students are often required to work through complex, open-ended and iterative technical problems. The proportion of students using generative AI tools such as ChatGPT for assessments has jumped from 53% in 2024 to 88% in 2025 (Freeman, 2025). the same tools can also be used to generate text, code, design justifications or assessment outputs in ways that obscure the student's own judgement and learning. This creates a direct challenge for academic integrity because traditional assessment products may no longer provide sufficient evidence of student process, authorship or understanding (Cochrane & Ryan, 2023).

Recent work on AI and academic integrity has emphasised that the problem is not simply technological but educational and cultural. Students may understand academic misconduct in general terms yet still struggle to identify the boundary between legitimate support and inappropriate substitution in practice (Risquez et al., 2013). Moya et al. (2024) similarly highlight the need for proactive institutional and pedagogical responses to AI in higher education. Dawson (2020) frames assessment security as a design issue rather than a matter of surveillance alone, while McCabe (2005) argues that academic integrity is a shared responsibility across the learning community. This perspective is important in AI-supported assessment because detection-based approaches alone are unlikely to cultivate ethical judgment or professional responsibility.

One response to this challenge is to design an assessment that embeds integrity into the learning process. Reflective practice offers a mechanism for making student decision-making visible. Gibbs' Reflective Cycle provides a structured process through which students can describe their actions, evaluate consequences, analyse their choices and plan future practice (Gibbs, 1988; Bulman & Schutz, 1997; McDermott & Anselmo, 2024). In the context of AI, reflection can require students to explain how AI was used, what was accepted or rejected, how outputs were checked, and where human judgment remained essential. This approach shifts attention from simply policing final outputs to examining the learning process through which those outputs were produced.

The CDIO framework is particularly suited to this form of assessment because it emphasises active, applied, and iterative engineering learning across the phases of Conceive, Design, Implement, and Operate. CDIO assessment can foreground process evidence, prototyping, technical decision-making and reflective evaluation. This makes it more resilient to AI misuse than static assessments that focus only on a written report or final answer. AI may legitimately support aspects of a CDIO task, particularly early ideation or clarification, but students must still demonstrate engineering judgement in selecting, implementing and defending their solution.

Existing guidance, such as the AI Assessment Scale and Traffic Light System, helps students distinguish between acceptable and unacceptable AI use (Perkins et al., 2023). Green Zone use may include brainstorming and clarification; Amber Zone use may include structuring or support that requires careful oversight; and Red Zone use includes generating final arguments, final conclusions or complete assignment

sections. However, guidance alone does not ensure that students will consistently apply these boundaries. A practical assessment mechanism is required to connect AI-use guidance with student accountability, reflection and grading. This study investigates how a structured AI Reflection Coefficient Model can promote academic integrity, ethical AI use and reflective practice within a CDIO-aligned engineering assessment. The research question is: How can reflective assessment practices promote academic integrity in AI-supported CDIO engineering assessment?

CONTEXT OF THE STUDY

The study was conducted in the Automated Manufacturing Systems module (ENGR0815) at Technological University of the Shannon (TUS) Midwest. The module is delivered to Year 4 Precision Engineering students and includes practical, design-based work aligned with the CDIO framework. Fifteen students participated, representing the full cohort enrolled in the module.

The assessment intervention was embedded in a CDIO-aligned technical design assignment. Students were required to conceive, design, implement, and operate a simple material-handling system or end effector powered by a single NEMA 17 stepper motor and controlled by an Arduino Uno. The system was required to handle a 2 cm cube with precise control within a 30 cm spatial constraint. Deliverables included the design concept, CAD evidence, a physical prototype, the control approach, and a technical explanation of the system.

AI use was permitted for ideation, clarification, coding support, design inspiration and concept exploration. Students were not permitted to use AI to replace final student judgement, final technical argument, final design justification or final submission content. This distinction was communicated using the Traffic Light System (Perkins et al., 2023). Students subsequently submitted structured reflections on their use of AI, primarily in audio format, to explain how AI supported or influenced their assignment process.

AI REFLECTION COEFFICIENT MODEL

The AI Reflection Coefficient Model was developed by the authors for this study as a practical grading mechanism to connect technical performance with reflective evidence of responsible AI use. The model is intended to move academic integrity from a retrospective detection activity into an embedded assessment design feature. Students are assessed not only on the technical quality of their assignment but also on the transparency, criticality and ethical reasoning demonstrated in their AI reflection.

The model combines three elements. First, Gibbs' Reflective Cycle structures the reflection by encouraging students to describe, evaluate and analyse their use of AI and to identify future strategies for responsible use. Second, the Traffic Light System provides a shared vocabulary for distinguishing encouraged, cautionary and prohibited AI practices. Third, a five-criterion rubric assesses the quality of the reflection using the following criteria: Transparency, Critical Reflection, Ethical Awareness, Action Plan for Future Use, and Authenticity. Appendix A, Table 4, outlines the objective grading criteria rubric (Cunningham, S. M., 2025a).

The coefficient calculation was developed by the authors for this study as a practical grading mechanism to connect technical performance with reflective evidence of responsible AI use. The final coefficient grade was calculated as shown in Eqn. (1):

$$[Assignment\ Grade] \times \left(\frac{[AI\ Reflection\ Grade]}{100}\right) = Coefficient\ Grade \quad (1)$$

Example: Students score 80% on the assignment and 65% on the AI reflection, final grade:

$$[80] \times \left(\frac{[65]}{100}\right) = 52\%$$

For example, if a student achieved 80% on the technical assignment and 65% on the AI reflection, the final coefficient grade would be 52%. A minimum threshold was also applied to protect assessment integrity. Where a student scored below 50% on the AI reflection, the student was required to resubmit the reflection or the final report grade was capped at 60%, depending on the assessment context and academic judgement.

The model is not intended to function as an AI detection system. Where discrepancies were suspected between declared AI use and the submitted work, the reflection provided a basis for further dialogue, clarification or reflective review with the student. In this sense, the model functions as a reflective and dialogic integrity tool rather than a mechanism for objectively detecting undeclared AI use.

METHOD

This study used an exploratory practitioner-inquiry design combining qualitative thematic analysis with descriptive quantitative analysis of rubric scores. The intervention was implemented within one final-year engineering module and was designed to examine how structured AI reflection could support ethical engagement with AI in a CDIO assessment context.

Participants were fifteen Year 4 Precision Engineering students enrolled in ENGR0815. All students received guidance on permitted and prohibited AI use through the Traffic Light System and completed the CDIO design assignment described above. Students submitted reflections on AI use after completing the assignment. Reflections were recorded as audio submissions where possible and were subsequently reviewed for evidence of transparency, critical reflection, ethical awareness, future planning and authenticity.

Data sources included student AI reflections, survey responses on AI use, reflection rubric scores and lecturer observations of the assessment process. The survey and reflections were used to identify recurring themes in students' experiences of AI-supported assessment. Thematic coding focused on reported drawbacks of AI, plans for transparent use, initial hesitation, perceived support for learning, effects on critical thinking and reported over-reliance. Reflection rubric scores were analysed descriptively. Six anonymised cases are presented to illustrate variation in student engagement across high, mid-range and low reflection performance. These cases are not used as a statistical sample but as illustrative cases to support the interpretation of the rubric outcomes. Ethical approval was granted by the Faculty of Science and

Engineering Research Ethics Committee at the University of Limerick (Approval No. 2024_10_16_S&E). Participation was handled in accordance with the approved ethical protocol, and student examples are anonymised, Cunningham, S. M. (2025a).

Table 1. AI reflection rubric used to assess students' reflective engagement with AI

Criterion	Focus of assessment	Weight
Transparency	Clarity and specificity in documenting how AI was used, with examples and reference to permitted, cautionary or prohibited use.	20%
Critical Reflection	Depth of analysis of AI's impact on learning, including strengths, limitations and student decision-making.	30%
Ethical Awareness	Understanding of originality, academic integrity, responsible AI use and appropriate boundaries.	20%
Action Plan for Future Use	Specificity and practicality of strategies for improving future AI use.	15%
Authenticity	Evidence of a genuine, personal and process-based reflection rather than a formulaic declaration.	15%

RESULTS

The results are reported in two forms. First, cohort-level thematic findings are presented from the full group of fifteen students. Second, six anonymised cases are used to illustrate variation in reflective performance across the rubric criteria. This structure responds to the need to distinguish cohort-level patterns from illustrative examples.

Table 2. Theme frequencies from the full cohort (N = 15)

Theme identified in student reflections/survey	Number of students	Percentage of cohort
Reported drawbacks or limitations of AI	12	80%
Planned transparent AI use in future work	11	73%
Hesitant or unsure at the start of the assignment	7	47%
Reported that AI helped critical thinking	4	27%
Felt that AI-supported learning	3	20%
Reported over-reliance on AI	3	20%

Thematic analysis showed that students recognised both the usefulness and limitations of AI. The most frequent theme was the recognition of AI's drawbacks, identified by 12 students. These drawbacks included inaccurate or shallow outputs, generic suggestions and concerns about over-reliance. Eleven students described plans for a more transparent future AI use, including cross-checking AI outputs, documenting AI support and restricting AI to ideation or clarification. Seven students

reported hesitation or uncertainty at the start of the assignment, often because they were unsure where the boundary between support and misconduct lay.

These findings suggest that the reflective task made students more aware of the practical and ethical uncertainties associated with AI use. Students appeared willing to use AI, and many recognised its limitations, but fewer were able to articulate how AI contributed to deeper learning. This indicates the need for stronger scaffolding around reflective and ethical reasoning.

Table 3. Illustrative anonymised AI reflection rubric scores for six students

Student	Transparency (20)	Critical reflection (30)	Ethical awareness (20)	Action plan (15)	Authenticity (15)	Total
Student A	16	22	18	7	13	76%
Student B	9	12	8	7	12	48%
Student C	12	15	8	6	12	53%
Student D	16	21	10	6	13	66%
Student E	18	26	18	10	14	86%
Student F	16	21	12	6	13	68%
Mean	14.5	19.5	12.3	7.0	12.8	66.2 %

The illustrative cases show that reflection quality varied considerably. Student E achieved the highest overall reflection grade (86%) and demonstrated strong transparency, critical reflection and ethical awareness. Student A also demonstrated strong reflective engagement but had a weaker future action plan. Students D and F provided honest, technically descriptive reflections but gave less developed attention to ethical reasoning and to future AI-use strategies. Students B and C achieved lower reflection grades because their reflections provided limited evidence of critical evaluation or ethical framing, even though their technical project work may have been stronger.

Across the six illustrative cases, the mean overall AI reflection grade was 66.2%. The strongest criterion was Authenticity, with a mean of 12.8 out of 15 (85.6%), suggesting that students could provide personal accounts of their process. The weakest criterion was Action Plan for Future Use, with a mean of 7.0 out of 15 (46.7%). This suggests that students found it easier to describe what had happened than to translate that experience into a future strategy for responsible AI use. Ethical Awareness also required development, with a mean of 12.3 out of 20 (61.7%). These patterns indicate that reflective AI assessment requires iterative practice and formative feedback if students are to move beyond procedural description.

DISCUSSION

The findings suggest that structured reflection can make AI use more visible in CDIO assessment. Students were required to explain how AI contributed to the Conceive, Design, Implement and Operate phases of their technical work, rather than simply submitting a final product. This process supported academic integrity by creating an assessment space in which students had to account for their use of AI, evaluate its contribution and identify its limitations.

The cohort-level themes show that students were alert to the drawbacks of AI, particularly inaccurate, shallow or generic outputs. This is encouraging because it suggests that students were not simply accepting AI responses uncritically. However, the smaller number of students who explicitly described AI as supporting learning or critical thinking indicates that AI literacy remains uneven. Students may use AI frequently without yet having a mature language to explain how it supports or constrains their learning. This supports the argument that academic integrity guidance must be accompanied by opportunities for practice, feedback and reflective development.

The Traffic Light System provided useful boundary language (Perkins et al., 2023), but the results suggest that it was not yet fully internalised. Several students used AI in ways that were broadly consistent with Green or Amber Zone use, yet did not explicitly refer to the framework in their reflections. This indicates that guidance should not be treated as a one-off briefing. Future iterations should integrate the Traffic Light System into formative checkpoints, peer discussion and rubric feedback so that students learn to apply it as part of their own ethical decision-making.

The coefficient model assigned an assessment value to both the process and the product. This is important in AI-supported assessment because the final artefact alone may not reveal whether students have exercised engineering judgement. By moderating the technical grade through reflective evidence of responsible AI use, the model communicates that how students reach a solution matters. This aligns with CDIO principles because students are expected to justify design decisions, demonstrate implementation choices and evaluate operation in context.

Audio reflections may provide a more personal, process-oriented account of students' decision-making than a written declaration alone. However, it should be understood as a reflective and dialogic integrity tool rather than a detection mechanism. The purpose is not to prove whether AI has been used, but to create a structured opportunity for students to explain their reasoning, acknowledge uncertainty, and discuss ethical boundaries. Where inconsistencies are suspected, the reflection can support further academic dialogue rather than an automatic penalty. The model can also be understood through the lens of Legitimate Peripheral Participation (Lave and Wenger, 1991). Students begin by using AI for relatively low-risk Green Zone activities such as ideation and clarification. Through feedback and reflection, they encounter more complex Amber Zone decisions requiring judgment and accountability. Over time, repeated reflective practice may help students internalise the norms of an academic and professional engineering community. This reinforces McCabe's (2005) view that integrity is a shared responsibility rather than a rule imposed solely on students.

CONCLUSION

This paper presented the AI Reflection Coefficient Model as an integrity-by-design approach for AI-supported CDIO assessment. The model combines Gibbs' Reflective Cycle, the Traffic Light System and a weighted reflection rubric to connect technical performance with evidence of responsible AI use. In the context of a Year 4 Precision Engineering module, the model helped make AI use more visible and encouraged students to consider transparency, ethical awareness and the limits of AI-generated support.

The findings suggest that reflective assessment can support academic integrity by shifting attention from final output alone to the student's learning process, judgment, and accountability. However, the implementation also shows that reflection must be scaffolded. Students recognised AI limitations but often required further support to articulate ethical reasoning and future strategies for responsible use. The weakest rubric area was Action Plan for Future Use, indicating that future iterations should include more structured formative feedback and exemplars. The study is exploratory and limited by its small cohort, single-module implementation and use of illustrative rubric cases rather than full cohort rubric statistics. The findings should therefore be interpreted cautiously. Future work should apply the model across larger cohorts, multiple CDIO modules and repeated assessment cycles, with more robust longitudinal data on AI use, technical performance and reflective development. Despite these limitations, the model offers a practical contribution to CDIO engineering education by embedding academic integrity within the assessment design rather than treating it solely as a post-submission compliance issue.

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BIOGRAPHICAL INFORMATION

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APPENDIX A

Table 4: A five-criterion rubric evaluated each student's AI reflection, aligning with the study's LOs and integrity-by-design approach.

Criteria	Excellent (80-100%)	Good (60-79%)	Satisfactory (40-59%)	Poor (0-39%)	(100%)
Transparency	Thorough and clear documentation of AI use, with specific examples aligned to the Traffic Light System.	Describes AI use but lacks some specificity or alignment.	Provide a partial or unclear description of AI use; examples are vague.	Minimal or no description of AI use or misrepresentation of usage.	20%
Critical Reflection	Deep reflection on AI's impact on learning, with thoughtful analysis of strengths and limitations.	Reflects on AI use but lacks depth in the analysis of impacts on learning.	Basic reflection with limited insight into how AI influenced the work.	There is little to no reflection on AI use or overly simplistic responses.	30%
Ethical Awareness	Strong understanding of ethical AI use, including originality and academic integrity.	Some awareness of ethics, but lacks detailed consideration of integrity.	Limited mention of ethical considerations; fails to address key issues.	No engagement with ethics or misuse of AI.	20%
Action Plan for Future Use	A clear and detailed plan for improving AI use in future assignments.	General ideas for future use, but lacking specific strategies.	Basic action plan with limited strategies for improvement.	There is no action plan for future AI use.	15%
Authenticity	Engages deeply with the reflection, providing a genuine and personal response.	There is some engagement, but it lacks depth.	Reflection feels formulaic or lacks personal engagement.	There is little to no personal engagement or insight into AI use.	15%

MATHEMATICS LEARNING BELIEFS OF FIRST-YEAR ENGINEERING STUDENTS

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ABSTRACT

Students' beliefs about mathematics influence their learning behaviour and, potentially, achievement. This investigation surveyed two large classes of first-year engineering students on entry to university and at the end of their first-year mathematics module. One class began their degree programme in academic year 2018/19 and the other, whose secondary education was disrupted by the covid-19 pandemic, started university in 2023/24. The students had a strong appreciation of the value of mathematics to their studies and career and a strong acceptance of struggle; these beliefs strengthened over the module. Beliefs associated with a growth mindset were dominant and student confidence was generally high. However, the 2023/24 class was less assured than the 2018/19 class. Some increase in confidence was observed over the year for the latter group, this being more noticeable for the students of higher ability, but there was little change in confidence for the 2023/24 class. Females believed more strongly in the value of mathematics and seemed more strongly to enjoy trying to solve new problems. Self-efficacy was relatively high and increased over the year. It is suggested that the teaching and learning methods – weekly practice, frequent opportunities for peer review, inclusion of problems with engineering applications – had a positive impact on students' beliefs.

KEYWORDS

mathematics, learning beliefs, self-efficacy, first-year engineering students, pandemic, Standards: 8, 11.

INTRODUCTION

Beliefs and attitudes towards mathematics, including enjoyment, confidence and value, seem to be positively associated with achievement in mathematics at secondary level (Wen & Dubé, 2022). Self-reinforcing cycles have been observed, with success in mathematics leading to better attitudes and increased confidence, resulting in greater persistence and further success. Conversely, failure in mathematics can lead to negative attitudes and lower confidence, resulting in reduced effort and further failure (Ernest, 2003). Beliefs and attitudes can be distinguished – beliefs are formed based on the information available and they lead to attitudes, from which intentions and then behaviours may result (Fishbein & Ajzen, 1975; Parsons, 2014). Note that mathematics anxiety, being an emotional factor, is not considered under the heading of beliefs and attitudes towards mathematics.

Resilience is a desirable attribute in general. It is the quality of being able to respond positively in the face of difficulties (Kooken *et al*., 2016). Mathematical resilience is a term that describes both the process of becoming positioned to deal with difficulties that arise when learning mathematics and the outcome of adapting successfully to those difficulties or challenges. Mathematically resilient learners have the self-efficacy, flexibility, motivation and perseverance needed to overcome difficulties (Lee & Johnston-Wilder, 2024). Mathematical resilience encompasses a collection of attitudes and behaviours that can be divided into four categories – growth mindset, struggle, value and support.

A growth theory of learning mathematics refers to the belief that people can improve their mathematical abilities through application and instruction (Dweck, 2008). Having a growth mindset should facilitate perseverance when confronted with challenges. In contrast, those with a fixed mindset may regard difficulties as an indication that they have reached the limit of their understanding. Struggle refers to the belief that sometimes much effort is required because mathematics can be a challenge to learn – not because of personal incompetence or limitations. In theory, students who understand that struggling with mathematics is not unusual should have more tolerance and stronger staying power in the face of difficulties (Kooken *et al*., 2016). Value refers to the extent to which students find studying mathematics important in attaining their goals (Kooken *et al*., 2016). When learning and achievement associated with a subject is valued, students will become more willing to engage actively with it (Deci *et al*., 1991).

Mathematics confidence is associated with an expectation of attaining good results, assurance of ability to handle difficulties, feeling good about mathematics as a subject, and lacking nervousness or worries about learning mathematics (Galbraith & Haines, 1998; Pierce *et al*., 2007). Self-efficacy relates to confidence to perform a specific task. This can be considered a belief regarding whether the mathematical task can be performed successfully (Parsons, 2014). Evidence shows significant relationships between confidence and achievement (Parsons, 2014) and that confidence promotes positive cycles of further effort and achievement (Parsons *et al*., 2011).

Given the connection between beliefs and behaviour, and potentially achievement (Pierce *et al*., 2007), it is of interest to investigate students' beliefs regarding mathematics as they begin their undergraduate studies. The following research questions have been proposed:

- What beliefs do first-year engineering students hold about learning mathematics?
- How do their beliefs change over the first year of their degree programme?
- What differences in beliefs were evident between students beginning their degree programme before and after the covid-19 pandemic?

The paper describes the subjects of the investigation, the learning environment and the research instrument. It presents the findings of the research under categories of value, struggle, growth, confidence and self-efficacy. An explanation for the results is offered along with implications for student persistence.

METHODOLOGY

Background

The author is module coordinator and lecturer for Mathematics 1, a core module (20 CATS points) for first-year aerospace, mechanical and product design engineering students in Queen's University Belfast. Students are not permitted to proceed in their degree without passing this first-year mathematics module within two attempts. The first half of the syllabus is mainly a repetition of secondary-level topics (logarithms, polynomial equations, partial fractions, trigonometry, complex numbers, differentiation and integration) while the second half has newer topics (including matrices, differential equations, vectors, Laplace transforms and descriptive statistics). Teaching takes place over 25 weeks with a two-hour lecture and one-hour feedback session per week. A formal teaching style is generally employed in lectures with effort made to present the material in a logical manner. Numerous worked examples are included to help reinforce the material being taught while typical engineering applications illustrate the usefulness of mathematics to engineers.

The class size has ranged 155 – 195 since 2016. Most have come through the UK A-level system with 52% having at least grade A in A-level Mathematics during the period 2016-2020; this proportion has increased to 75% during 2022-2025. On average, 7% of the A-level students have completed Further Mathematics. Entrance requirements for aerospace, mechanical and product design engineering students in our university were identical during the period of this research.

Subjects

Two groups of first-year aerospace, mechanical and product design engineering students enrolled in Mathematics 1 were involved in this study – those who began their degree programme in academic year 2018/19 and those who began in 2023/24.

Questionnaire design

The research instrument was a questionnaire, designed for our particular setting (Pierce *et al*., 2007) but based on the literature. The questionnaire contained 23 items. The first three items were used to collect biographical information – the students' secondary-level qualification in mathematics, whether they achieved an A-level in Further Mathematics, and gender. The remaining 20 items (Table 1) were used to assess students' beliefs towards learning mathematics. Items 1 – 15 were developed from the literature (Kooken *et al*., 2016; Fogarty *et al*., 2001) and are related to factors associated with mathematical resilience and to confidence. In Table 1, these are categorised as value (V), struggle (S), growth (G) and confidence (C). Responses were invited on a scale: strongly agree, agree, neither agree nor disagree, disagree, strongly disagree. Items 16 – 20 were used to measure self-efficacy (SE); as recommended (Bandura, 1997; Nielsen & Moore, 2003), their content is specific and relates to topics relevant to engineering mathematics. Responses were invited on this scale: highly certain can do, certain can do, moderately certain can do, could make an attempt, cannot do at all.

Table 1. Items on the mathematics learning beliefs questionnaire

item number	item	category
1	Maths will be useful to me in my life's work.	V1
2	Having a solid knowledge of maths helps me understand more complex topics in my field of study.	V2
3	Maths develops good thinking skills that are necessary to succeed in any career.	V3
4	Good mathematicians experience difficulties when solving problems.	S1
5	Everyone makes mistakes at times when doing maths.	S2
6	Struggle is a normal part of working on maths.	S3
7	Maths can be learned by anyone.	G1
8	If someone is not good at maths, there is nothing that can be done to change that.	G2
9	People are either good at maths or they aren't.	G3
10	I have less trouble learning maths than other subjects.	C1
11	When I have difficulties with maths, I know I can handle them.	C2
12	I have a mathematical mind.	C3
13	I enjoy trying to solve new mathematical problems.	C4
14	I find maths frightening.	C5
15	I find maths confusing.	C6
16	Rate your capability to rearrange equations and formulae.	SE1
17	Rate your capability to resolve a fraction into its partial fractions.	SE2
18	Rate your capability to differentiate products and quotients.	SE3
19	Rate your capability to integrate by parts or by substitution.	SE4
20	Rate your capability to solve first-order differential equations by separating the variables.	SE5

Procedure

The questionnaires were conducted using electronic systems but at an in-person class led by the author. In the 2018/19 year, the questionnaire was first introduced at the beginning of the first class of Mathematics 1. This was at 9.05 am on the students' second day of their degree programme. The lecturer explained the purpose of the research and administered the survey, deliberately before introducing the module, so that students' responses would not be influenced by thoughts about the mathematics they were about to undertake. The questionnaire was hosted on SurveyMonkey and students responded using an electronic device, typically a smartphone. The questionnaire was repeated (identical content and same administrative procedure) at a mathematics lecture in week 23 to measure students' beliefs at the end of the teaching phase of the module. By this stage, students had completed a significant amount of formative, continuous assessment (a weekly worksheet, peer review and reflection) but summative assessment (submission of log book and final examination) had not yet taken place (Cole & Fraser, 2025). In 2023/24, the process was repeated with the same questionnaire being distributed at the beginning of the week 1 lecture and in week 23. The only change was that Microsoft Forms replaced SurveyMonkey as the survey platform.

Completion of the questionnaires was voluntary (although encouraged) and anonymous. Mean time taken to complete them was two and a half minutes (week 1 questionnaires) or two minutes (week 23 questionnaires).

RESULTS

Table 2 shows the biographical data of the two populations. Response rates to the survey were high in week 1 (84% and 86% in 2018/19 and 2023/24 respectively); a high attendance at the first class of a new module would be expected. The response rates in week 23 were lower (57% and 73% in 2018/19 and 2023/24 respectively); lecture attendance tends to decline over the year so lower figures are to be expected. Response rates in week 23 were lower for males than for females (56% v 61% in 2018/19, 70% v 79% in 2023/24). Considering the larger sub-groups according to secondary mathematics qualification, response rates in week 23 were lower for those with lower grades (for example, 88%, 70%, 44% for A-level grade A*, A and B students respectively in 2018/19).

Note that A-level is a subject-specific qualification taken in the UK typically by school students aged 16 – 18. Leaving certificate is the equivalent award in the Republic of Ireland. In Table 2, "other (UK)" represents UK students with alternative qualifications to A-levels (for example, vocational). "International" refers to students from outside the UK and Republic of Ireland.

Table 2. Number of students participating in research study

		number of students	response rate (%)	gender		secondary qualification in mathematics						
				male	female	A-level grade A*	A-level grade A	A-level grade B	A-level grade C	other (UK)	Leaving Cert	inter-national
2018/19	class size	160		127	33	16	57	57	1	10	8	11
	week 1	134	84	107	27	16	49	48	1	7	8	5
	week 23	91	57	71	20	14	40	25	0	4	7	1
2023/24	class size	160		121	39	30	73	34	0	2	17	4
	week 1	138	86	102	36	30	60	28	0	2	16	2
	week 23	116	73	85	31	25	57	19	0	1	13	1

Table 3 presents responses to the items related to value, struggle, growth and confidence (items 1 – 15) for the two classes in week 1. A red – white colour scale is used to highlight responses of large magnitude. In both years, there was generally strong agreement as to the value of mathematics in studies and work. Across the questionnaire in each year, the strongest agreement for any item was for item 1. There was strong agreement that struggle is a normal experience when working on mathematics. This feeling was stronger for the 2023/24 class. Responses under the category of growth showed greater variation, with a large proportion of neutral responses for items 7 and 9. However, the distribution of responses had a similar profile in both years. While most agreed that mathematics can be learned by anyone, neutral responses or disagreement represented 25% or 29% of the class in the two years. A small proportion agreed and many were neutral (27% or 28% in the two years) that people were either good at mathematics or not. However, in both years, there was strong disagreement with the statement that nothing could be done for those considered not good at mathematics.

Many of the responses to the confidence items were neutral although, in general, they indicated that high levels of confidence existed. This was true regarding being able to handle difficulties, having less trouble with mathematics than other subjects, and enjoying solving new problems. While responses to items 10 – 13 showed a similar profile in 2018/19 and 2023/24 on entry to university, responses to items 14 and 15 showed differences. A large proportion of both classes disagreed that they found mathematics frightening but this disagreement was stronger in 2018/19. While most students (55%) in 2018/19 disagreed that they found mathematics confusing, many were neutral (39%). However, in 2023/24, there was a much higher agreement with the sentiment (20%) and only 41% disagreeing that they found mathematics to be confusing.

Table 3. Measures of agreement to items related to value, struggle, growth and confidence. A red – white scale is used where red indicates a high magnitude and white indicates zero.

			value			struggle			growth			confidence					
			Maths will be useful to me in my life's work.	Having a solid knowledge of maths helps me understand more complex topics in my field of study.	Maths develops good thinking skills that are necessary to succeed in any career.	Good mathematicians experience difficulties when solving problems.	Everyone makes mistakes at times when doing maths.	Struggle is a normal part of working on maths.	Maths can be learned by anyone.	If someone is not good at maths, there is nothing that can be done to change that.	People are either good at maths or they aren't.	I have less trouble learning maths than other subjects.	When I have difficulties with maths, I know I can handle them.	I have a mathematical mind.	I enjoy trying to solve new mathematical problems.	I find maths frightening.	I find maths confusing.
		item number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2018/19	week 1	% strongly agree	65.4	61.7	54.1	32.6	57.1	30.1	28.6	1.5	0.8	23.5	12.2	19.8	21.4	0.8	0.8
		% agree	33.8	36.1	39.1	46.2	40.6	60.2	42.9	1.5	12.8	49.2	61.1	66.4	61.8	5.3	4.5
		% neutral	0.8	2.3	4.5	12.1	1.5	7.5	17.3	9.0	27.8	23.5	23.7	12.2	13.0	18.2	39.4
		% disagree	0.0	0.0	2.3	6.8	0.8	2.3	11.3	57.1	45.1	3.8	3.1	1.5	3.8	60.6	47.0
		% strongly disagree	0.0	0.0	0.0	2.3	0.0	0.0	0.0	30.8	13.5	0.0	0.0	0.0	0.0	15.2	8.3
2023/24	week 1	% strongly agree	63.8	51.4	37.0	39.1	61.6	47.1	20.3	0.0	0.0	21.7	9.4	22.5	21.0	0.7	1.4
		% agree	34.1	47.8	52.9	44.9	37.0	45.7	55.1	2.9	9.4	53.6	63.8	56.5	57.2	10.9	18.8
		% neutral	2.2	0.7	5.8	7.2	0.7	6.5	15.9	9.4	26.8	14.5	19.6	18.8	18.8	23.9	39.1
		% disagree	0.0	0.0	4.3	8.7	0.7	0.7	7.2	60.1	50.0	8.7	6.5	2.2	2.9	49.3	37.7
		% strongly disagree	0.0	0.0	0.0	0.0	0.0	0.0	1.4	27.5	13.8	1.4	0.7	0.0	0.0	15.2	2.9

Table 4 shows percentage point differences between male and female responses to the items related to value, struggle, growth and confidence (items 1 – 15) for the two classes in week 1. In both years, females were more strongly convinced of the value of mathematics, especially regarding its use in life's work. Different beliefs were also evident in the category of struggle, however, the profiles were different in the two years. In 2018/19, males more strongly believed that struggle was normal and that everyone makes mistakes when working at mathematics, whereas in 2023/24 females more strongly agreed with these statements. In 2018/19, there was slightly stronger agreement from males that mathematics can be learned by anyone, but females held this belief more strongly in 2023/24. Differences between male and female beliefs under the category of confidence were less obvious, however, females in both years more strongly enjoyed tackling new problems. In 2018/19, males disagreed more strongly that they found mathematics confusing, but responses to this item in 2023/24 showed little dependence on gender.

Table 4. Percentage point differences between males and females in levels of agreement to items related to value, struggle, growth and confidence. Red indicates a higher value for females, blue indicates a higher value for males, and white indicates no difference.

			value			struggle			growth			confidence					
			Maths will be useful to me in my life's work.	Having a solid knowledge of maths helps me understand more complex topics in my field of study.	Maths develops good thinking skills that are necessary to succeed in any career.	Good mathematicians experience difficulties when solving problems.	Everyone makes mistakes at times when doing maths.	Struggle is a normal part of working on maths.	Maths can be learned by anyone.	If someone is not good at maths, there is nothing that can be done to change that.	People are either good at maths or they aren't.	I have less trouble learning maths than other subjects.	When I have difficulties with maths, I know I can handle them.	I have a mathematical mind.	I enjoy trying to solve new mathematical problems.	I find maths frightening.	I find maths confusing.
		item number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2018/19	week 1	% strongly agree	-20.2	-10.9	-6.4	8.4	15.9	14.5	8.0	-2.8	-3.7	-4.3	-4.0	-4.0	-21.3	-3.8	0.9
		% agree	19.2	8.1	-2.1	-16.4	-18.8	-17.5	2.7	1.9	2.1	-0.9	9.0	-8.3	19.6	1.8	-8.7
		% neutral	0.9	2.8	5.7	-3.4	1.9	4.8	-10.8	-7.3	-11.6	5.3	0.7	10.4	-3.0	-1.3	-3.6
		% disagree	0.0	0.0	2.8	8.6	0.9	-1.8	0.2	2.0	5.5	-0.1	-5.8	1.9	4.8	8.4	15.4
		% strongly disagree	0.0	0.0	0.0	2.9	0.0	0.0	0.0	6.1	7.7	0.0	0.0	0.0	0.0	-5.1	-4.0
2023/24	week 1	% strongly agree	-19.0	-9.3	-6.4	-10.9	-18.1	-15.2	-10.1	0.0	0.0	-0.7	-2.3	0.3	2.1	1.0	2.0
		% agree	19.8	8.3	0.2	4.4	19.9	9.2	-0.7	0.2	1.5	-10.1	-0.2	1.3	-9.0	-4.1	2.9
		% neutral	-0.8	1.0	4.1	2.3	-2.8	8.8	2.8	9.0	-16.3	0.8	3.9	-4.6	6.7	9.8	4.1
		% disagree	0.0	0.0	2.1	4.2	1.0	-2.8	6.0	-5.1	7.5	8.0	1.3	2.9	0.2	-4.7	-5.4
		% strongly disagree	0.0	0.0	0.0	0.0	0.0	0.0	2.0	-4.1	7.4	2.0	-2.8	0.0	0.0	-2.0	-3.6

Table 5 presents a comparison of beliefs at the beginning and end of the teaching phase of the module for both classes. Given that beliefs showed some variation with secondary-level mathematics grade, and given that response rates to the questionnaires varied according to that secondary-level grade, table 5 is restricted to students with A-level Mathematics grade A. Including the whole class would mean a different profile of students in the weeks 1 and 23 responses and would therefore invalidate the comparison.

Table 5. Measures of agreement to items related to value, struggle, growth and confidence for students with A-level Mathematics grade A. A red – white colour scale is used where red indicates a high magnitude and white indicates zero.

			value			struggle			growth			confidence					
			Maths will be useful to me in my life's work.	Having a solid knowledge of maths helps me understand more complex topics in my field of study.	Maths develops good thinking skills that are necessary to succeed in any career.	Good mathematicians experience difficulties when solving problems.	Everyone makes mistakes at times when doing maths.	Struggle is a normal part of working on maths.	Maths can be learned by anyone.	If someone is not good at maths, there is nothing that can be done to change that.	People are either good at maths or they aren't.	I have less trouble learning maths than other subjects.	When I have difficulties with maths, I know I can handle them.	I have a mathematical mind.	I enjoy trying to solve new mathematical problems.	I find maths frightening.	I find maths confusing.
		item number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2018/19	week 1	% strongly agree	67.3	57.1	55.1	39.6	57.1	34.7	24.5	0.0	0.0	18.8	12.5	22.9	17.0	0.0	2.1
		% agree	32.7	42.9	36.7	39.6	40.8	59.2	49.0	2.0	18.4	56.3	64.6	66.7	61.7	4.2	4.2
		% neutral	0.0	0.0	6.1	14.6	0.0	6.1	16.3	8.2	22.4	22.9	20.8	10.4	17.0	12.5	31.3
		% disagree	0.0	0.0	2.0	6.3	2.0	0.0	10.2	61.2	44.9	2.1	2.1	0.0	4.3	66.7	52.1
		% strongly disagree	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.6	14.3	0.0	0.0	0.0	0.0	16.7	10.4
	week 23	% strongly agree	85.0	80.0	57.5	52.5	70.0	30.0	27.5	0.0	0.0	38.5	12.5	20.0	15.0	2.5	2.5
		% agree	12.5	20.0	42.5	40.0	27.5	57.5	47.5	2.5	10.0	51.3	67.5	70.0	52.5	10.0	2.5
		% neutral	2.5	0.0	0.0	5.0	0.0	10.0	15.0	7.5	32.5	10.3	17.5	10.0	22.5	10.0	25.0
		% disagree	0.0	0.0	0.0	2.5	2.5	2.5	7.5	67.5	40.0	0.0	2.5	0.0	5.0	62.5	60.0
		% strongly disagree	0.0	0.0	0.0	0.0	0.0	0.0	2.5	22.5	17.5	0.0	0.0	0.0	5.0	15.0	10.0
2023/24	week 1	% strongly agree	75.0	55.0	38.3	40.0	61.7	46.7	16.7	0.0	0.0	11.7	8.3	25.0	15.0	0.0	0.0
		% agree	23.3	45.0	50.0	43.3	36.7	50.0	58.3	1.7	6.7	65.0	70.0	56.7	61.7	8.3	16.7
		% neutral	1.7	0.0	10.0	10.0	1.7	1.7	18.3	10.0	26.7	11.7	18.3	16.7	23.3	28.3	45.0
		% disagree	0.0	0.0	1.7	6.7	0.0	1.7	5.0	56.7	53.3	11.7	1.7	1.7	0.0	48.3	35.0
		% strongly disagree	0.0	0.0	0.0	0.0	0.0	0.0	1.7	31.7	13.3	0.0	1.7	0.0	0.0	15.0	3.3
	week 23	% strongly agree	70.2	52.6	45.6	52.6	64.9	49.1	21.1	0.0	0.0	22.8	19.3	24.6	15.8	0.0	1.8
		% agree	29.8	47.4	45.6	42.1	33.3	43.9	52.6	0.0	21.1	50.9	56.1	57.9	54.4	10.5	22.8
		% neutral	0.0	0.0	5.3	5.3	1.8	7.0	15.8	14.0	29.8	14.0	12.3	17.5	22.8	19.3	29.8
		% disagree	0.0	0.0	1.8	0.0	0.0	0.0	10.5	70.2	35.1	8.8	10.5	0.0	7.0	50.9	38.6
		% strongly disagree	0.0	0.0	1.8	0.0	0.0	0.0	0.0	15.8	14.0	3.5	1.8	0.0	0.0	19.3	7.0

While students in both years were convinced of the value of mathematics at the beginning of their university career, that belief had strengthened by the end of the year, especially for the 2018/19 class. Under struggle, responses to item 4 showed notable changes over the year – both classes agreeing more strongly that good mathematicians experience difficulties when solving problems. For the 2018/19 class, beliefs regarding growth showed little change over the year. However, for the 2023/24 class, disagreement with the statement that people are either good at mathematics or they aren't had weakened by week 23, yet there remained strong disagreement with the suggestion that nothing could be done for those not good at mathematics. In 2023/24, beliefs regarding confidence showed little change by week 23. In 2018/19, by the end of the teaching phase, enjoyment in solving problems had declined slightly but students felt more comfortable learning mathematics compared to other subjects.

Self-efficacy was examined through items 16 – 20 which referred to fundamental procedures in engineering mathematics. These topics are all on the secondary-level curriculum (in the UK) but are reinforced during the first-year module in university. Students entering university in 2023/24 were a lot less confident in their abilities compared to those entering in 2018/19. This was particularly noticeable regarding calculus operations, especially integration and solving differential equations, and, to a lesser extent, regarding rearranging equations and formulae. In both years, students were much more confident in their abilities by week 23.

DISCUSSION

The mathematics learning beliefs questionnaire can be used to identify students whose beliefs may lead to a lack of persistence in mathematics (Kooken *et al.*, 2016). Students at the start of their degree programmes agreed particularly strongly with items associated with value indicating that they already had a strong appreciation of the importance of mathematics to their studies and career. This is important as students can then be expected to engage willingly and actively with the subject (Deci *et al.*, 1991). The results also showed a strong acceptance of struggle; this was especially the case for the 2023/24 students whose secondary education

had been disrupted during the covid-19 pandemic. This is also encouraging since students who understand that struggle is inherent in the study of mathematics, even for experts, will be more tolerant and persistent when facing difficulties (Kooken *et al*., 2016). Beliefs associated with a growth mindset were dominant across both classes and there was strong rejection of the notion that nothing can be done for those deemed not good at mathematics. A growth mindset is a valuable asset at the beginning of university as it should help perseverance.

Student confidence was generally high in both classes although there were some interesting differences between them. The 2023/24 class, while mainly disagreeing that mathematics was frightening, were less assured than their 2018/19 counterparts. Similarly, the modal response regarding whether mathematics was confusing was neutral in 2023/24 whereas the 2018/19 class mainly disagreed. This might be further evidence of an impact of the covid-19 pandemic on students' beliefs about mathematics. The 2023/24 class would have been approaching the end of their fourth year in secondary school when the pandemic was declared in March 2020. Students in the UK take the General Certificate of Secondary Education (GCSE) qualification during their fourth and fifth years of secondary school (aged 15 and 16). Assessment is mainly by examinations. Therefore, the class beginning university in 2023/24 would have experienced, over the course of the pandemic, online teaching, studying more independent of teachers, absence of the final GCSE examinations in summer 2021, and adjustments in the assessment at A-level in 2021/22. This substantial disruption at a crucial stage of their education may have influenced feelings of confusion and fright towards mathematics, although it is important to note that these views were held by only a small minority within the class.

Females more strongly believed in the value of mathematics to their work and understanding compared to males. Gender differences in responses regarding struggle were inconsistent over the two classes. Differences in male and female confidence were slight, although females seemed more strongly to enjoy trying to solve new problems. The results regarding confidence do not obviously concur with the established view that secondary-school girls have lower confidence in their mathematical ability than boys of the same age (Raabe & Block, 2024).

Some changes were evident over the teaching phase of the module. Students' appreciation of value increased, as did their belief that good mathematicians experience difficulties (struggle). For the 2023/24 class, there was little change in confidence over the year. Some increase in confidence was observed in 2018/19 and this was more prominent for the students of higher ability (grade A* at A-level). These results contrast with those of Code *et al*. (2016) who observed declines across a range of categories (including confidence, persistence, mindset, interest) over an academic year for first-year students studying calculus. This was described as a move away from "expert-like orientations" to mathematics over the duration of the academic year. The authors speculated that this was related to the nature of first-year mathematics modules, with their emphasis on procedural repetition and solution of low-level, inauthentic problems. Code *et al*. (2016) advocated the development of mathematical thinking and more emphasis on deeper approaches to learning at undergraduate level. The findings of the current study therefore give encouragement that the teaching and learning methods, and including problems with engineering applications, had a positive impact on students' beliefs.

The self-efficacy ratings in week 1 depended on prior mathematical grade. While the 2023/24 students were generally less confident at the start, particularly in differentiation and integration, their level of confidence by the end of the teaching phase was largely similar to that of the 2018/19 class, although still lagging in integration. An exception concerned the A-level grade B students of 2023/24 who expressed confidence similar to that of the 2018/19 students in

algebraic topics (rearranging equations, partial fractions) at the start of the module. It isn't clear whether this was justified or a misplaced overconfidence in abilities in these areas.

The relatively high levels of self-efficacy are important given the moderate, positive correlation between self-efficacy and performance noted elsewhere (Hackett & Betz, 1989). Moreover, significant positive correlations have been found between self-efficacy and attitudes towards mathematics, including confidence, usefulness of mathematics, and effectance motivation (Hackett & Betz, 1989). The improvements in self-efficacy reported over the duration of the module may be related to the weekly, structured practice, frequent opportunities for peer review, and maintaining positive feelings regarding value of mathematics in studies and career. Certainly the self-efficacy results will have been influenced by the context of the survey (module and stage of education) (Brennan & Hugo, 2017).

Further analysis is needed to investigate statistical significance. Other limitations include the questionnaire responses being anonymous; this precludes tracking individuals to examine changes in beliefs over time and correlation with performance. Relating beliefs to the teaching and assessment methods could be considered more deeply through interviews. Finally, it would be of interest to study how the results would differ for students from other disciplines.

CONCLUSIONS

The first-year engineering students showed beliefs associated with mathematical resilience. While confidence was generally high, the class whose secondary education was disrupted by the covid-19 pandemic was less assured than the 2018/19 class. Self-efficacy was relatively high and increased over the year. There is some evidence that the teaching and assessment methods had a positive impact on students' learning beliefs.

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BIOGRAPHICAL INFORMATION

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SELF-PACED ASSESSMENT APPROACH COMBINING ROBUSTNESS AGAINST AND LEARNING WITH GENERATIVE AI

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ABSTRACT

The rise of Generative AI and its heavy usage by students have caused many educators to return to traditional supervised exams, even if this has potential pedagogical disadvantages. It is important to find forms of assessment which avoid the disadvantages of the exam, yet are robust against AI cheating, and possibly also facilitate student learning with AI where this is appropriate. The course IT1001 at the NTNU uses self-paced mastery learning combining frequent tests and incremental project work. This may be a course design enabling robustness against AI and constructive usage of AI, as the supervised tests work as a gatekeeper against AI cheating, while the project allows students to creatively explore AI usage. However, the AI usage as so far been rather ad hoc, with limited learning resources. This paper seeks to analyze whether students consider AI a useful learning tool in the course, and what tasks they have been using AI for. Results indicate that they consider AI as a useful tool, but less so in 2025 than in 2024, and not outcompeting the learning resources provided by the teacher. AI has been used for several different tasks related to programming, but not so much for massive outsourcing of work in terms of code generation. Rather, the most frequent types of usage were error finding and idea generation. The paper concludes by outlining how the coverage of AI can be improved for the next run of the course.

KEYWORDS

Programming, Mastery learning, Generative AI, Project-based learning, STEM teacher students, Standards: 2-5, 7, 8, 11.

INTRODUCTION

The rapid increase in the availability and capabilities of Generative AI during the last couple of years has caused many university educators to abandon unsupervised forms of assessment such as take-home exams and coursework, due to fears that delivered work does not reflect the students' own competence (Ward et al., 2024). Unfortunately, this may lead towards less innovative forms of assessment, such as the traditional unseen, supervised end-of-course written exam. While some learning outcomes may be appropriately assessed by such exams, empirical research has indicated that the exam has many disadvantages in terms of student anxiety, superficial cramming, and bias towards certain learning outcomes, often having an inhibiting effect on learning (Boud, 2012; French et al., 2024). Hence, the challenge is to find forms of assessment which are, on the one hand, robust against cheating by generative AI, while on the other hand avoiding the disadvantages of the traditional end-of-course exam. Moreover, students must also learn to use AI constructively as that may be highly relevant for their future professional practice (Khan et al., 2025).

At the NTNU, the course IT1001, introductory programming for first semester STEM teacher students, is run according to a self-paced mastery learning model. Instead of an end-of-course exam, it has a series of module tests during the semester – and these are supervised to be as secure as an exam. Self-pacing and frequent lower-stakes tests has been shown to improve student agency and reduce anxiety compared to one high-stakes exam (Bell, 2023; Emeka et al., 2023). In parallel with the tests, students are doing an individual programming project throughout the semester. Here, they are allowed to use AI, but so far, the degree of AI usage is up to the student, with limited learning resources provided. For the next run of the course, learning outcomes have been rewritten to aim for a more systematic approach to AI usage. To have a better idea of what learning resources should be provided, it is interesting to know how students are using AI, whether there are other potential uses that they miss, and what opinions they have about AI usage. Our research questions for this paper are as follows:

RQ1. To what extent do the students consider Generative AI a useful tool in the course?

RQ2. How have the students been using Generative AI on the course?

Although the research is related to one specific course, we believe that many educators are facing similar challenges related to understanding student AI usage, encouraging constructive usage and discouraging usage that inhibits learning.

The rest of this paper is structured as follows: The second section goes through background and related work. The third section discusses the research method. The fourth section presents findings, and the fifth section provides a discussion of the findings and ideas for how AI can be addressed more constructively and systematically in the project work.

BACKGROUND AND RELATED WORK

Background: Mastery Learning

The general idea of mastery learning, as thought out by pioneers Keller (1968) and Bloom (1968), is that not all students learn at the same pace. By dividing a course into a sequence of modules, where each student must master one module before continuing to the next, different paces can be accommodated, leading to *self-paced* (i.e. student-paced) approaches, as opposed to teacher-paced courses where all students must proceed at the same pace to keep up with a series of lectures or assignment deadlines. Mastery learning was somewhat

popular in the 1970's and had promising empirical results yet gradually slipped into obscurity (Eyre, 2007). However, IT can mitigate some of the challenges with mastery-learning, such as the labor-intensive testing approach, and in recent years there has been increased use of mastery-learning in introductory programming (Alvarez et al., 2025), as well as in other engineering subjects (Pérez & Verdín, 2023).

The course design

The course IT1001 at the NTNU is programming in Python for first semester STEM teacher students. It is run every autumn and has 7.5 ECTS credits. The course uses self-paced mastery learning inspired by Keller's (1968). Personalized System of Instruction. There are 9 modules, as shown in Figure 1, and these must be taken in sequence. To take an A the student needs to pass all 9 modules, while a student who is satisfied with the lowest passing grade E only needs the first 5.



Figure 42. The modular design of IT1001

To take a module, a student needs to pass a test for the module (90% threshold) and deliver an approved increment of an individual programming project. The design of the course has been presented previously in (Sindre & Hansen, 2024, 2025) – analyzing in more detail the experiences from the first and second offerings of the course, and interested readers may check those sources to find out more details about the course design. The novelty of this paper is inclusion of experiences from the third run, and a special focus on the students' AI usage, which has not been analyzed in previous publications. The experiences from the third run (autumn 2025) resembled the second run. As shown in Figure 2, a clear majority of students were satisfied or very satisfied and thought that the course was better than other courses they took in parallel.

Related research

There have been several recent publications investigating students' use of generative AI in introductory programming courses. Amoozadeh et al. (2024) made a case study observing how students used GenAI on programming assignments, finding that about 1/3 simply submitted the entire task description and copy-pasted the solution without much critical reflection, which inhibited their learning. Prather et al. (2024) found that AI usage on assignment tasks was widening the gap – clever students were able to become more effective by using AI, while weaker students ended up learning less with AI than they might have done without it. Xue et al. (2024) similarly looked at AI usage in programming assignments, finding that it did not have a significant effect on learning outcomes in terms of post-test performance, but that students using GenAI tended to stop using other resources (like, e.g., StackOverflow). Erez et al. (2025) investigated students' views about GenAI, finding that they appreciated the efficiency but were afraid of becoming dependent on such tools.

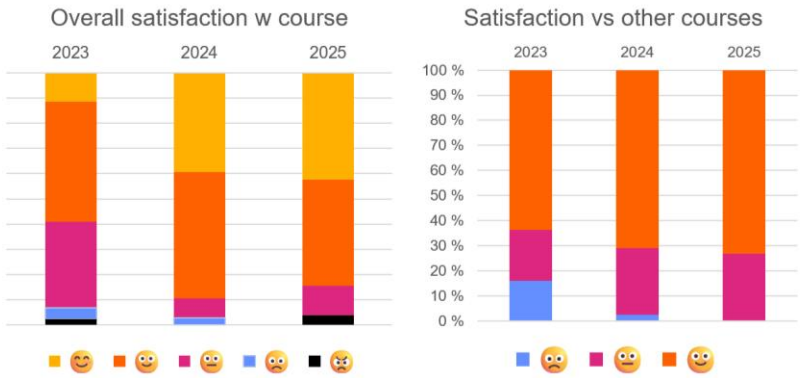


Figure 43. Overall satisfaction (left, 5-point Likert scale) and versus other courses (right, 3-point scale: better/same/worse) for IT1001 through years 2023-2025.

Specifically in the CDIO context, (Rytilahti & Kaila, 2024) investigate how easy it is to cheat at programming assignments with AI, finding that it successfully solves most introductory-level tasks. Medhioub and Sifi (2024) propose a way to integrate AI in project-based learning according to CDIO principles, in particular suggesting iterative delivery and dynamic task shifts in the project team to promote learning in the presence of AI. Karoui and Bettaieb (2024) investigate student perceptions on how AI usage affected their time efforts and learning. Saeidlou et al. (Saeidlou et al., 2024) discuss how GenAI is not just a threat but also a new learning opportunity in CDIO projects. By making students more effective, they can achieve shorter project cycles, possibly getting through all four steps C-D-I-O where they would previously have managed fewer. Nikolic et al. (2025) provide a CDIO-based framework with guidelines for integrating generative AI into project-based courses.

RESEARCH METHOD

The research questions are investigated through questionnaire responses, as our student interviews did not focus specifically on AI, and there were no log data collected about AI usage since any such usage took place outside the LMS. In all three runs of the course, the questionnaire survey was done in week 11 of the 14-week semester. Performed in the compulsory attendance seminar, the survey achieved a high response rate: 2023 N=44 (92%); 2024 N=38 (95%); 2025 N=26 (90%). The questionnaire contained 47 questions in total. In this paper we focus specifically on those related to AI. In 2023, there were no questions directly about AI, so the only opportunity for the students to say something about it would be in a free-text question whether the student used any other learning resources than those provided by the teacher. In the surveys of 2024 and 2025, however, AI was specifically addressed in 3 questions:

- How useful was AI as a learning resource? (5-point scale, from “Not at all” to “Very useful”)
- To the extent that you used AI, which tools did you use, and how? (free text).
- Which learning resources do you use when working on the project? (multiple selection, where AI was one of several options that could be checked).

The Likert scale and checkbox questions were analyzed automatically by descriptive statistics, while the responses to the free text question were analyzed manually by one of the researchers, counting occurrences of mentions of various tools and usages of AI and coding these to typical tasks performed by students in the course.

The research project and data collection has been approved by SIKT (Norwegian Agency for Shared Services in Education and Research).

RESULTS

RQ1. Extent and perceived usefulness of AI usage

In 2023, 22 of 44 respondents (50%) acknowledged AI usage in the free-text question about using resources beyond those provided by the teacher. For 2024 and 2025, the checkboxes for usage of various learning resources in the programming project gave the results shown in Figure 3. As the diagram shows, AI was the most used resource of those asked both in ’24 and ’25. Nevertheless, the percentage of respondents who reported AI usage in their project dropped from 83% to 62%, getting closer to the 50% in the free-text field in the 2023 survey.

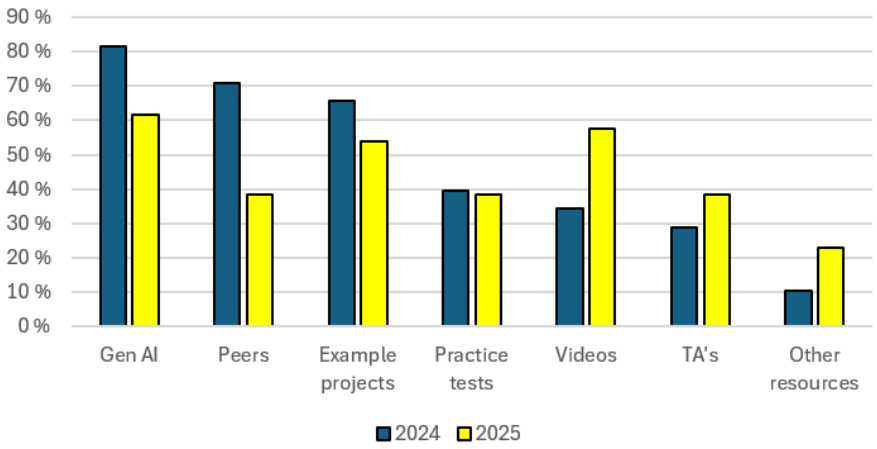


Figure 3. Student usage of resources in the project, by % of respondents in 2024 and 2025

While the checkbox question whose results are shown in Figure 3 was asked specifically in the context of the project, Likert scale questions on the usefulness of various learning resources were asked for the whole coursee. These responses are synthesized in Figure 4, with learning resources ranked by popularity (average score on the 5-point Likert scale). Both in 2024 and 2025, the formative practice tests came out on top – unsurprisingly, since they drew random tasks from the same question banks as the summative tests, thus providing a good opportunity to test preparation through quick feedback. Generative AI came second in 2024 (bar 3 from the top), with an average score of 4.08. However, in 2025 (bar 6 from the top), students seem to have considered it less useful, as its average score fell to 3.58 and it dropped below the teacher’s screencast videos in terms of student-reported usefulness.

As can be seen in Figure 4, GenAI was still considered more useful than the Example Projects and the Jupyter Notebooks. Both these were resources made by the teacher (like the Practice tests and Videos). The example projects illustrated how an individual programming project could be extended increment by increment in accordance with the requirements for modules I, H, … E, …, cf. Figure 1. The Jupyter Notebooks illustrated with code examples and explanatory text the purpose and workings of various programming concepts in Python, with opportunities for the students to modify the code to try out different scenarios. However, the difference up to AI decreased, as these two other resources improved from ‘24 to ’25, while AI received somewhat less enthusiasm.

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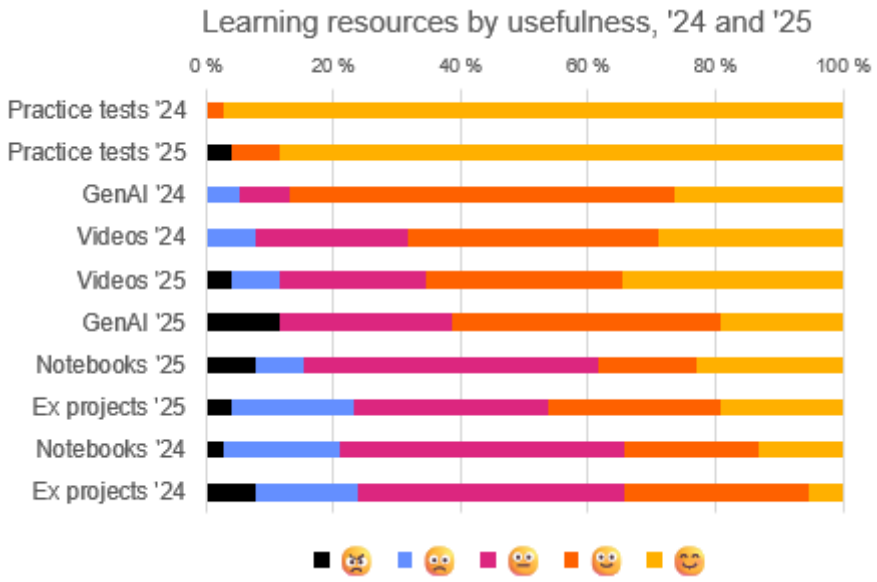


Figure 4. Students' rating for learning resources in the course, from "not at all useful" (black), through "low" (blue), "neutral" (red), "high" (orange) usefulness, to "very useful" (yellow), showing percentage distributions of answer options.

RQ2. What tasks AI was used for

The free text responses about AI from all three years were analyzed to see if students mentioned what tasks they had used AI for, and this was coded in some broad categories:

- **Code comprehension**: The student struggles to understand some code, thus asking AI for a step-by-step explanation of what the code does.
- **Concept explanation**: The student asks AI for a general explanation of a certain concept, without reference to specific code (e.g., how does a Python for-loop work?).
- **Code generation**: The student asks AI to generate a piece of code according to requirements given in the prompt.
- **Code improvement**: The student has written some code which may work but is messy and asks AI to improve its style or structure, while maintaining the wanted output.
- **Data/content generation:** The student uses AI for generating data that the program will use, e.g., a file containing synthetic data for a Science subject simulator or a collection of multiple-choice questions for a quiz program.
- **Error finding**: The student's project code does not work as expected, and the student struggles to figure out why – and then feeds the code into GenAI to get an explanation where the error is, potentially also a suggested fix.
- **Project requirement check / explanation**: The student asks AI to explain in more detail the requirements that the teacher has given for a project increment, or to check if the code that the student has made so far satisfies these requirements.
- **Idea generation**: The student is lost for ideas on how to proceed, e.g., what new features to add in their project, and asks AI for suggestions.
- **Discipline knowledge**: Rather than needing help with code, the student needs to refresh relevant knowledge from the scientific discipline that the program is about. E.g., the student needs to check some Physics formula for planetary orbits.

- **Test task explanation**: The student struggles with understanding a practice test task, e.g. why is a certain answer right or wrong, and asks AI for an explanation.
- **Unspecified**: The free-text response acknowledges AI usage, but does not explain what it was used for,

The result of the coding, indicating how many responses fell in various categories, is shown in Table 1. The sum of the usage counts exceeds the number of respondents because many mentioned several different purposes that they had used AI for.

Table 21. Student-reported usage of AI

	2023	2024	2025	Total
Respondents (N=…)	44	38	29	111
AI users (%)	22 (50%)	34 (89%)	21 (81%)	78
Various usages of AI				
Error finding	8	18	9	35
Idea generation	5	18	5	28
Test task explanation	3	7	6	16
Code generation	2	3	5	10
Code improvement	3	3	2	8
Code comprehension	2	2	1	5
Prog concept explanation	1	1	3	5
Requirement check / explan.	1	4	0	5
Unspecified	3	1	0	4
Data / content generation	0	1	1	2
Discipline knowledge	0	1	0	1

DISCUSSION AND CONCLUSION

Interpretation of findings, answer to research questions

Our RQ1 was “To what extent do the students consider Generative AI a useful tool in the course?”. Over the three years, 70% of questionnaire respondents acknowledge use of AI, with a rising trend from ’23 to ’24, then a drop from ’24 to ’25. Especially for ’23, the AI usage may be underreported, since it could only be mentioned in a free-text field that some respondents will have left blank, whereas the ’24 and ’25 questionnaire provided a simple checkbox whether AI had been used or not. However, it is not at all surprising that AI usage would increase from ’23 to ’24, since there was increasing awareness in society during 23/24 about the capabilities of generative AI. What is more surprising is the apparent drop in AI usage from ’24 to ’25 (cf. Figure 3), which is also consistent with less positive views on the utility of AI, both in absolute terms and relative to some of the teacher-provided learning resources (cf. Figure 4). A possible explanation might be that the students starting in 2024 were still on the initial optimism wave of generative AI, impressed with the wonders this technology could achieve, while the freshmen of 2025 had become more skeptical. For instance, in 2024 our university did not have a systematic approach about AI to the newly enrolled students, whereas in 2025, study program leaders were equipped with a 40+ page slide set about AI, for presentation sometime during the intro week. These slides both explained some possible uses of AI but also warned against dangers, such as GDPR and copyright issues, hallucinations resulting in low quality of delivered work, poor learning and weak study results. Moreover, there had been some recent scandals in Norway related to

uncritical AI usage, such as one in Tromsø municipality which received a lot of national media coverage in March 2025 (Gerrard, 2025).

Our RQ2 was “How have the students been using Generative AI on the course?” The analysis of the free-text answers indicated that the two most popular usages were error finding in project code and idea generation for the project, and in third place explanations of tasks that the students encountered in the practice tests. Code generation was only in fourth place, reported by approximately 10% of the respondents. This is a positive finding, since it would have been concerning if a lot of students just let AI generate all or most of the code in their project, hardly learning to write code themselves, which was a key learning goal of the course.

Threats to validity

One threat to validity is the fact that the questionnaire was conducted with three weeks left of the semester. It will thus not account for the students’ behavior and experiences through the full course. Specifically for our research questions, some more students may have used AI in the last three weeks who did not use it before. Another threat is related to the free text responses. Some usages of AI may have been underreported by the students, and it is also a weakness that only one researcher coded the free-text responses – two would have been better to mitigate bias and estimate reliability. The comparison is also complicated by the fact that the 2023 survey did not ask explicitly about AI – there was less focus on AI that year. As for generalizability, it is a weakness that it is just one course with few students. However, fairly similar courses have been used elsewhere, for instance (Toti et al., 2023) with 300 students.

Conclusion and further work

Having competence on pros and cons of using AI is especially relevant for teacher students. As future high school teachers, they must leverage opportunities that AI gives them for making their teaching more effective, as well as relate to their students’ usage of AI – for better and for worse – to give them pedagogically sound advice on do’s and don’ts. The course IT1001 is already fairly robust against AI cheating due to the supervised tests, but AI usage in the project has been rather ad hoc. For the next iteration of the course (autumn 2026) we will add learning resources and project requirements to ensure a more systematic approach to AI usage, both in conception, design, and implementation of the individual programming projects. The guidelines provided in (Nikolic et al., 2025) will certainly be useful for this purpose. On the one hand, it may be seen as particularly relevant to make learning resources for using AI on tasks that came high in the list in Table 1, such as error finding and idea generation. However, it may be equally relevant to make learning resources for tasks where few students have reported AI usage so far, such as data/content generation, disciplinary knowledge (e.g., Physics, Chemistry), and pedagogical knowledge (e.g., if a student is making a quiz program, asking AI for guidelines on “What are guidelines for writing good multiple-choice questions?”) These are tasks that lie outside the key learning goals of IT1001 (e.g., being able to understand and make code), and by offloading such other tasks, the student may be able to concentrate more on the coding challenges. Hence, more systematic use of AI in the projects may enable students to develop cooler and more inspiring software products, possibly to learn more with AI than they might have done without it.

ACKNOWLEDGEMENTS

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BIOGRAPHICAL INFORMATION

Guttorm Sindre holds MSc and PhD degrees in Computer Science (1987, 1990). He has been a full professor at NTNU since 2003. He was the leader of the Excited Centre for Excellent IT Education from 2016-21. Sindre has teaching experience across a wide range of IT topics, from CS1 to PhD level research courses. His research has focused on computing education, in particular didactics of introductory programming, self-paced mastery learning, automated question genres, project-based learning, and assessment integrity.

Gabrielle Hansen is a senior researcher in the Department of Computer Science. She holds an MSc in Psychology and a PhD degree in Pedagogy with a thesis focusing on the use of feedback in higher education. She has been involved as a researcher in the Excited centre, and in the SEED Centre for Science and Engineering Education at the NTNU, working on educational improvement interventions and the coaching of teachers during such processes. She is currently working full-time for SEED, leading a project on flexible higher education.

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STEERING TOGETHER: STUDENT AND STAFF PERSPECTIVES ON AUTONOMY IN FINAL YEAR PROJECTS

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ABSTRACT

Final year projects (FYPs) form an integral part of most undergraduate engineering degrees, aiming to assess a broad range of skills and qualities, many of which will have been developed as students have progressed through their university journey. While there is a consistent structure of assessment, allocation and delivery, these capstone modules have in-built flexibility. Although many students select their project from a pool developed by academic staff, several institutions offer a self-proposal process whereby students develop their own project. The authors were keen to explore why self-proposal has such a low uptake within their department, and whether this was common across other institutions. This paper offers a broad overview of a research project aiming to gain perspectives from staff and students, employing data analysis, surveys and focus groups. There were notable findings from the study, demonstrating that students who self-propose their project are likely to achieve grades up to 8% above average. Additionally, several key benefits and challenges, identified by students and staff are discussed, with students from different institutions facing similar challenges and barriers to those from the author's institution. The study concludes that increased support for students choosing to self-propose would extremely beneficial, alongside work to mitigate some of the potential issues raised by both staff and students to ensure success. This paper forms the foundation of further publications, which are planned for the near future, offering a more detailed analysis and discussion of the results.

KEYWORDS

PBL, Project Based Learning, Final Year Projects, Student Partnership, Co-Design, Standards: 5, 7, 8, 11

INTRODUCTION

Final Year Projects (FYPs) have been a prominent part of engineering undergraduate degree programmes for well over fifty years (Kolmos, 1996). Typically, an individual major project, coalesces the skills and knowledge developed throughout an engineering degree programme and equips students as they begin their careers. They have long been cited as a key aspect of undergraduate engineering courses (Blicblau, 2004; Hurst et al., 1993; Ku & Goh, 2010; Venturi, 2025), representing the last stage of training before entering the job market (Venturi, 2025). They grant students the opportunity to develop a wide range of competencies including technical, interpersonal, organisational, planning, analytical and risk assessment skills, alongside interprofessional competence and ethical sensitivity (Picard et al., 2022). Although projects provide a multitude of benefits for students, they can prove challenging from an institutional point of view, and many administrative hurdles are associated with facilitation. These include pairing project fields and supervisors with students and ensuring that project scopes and student workloads are fair and equal across cohorts. Assessing projects can also be complex, as it involves ensuring students are credited for their efforts while maintaining assessment integrity and a consistent approach to appraisal.

Within the School of Mechanical and Aerospace Engineering at the authors' institution, students beginning their FYP have a number of options. Most students select their project from a list of projects designed by academic staff with project objectives and descriptions provided to assist students considering projects. Some of these projects are industrially backed, developed in association with an external company, based on a real-world problem. Students rank a number of options in order of their preference, and a minimum-cost maximum-flow algorithm assigns projects to students. In the years 2020-2021, 2021-2022 and 2022-2023, 94%, 97% and 98% of students respectively were allocated a project from their top 6 preferences. Students also have the option to design and propose their own project, but this is a largely underutilised option. Students may also embark on a project aligning with the formula student programme. Between 2020-2024, a total of 11 students chose to propose their own project, with the remaining students selecting from the pre-defined list (approximately 200 students per year). This is despite research suggesting extensive benefits to students and students who self-propose with these students tending to achieve higher grades. This low uptake must be explored, alongside unpacking the benefits for students and staff, and the challenges they encounter throughout. The overarching research question for the study is: How do students and staff perceive the benefits and challenges of final-year projects designed by staff, and what are their views on the potential advantages and drawbacks of student-proposed projects?

METHODOLOGY

Several approaches were employed to begin addressing the research question. Ethical approval was sought from the Faculty Research Ethics Committee to conduct staff and student surveys, student focus groups, and staff workshops. Following approval, invitations to participate in various aspects of the study were distributed by email to staff and students within the Engineering and Physical Sciences Faculty at the author's institution. Participants from other UK institutions were invited through the UK and Ireland Engineering Education Research Network mailing list, alongside contacts of the Author's department. Data analysis was also conducted, utilising FYP data held within the department. Although full data analysis is still underway, this paper will give an overview of some key findings from the various methods, and further publications containing full analysis will follow.

RESULTS AND DISCUSSION

Data analysis

Using data relating to final year projects held by the author's department, analysis was conducted to identify any trends of note. There were several interesting findings, specifically around the correlation of project selection to project outcome. Figure 44 compares both self-proposed projects and formula student-based projects to the overall average project outcome for their respective academic year. The graph clearly shows for both the 2022/2023 and 2023/2024 academic year that students who embark on a project they have proposed themselves, or one related to the formula student programme will attain a project mark up to 8% higher than those who select their project from a list. Formula student project data is highlighted, as students are involved in the developmental process of these projects. It's difficult to conclude whether these higher results occur as a result of students self-proposing, or if the population who chose to self-propose would have attained a high mark regardless. Additionally, as only a small number of students currently self-propose, this data gives only an indication of a trend that requires further measurement, with larger samples of self-proposing students and ongoing annual data being added. Figure 45 compares mean project marks from students enrolled on the Bachelor's (BEng) programme to those on the integrated Master's (MEng) programme. As should be expected, master's students year-on year perform around 10-15% better than bachelors. A mean line for each set of results is also shown and demonstrates little deviation (<2.8%) from the average year on year. Marks for BEng students in 2020-2021 and 2021-2022 are lower (3.2% and 1.0% respectively), likely due to the impact of the Covid-19 pandemic. Both results are provided to show a small sample of the output from the analysis, full analysis and discussion of all aspects of the data is beyond the scope of this paper.

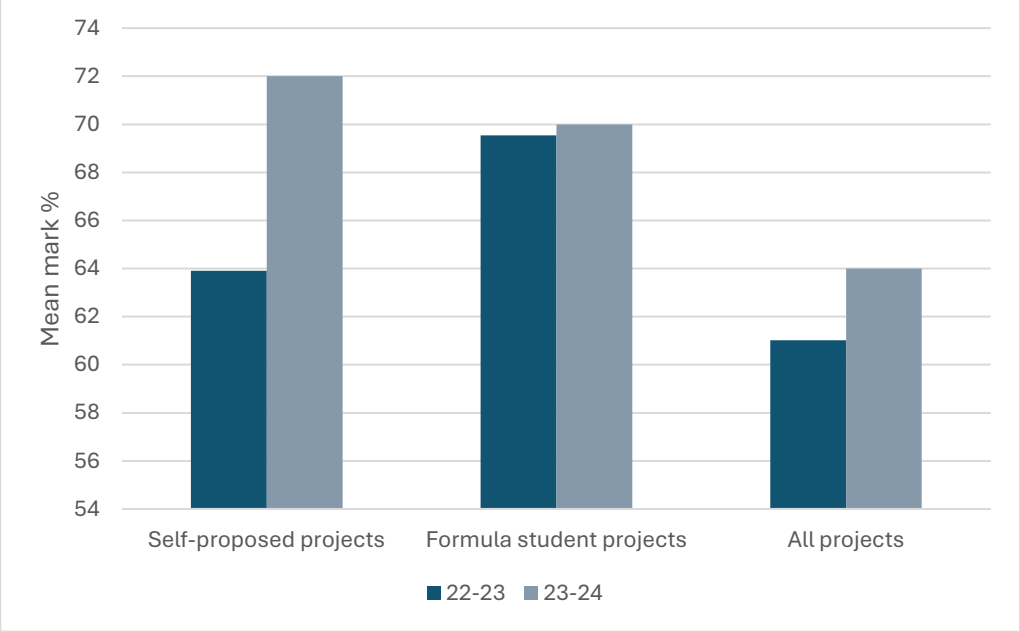


Figure 44: Project selection vs Mean student outcome

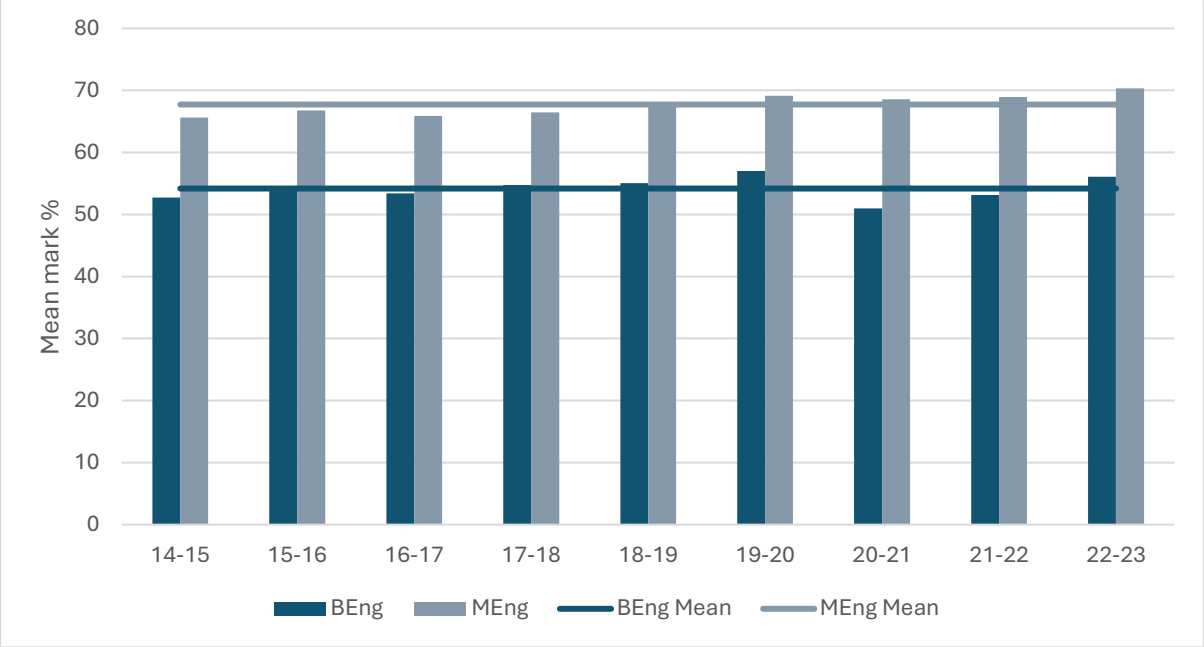


Figure 45: Student pathway vs Mean student outcome

Surveys

Surveys were created to gather preliminary data from staff. The survey gathered data about each participant and their unique perspective. It asked questions relating to FYPs, for example how projects are assessed, the training students are provided with prior to beginning, and how they feel giving students increased freedom within project creation would influence their outcome. 20 responses were received, representing an approximate 27% response from invited participants. Table 22 outlines some key benefits identified by staff in open-ended question responses. For ease, these have been grouped by benefit themes, with direct quotes provided. Figure 46 illustrates the barriers identified by staff, with workloads, time and consistency the most common themes discussed. As before, these results provide a broad overview of some key outcomes from this research package, and a detailed analysis is beyond the scope of this paper.

Table 22: Benefits of introducing more optionality and co-design to Final Year Projects as discussed by staff in surveys

Benefits	Quotations
Higher level of engagement, interest and enthusiasm	“Should theoretically increase engagement with the project, enthusiasm and ownership of the deliverables”
	“Better buy in”
	“Students who are allowed optionality and co-design are more enthusiastic, more interested, and more vested in their project”

	“Students being more engaged and attentive to their final year project, as the determined topic may be of greater interest to them”
	“[More] beneficial/attractive for the students”
	“Engagement and enthusiasm would increase, [Allowing students to display] their potential and understanding more clearly”
	“More engagement from students”
	“Optionality could increase student engagement / motivation.”
Provides students with ownership	“There is also a sense of empowerment by the student. Finally, the projects allow more creativity”
	“Anecdotally, when there is such choice there is also additional ownership, ultimately leading to better outcomes”
	“Self-proposed or co-designed projects may run better if the student believes they have more autonomy.”
More flexibility to choose something they’re interested in	“more options are always better to give the flexibility to the student to choose a project that they interested in”
	“Students can choose the direction/application they are most passionate about”
	“[Allows] students with specific interests and creativity to pursue them”
	“[Allows students to] specialise. Students are given considerable flexibility by each supervisor within the project itself when conducting the research”
	“[There] is certainly some merit to some form of choice- could give some great level of autonomy and might help self-motivate”
Benefits for supervisors	“Meaningful engagement with the supervisor goes up significantly”
	“Take[s] pressure off academics to come up with project titles.”



Figure 46: Barriers of introducing more optionality and co-design to Final Year Projects as discussed by staff in surveys

Focus groups

To gather insight from students, focus groups were selected. Students from the author's faculty were invited to participate, and invitations were distributed to external institutions via contacts of the department. 13 students were recruited, some who self-proposed their project and some who selected their project from a list. The outline was designed using open-ended questions, with the aim of sparking lively discussion within groups. At the beginning of each group, an explanation was given to provide some context and outline some basic guidelines for participation, with an emphasis on the need for confidentiality in line with the ethics protocol and explaining the planned output from the study. Following the introduction, students were asked to introduce themselves, explaining their pathway and engineering discipline before giving an overview of their final year project. 13 students participated in focus groups at which point the research team were satisfied that saturation occurred as new themes were no longer emerging from the data (Hennink & Kaiser, 2022). Discussions with students were transcribed, then independently analysed by 2 members of the team to identify the key themes raised, Figure 47. Table 23 shows the sub-themes or coding for each theme. Both figures show the foundation for a more detailed analysis, which will be outlined in a subsequent journal paper.

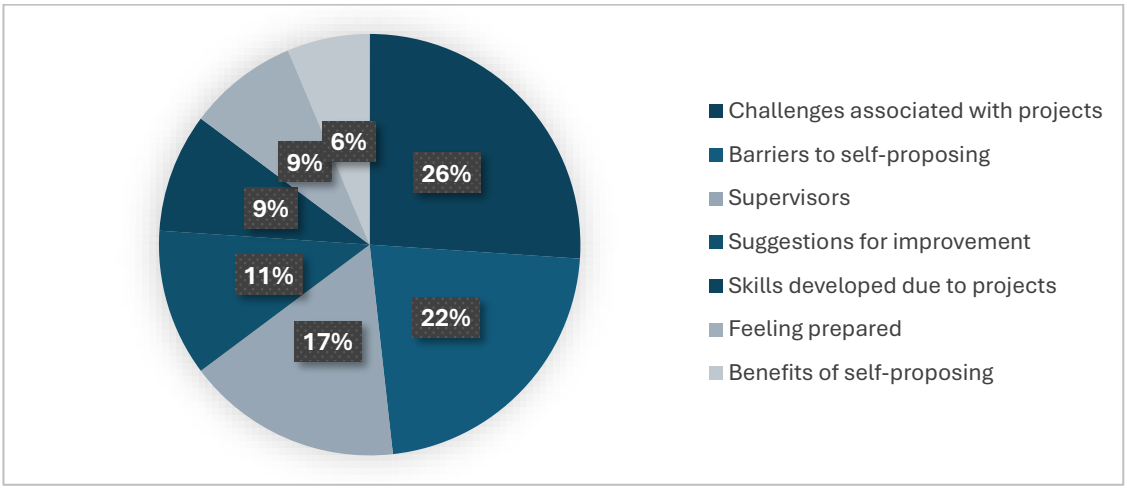


Figure 47: Distribution of student comments within analysis themes

Table 23: Themes identified within student focus groups

Theme	Sub-theme
Challenges associated with projects	Lack of technical skills, lack of transferable skills, literature review, online learning, project administration, workload
Skills developed due to projects	Technical skills, transferrable skills, useful project output
Suggestions for improvement	Earlier teaching, emulate research group/peer support, opportunities for conversations with staff
Barriers to self-proposing	Academic staff, easier/safer to select from a list, getting started, lack of knowledge, lack of passions, risk, time, unguided
Benefits of self-proposing	Alignment with career plan, alignment with interests, choosing supervisor
Supervisors	Expertise, negative experience, positive experience, project success is dependent on supervisor, relationship/familiarity with research/supervisors
Feeling prepared	Placement, prior learning, project support structure

CONCLUSIONS, LIMITATIONS AND FUTURE RESEARCH

This paper provides a broad overview of results to date, highlighting the attitudes of staff and students towards self-proposed projects. A number of methods were employed to gather insight from these perspectives. Both staff and students clearly understand the benefits self-proposal could bring, noting that student motivation will likely increase, as self-proposed projects will be based on student interests. Additionally, the process offers students experience of every aspect of running a project, from scoping, feasibility and seeing it through to completion. This gives students additional freedom and ownership of their project.

Key takeaways include:

Data analysis

The data analysis process, in the early stages of the project, identified that students who self-propose their project perform well above average when compared against students selecting from a list.

Survey

The survey unpacked a wide variety of benefits from the perspective of staff, with many noting the likely increase in interest and motivation from students. The surveys also identified

challenges to be expected throughout, namely expected staff workload and lack of available time for staff and students, which will require mitigation moving forward.

Focus groups

The survey responses fed into the design of focus groups with students, shaping questions around the benefits and barriers from student perspectives. Many students anticipated similar benefits to those identified by staff, with students recognising the benefits of shaping a project around their career plan, and therefore boosting their CV.

Limitations

As noted previously, within the data analysis process, only a small number of students self-proposed, and so comparison with average marks would be more definitive with a larger sample size. For the same reason, a low proportion of focus group participants were students who self-proposed, and, again, additional perspectives from these students would provide richer insight. Further analysis is also required to establish whether elevated marks from self-proposed projects are due to higher performing students choosing to self-propose, or a direct result of project selection.

Future work

Despite a diverse population, the study demonstrates consistent outcomes, with numerous benefits available to both staff and students, alongside identifying some barriers to be expected with implementation. Work on a number of journal paper publications, featuring more detailed analysis of the research to date is underway. These will include further discussion of the challenges, and suggestions for mitigation.

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INTEGRATING ARTIFICIAL INTELLIGENCE INTO ENGINEERING EDUCATION: A CDIO-ALIGNED INSTRUCTIONAL DESIGN APPROACH

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ABSTRACT

Artificial Intelligence (AI) has emerged as a transformative technology in engineering education; however, its pedagogical value depends on structured integration within established educational frameworks. This study investigates the impact of AI-supported instruction on student academic achievement when designed and implemented in alignment with the CDIO (Conceive-Design-Implement-Operate) framework. A quasi-experimental research design was employed in an undergraduate engineering course in Digital Logic. The experimental group participated in AI-supported, CDIO-aligned learning activities emphasizing active learning and integrated learning experiences, while the control group received traditional instruction. Student achievement was measured using pre- and post-tests, and data were analyzed using analysis of covariance (ANCOVA) and effect size calculations. The results demonstrate a statistically significant improvement in learning outcomes for students exposed to AI-supported instruction. The findings provide empirical evidence that AI, when embedded within CDIO-aligned pedagogy, enhances student achievement and supports evidence-based curriculum innovation in engineering education. Specifically, the experimental group achieved a mean post-test score of 82.60 compared to 77.31 in the control group, and ANCOVA results showed a statistically significant difference ($F(1,133)=22.47$, $p<.001$).

KEYWORDS

Artificial Intelligence, Engineering Education, Active Learning, Student Achievement, CDIO Standards 2, 5, 7-8, 11-12

INTRODUCTION

Engineering education is undergoing rapid transformation due to advances in digital technologies and artificial intelligence. Contemporary engineers are expected not only to master disciplinary knowledge but also to apply analytical reasoning, problem-solving, and adaptive skills in complex, technology-rich environments. Despite the efficiency of lecture-based instruction in conveying concrete knowledge, it often fails to cultivate active learning habits or higher-order competencies (Fan et al., 2025). This aligns with the "logical chain" theory in engineering education, which posits that Learning Behaviors drive Competence Development, which in turn results in Academic Achievement (Prince, 2004). However, the impact of AI remains a subject of ongoing academic debate. While GenAI has been used to enhance learning efficiency, initiative, and creativity, some scholars caution against the potential "competence paradox." Castillo and Saavedra (2024) argue that students in AI-assisted environments may develop proficiency in data analytics but lack the "experiential scaffolding" required to navigate novel, real-world ambiguities. Conversely, Chiang et al. (2024) found that virtual and online learning environments can actually foster superior problem-solving skills compared to face-to-face settings. They attribute this effect to increased opportunities for self-directed exploration, which builds students' confidence and autonomy.

As a result, engineering education institutions are increasingly exploring AI-supported instructional approaches to enhance learning effectiveness. The CDIO framework provides a comprehensive structure for curriculum design, teaching, learning, and assessment in engineering education. CDIO emphasizes the education of engineers who can conceive, design, implement, and operate complex engineering systems in real-world contexts. Within this framework, learning experiences must be active, integrated, outcome-based, and continuously evaluated. Despite growing interest in AI-enhanced learning, many implementations lack alignment with robust pedagogical frameworks and are introduced without systematic evaluation of learning outcomes. This study addresses this gap by examining the effect of AI-supported instruction embedded explicitly within CDIO-aligned learning experiences. The primary research question guiding this study is: Does AI-supported instruction, designed in alignment with CDIO Standards, significantly improve student academic achievement compared to traditional instruction**?**

CDIO FRAMEWORK AND PEDAGOGICAL ALIGNMENT

The CDIO (Conceive–Design–Implement–Operate) framework provides a comprehensive model for engineering education that integrates curriculum design, teaching, learning, and assessment around the lifecycle of real-world engineering systems. In this study, "CDIO-aligned" refers specifically to the intentional alignment of instructional activities, learning outcomes, and assessment practices with selected CDIO Standards and syllabus competencies, particularly those emphasizing active learning, systems thinking, and professional skills development.

Guided by this framework, learners move beyond rote memorization toward deep learning by applying technical foundations to the conception, design, implementation, and operation of complex systems. This approach not only strengthens core engineering competencies but also fosters leadership capacity and ethical awareness needed to navigate the societal implications of contemporary research and development (Malmqvist et al., 2023; Rosén et al., 2024).

Within this context, AI-supported instruction can be interpreted through Biggs & Tang's (2011) Constructive Alignment model. As a teaching and learning activity, AI integration is considered "aligned" insofar as it supports the intended CDIO syllabus learning outcomes and is reinforced through outcome-based assessment practices, particularly those reflected in CDIO Standard 11.

CDIO Standard 2: Learning Outcomes

CDIO Standard 2 (Learning Outcomes) emphasizes that intended learning outcomes should be consistent with the CDIO Syllabus and include disciplinary knowledge as well as personal and interpersonal skills. In this study, AI-supported activities were aligned with course learning outcomes in Digital Logic, reinforcing conceptual understanding while supporting analytical reasoning and problem-solving. Learning outcomes addressed included as follows:

- Understanding and application of Digital Logic concepts
- Analytical reasoning and system-level thinking
- Independent problem-solving and reflective learning

CDIO Standard 5: Design-Implement Experiences

CDIO Standard 5 (Design-Implement Experiences) requires that students engage in design and implementation tasks. AI was integrated as a cognitive scaffold during these phases, enabling students to analyze problems, generate solutions, and iteratively refine their designs.

- Students used AI-supported prompts to:
- Decompose engineering problems
- Test logical designs
- Evaluate alternative solutions

CDIO Standard 7: Integrated Learning Experiences

CDIO Standard 7 (Integrated Learning Experiences) highlights the integration of technical knowledge with professional skills. The instructional design combined Digital Logic concepts with AI-facilitated inquiry and reflection, supporting deeper understanding and application.

CDIO Standard 8: Active Learning

CDIO Standard 8 (Active Learning) emphasizes student engagement through experiential and interactive learning. AI-supported instruction promoted active learning by encouraging exploration, questioning, and self-directed problem solving rather than passive content consumption.

CDIO Standards 11 and 12: Assessment and Evaluation

CDIO Standard 11 (Learning Assessment) and Standard 12 (Program Evaluation) guided the research methodology through the use of valid assessment instruments and systematic comparison between instructional approaches.

Table.1 summarizes the alignment between the instructional design, research methodology, and the relevant CDIO Standards addressed in this study.

Table 1. Alignment of the Study with CDIO Standards

CDIO Standard	CDIO Standard Description	Implementation and Evidence in This Study
Standard 2	Intended learning outcomes are aligned with the CDIO Syllabus and include disciplinary knowledge as well as personal and interpersonal skills	Course learning outcomes in Digital Logic were explicitly aligned with AI-supported activities to strengthen conceptual understanding, analytical reasoning, and problem-solving skills
Standard 5	The curriculum includes design-implement experiences that are integrated into the program	Students engaged in AI-supported design and implementation tasks, using AI as a cognitive scaffold to analyze problems, generate solutions, and iteratively refine digital logic designs
Standard 7	Integrated learning experiences combine disciplinary knowledge with personal and interpersonal skills	Instructional activities integrated Digital Logic content with AI-facilitated inquiry, reflection, and reasoning to support deeper learning and application
Standard 8	Active learning methods engage students directly in the learning process	AI-supported instruction promoted active learning through exploration, questioning, self-directed problem solving, and iterative feedback
Standard 11	Assessment methods measure the achievement of intended learning outcomes	Student achievement was evaluated using validated pre- and post-tests aligned with course learning outcomes and analyzed using ANCOVA
Standard 12	Program evaluation processes ensure continuous improvement based on evidence	A systematic comparison between AI-supported and traditional instruction provided evidence for instructional effectiveness and curriculum enhancement

INSTRUCTIONAL DESIGN AND AI INTEGRATION

The AI-supported instructional model was designed to complement, not replace, instructor-led teaching. AI tools were embedded into learning activities to support:

- Conceptual clarification
- Guided inquiry
- Formative feedback

The instructor remained responsible for instructional planning, facilitation, and assessment, while AI functioned as an adaptive learning support.

- Learning activities followed the CDIO learning cycle and included:
- Problem conception and analysis
- Logical design and modeling
- Implementation and testing
- Reflection and evaluation

RESEARCH METHODOLOGY

This study employed a mixed-methods, quasi-experimental research design, integrating both quantitative and qualitative approaches to evaluate the effectiveness of AI-supported instruction within the CDIO framework. A pre-test-post-test control group design was used. Participants (N = 136) were assigned to two groups based on pre-existing class groupings:

- Experimental group: Received AI-supported instruction aligned with CDIO standards.
- Control group: Received traditional lecture-based instruction, with no use of AI tools permitted during class assignments.

Quantitative Instruments and Analysis

Student achievement was measured using instructor-developed achievement tests aligned with Digital Logic course learning outcomes. These assessments were reviewed for content validity by subject matter experts to ensure alignment with the course syllabus and CDIO-based learning objectives prior to administration. The same test instrument was used for both pre-test and post-test measurements.

Data were analyzed using as follows:

- Descriptive statistics for pre- and post-test scores
- Independent-samples t-tests for group comparisons
- Analysis of Covariance (ANCOVA) to control for baseline differences
- Effect size calculations (Cohen's d, partial η^2)

Qualitative Data Collection and Analysis

To gain insights into student experiences with AI integration, semi-structured interviews and open-ended responses were collected from a subset of the experimental group. Responses were analyzed using thematic analysis to explore perceptions of AI as a cognitive support tool and its role in active, integrated learning experiences.

Instructional Intervention: The 5S Prompting Strategy

We developed a 5S Prompting Framework that guided students in interacting with AI (e.g., ChatGPT). This framework supported structured inquiry and reflection throughout the CDIO phases (Conceive-Design-Implement-Operate).

Table. 2 illustrates how each step of the 5S Prompting Framework supports specific phases of the CDIO (Conceive- Design-Implement- Operate) learning cycle, demonstrating the pedagogical alignment between AI-supported prompting strategies and CDIO-based instructional design.

Table 2. Mapping of the 5S Prompting Framework to CDIO Learning Phases

5S Step	Purpose	Example Function in CDIO Phase
Set the Scene	Define context and AI role	***Conceive:*** Clarify system boundaries with AI as expert
Specify	Provide task constraints	***Design:*** Define input parameters and methods
Structure	Request logical organization	***Design/Implement***: Request tabular or step-wise output

Simplify	Request analogies for conceptual clarity	***Implement:*** Reinforce understanding through simplification
Share Feedback	Reflect and compare results	***Operate:*** Debug and verify personal understanding

Students were instructed to document their 5S sequences and apply the framework during lab tasks, supporting CDIO-aligned design-implement experiences.

RESULTS

A total of 136 students completed both the pre-test and post-test assessments. The baseline performance of both groups was comparable, confirming initial equivalence as follows:

- Control group (n = 58): M = 69.93, SD = 5.94
- Experimental group (n = 78): M = 69.91, SD = 6.02

Following the intervention, the experimental group exhibited statistically significant improvement in learning outcomes.

Table 3. Post-Test Performance

Group	Post-test Mean (SD)	Median
Control	77.31 (7.33)	79.00
Experimental	82.60 (5.99)	84.00

An independent-samples t-test showed that the experimental group significantly outperformed the control group:

- $t(134) = 4.88$, $p < .001$, Cohen's $d = 0.72$ (large effect)

An ANCOVA, controlling for pre-test scores, confirmed the intervention effect:

- $F(1, 133) = 22.47$, $p < .001$, partial $\eta^2 = 0.14$

Qualitative Findings

The study sample consisted of 136 engineering students enrolled in a Digital Logic course (2 ECTS credits; 48 total instruction hours), of whom 58 were assigned to the control group and 78 to the experimental group. The course structure included 16 hours of lectures and 32 hours of seminar-based instruction.

To complement the quantitative findings, a qualitative component was incorporated using semi-structured interviews. A subset of participants from the experimental group (n=8) was selected using random sampling to capture a range of student experiences with AI-supported instruction. Each interview lasted approximately 20 minutes and followed a semi-structured protocol designed to explore students' perceptions of AI as a cognitive support tool, its role in problem-solving, and its influence on learning engagement.

Interview data were analyzed using thematic analysis. Responses were transcribed, coded iteratively, and organized into emergent themes reflecting common patterns in student

experiences. These qualitative insights were used to contextualize and interpret the quantitative results.

Thematic analysis of qualitative responses revealed several recurring themes:

- AI as Scaffolding: Students described the AI as a "logical thinking partner."
- Prompting Clarity: The 5S strategy helped students articulate problems clearly.
- Learning Ownership: Students valued the self-directed, feedback-driven environment.

These findings suggest that AI-supported instruction, when aligned with CDIO principles, not only improves academic performance but also enhances cognitive engagement and student agency.

This study provides empirical evidence that AI-supported instruction, when explicitly designed in alignment with CDIO Standards, enhances student academic achievement and supports constructive, student-centered learning.

Alignment with CDIO Principles

- Standard 2 (Learning Outcomes): Improved analytical reasoning and digital logic mastery
- Standard 5 (Design-Implement): AI prompted iterative problem-solving
- Standard 7 (Integrated Learning): Combined technical and reflective skills
- Standard 8 (Active Learning): Enabled exploratory, feedback-rich inquiry
- Standards 11 & 12: Assessment and evaluation validated the intervention's effectiveness

The AI engagement was measured through in-class assignments for Digital Logic class. The students in the experimental group was allowed using AI during class, whereas the control group was not allowed AI usage. The strong correlation between AI engagement and student performance ($r = 0.804$) further indicates that students used AI not merely for answers but as a cognitive partner, facilitating the development of higher-order thinking skills. This aligns with the UNESCO educational pillars of learning to know, to do, and to live together (Delors, 1996), reinforcing the social and intellectual dimensions of collaborative, technology-enhanced learning. The statistically significant improvement observed in the experimental group ($\Delta=12.69$ vs. $\Delta=7.38$) suggests that AI-supported instruction effectively promotes deeper learning aligned with CDIO Standard 8 (Active Learning).

The integration of AI tools within CDIO also addresses critiques such as those posed by Baylis (2007) regarding unstructured collaboration. In contrast, our 5S Prompting Framework ensures structured interaction, reducing ambiguity and promoting clarity in problem decomposition, hypothesis testing, and logical reasoning.

Descriptive statistics indicated initial equivalence between groups (Control: $M=69.93$, $SD=5.94$; Experimental: $M=69.91$, $SD=6.02$). Following the intervention, the experimental group's mean post-test score was 82.60 ($SD=5.99$), significantly higher than the control group's 77.31 ($SD=7.33$). Independent-samples t-test results confirmed this difference ($t(134)=4.88$, $p<.001$, Cohen's $d=0.72$). ANCOVA controlling pre-test scores further validated the intervention effect ($F(1,133)=22.47$, $p<.001$, partial $\eta^2=0.14$).

CONCLUSION

This study demonstrates that AI-supported instruction, when explicitly aligned with CDIO standards, results in significant and meaningful gains in student learning outcomes. The experimental group achieved higher post-test performance, supported by a large effect size and strong student-AI engagement correlation. These findings highlight the value of integrating AI tools within structured educational frameworks, such as CDIO, to enhance student-centered, inquiry-driven learning in engineering education.

From a practical perspective, the 5S Prompting Framework provides a scalable model for integrating AI into CDIO-based curricula, ensuring academic rigor while fostering critical thinking, reflection, and lifelong learning competencies. Future research should explore the long-term impact of AI-supported instruction across disciplines and its potential to support curriculum-wide innovation in engineering programs.

These findings offer several key takeaways for CDIO educators. First, AI tools can serve as effective cognitive scaffolds when integrated through structured prompting strategies such as the 5S Framework. Rather than replacing instruction, AI supports students in navigating complex problem-solving tasks by promoting clarity, logical reasoning, and reflective learning. Second, embedding AI-supported activities within the design-implement-operate phases of the CDIO cycle enhances deeper learning by fostering iterative exploration, hypothesis testing, and real-time feedback. Finally, the use of pre and post-assessment data provides strong empirical support for the validity and effectiveness of AI-enhanced, CDIO-aligned instructional models. These results reinforce the potential of combining pedagogically grounded design with emerging technologies to advance engineering education.

This study is subject to several limitations. First, it was conducted within a single course at a single institution, which may limit the generalizability of the findings to other disciplinary, institutional, or cultural contexts. Second, the relatively narrow scope of implementation constrains the ability to assess the scalability of AI-supported instruction across multiple courses or programmatic levels. Third, the potential for a Hawthorne effect cannot be excluded, as participants in the experimental group may have altered their behavior due to increased attention or the novelty of AI integration. Future research should replicate this study across diverse institutional settings, disciplines, and course formats, and consider multi-course or program-level implementations to strengthen external validity.

The authors declare that no AI tools were used in the preparation, analysis, or writing of this manuscript. All content was developed and analyzed solely by the authors.

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FROM RESTRICTING TO INTEGRATING AI: A UNIVERSITY-WIDE STRATEGY FOR DIGITALIZATION AND AI IN ENGINEERING EDUCATION

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ABSTRACT

Many engineering programs initially responded to generative AI by trying to restrict student use, mainly to protect academic integrity, while work life demands AI-literate graduates across all disciplines and regulation such as the EU AI Act raises requirements for transparency, safety and accountability. Against this backdrop, Chalmers University of Technology has developed a university-wide Strategy for Digitalization and AI in Education that shifts focus from blocking AI to systematically integrating digitalization and AI into curricula, learning processes, pedagogy, faculty competence, support services and the digital infrastructure. A central feature is a three-level learning-outcome model ("for all, for many, for some") that guarantees basic digital and AI literacy for every student, offers discipline-specific deepening for many, and provides advanced expertise for some in specialized master's programs. Pedagogical principles stress that digital tools and AI should support rather than replace student thinking and effort, and that assessment must remain valid and fair in an AI-rich environment. The strategy, grounded in current-state and SWOT analyses, is implemented through Chalmers' matrix governance with program-level ownership, shared guidelines, coordinated faculty development, and investments in infrastructure. The paper presents the strategy as a roadmap for aligning pedagogy, regulation and labor-market demand, and discusses implications for curriculum design, assessment and faculty competence.

KEYWORDS

Digitalization, AI, Curriculum design, University strategy, Standards: 2, 3, 7, 9, 11

INTRODUCTION

The rapid development of AI has reshaped how engineering students learn, write, code, and collaborate, with most now using AI tools for drafting, summarizing, coding, and problem solving in ways that challenge traditional assessment practices (Stöhr et al., 2024; Ovi et al., 2025). Many Western universities initially responded by restricting AI in exams and assignments and tightening plagiarism control, framing AI mainly as a threat to academic integrity (Chen, 2025), whereas some global competitors, including several Chinese universities, require students to use AI in assignments and capstone projects, provided the use is documented and technically grounded (Chen, 2025). Studies show that generative AI is already deeply embedded in student workflows, making blanket restrictions poorly aligned with practice, and highlight student preferences for structured, discipline specific guidance and adapted assessment rather than prohibitive policies (Jooste *et al*., 2025). At the institutional level, analyses of university policies reveal fragmented strategies that emphasize integrity while offering limited direction for curriculum design, pedagogy, and faculty development (Jin *et al.,* 2025). These findings underscore the need for integrated, institution level approaches to generative AI in engineering education, motivating the structured learning outcome framework proposed in this paper.

Interviews with Chalmers students mirror international findings. Many describe lectures as a way to obtain structure and overview while relying almost entirely on AI during self-study to summarize texts, support problem solving and provide explanations. Textbooks are no longer their primary source. At the same time, students often express a rather naive view on source criticism, bias, copyright, and the broader social and environmental impact of large AI services. These observations are consistent with Leino Lindell and Stöhr's (2026) recent interview study, which shows how generative AI reshapes engineering students' norms and practices. They identify transformations in students' self-directedness, their views of the aims of learning, their expectations of teachers and the ethical rules they apply to AI use, concluding that institutions need context-sensitive strategies rather than implicit or blanket bans.

A scenario-based study by Leino Lindell and Stöhr (2025) explores educators' perspectives through six near-future scenarios, highlighting tensions between efficiency-driven AI use and pedagogical values and pointing to both manageable challenges and potentially paralyzing contradictions for higher education. Together, these studies suggest that responsible implementation of AI in engineering education requires strategies that respond to changing student practices, support teachers and align institutional rules and infrastructures with rapidly evolving technologies.

Regulation and labor-market expectations reinforce this need. The EU AI Act (European Union, 2024) defines AI systems and risk categories and sets out obligations for high- and limited-risk systems, including transparency, documentation and human oversight. Educational settings are affected when AI is used for assessment, personalized feedback, or admissions. For engineering programs, AI competence must therefore encompass not only technical skills but also understanding of regulation, safety, bias, privacy, and accountability. Industry reports likewise highlight growing demand for AI-literate graduates in all engineering and business domains, emphasizing interdisciplinary collaboration, data-driven decision making, and ethical awareness (Ellucian, 2024).

Chalmers' previous digitalization strategy from 2017 did not address AI and, thus, required substantial revision. In a situation where student use of AI is already pervasive, labor-market expectations are rising, and regulation is tightening, isolated course-level initiatives are insufficient. A clear, university-wide roadmap is needed to ensure that digitalization and AI are

integrated systematically and at scale, so that all students develop the necessary competences. This paper presents the rationale, current state and analyses that motivated the new Chalmers Strategy for Digitalization and AI in Education, outlines the development process, and describes the resulting vision, goals and implementation roadmap for integrating digitalization and AI into engineering education at Chalmers. Adopting a design-based, research-informed perspective (Baumgartner et al., 2003), the paper further examines how such a strategy can be developed and implemented in alignment with pedagogical principles, regulatory requirements, and labor-market needs.

RESEARCH DESIGN AND METHODOLOGY

This study followed a design-based and action-oriented research approach, where the development of the strategy constituted both the object of study and a structured process of change (Baumgartner et al., 2003). The research was conducted in an institutional context characterized by rapid technological change, evolving student practices, and increasing regulatory and labor-market demands. The strategy development process was therefore used to explore how digitalization and AI can be systematically integrated into engineering education.

The research combined multiple complementary methods:

- Document analysis (existing policies, prior strategies)
- Current-state and SWOT analyses across programs, infrastructure, and support functions
- Iterative co-design within a cross-functional expert group
- Stakeholder consultation (program leaders, faculty, students, and industry representatives)
- External benchmarking of AI strategies and practices in higher education

The work was iterative, involving cycles of analysis, design, feedback, and refinement. From a research perspective, this can be understood as iterative design inquiry integrating empirical observations, theory, and stakeholder input.

The outcome is twofold: (i) the Chalmers Strategy for Digitalization and AI in Education as a designed artifact, and (ii) insights into how such strategies can be developed and implemented

CURRENT STATE AND SWOT ANALYSIS AT CHALMERS

The development of the Chalmers Strategy for Digitalization and AI in Education began with a current state analysis and a SWOT analysis across programs, infrastructure and support functions. The working group carried out this scanning and SWOT work jointly, and iteratively revised its conclusions based on feedback from specialists and stakeholders inside and outside Chalmers to ensure broad ownership and anchoring of the results.

Current state analysis

The analysis confirmed that Chalmers has a strong foundation to build on including established digital systems (LMS, examination systems, software platforms), a clear campus profile where digital tools such as simulations, virtual labs and digital exams are already used, and a growing number of initiatives around AI in education, research and administrative support.

At the same time, several critical weaknesses and gaps were identified. The integration of digitalization and AI varies substantially between programs, meaning that some student groups risk graduating without essential competencies. In several engineering programs, coverage of programming and mathematical statistics is limited, despite these being fundamental for working with digitalization and AI in technical development. Infrastructure for advanced AI education is insufficient. Local resources for deep learning, large models, and big data are lacking, and students have restricted access to computing resources in courses and projects.

There is also a lack of structured, continuous professional development for faculty in digital pedagogy and AI. This leads to varying levels of knowledge, uncertainty about which tools to use, and divergent views on how and to what extent students should use AI in their learning, with a risk of unequal treatment. Guidelines for student use of AI at course and program level are often unclear or absent. Several digital tools and systems are underutilized, meaning that earlier investments do not realize their full potential.

On the support side, work has begun on data-driven processes and AI-supported systems in administration and the library, but these efforts are still in an early phase and need coordination and formalization. Meanwhile, students already use generative AI extensively and independently, often as shortcuts rather than as learning support, echoing international patterns of changed study behavior and reduced campus engagement (Ovi *et al.*, 2025; Leino Lindell & Stöhr, 2025).

Externally, demand for AI competence in industry and society is growing rapidly, creating strong potential for Chalmers but also pressure to act. At the same time, the EU AI Act introduces stricter requirements on transparency, data protection and risk management for AI systems in education, while fast technological change risks making current tools and skills quickly obsolete.

SWOT

The SWOT analysis structured these findings into internal strengths/weaknesses and external opportunities/threats in Table 1.

Table 1. SWOT for digitalization and AI in education at Chalmers

Strengths	• Established digital systems • Experience from earlier educational reforms • Strong AI/digital competence in research and some teaching initiatives
Weaknesses	• Uneven and sometimes insufficient integration of digitalization and AI across programs • Gaps in programming and statistics in some engineering programs • Limited and fragmented faculty development in digital pedagogy and AI • Underutilized digital tools • Many separate digitalization and AI initiatives lacking clear coordination, prioritization and communication • Unclear or missing guidelines for student use of AI
Opportunities	• Strong labor-market demand for AI-competent graduates across sectors • Potential to improve learning, flexibility and retention via digitally and AI-enhanced pedagogy • Use of AI and learning analytics to support students and program quality management • Initiatives and experimentation in digitalization and AI that foster a culture of innovation and interdisciplinary exploration • National and international collaboration on AI in higher education
Threats	• Loss of competitiveness if AI is not systematically integrated in curricula • Rapid technological change making current tools and skills obsolete • Stricter requirements on data protection and AI (*e.g.*, the EU AI Act). • Risk that assessment validity, academic integrity and deep learning are undermined if AI use is not explicitly managed • Growing dependence on large non-EU technology providers.

Main Challenges

From the current state and SWOT analyses, three overarching, interrelated challenge areas were identified that must be addressed in a coordinated way, as failure to do so risks weakening the quality, relevance and competitiveness of Chalmers' education.

1. **Pedagogy, content, guidelines, and ethical use of AI**. Digitalization and AI now affect both how they are integrated into courses and projects and how students are expected to use it. Digitalization and AI are still unevenly embedded in programs, which risks some students graduating without essential competences. To stay at the forefront, AI and digitalization must be built into curricula at all levels, from mathematical and technical foundations to applications, tools, and an understanding of sustainability and ethics, and this must be supported by continuous faculty development in digital didactics and AI, as well as robust, ethical, and legally sound assessment practices.
2. **Changed student behavior and learning culture**. Generative AI is rapidly reshaping the ecology of learning and has already changed how students plan and carry out their

studies. Many use AI tools as shortcuts rather than as learning support, which can undermine deep learning and reduce campus attendance. Chalmers needs a pedagogy and learning culture that promotes motivation, academic integrity and collaboration in an environment where AI is a natural part of education, while campus remains a central meeting place for learning, creativity and community.

3. ***Infrastructure for advanced digitalization and AI***. Chalmers currently lacks a coordinated, scalable infrastructure that fully supports education and development in AI and digitalization. AI-intensive courses, such as deep learning, large-scale simulation and data analysis, require access to powerful computing resources, large datasets, and local language models (LLMs). A shared infrastructure is crucial for pedagogical innovation, secure data management, and ethically sound use of AI in line with the EU AI Act, and it forms an essential backbone for implementing the strategy.

These main challenges became central design drivers for the new Digitalization and AI strategy for education at Chalmers.

DEVELOPMENT OF THE CHALMERS DIGITALISATION AND AI STRATEGY

Working group and mandate

The Vice Rector of Education mandated a cross-functional working group to develop a strategy and roadmap for digitalization and AI in BSc and MSc education at Chalmers. The group was chaired by a dean of education (with CDIO and curriculum-design expertise), and included:

- three educational leaders (faculty) from three different disciplines/departments,
- an educational developer (faculty),
- a specialist in AI ethics (faculty),
- a director of studies from the Student and Education Office,
- a digital strategist and a head of unit from IT Systems and Services,
- a staff scientist specializing in ML/AI from Computing and Digital Infrastructure Unit,
- a librarian with responsibility for information literacy, and
- two student representatives with backgrounds in cognitive science and neuroscience, currently enrolled in master's programs in pedagogy and AI.

This composition reflected the intention that digitalization and AI should be addressed as both a pedagogical and an organizational issue, not only as a technical one. The breadth of the group ensured that all key dimensions of digitalization and AI in education were considered, from learning and assessment to infrastructure, ethics to support and governance. It also provided the necessary expertise to formulate a robust strategy and the organizational legitimacy needed for it to be accepted and implemented across the university.

Process

Between April and October, the working group followed an iterative, mixed-method process. The cross-functional group met roughly every second week, using the meetings to discuss draft texts, carry out joint current-state mapping and SWOT analyses, and align emerging ideas with Chalmers' overall vision and priorities. Between meetings, members worked individually on sections where they had expertise and reviewed successive full-draft versions. The work combined analysis of existing Chalmers policies and initiatives, external benchmarking of digitalization and AI strategies in higher education, and dialogue with AI

specialists in industry and consultation with program boards and educational schools. The group also reported back to the executive committee for education led by the Vice Rector of Education and invited early feedback from internal experts, key industrial partners and an external AI specialist. The process explicitly drew lessons from earlier large-scale reforms at Chalmers such as CDIO, education for sustainable development and entrepreneurial learning where matrix governance and strategies were crucial for implementation (Karlsson-Bengtsson *et al.*, 2021).

THE CHALMERS STRATEGY FOR DIGITALIZATION AND AI IN EDUCATION

Vision and scope

The strategic vision is that Chalmers shall be a leading technical university where digitalization and AI are integrated in education, research and support services in ways that strengthen learning, quality and industrial and societal relevance. It defines digitalization as the use of digital technologies to develop, streamline and renew educational processes, content and learning environments, and adopts the EU definition of AI systems (European Union, 2024, Artificial Intelligence Act, Art. 3). There, "AI system' means a machine-based system that is designed to operate with varying levels of autonomy and that may exhibit adaptiveness after deployment, and that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments".

The strategy is explicitly framed as a steering document to ensure that digitalization and AI are systematically and sustainably embedded in all programs in a way that equips every student with technical competences, and ethical awareness, and that supports inclusive, sustainable and future-oriented learning. The strategy covers content and learning processes, pedagogy, faculty competence and role, support services and digital infrastructure, and is implemented via an action plan with defined responsibilities and periodic revision. The action plan and its implementation follow Chalmers' matrix-based organization and existing quality cycles, where educational schools commission and agree on AI-related course content and program development with departments through annual agreements (Karlsson-Bengtsson *et al.*, 2021).

Digitalization and AI in education and learning processes

Digitalization and AI are explicitly framed as enablers of learning, innovation, creativity and preparation for future working life, rather than as purely technical add-ons. All students are expected to develop knowledge and skills required to understand, apply and critically evaluate AI technologies and the material they generate, to interact with AI tools in a responsible and purposeful way, and to reflect on the social, societal and environmental consequences of their use.

A central design feature is a three-level model for digitalization and AI-related learning outcomes and opportunities across the curriculum: *for all, for many, for some.* The *for all* level is expressed in terms of explicit learning outcomes which will be part of the outcomes for each educational program.

For all (mandatory for every student): All students should develop AI literacy, *i.e.*, the ability to understand, use and critically evaluate digital and AI technologies and the material they generate. This includes being able to:

- describe opportunities and implications of digitalization and AI for society, profession and discipline,
- explain basic principles of AI and recognize common limitations and biases,
- use digital and AI tools within their field to solve or explore problems,
- assess the reliability and appropriateness of AI-based tools and apply principles for ethical and sustainable use,
- actively seek transparency in AI use by questioning sources, answers, and limitations of AI-generated outputs, and
- use AI in learning ways that support metacognitive practices.

For all engineering students, this also includes being able to:

- explain the mathematical and technical foundations of digital technology and AI (linear algebra, optimization, statistics, programming), and
- apply and evaluate AI techniques for analysis, modelling, and simulation in their technical area.

For many (elective deepening): A broad selection of elective courses should be offered allowing many students to deepen their knowledge of digitalization and AI within their discipline, including:

- exploring advanced AI methods and applications,
- practicing identification, development and implementation opportunities for digitalization and AI in technology, design, and systems development,
- use AI for advanced analysis, simulation, and innovation,
- developing general competencies such as analytical and critical thinking, problem-solving, creativity, and ethical responsibility when working with digital and AI-based solutions, and
- further development of analytical, critical, and ethical competences in AI-related work, guided by the FATE framework (fairness, accountability, transparency, and ethics; Memarian & Doleck, 2023).

For some (specialized master's program and tracks): Selected master's programs should offer deep specialization to:

- develop future digital and AI tools,
- contribute to research and development of foundational methods within AI,
- identify, design and implement new applications of AI,
- lead strategic digitalization in industry and society, and
- design, apply, and maintain responsible, ethical and secure AI systems.

This three-level model allows Chalmers to guarantee a common minimum digital technical competence base and AI literacy for all graduates, while still developing deep expertise among those students who are interested and need it for their future careers, including those who will work at the technological frontier. Among the learning goals of this model, AI ethics is framed in terms of FATE (Memarian & Doleck, 2023). In this context, ethics emphasize students' responsibility to critically engage with AI, avoid competence illusion, and maintain transparency and accountability for AI-supported reasoning and learning outcomes.

Pedagogical principles

In alignment with Chalmers' long-term vision and strong culture of innovation, Chalmers' AI strategy seeks to encourage students to explore, master, and ultimately contribute to shaping the future of AI. This implies that AI must be meaningfully integrated into pedagogy, rather than the pedagogy being adapted to AI. The strategy emphasizes that digital technology and AI must be pedagogically justified, not technology-driven. Key principles include:

- Digital tools and AI should support individualized formative feedback, deeper subject understanding, problem-solving and metacognitive practices, rather than shortcuts to ready-made solutions.
- Exams and assignments must remain valid and fair in a digital and AI-rich environment and should be designed so that AI cannot be employed, for instance through oral exams or monitored written exams, when a learning outcome requires that AI is not used (*e.g.*, to secure core analytical skills).
- The use of AI is regulated at course level and clearly linked to learning outcomes and assessment criteria. Examiners are responsible for communicating what forms of digital and AI use are allowed or required in each course and assignment.
- All AI use follows a risk-based approach, where high-risk contexts (e.g., assignments, certifications, grading) require greater transparency and human oversight than in low-risk contexts (*e.g.*, formative learning activities).

The key principles stress that digital technologies and AI are tools for learning. It is essential to distinguish between learning activities and assessment. Furthermore, pedagogical research at Chalmers aims to explore when and how digital technology and AI best support learning, providing evidence on effective digital and AI-supported teaching methods and their impact on understanding, motivation and equity.

Faculty competence and role

Faculty must be well equipped to understand and continuously evolve in the use of digital and AI-based tools and processes in education. This requires basic understanding of the technical development, as well as domain-specific up-to-date knowledge of relevant tools and applications, and the ability to reflect on and integrate these in education content, learning outcomes, and forms of teaching and assessment. This includes awareness of the pedagogical, ethical, and societal challenges posed by digitalization and AI, including integrity, bias, transparency, and responsibility.

To achieve this, all faculty have a responsibility to continuously reflect on and evolve their teaching practice, support for such evolution must be available both in terms of access to continuous skill development and in terms of sufficient time to engage with it. Our faculty must not only be users but also evaluators, developers and role models that can prepare students for a society where digitalization and AI drive rapid change.

The obligation placed on faculty, instructors, and pedagogical leaders in Chalmers' AI strategy should be understood as acknowledging that the design of metacognitive support necessarily varies across disciplines and according to the specific tasks and learning outcomes in question.

Support services and Library

The Chalmers operations support function enables institution-wide support in line with educational, research, and management needs as well as regulatory requirements, providing personalized student guidance and AI-based decision support for educators, while improving administrative efficiency through automation without compromising integrity or quality.

Chalmers Library plays a significant role in AI-related information literacy and evaluation of AI-based tools for students and staff by providing access to information resources and digital tools, and by integrating AI-related information and media literacy into its teaching.

Digital infrastructure

An accessible and robust digital learning environment is identified as a basic condition for high-quality education. Students should have secure, simple and platform-independent access to the software, hardware and digital tools needed to develop competences relevant both for their studies and for their future professional lives, regardless of location and program affiliation. This includes:

- Standard software and advanced tools (*e.g.*, CAD, simulation, AI/ML, visualization).
- Virtual environments for medium-scale computation.
- Locally provided infrastructure for more demanding AI and simulation workloads, including locally trained AI models where needed.

The vision is that advanced AI and large-scale simulation needs can be met via Chalmers' own infrastructure or controlled environments, enabling secure handling of personal and sensitive data. This, in turn, opens possibilities for personalized support, adaptive learning and advanced analytics without compromising privacy or data protection. Resources are to be made available in a pedagogically sound and resource-efficient way to strengthen students' learning, innovation capacity, and technical competence. Essential digital and AI-based tools are to be afforded to the faculty for maintaining up-to-date knowledge of relevant tools for pedagogy, evaluation and development of programs and courses.

IMPLEMENTATION

Implementation is driven by a university-level action plan that specifies goals, responsibilities and follow-up mechanisms across programs, professional development for faculty members, infrastructure and support services, and builds on Chalmers' matrix organization and its management model as described by Karlsson-Bengtsson *et al.* (2021). Key elements are:

1. University-level principles for AI use in education. Guidelines and ethical frameworks are developed jointly by educational developers and specialists in higher education and ethics.
2. Program-level ownership. Heads of programs translate the "*for all, for many, for some*" model into program-specific learning outcomes, mapped across the curriculum, and negotiate responsibilities and development needs with departments in annual processes. Heads of programs allocate development funding for these developments.
3. On the infrastructure side, a steering group for learning support, together with Chalmers IT organizations develop scalable, robust infrastructure, including local computational resources, locally trained AI models and environments for simulation.

4. Faculty competence development. All teachers are offered opportunities to strengthen their digital didactics and AI competence through pedagogical courses and workshops.
5. Continuous evaluation through program reviews, course evaluations, faculty development and infrastructure usage.

Overall, the strategy functions as a roadmap for implementation and follow-up. The Vice Rector for Education, together with the executive committee for education, is responsible for steering, prioritizing and periodically revising the strategy approximately every three years, and for ensuring that its directions are translated into concrete actions across programs, support functions and infrastructure.

DISCUSSION AND CONCLUSIONS

From blocking AI to including and guiding AI-supported learning

Chalmers, like many universities, initially addressed generative AI by restricting its use in examinations due to concerns about cheating and plagiarism, but its new strategy represents a clear shift from blocking AI to actively guiding AI supported learning, moving from trying to keep AI out of the learning process to helping students and staff use it critically, responsibly, and in ways that deepen understanding rather than bypass it (Prather et al., 2024). The aim is to enhance student learning without replacing students' own effort, analysis, or reflection. Instead of drawing a strict line between AI as course content and AI used in assessments, the strategy emphasizes the need for metacognitive scaffolding that supports students' development of metacognitive abilities. Within this approach, the integration of digital tools and AI systems should be designed to function as cognitive offloading by reallocating cognitive capacity to enable deeper and more complex problem solving rather than providing an outsourcing shortcut that circumvents the thinking process itself (Risko & Gilbert, 2016).

The three-level learning model ("for all, for many, for some") makes AI literacy a central learning outcome, giving all students basic understanding, many develop practical competence, and some advanced expertise (Walter, 2024). It also includes ethical principles aligned with FATE to support responsible AI use in learning (Memarian & Doleck, 2023). In this way, the strategy follows international calls to move from prohibition to clear and structured integration of AI in teaching, while still addressing integrity and equity.

Aligning pedagogy, regulation and labor-market demand

By defining learning outcomes for all students that include understanding AI's societal implications and being able to critically assess AI tools, Chalmers responds to employers' demand for AI-competent graduates across disciplines, not only in specialist roles. Employers increasingly expect engineers in all disciplines to be able to use digital and AI-based tools for modelling, simulation and computation, and to be able to retrieve relevant information for analysis and decision-making. All students therefore need a basic understanding of the mathematical and technical foundations of digitalization and AI, including statistics and coding, to interpret, evaluate and meaningfully use these tools. The *for some* level, with specialized master's programs, targets the need for experts who can develop new digital tools and methods, AI methods, applications and governance models.

At the same time, strong emphasis on ethics, assessment validity and secure infrastructure reflects regulatory demands for transparency, safety and data protection. Courses and exams

are expected to make the role of AI explicit, rather than ignoring it, and to balance openness to innovation with compliance and trust.

Implications for CDIO community

The Chalmers strategy illustrates how a technical university can move from fragmented initiatives to a coherent, multi-level approach to digitalization and AI in education. Several implications may be particularly relevant:

- The three-level learning-outcome model ("*for all, for many, for some")* offers a simple structure for embedding AI across programs.
- Learning outcomes need to be formulated so that AI supports, rather than undermines conceptual understanding. This includes:
    - distinguishing between outcomes requiring independent mastery and those where AI-supported problem solving is appropriate,
    - designing outcomes that emphasize explanation, reasoning, and critical evaluation, not only solution generation, and
    - ensuring that students can interpret, validate, and critique AI-generated outputs, rather than relying on them uncritically.
- Assessment must distinguish between tasks where AI can legitimately be used and tasks where independent mastery is required.
- A matrix organization with strong program leadership can be a powerful organizational framework for integrating AI as a cross-cutting theme, provided that Heads of Program have mandate, resources and support.
- Teachers' roles gradually expand from being mainly subject experts to also guiding students in how to work well with AI in their discipline, courses and projects.
- Faculty competence needs to develop both in terms of digitalization and AI within their own fields and in terms of pedagogical use of digital and AI tools in courses and projects.
- Digital infrastructure, including local AI models and services, must be designed to support authentic problem solving, pedagogical needs, and regulatory requirements.

For the CDIO community, this underlines that AI is not only a new technical topic but also a driver of change in learning outcomes and integrated curriculum (Standards 2 and 3), teaching and integrated learning experiences (Standard 7), assessment (Standard 11), faculty competence (Standard 10) and curriculum agility efforts.

Methodological reflections and contributions

This study illustrates how the development of a university-wide educational strategy can be approached as design-based research, where the strategy functions as a designed artifact and the process as a structured inquiry into integrating digitalization and AI in engineering education. Key insights include the importance of cross-functional collaboration, iterative co-design with stakeholders, and the use of analytical tools (e.g., current-state and SWOT analyses) to link empirical observations to strategic decisions. More broadly, the findings suggest that institutional strategy development in rapidly evolving areas such as AI should be understood as a research-informed design process, integrating empirical evidence, theory, and practice.

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LINKING STUDENT ATTENDANCE TO COURSE RESULTS

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ABSTRACT

Student attendance is widely regarded as an important factor influencing engagement and academic success in engineering education, yet maintaining consistent onsite participation continues to pose challenges. At the same time, little is known about how attendance at different types of learning activities relates to performance within individual courses, particularly in the context of introductory engineering education where students form foundational study habits. This study examines attendance patterns in a first-year, project-based mechanical engineering course, using a QR-based digital tool integrated into the learning management platform to document participation across lectures, workshops, supervision sessions, and project activities. The tool was introduced as a neutral documentation mechanism rather than an assessment component, allowing attendance to be recorded unobtrusively in both compulsory and voluntary activities. The results show clear variation in attendance across activity types, with high participation in early and mandatory sessions and somewhat lower attendance in later or skills-oriented activities. Analysis reveals a weak positive correlation between attendance and both individual and group performance, aligning with established findings in educational research. Subgroup analyses suggest that attendance–performance relationships may vary across age and gender groups, pointing to areas of interest for future work. Beyond the empirical results, the study demonstrates the practical feasibility of systematic attendance tracking on a large scale. Students showed no resistance to the tool, indicating that the method is straightforward to implement and well tolerated. The ability to visualize attendance across the course offers instructors a valuable basis for reflective teaching and for identifying which activities may benefit most from strong student presence.

KEYWORDS

Attendance, Education, Engineering, Performance, Absenteeism, Standards: 4, 8, 11

INTRODUCTION

As engineering educators in higher education, we aim to support students in succeeding academically, and student presence is a key factor in fostering meaningful engagement. Recently, onsite attendance has become an area of increasing concern, as absenteeism may negatively affect learning outcomes and make it more difficult for students to complete their courses. Although the importance of active participation is well recognized, achieving consistent attendance remains challenging.

With the introduction of a QR code scanning tool integrated into the learning management system Canvas, we can now measure attendance systematically and relate it to student performance. Since courses differ in subject matter and pedagogical structure, an in-depth analysis of a single course may reveal more targeted opportunities for improvement.

The course Introduction to Mechanical Engineering, redesigned and launched in 2025, was selected for this analysis. Its structure provides a suitable context for examining how attendance relates to performance and for identifying insights that may guide future course development. Introducing attendance tracking in an introductory course is also strategic, as it may shape students' early study habits and potentially promote higher attendance throughout the entire program. Furthermore, the act of measuring attendance may itself influence student behavior. Against this background, analyzing the course data offers an opportunity to identify factors that could support improved learning outcomes.

aim and Research Questions

The aim of this study is to analyze how student attendance correlates with academic performance in a project-based course for first year mechanical engineering students at Chalmers University of Technology. The study focuses on relationships between attendance, individual and group results, and whether the results vary by age and biological gender. The following research questions have been guiding the project:

- What is the relationship between student attendance and individual versus group performance in the course?
- What is the relationship between student demographics, age and biological gender, and their attendance patterns and academic performance in the course?

Furthermore, we hope that this study, together with future investigations, will help clarify which implementations of an attendance-tracking tool have the greatest potential to enhance the students' fulfillment of learning outcomes.

Scope and limitations

- This study is limited to first year students enrolled in the mechanical engineering program at Chalmers University of Technology.
- The study is limited to the research of one project-based course and does not include other types of courses.
- This study does not compare different tools or ways to track student attendance.
- The demographic analysis is limited to the variables available in the dataset, namely age and legal gender.

THEORY

Higher attendance rates have been linked to improved academic performance. Cred et al. (2010), in meta-analysis on this topic, concluded that there is a strong relationship between attendance and achievement and suggested that initiatives to improve attendance rates could enhance college grades. Supporting this, a study of electronic engineering courses at the University of Alcalá found that students with full course attendance had a 91% pass rate as well as a 97% attendance in the exams (De Andres Rubio et al., 2024). The results also showed that the average course grade rose alongside increased attendance. Similarly, Gudjonsdottir (2024) analyzed eleven courses in the field of mathematics and physics and reported that students who attended all lectures had scored 2-22% higher on exams compared with those with less attendance.

While higher attendance generally correlates with better academic outcomes, this effect may depend on the design of the course. Gal et al. (2011) conducted a comparative study between two physiology courses. One course was taught using a traditional approach with lectures and laboratory work, and one course using a more active approach with added problem-based learning, discussion, and teamwork. In their analysis of exam results and attendance, Gal et al. (2011) found a significant difference in exam scores in the active teaching group, where students with poor attendance got a lower result. This indicates that students struggle to compensate for missed activities courses with more active learning, whereas traditional methods allow for easier compensation through available textbooks. The study concludes that attendance is particularly important in physiology courses that practice active learning methods.

Reasons for students not participating in course activities vary. According to Nilsson et al. (2025), the decision to attend or not is often strategic, influenced by factors such as prioritizing other courses, perceived poor teaching quality in combination with illness or procrastination, and substituting course content with online alternatives.

In contrast with other studies emphasizing increased attendances as a primary goal, Nilsson et al. (2025) suggests a different focus. They suggest a focus on developing teaching methods that enhance understanding and skill development. Teaching methods are also mentioned by Freyhult (2017). In an analysis of physics students' responses to questions regarding attendance, Freyhult found that the main thing that students thought would improve attendance was more problem-based and active teaching methods.

Monitoring students' attendance could influence the attendance rates, according to Heru et al (2024). They studied how an attendance system changed the student's behavior in vocational high schools, where they compared two groups of students. The findings revealed that the implementation of a web-based attendance system improved both motivation and attendance. This system included both the opportunity for parents to monitor their children and for students to get real-time feedback. Heru et al. (2024) also argue that this type of system contributes to promoting the habit of attending and responsibility, which could make them more prepared for their future work life.

METHOD

The study was conducted in the course IMS165, *Introduction to Mechanical Engineering*, a 7.5 ECTS project-based course given during the first semester of the Mechanical Engineering program at Chalmers University of Technology in autumn 2025. The course enrolled 247 first-year students (55 legally female and 192 legally male). The students were organized into 9 classes, each with 5 project groups of five to six students.

The course included lectures, supervision, workshops, laboratory exercises, hands-on project activities related to product development (product development hereafter “PU”), CAD, presentation, and report writing. Assessment comprised an individual quiz (“PU Quiz 1”) and a group-based project. The quiz was graded on a 0 – 100 point scale, while the project report used a 3–5 scale with decimal increments.

The course was designed according to the principles of constructive alignment with close integration between learning outcomes, learning activities, and assessments. Each learning activity was mapped to one or more learning outcomes, and the corresponding assessments (PU Quiz 1) were built upon these activities to evaluate the same learning outcomes. The project report as an assessment method was primarily assessing a single learning outcome (regarding report writing).

Student attendance was recorded using NVO Attendance, a QR-code system integrated into the Canvas learning management system. Attendance was registered by students scanning a dynamically updating QR code displayed in the classroom, preventing off-site registration. In cases of technical issues, attendance was manually recorded by the instructor. The system was introduced at the start of the course as a tool for documenting participation patterns rather than as a control or assessment mechanism; attendance at non-compulsory sessions was voluntary and not linked to grading.

Attendance was recorded across lectures, workshops, supervision sessions, and project-related activities, covering a total of 23 scheduled sessions. Of these, 10 were supervision sessions and 10 were optional lectures. After course completion, attendance data was exported from Canvas, resulting in a dataset with one row per student. The dataset included demographic variables (age, legal gender, class section, and project group), binary session-level attendance indicators (present = 1 / absent = 0), and performance outcomes in the form of individual quiz scores and group project results.

Data Analysis and Ethical Considerations

Exploratory data analysis (EDA) was applied to examine relationships between attendance patterns, course activities, and both individual and group-based performance outcomes, including quiz results and project performance. The analysis focused on data visualization to identify visual patterns, tendencies, and variation, rather than to establish causal or statistical relationships. Attendance and performance data were processed in Microsoft Excel and visualized using the statistical software JMP.

All data was anonymized prior to final analysis. Personal identifiers were removed, and demographic information was used solely for analytical purposes. Students were informed about the study and could opt out without academic consequences. Data analysis was conducted after final course grades had been assigned, and all results are reported at an aggregated level.

RESULTS

Attendance rates varied across different course activities, see Figure 48. The highest rates were at the mandatory (M) sessions, with 94-96% attendance. The introduction lecture and first PU lecture had 92% respectively, 87% attendance. The following PU lectures were around 70%. Student participation varied in the supervisions from 85% to 64%. The lowest attendance was recorded in the lecture about oral presentation with 52%.

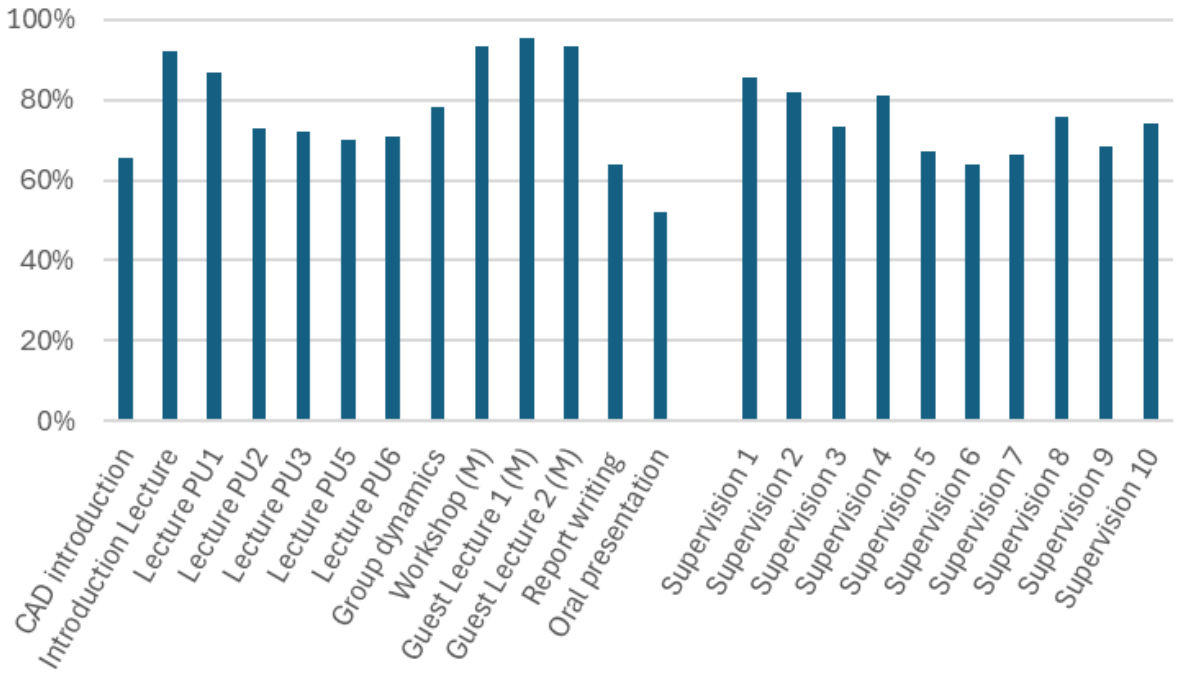


Figure 48. Attendance rates across different course activities

Quiz score increased with overall attendance for both female and male students, as seen in Figure 49, with a weak correlation. Separate linear regression models indicated different slopes for the two groups, with estimated slopes of 0.62 for female students and 1.17 for male students, respectively. The project grade and overall attendance also show a weak correlation. No statistically significant difference in overall quiz score was observed between female and male students when attendance was not considered ($p > 0.05$).

Further visual evaluation of the data suggests that, in most age groups, quiz scores tend to increase with higher attendance for both genders. In contrast, the 23–30 age group shows a different tendency, where higher attendance appears to coincide with lower quiz scores for both female and male students. When viewing quiz score distributions by age group alone, no clear or systematic differences between age groups are visually apparent, indicating substantial overlap in performance outcomes across ages ($p > 0.05$).

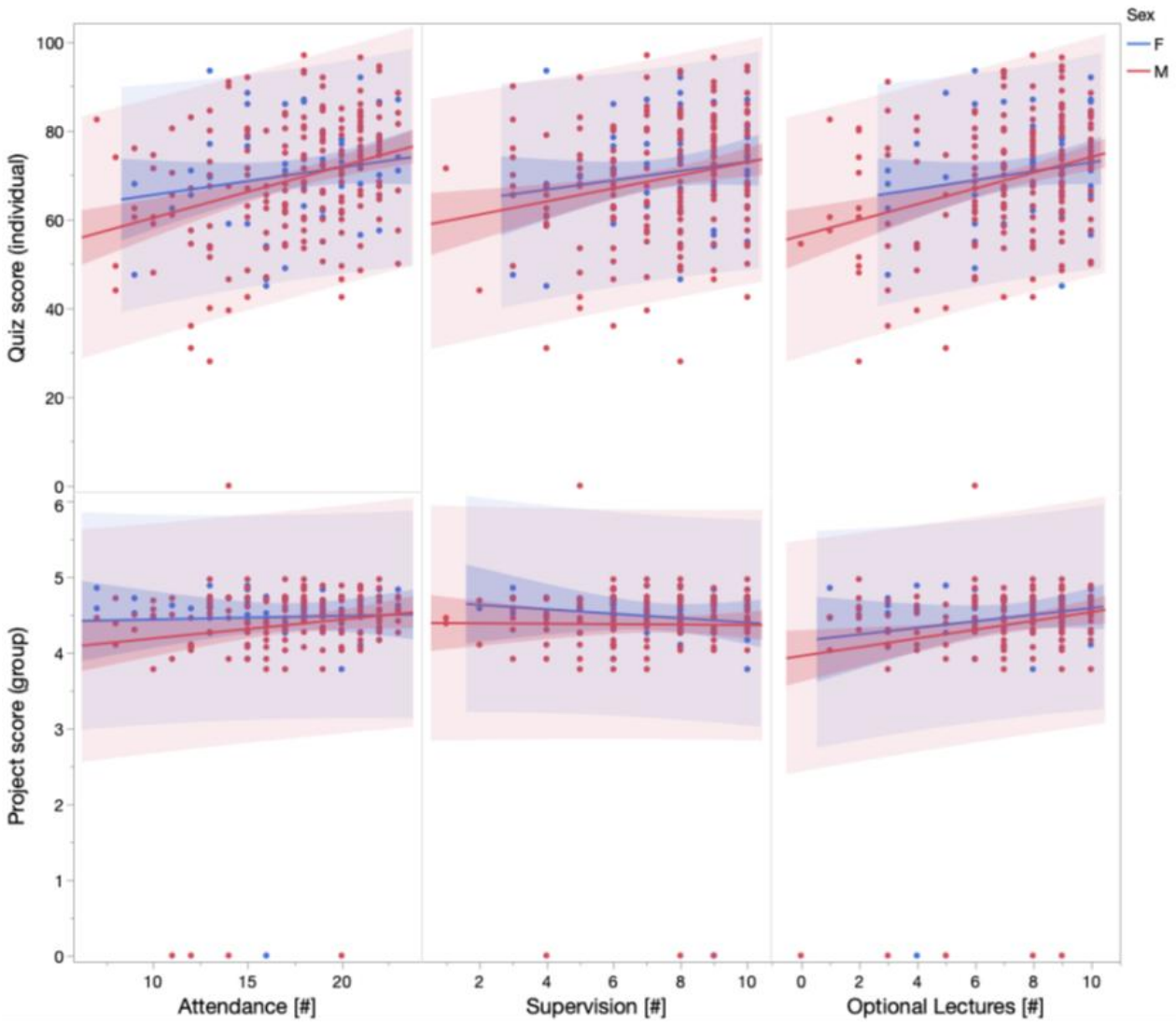


Figure 49. Quiz score and project score as a function of attendance, stratified by legal gender. Solid lines represent fitted linear regression models

Figure 50 illustrates an example of the type of visualization that can be produced from the collected data. The figure allows for an examination of different performance intervals on both the quiz and the group project. By following the lines extending from each performance interval, the corresponding attendance patterns can be traced. The visualization shows that teams with lower project scores tended to have lower attendance at supervision sessions compared to teams with higher project scores.

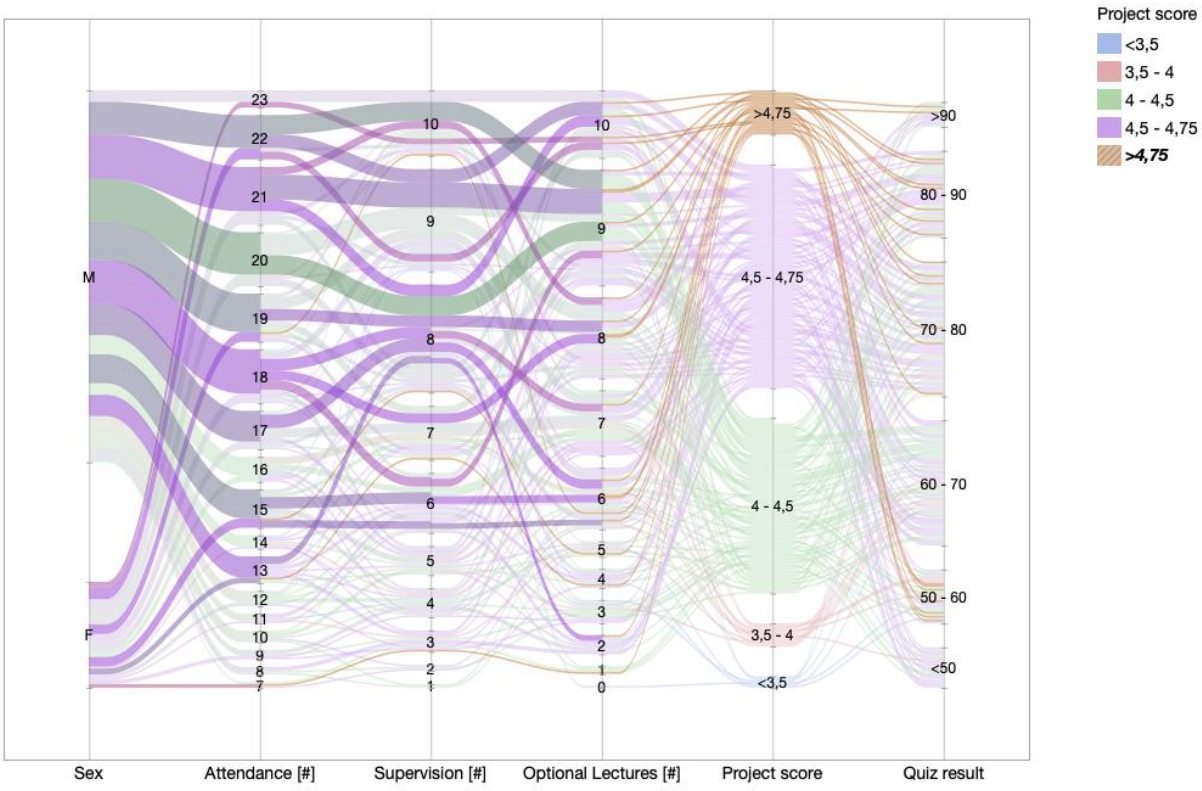


Figure 50. Exploratory visualization of attendance patterns and performance outcomes, highlighting project score. Each line represents a student, with color indicating project score. The figure illustrates tendencies between overall attendance, supervision, optional lectures, and both project and quiz performance

DISCUSSION

The results show a weak positive correlation between both quiz score and group score and overall attendance. Which is consistent with previous findings by Credé et al (2010) and Gudjonsdottir (2024). In most age groups (18–23), higher attendance was associated with higher quiz scores. In contrast, the 23–30 age group showed a negative association between supervision attendance and quiz performance.

This pattern should be interpreted with caution, as the 23–30 group comprised fewer students and exhibited wider confidence intervals, indicating higher uncertainty and sensitivity to individual observations. Rather than suggesting that supervision has a negative impact, the observed pattern may be explained by strategic attendance behaviors. As described by Nilsson et al. (2025), students may deliberately prioritize certain activities while using supervision selectively to address specific challenges, meaning that supervision attendance does not necessarily indicate higher overall engagement.

This type of exploratory data analysis can serve as a tool for reflection and course development rather than for evaluating individual activities, as the findings primarily reveal tendencies. The opportunity to visualize how activities relate to student performance may support productive discussions among teachers and examiners, as well as help identify areas of interest for deeper analysis and identify activities that matter the most for students' performance. By visualizing how course activities relate to student performance, it becomes

possible to first adopt a course-level overview and then zoom in on local patterns where specific activities appear to be more closely associated with learning outcomes.

Repeated tracking of courses could therefore make it possible to more confidently identify key activities where attendance is most important for learning outcomes. Such as during early concept lectures, supervision in critical project phases, or sessions close to deadlines. This could enable evidence-based decisions about scheduling, sequencing, and allocation of teaching resources, placing instructional effort where it appears to provide the greatest learning support.

No causal conclusions can be drawn regarding the effect of the tool on overall attendance levels, as no baseline data from previous course iterations are available in the studied course. Nevertheless, these observations point to an underexplored aspect of attendance research, where attendance tracking may function not only as a measurement tool but also as a behavioral intervention. During the course there have been occasions when students have actively requested to register attendance even when it was voluntary. Other students reported monitoring their attendance status and aiming to maintain a high attendance record. Teachers also noted that more students than expected were present during scheduled class time. While these observations are anecdotal, they suggest that making attendance visible may affect how students perceive and engage with course activities.

These results are limited to first-year students and were obtained in one of the first courses in the program, which makes the findings specific for this group. Conducting a similar analysis in second-year courses to examine how increased experience in university studies affects the results would therefore be valuable. Additionally, analyzing different types of courses could provide a better understanding of how participation in learning activities relates to learning outcomes.

The findings should also be interpreted in relation to the relatively homogeneous study context, as all participants belonged to the same programme, year, and course. The present analysis only considered age and legal gender, while factors such as cultural or ethnic background, socioeconomic conditions, commuting situation, previous educational experience, and study habits were not examined. Although the cohort may be relatively homogeneous in several of these respects, including such variables in future studies could help explain and provide a more nuanced understanding of student attendance.

CONCLUSION

Our analysis indicates a weak correlation between attendance and performance on both quizzes and project work in the course. More importantly, the study demonstrates the value of having a reliable tool that enables systematic measurement of attendance across different learning activities. This provides a foundation for future investigations into how specific pedagogical components influence student learning and, in the longer term, may support the evaluation and refinement of instructional practices.

A notable outcome is the seamless implementation of the attendance tool: none of the 250 students enrolled in the course expressed concerns or objections, suggesting that the method is unobtrusive and easily reusable from an instructor’s perspective. The main effort going forward will lie in analyzing the growing body of data and, crucially, in translating these insights into actionable improvements for teaching and learning.

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LEARNING OUTCOMES OF DIGITAL TWINS IN ENGINEERING EDUCATION: A SYSTEMATISED REVIEW

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ABSTRACT

Interest in educational applications of Digital Twins (DTs) is growing, but translation of theoretical benefits to measurable student experiences has not been investigated in depth. This systematised review evaluates empirically measured learning effects caused by Digital Twins in engineering education, in comparison to traditional teaching methods. It aims to identify key learning outcomes and experiences caused by DTs across cognitive, behavioural, and affective dimensions, and to assess current strength of evidence supporting their use in education. A keyword search of Scopus, Web of Science, and IEEE Explore yielded twenty-six papers. Strength of evidence was found to be tentative for behavioural outcomes, but more promising for cognitive outcomes, especially when DTs are used as an enabling technology for new ways of teaching and learning. Affective outcomes were found to be under-researched. Other research gaps include formalised qualitative outcomes, long-term effects, and experiences of marginalised students. To prevent misconceptions about technological feasibility and benefit, greater transparency is required when defining and describing Digital Twin implementations.

KEYWORDS

Digital Twins, Engineering Education, Experiential Learning, Standards: 2, 6-8

INTRODUCTION

Digital Twins (DTs) are gaining popularity in industry and academia (Kaur & Bhatia, 2025). Beyond their original context of product management, DTs are now expanding into increasingly diverse fields both within and outside of engineering. One such area is engineering education, where Digital Twins offer several theoretical benefits.

Interaction with a DT can encourage students to be agents of their own learning, aligning with constructivist principles of meaning-making (Piaget, 1971). Support for active and experiential learning also aligns with the Conceive, Design, Implement, Operate (CDIO) framework for engineering education (*Worldwide CDIO Inititative*). Kolb's Experiential Learning Cycle (Kolb, 1984) proposes that the ideal process of learning occurs in a cycle of experiencing, reflecting, thinking, and acting. Digital Twins bridge the theoretical and practical worlds (Grieves, 2005), which may encourage a more natural transition from thinking to acting. Furthermore, because virtual models may not have the same resource and safety constraints as physical environments, use of DTs to support laboratory activities can overcome barriers to the "acting" stage of the cycle (Ağca, 2023). Finally, DTs involve real-time data and provide immediate feedback (Madni et al., 2019), prompting reflection and allowing learners to repeat the learning cycle multiple times during an activity.

However, whether these theoretical benefits translate to learning is unclear. Evidence that a Digital Twin approach improves learning outcomes is largely through case studies. This review aims to evaluate strength of literature at this early stage, identify the most promising outcomes for targeted application, and highlight research gaps.

BACKGROUND

The idea of a Digital Twin was introduced in a lecture series in 2002 by Michael Grieves as part of the Product Lifecycle Management concept, and expanded in later literature (Grieves, 2005, 2011; Grieves & Vickers, 2017). In this context, it denotes a high-fidelity virtual copy that is linked to a physical product in real-time. Historical data are collected and stored by the DT throughout the product's lifecycle in order to "de-silo" the manufacturing process. This equips engineers with information to monitor an existing object and to explore hypothetical future scenarios. The virtual model is an extension of humans' ability to construct mental models, and visualisation is an integral part of the DT. Expansion into other domains has led to a greater variety of definitions, reflected in academic literature (Jones et al., 2020) and standards (Wang et al., 2024). Varying aspects include fidelity, nature of the physical entity, and level of connection between virtual and physical entities. Current usage of the term "Digital Twin" can often overlap with the established concept of a virtual simulation or digital model. This paper acknowledges all interpretations of the term, but explores these during analysis.

In education, reviews by Alghamdi et al. (2025) and Bachmann et al. (2024) highlight Digital Twins as an emerging but promising technology. However, they also identify a lack of empirical validation, particularly through long-term studies, and note security, privacy, and scalability as challenges. In engineering education, reviews by Kotecha et al. (2025) and Shaikh et al. (2024) both conclude that DTs have potential, while a bibliometric review (Chamorro-Atalaya et al., 2024) demonstrates growth in this area. These papers analyse DTs' applications, but their coverage of learning outcomes and experiences is very limited. Assessment of specific learning outcomes is important to understand how theoretical potential translates to students. In specific engineering fields (Kumar Karanam & Hartman, 2025; Omrany et al., 2025) DTs'

effects on measured learning outcomes have been identified. To the authors' knowledge, no reviews consider this area within engineering education as a whole.

Literature reviews in this area also tend to evaluate educational tools based on outcomes only. Meanwhile, this review adopts a constructivist approach, arguing that measurable teaching and learning *experiences* are as important as the outcomes they lead to, as argued by a previous review in a similar area (Sellberg et al., 2024). Both qualitative and quantitative measures of learning are therefore considered.

This review builds on previous literature by examining how the proposed benefits of DTs in engineering education translate to tangible student learning outcomes and experiences. It aims to address the following research questions:

- How strong is the evidence to support use of Digital Twins in engineering education?
- What learning outcomes and experiences (cognitive, behavioural, and affective) emerge from the literature when Digital Twins are compared to traditional teaching?
- What gaps, challenges and barriers limit the strength of evidence?

METHODS

To address the research questions, the PICO framework (Richardson et al., 1995), was used to clarify eligibility criteria. Two comparison points were considered eligible under the umbrella of "traditional teaching" stated in the research questions; campus management applications were not considered. The "Outcome" section was left open for investigation (see Table 1).

Table 1: PICO framework to define eligibility criteria

Category	Eligibility	Method
Population	Students and teachers in higher engineering education	Search strategy, inclusion strategy
Intervention	Intervention must be described as a "Digital Twin"	Search strategy, inclusion strategy
Comparison	Physical laboratories (experiments, demonstrations, practical coursework)	Inclusion strategy
	Theoretical teaching (lectures, worksheets, theory-based exams)	Inclusion strategy
Outcome	To be investigated; at least one measured effect required	Inclusion strategy

Search Strategy

A systematised review approach was taken for this study (Grant & Booth, 2009). This follows a similar process to a systematic review, but omits steps that require multiple independent reviewers. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) reporting methodology was used to describe all stages transparently (Page et al., 2021). Figure 1 illustrates the review process.

To constrain population and intervention, the search strategy ("digital twin" OR "virtual twin" OR "digital shadow") AND engineer* AND (educat* OR curricul*) was obtained through an iterative search. This was conducted on 9th December 2025 through Boolean search in Scopus, Web of Science, and IEEE Xplore, with minor syntax adjustments for each, on title, abstract and keywords. Literature reviews were excluded through databases' filtering tools.

Three papers were also found by hand search. All results were saved and manually deduplicated.

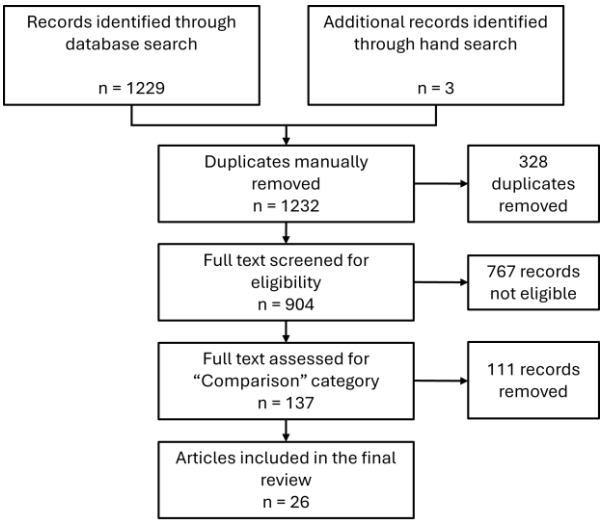


Figure 1: PRISMA flowchart for literature search and inclusion in this study

The following inclusion and exclusion strategies were applied manually to the full text of deduplicated literature. No constraints were put on date of publication; pre-print papers were also included. Though inclusion criteria aim to be as objective as possible, ambiguous cases remain where the primary researcher's judgement was required. The lack of independent review to validate these decisions is acknowledged as a limitation of the study.

Since this review focuses on outcomes, articles must include at least one empirical learning measure. This must be primary (e.g. not literature reviews) and must relate to students' learning (e.g. not system performance data alone). Both qualitative and quantitative measures of learning were accepted.

To remove superficial search results, articles that did not address the population or intervention were excluded. Only literature that referred to its intervention as a Digital Twin was included, regardless of implementation level, but evaluation of the varying definitions of Digital Twin in an educational context forms part of the analysis.

In some cases, Digital Twins featured in the learning outcomes themselves (for example, to prepare students to use DTs in industry). It was decided to exclude these papers from the study, and to focus on use of DTs as a teaching tool, not as a learning objective. Finally, fifteen papers that were not available in the authors' native language (English) were excluded. This is acknowledged as a limitation of the study that may centre Western education approaches. Geographic analysis of included papers has been provided for transparency.

Because literature was evaluated only by a single reviewer (the primary researcher), a formal risk-of-bias screening stage was not conducted. This is common in systematised reviews (Grant & Booth, 2009). However, articles with obvious quality concerns were removed during the screening stage. All included articles were also critically appraised for strength of evidence, which forms part of the review. Screening for the Comparison category of the PICO framework also occurred at this stage. Studies comparing the intervention to either theoretical teaching or in-person laboratories were included and classified. Ideally, this would involve control and experimental groups. However, though considered less strong, studies where students compared their own perceived learning to a clearly defined reference were also included.

Analysis Methods

Outcomes were classified into three dimensions (Rogaten et al., 2019): cognitive (knowledge and understanding), behavioural (actions and skills), and affective (attitudes and emotions). This involves some simplification – for example, academic grades could be considered both cognitive and behavioural – but gives a general idea of the learning effects linked to DTs.

Due to ambiguity surrounding the term, many interventions described as a Digital Twin do not match Grieves' definition (Grieves, 2005). To understand how the term is used in education, interventions were classified into three levels, proposed by Kritzinger et al. (2018). This is not the only way to classify DTs, but its focus on information flow aligns with the philosophy of Grieves' original concept. A low-level Digital Model involves no real-time connection between virtual and physical entities. A Digital Shadow involves a one-way connection from the physical entity to its virtual twin, so that the twin updates in real-time to reflect its physical counterpart. A fully-realised Digital Twin is bidirectional, so that the virtual entity can also influence the physical twin. Many studies avoided defining their Digital Twins; where this caused uncertainty, the intervention was categorised as a low-level Digital Model.

RESULTS

Figure 2(a) demonstrates a balance of journal articles and conference papers. Figure 2(b) shows that recent literature dominates, which reflects the novelty of the Digital Twin concept in education, but does limit ability to separate studies from the social and historical context of this time period. Finally, Figure 2(c) shows that literature represents multiple geographical regions; however, European and Western education is centred, which impacts generalisability.

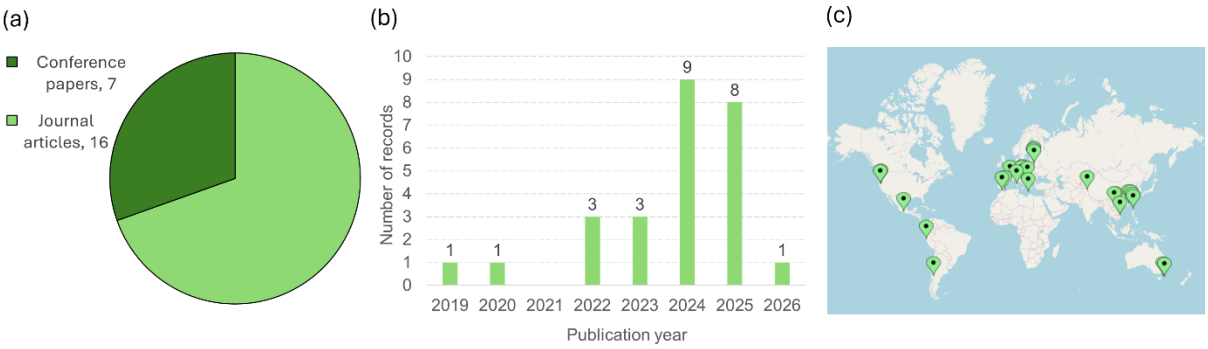


Figure 2: Analysis of included records by (a) type, (b) publication year and (c) location

Digital Twins Compared to Theoretical Teaching

Literature comparing Digital Twins to theoretical teaching (Table 2) focuses on improving understanding, providing real-world knowledge, and creating interactive learning experiences.

Table 2: Summary of literature comparing Digital Twins to theoretical teaching

Study	DT Level	Strength of Evidence	Dimensions
The Experience of Introducing Digital Twins Into the Educational Process on the Example of Training in the Repair of aircraft Equipment Units (ainakulov et al., 2023)	Model	Low	Behavioural
Effective Application of Operator Training Simulator in Experiential Education (Bělohlav et al., 2024)	Model	Low	Cognitive
Digital Twin-Enhanced Programming Education: An Empirical Study on Learning Engagement and Skill Acquisition (Lu & Hu, 2025)	Model	High	Affective, Behavioural, Cognitive
Exploration of the Application and Practice of Digital Twin Technology in Teaching Driven by Smart City Construction (Ning et al., 2024)	Model	Low	Behavioural, Cognitive
Digital Twin-Based Active Learning for Industrial Process Control and Supervision in Industry 4.0 (Ortiz et al., 2025)	Twin	Moderate	Behavioural
Digital Twin and Web-Based Virtual Gaming Technologies for Online Education: A Case of Construction Management and Engineering (Sepasgozar, 2020)	Twin	Low	Affective, Cognitive
Application of Digital Twin Technology in Mining Machinery Education (Su et al., 2025)	Model	Low	Behavioural, Cognitive
Interactive Application as a Teaching aid in Mechanical Engineering (Weis et al., 2024)	Model	Low	Cognitive
The Impact and Diversity of Digital Twin Technology and Immersive Learning in Education: A Case Study of the University “Aleksandër Moisiu” (Zeneli & Cerma, 2026)	Model	Low	Affective
Research on Innovative Models of Industry-Education Integration to Promote Sustainable Education in Agricultural Machinery Majors (H. Zhang et al., 2025)	Model	Low	Behavioural
The Effectiveness of a Digital Twin Learning System in Assisting Engineering Education Courses: A Case of Landscape Architecture (J. Zhang et al., 2024)	Shadow	High	Affective, Behavioural, Cognitive
Design and Implementation of a Virtual Experimental Teaching System for Deep Energy Exploitation Based on Digital Twin Technology (Zhao & Zhu, 2024)	Model	Low	Cognitive

Behavioural Outcomes and Experiences

Improvement in academic results is reported by Su et al. (2025) and J. Zhang et al. (2024). Though the first set of results is inseparable from effects of Covid-19, the second is stronger; differences between experimental and control groups were significant to $p < 0.001$. More industry-oriented performance improvements were found by Ortiz et al. (2025) and H. Zhang et al. (2025).

Lu & Hu (2025) designed a smart classroom with virtual models for students in a first-year programming course. Students reflected on their experience, with questions targeting cognitive, behavioural, and emotional engagement. Behavioural engagement was found higher within the experimental group than the control, to significance of $p < 0.001$. Learning logs also reflect that students using DTs were able to use their time more efficiently.

Cognitive Outcomes and Experiences

There is a lack of consensus on several cognitive aspects. Improvement to self-reported understanding is reported by Weis et al. (2024), but Zhao & Zhu (2024), who created dynamic models to teach fracture processes, did not find significant differences in theoretical comprehension tests. Similarly, qualitative feedback in (Bělohlav et al., 2024) indicates increased creative thinking after use of a virtual distillation column, but J. Zhang et al. (2024) found no significant difference in creativity between experimental and control groups, although testing methods for this lack detail and cannot be assessed for construct validity.

Despite these conflicts, there is convincing evidence that Digital Twins can introduce new ways of thinking. Zhao & Zhu (2024) reported observations of increased confidence, more active learning, and greater practical understanding in students who were exposed to a DT, albeit in a very small sample. J. Zhang et al. (2024) found improvements in critical thinking, though testing methods remain undefined. Lu & Hu (2025) found that self-reported engagement in the cognitive dimension was significantly higher in the experimental group; through tests of cognitive skills, they also found significant improvement in syntax, algorithmic thinking, and debugging ability, with algorithmic thinking being particularly notable. Qualitative evidence suggests that this was due to DTs providing context to abstract concepts. Also of note, lower-performing groups demonstrated greater improvement; Lu & Hu suggest that DTs' alternative visualisation methods may act as an equalising technology. Whether any of these changes to thinking translate to long-term effects, however, remains unknown.

Affective Outcomes and Experiences

Little evidence is available on the affective impact of DTs compared to traditional teaching. Zhao & Zhu (2024) found that learning experience improved with use of DTs, while learning motivation was unchanged, but its measurement method is unclear. Lu & Hu (2025) found that DTs significantly improved self-reported emotional engagement; of note was their potential to reduce anxiety due to lower-stakes experiences of failure. Students reported that they could take risks because they were less afraid of causing errors, facilitating adventurous exploration of edge cases. Meanwhile, students in the control group reported frustration when receiving error messages without context. Reduction of anxiety is relevant to domains outside of this study's computer science application, and may warrant investigation in other contexts.

Digital Twins Compared to Physical Labs

Literature comparing Digital Twins to physical labs (Table 3) focuses on increasing availability of hands-on opportunities, improving efficiency, and attaching meaning to laboratory work.

Behavioural Outcomes and Experiences

Evidence for behavioural benefit is very tentative. Tang & Li (2023) replaced a physical controller with a virtual model and observed improvement in grade distributions between comparison and intervention years. However, this result lacks generalisability on its own, as the study is highly ecological. The only other study that measured academic outcomes compared to physical labs (Liljaniemi & Paavilainen, 2025) found no significant differences. Meanwhile, there is mild evidence that DTs improve accuracy and efficiency compared to physical labs. Azkarate Fernández et al. (2019) found that virtual commissioning increased self-reported learning efficiency in a programming exercise due to early error detection, reduction of downtime, and ability to work in parallel. This is limited by a lack of formal qualitative reporting combined with a small sample size, leading to polarised results.

Qualitative evidence from Deniz et al. (2022) suggests that DTs provide access to a greater range of experiences and roles than hands-on labs. Finally, Darejeh et al. (2025) found that use of virtual reality (VR) to teach composite manufacturing processes worsened task completion time, but Liljaniemi & Paavilainen (2025) found that this gap decreased over time.

Table 3: Summary of literature comparing Digital Twins to physical labs

Study	DT Level	Strength of Evidence	Dimensions
Reimagine Lab: Bridging the Gap Between Hands-On, Virtual and Remote Control Engineering Laboratories Using Digital Twins and Extended Reality (Alsaleh et al., 2022)	Shadow	Moderate	Affective
Virtual Commissioning of a Robotic Cell: An Educational Case Study (Azkarate Fernandez et al., 2019)	Model	Moderate	Behavioural, Cognitive
Photogrammetry as a Method of Educational Innovation. Civil Engineering Student Case Study (Ballinas-González et al., 2024)	Model	Low	Affective, Cognitive
Virtual Reality and Digital Twins for Mechanical Engineering Lab Education: Applications in Composite Manufacturing (Darejeh et al., 2025)	Model	Moderate	Behavioural, Cognitive
Combining Virtual Reality With Mixed Reality for Efficient Training in Battery Manufacturing (Denisart et al., 2024)	Model	Low	Behavioural, Cognitive
Online (Remote) Teaching for Laboratory Based Courses Using "Digital Twins" of the Experiments (Deniz et al., 2022)	Model	Moderate	Affective, Cognitive
User Acceptance of a Modular Interactive Digital Twin of the Production Department for Virtual Reality (Dvořák et al., 2022)	Shadow	Moderate	Cognitive
RHL-Butterfly: A Scalable IoT-Based Digital Twinning Platform for Embedded Systems and Remote Laboratories (Guo et al., 2025)	Model	Low	Affective
Digital Twinning and Remote Engineering for Immersive Embedded Systems Education (Hussein et al., 2023)	Model	Low	Affective, Cognitive
Enhancing Engineering Education Through Immersive Environments – A Study of the Holodeck VR System in Hydraulics and Pneumatics (Liljaniemi & Paavilainen, 2025)	Model	Moderate	Affective, Behavioural, Cognitive
Educational Metaverse (Martínez-Gutiérrez et al., 2024)	Model	Low	Affective
Integrating Digital Twins of Engineering Labs Into Multi-User Virtual Reality Environments (Norambuena et al., 2025)	Shadow	Moderate	Affective, Cognitive
Research And Practice of PLC Experiment Teaching Based on OBE and Digital Twin (Tang & Li, 2023)	Shadow	Moderate	Behavioural
Virtual Labs for Higher Education in Industrial Engineering (Terkaj et al., 2024)	Shadow	Low	Affective, Cognitive

Cognitive Outcomes and Experiences

Evidence for cognitive outcomes is mainly, but not wholly, positive. Ballinas-González et al. (2024) and Hussein et al. (2023) found improvement in self-reported understanding, while Denisart et al. (2024) and Dvořák et al. (2022) found improvement in post-tests of comprehension and recall. However, lack of statistical analysis obscures significance, especially as several studies have small samples. There is also a possible improvement in cognitive load: Darejeh et al. (2025) found that mental and physical demand was lower in the

experimental group, though lack of distinction between VR and DTs is a limitation. Thematic analysis by Hussein et al. (2023) identified that a virtual parking lot helped with design approach and was more intuitive than traditional breadboards, but was harder to debug.

The potential of DTs to enable new ways of thinking is evident here. Qualitative responses in (Deniz et al., 2022) found that students could easily repeat virtual experiments, and could vary parameters to edge cases, echoing findings by Lu & Hu (2025) in theoretical teaching. Liljaniemi & Paavilainen (2025) observed more active engagement, spatial awareness, and confidence in students using virtual laboratory exercises, though these themes were not formally reported. In (Norambuena et al., 2025), students interacting with a virtual engine reported greater self-reported safety, participation, and communication, although lack of counterbalance may introduce recency effects. However, there is also evidence that aspects of physical labs are missing from DTs. Terkaj et al. (2024) used Digital Twins of physical labs within industrial engineering courses, and the limited feedback available suggests that students would miss access to physical instruments. Deniz et al. (2022) also found that simplifications in the DT could prevent learning experiences caused by making errors.

Affective Outcomes and Experiences

There is a moderately strong body of evidence for DTs' ability to engage and motivate students. Ballinas-González et al. (2024) and Liljaniemi & Paavilainen (2025) found improvements in self-reported engagement with Digital Twins. In (Norambuena et al., 2025), self-reported interest in a virtual engine was higher than a physical experiment, and 80% of students favoured the intervention. Using the System Usability Scale, Alsaleh et al (2022) found that usability was noticeably higher for a Digital Twin of a 3D crane than for traditional desktop experiments. However, these measures are vulnerable to the influence of novelty effects, especially as most were not counterbalanced. Meanwhile, several studies evaluate feelings of immersion and realism, with varying results. Qualitative feedback in (Deniz et al., 2022) indicated that a virtual experiment platform decreased feelings of realism, but Guo et al. (2025) and Martínez-Gutiérrez et al. (2024) reported that virtual and physical experiences did not feel different to students. Note that this measure is also prone to publication bias.

Compared to cognitive experiences, very few studies examine emotional experiences during the learning process. Qualitative feedback in (Deniz et al., 2022) highlighted a possible detriment to collaboration and social aspects, and similar feedback in (Liljaniemi & Paavilainen, 2025) expressed that virtual experiences did not give the same feeling of achievement from creating a physical product. These fragmented negative aspects point to a possible neglect for emotional experiences, which could be explored in future research.

DISCUSSION

Evidence supporting educational applications of Digital Twins is positive but tentative. No single quantitative outcome is conclusively linked to DTs, and though positive results dominate, this may be due to publication bias. Contradiction within several measures also indicates that consensus has not been reached. However, evidence of improved cognitive outcomes and experiences is most promising, especially where combination with curriculum reform stimulates different ways of thinking. The fact that DTs can enable students to learn actively, in context, and through failure is supported by diverse qualitative evidence. It is proposed that Digital Twins can be used as a platform to introduce ways of learning that may not otherwise arise naturally, but that benefit also depends on underlying teaching values.

Main gaps and barriers to research are identified as follows. Affective outcomes and experiences are particularly underrepresented. Very few studies compare affective outcomes between DTs and theoretical teaching, and though there are more affective outcomes reported for laboratory applications, almost all of these are limited to motivation and perceived realism. Meanwhile, a breadth of emotional experiences during learning could merit research, as well as development of emotionally charged outcomes such as empathy and collaboration.

Many qualitative results are not directly reported. This limits understanding of the student experience, as indirect data involve an extra degree of interpretation. Since several papers mention student feedback, qualitative data appear to be available, but they are not translating to publication. This highlights an opportunity to draw from these data in more depth using formal qualitative analysis techniques.

Lack of clarity over the term “Digital Twin” limits homogeneity. Realisation level varies between studies, with only two studies implementing a full Digital Twin, and many studies implementing a low-level Digital Model. Several papers do not clearly define their own Digital Twin, and greater transparency in future research would prevent misconceptions about technological feasibility. Furthermore, several learning benefits identified in this review can be achieved by low-level Digital Models alone. Whether benefit improves with level of realisation, or whether simpler tools are sufficient, could be a topic for future review.

As found by Alghamdi et al. (2025), lack of long-term analysis remains a limitation. It is unknown whether benefits are retained in subsequent years, or whether they translate to professional environments. Not all benefits must be long-term; some immediate impacts, such as reduced anxiety and increased autonomy, are notable on their own. However, many of the behavioural and cognitive outcomes in this review would benefit from longitudinal evaluation.

Finally, most included studies do not state the gender balance of participants. Where it is stated, all studies use a male-majority sample, and so averages will bias towards the male experience. While this may reflect the current makeup of engineering students, learning requirements of female students may be different due to gendered experiences, expectations, and challenges in a male-dominated field. Future work could investigate whether benefits and disadvantages of DTs are equally received by all students.

CONCLUSIONS

While Digital Twins are not conclusively linked to any quantitative learning measure, there is evidence that they offer a platform for new learning experiences. When informed by pedagogical values and student needs, cognitive benefits can be realised, especially by prompting active, contextualised, and reflective thinking. Behavioural aspects are not as convincingly evidenced. Meanwhile, there is a gap to research emotional learning experiences and emotionally charged skills. In future work, there is also a need to understand experiences of marginalised groups, to conduct longitudinal research on outcomes, to be transparent about the level of technology implemented, and to consider formalising qualitative feedback.

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Artificial intelligence usage

Generative AI (Microsoft Copilot) was used to translate syntax of Boolean search strings between databases. All syntax was manually reviewed before use. No AI tools were used at any other stage in the research and writing of this review.

Data access

No new data were generated or analysed in this study.

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SUPPORTING STUDENT TEAMS TACKLING WICKED PROBLEMS: INTRODUCING CARDS OF AMBIGUITY

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ABSTRACT

Project- and challenge-based courses in higher engineering education that address wicked problems introduce ill-defined, real-world problems to students. In these courses, they experience various forms of uncertainty and ambiguity inherent to complex problems, stemming from unclear problem definition, contradictory information, unpredictable project directions, and contradictory feedback from various supervisors. Students vary widely in how they perceive and react to ambiguity and uncertainty: some find uncertainty stimulating and creatively liberating, while others experience confusion, anxiety, and avoidance. Interviews performed with educators and students at TU Delft revealed that throughout the various phases of such projects, students frequently experienced frustration, insecurity, and overwhelm. These emotional responses strongly shape learning, yet emotional competencies are rarely addressed explicitly in engineering education. We also saw that educators often struggle with finding appropriate materials and methods to guide students through the process without over-directing. Most educators lack the pedagogical approaches needed to support the development of reflective, collaborative, and emotional competencies needed for dealing with wicked problems. To address this gap, we introduce the *Cards of Ambiguity* - a serious game designed to help student teams reflect on and discuss potential responses to ambiguous and uncertain situations. It aims to reduce negative emotions, build confidence, and normalise uncertainty as an inherent part of tackling wicked problems.

KEYWORDS

Ambiguity, Uncertainty, Complex problems, Emotions, Serious game, Standards: 3, 7, 8 and 10

INTRODUCTION

Wicked problems in project-based education

Active and experiential learning methods, such as challenge-based learning in higher engineering education (Gallagher & Savage, 2023; Lavado-Anguera et al., 2024) are advocated by the CDIO Standard 8. These approaches integrate theoretical knowledge with practical applications through relevant real-world cases and pressing societal challenges presented by external stakeholders (Guerra et al., 2017). Besides increasing students' intrinsic motivation, these active learning formats help to prepare students for professional environments by fostering the development of transversal skills (formulated in the CDIO Standard 3 and 7), such as critical thinking, problem-solving, and creativity (Sari et al., 2024, van Uum, & Pepin, 2020). Given that real-world cases often transcend the boundaries of academic disciplines, project-based educational practices facilitate contextual and inter- or transdisciplinary learning (Michel, 2009).

Tolerance of Ambiguity and Uncertainty

Complex projects central to challenge -based learning are "challenged by potential disruptions characterized by growing volatility, uncertainty, and ambiguity" (Nachbagauer, 2021). While uncertainty and ambiguity can be defined distinctly - uncertainty referring to events or trends that are difficult to predict even with sufficient information, and ambiguity relating to situations in which information is incomplete, unclear, contradictory or subject to multiple interpretations (Taskan et al., 2022) – the terms are often used interchangeably (Budner, 1962; Winkler, 2016).

Individual differences in how people interpret ambiguous situations and respond to unfamiliar or incongruent cues (often referred to as tolerance of ambiguity or uncertainty) are well-documented (Budner, 1962; Ely, 1989). Individuals with low tolerance of ambiguity and uncertainty often struggle to adapt to complex situations, displaying avoidance behaviours, rigid thinking, and a strong preference for certainty (Furnham & Ribchester, 1995). In contrast, individuals with high tolerance tend to perform better in complex problem-solving (O'Connor et al., 2018). They demonstrate greater flexibility and creativity (Tegano, 1990), effective learning in new contexts (Fenton, 2019), and a more open attitude toward diversity (Wilkinson, 2006). These associations make the facilitation of tolerance of ambiguity an appealing learning goal, particularly in challenge-based learning (Saarikoski & Rybushkina, 2019).

The term "tolerance", however, may be insufficient to capture the range of learners' responses to ambiguity. First, learners must absorb new information that may contain unknowns, hold contradictory or incomplete information without prematurely rejecting it and integrate new information into existing cognitive structures. These steps require not just simply bearing uncertainty, but accepting it and embracing it. For these reasons, we propose replacing "tolerance of uncertainty" with the broader notion of "coping with ambiguity and uncertainty."

Coping with ambiguity and uncertainty in educational settings

To introduce the aspects of uncertainty and ambiguity in challenge-based courses addressing complex problems, we draw on the conceptual model developed by Hillen and colleagues (Hillen et al., 2017). This model underscores the significance of various sources of ambiguity and uncertainty, individuals' subjective perceptions of them, and the psychological responses (covering cognitive, emotional, and behavioural responses) they elicit.

Ambiguity sources

The student-centred approach of challenge-based education inherently introduces ambiguity and uncertainty. Students may choose topics beyond the teacher's expertise, pushing educators to act less as content experts and more as process facilitators (Bohm et al., 2020). For students, ambiguity arises when project scopes are unclear, key information is missing, the available or found data are contradictory, solution paths are unfamiliar, multiple solutions exist without established best practices, or project outcomes cannot be predicted (Tao, 2024).

They can experience individual uncertainty that arises from perceived deficits in knowledge, skills, or rules needed to solve the problem (Daalhuizen et al., 2009). Low self-efficacy reduces motivation, particularly when outcomes are uncertain (Bandura, 2001; Bandura & Wessels, 1994). Task uncertainty can arise from the unpredictability of inputs and outputs within the course (Daalhuizen et al., 2009, Griffin et al., 2007). Social uncertainty arises from insufficient information exchange or limited collaboration among team members or external stakeholders (Daalhuizen et al., 2009).

Perception of ambiguity and uncertainty

How students perceptive uncertainty varies according to individuals' backgrounds, experiences, and personality traits. Cultural and educational contexts also shape these perceptions. Research on design students shows that practice and experience strengthen learners' confidence in managing uncertainty. Students reported that discussing uncertainties, gathering and reviewing information, and seeking external models, feedback, or collaboration helped them mitigate the negative effects and change the negative perception of design-related uncertainty (Tracey & Hutchinson, 2018).

Responses to uncertainty and ambiguity

Some learners experience uncertainty as liberating and appreciate the agency or freedom of choice (Anselme, 2010; Tracey & Hutchinson, 2018). Ambiguity can also foster creativity by encouraging exploration beyond conventional boundaries. Suzawa (2013) argues that ambiguity is inherent to human knowledge and should be embraced through openness.The positive cognitive responses can range from acknowledging uncertainty, feeling attracted to it, and experiencing curiosity. However, when ambiguity levels become too high or when students cannot handle unclear information, this can evoke strong negative emotions, which then prevent students from learning and making important decisions (Levy & Schiller, 2023). Negative cognitive responses encompassed denial, aversion, distrust, self-doubt, confusion, and catastrophizing. The emotional responses cover the range from comfort, enjoyment, and excitement to discomfort, stress, anxiety, fear, depression, and anger.

Some negative behavioural responses aimed to prevent the negative effects of uncertainty—such as avoiding ambiguous situations—while others sought to manage these effects once they arose, for instance by exerting control over manageable factors. Information seeking, adaptation, functional engagement, deliberation, and disclosure can be labelled as positive behavioural responses. In contrast, avoidance, dysfunction, decision paralysis, non-disclosure, resignation, and control-oriented behaviour were classified as negative responses (Hillen et al., 2017). This is in line with other studies, which highlight that wicked problems require not only cognitive skills and logical reasoning but also emotional competencies (Lönngren et al., 2023).

With this background knowledge, we were interested in how engineering students experience project- and challenge-based courses at TU Delft. We have interviewed educators and students to answer the following questions: (1.) What challenges do students encounter when working with wicked problems? (2.) How do students cope with these challenges? (3.) How do teachers support students in navigating ambiguity and uncertainty? At the end of this paper, we discuss the findings with special attention to emotions that arise during these projects and introduce the Cards of Ambiguity game, designed to support student teams in dealing with ambiguity and uncertainty during courses tackling complex problems.

METHODS

In this project we focused on how complexity, ambiguity and uncertainty manifested in courses in which students were dealing with complex problems. We conducted interviews of approximately one hour with 21 education practitioners and 9 students across various engineering programmes at TU Delft, using purposive and snowball sampling (Cohen, 2002). First, we approached 21 educators, involved in multi-, inter- and transdisciplinary project- and challenge-based courses, as they interact with a large number of students, and they have experienced diverse cognitive, behavioural, and emotional responses of students through the years. To validate the educators' experiences, we also interviewed some students who followed such courses. We stopped the student interviews when we reached data saturation. The questions were designed to gain a detailed understanding of the challenges students faced related to ambiguity, complexity, and uncertainty, as well as the emotions they experienced and how these emotions influenced their approach to tackling these challenges. The data were organised into themes that informed the initial insights and hypotheses regarding the types of competencies needed to navigate wicked problems. The research design, including participant recruitment, data collection, and data management, was approved and guided by the Human Research Ethics Committee of TU Delft (19-Feb-2025, #5081).

The interview data were analysed using a reflexive thematic analysis approach. Transcripts were read multiple times to become familiar, then coded inductively to capture patterns in how students and educators experienced complexity, uncertainty, and ambiguity. Codes were gradually clustered into broader themes through an iterative process of comparing meanings, revisiting the data, and refining interpretations. Throughout the analysis, we engaged in memo writing to reflect on emerging ideas and to remain aware of our own assumptions. To support validity, several strategies were used. First, codes and themes were checked with participants to ensure accuracy of interpretations. Second, frequent review of raw transcripts along the analysis process ensured that interpretations remained grounded in participants' words and experiences. Finally, the iterative nature of the design-based research process strengthened validity because preliminary insights could be tested and refined in later cycles of data collection and intervention development.

RESULTS

Challenges experienced during the initial phase of projects with wicked problems

At the outset of projects involving wicked problems, students often struggled to establish a workable starting point due to the complexity and ambiguity of the problem space. They found it difficult to determine what mattered when interacting with real-world constraints and competing values. Although many recognized that issues such as sustainability or future-

oriented design involve intertwined technical, social, and ethical dimensions, they still found it hard to decide which aspects were relevant.

Ambiguity in problem definition further complicated the early stages. Students were also unsure what exactly the problem was. Although some were energized by abstract or controversial problems and proactively sought information, others responded with confusion and a sense of overwhelm, narrowing their attention to controllable elements and rushing to reach outcomes. Educators described this ambiguity as a confrontation with engineering identity, and students' mindsets are influenced by prior education.

"Engineering students are not so used to exploring wicked problems, because they think the world judges them on their solutions; It's their identity. And they've been taught their whole lives that there's one correct answer for everything. When it comes to less concrete things, they tend to go towards the efficient solution, which is oftentimes not the most innovative or the solution that gets to the core of the issue."

This stage was marked by frustration, confusion, and overwhelm, often leading students to rush toward simplified definitions, request detailed instructions, or label the project as vague. Many struggled to accept subjectivity and contradictory interpretations, preferring approaches that justified clear actions. Teachers, therefore, faced the challenge of offering guidance without over-specifying the task, leaving room for personalized learning.

Limited contextual understanding also shaped the early phase, especially in unfamiliar domains or projects with external partners. Students lacked insight into stakeholder priorities, constraints, and work practices, and were inexperienced in estimating timelines in real settings. Their initial ambition and confidence often diminished once they encountered unforeseen complexity. Some students avoided the human aspects of the work and focused on technical components, while others became uncertain about next steps due to the absence of a stable interpretive frame. Some teachers facilitated field visits to help promote students' contextual understanding as well as their motivation and interests in learning.

Challenges during the projects

After defining the problem, students moved into project planning and prototyping. Students noted that uncertainty manifested in this phase through unpredictable project directions, shifting requests, and conflicting disciplinary or personal constraints. Some struggled with ambiguity in communication with their peer students due to disciplinary gaps.

"There can be lots of communication challenges. Students from industrial design don't understand why something doesn't work because they don't have our technical knowledge, but we (biomedical engineering students) have a very technical mind. We focus on different things. People sometimes get confused and frustrated, and even avoid working together."

Projects also frequently unfolded in unexpected ways. Stakeholders changed their requests, and students revised their beliefs. These disruptions left many students feeling frustrated, stressed, and vulnerable. The resulting loss of orientation reduced motivation, leading some to lower their study ambitions. While some students struggled to adapt, negotiate with stakeholders, or persist in the face of uncertainty, others demonstrated proactivity, sought help, and maintained engagement despite time pressure and emotional discomfort. Both students and teachers emphasised that curiosity, positivity, and intrinsic motivation supported resilience, though educators found it challenging to foster these qualities.

Cross-disciplinary projects introduced additional difficulties when teachers and stakeholders from diverse backgrounds provided conflicting or expanding feedback. Students often felt overwhelmed and stuck with the process. Educators observed that perfectionism and low confidence hindered students' ability to navigate ambiguity. They argued that students needed to focus on the learning process rather than the perfection of outcomes.

Collaboration with peers, teachers, and stakeholders means confronting diverse professional and cultural backgrounds. When differences in working styles, expectations, or social norms were not openly communicated in the student teams, conflicts escalated, harming group dynamics and impeding learning. Unresolved tensions could affect psychological safety and student well-being. While some students embraced interpersonal differences and built strong social bonds, others avoided collaboration or felt marginalised. Both students and teachers agreed that effective collaboration is essential for engineering practice.

Challenges experienced at the end of the project

Students sometimes struggled to accept that no perfect solution exists when confronted with the inherent subjectivity and trade-offs of wicked problems. When multiple, even contradictory, outcomes were equally defendable and technically justified, students reported confusion, frustration, surprise, and dismissiveness. This often led them to seek standard answers, criticise alternative approaches, and reject divergent problem-solving paths.

Because projects could only address fragments of the broader complex problem, evaluation became more difficult to standardise. Yet students strongly desired clear rubrics to follow to achieve expected grades. Educators noted that many students sought reassurance and validation to reduce insecurity, and some complained about the perceived vagueness of assessment criteria. Emotions such as anger, frustration, and disappointment were common. Teachers attributed these reactions to limited confidence and difficulty accepting subjectivity.

Even when students produce project outputs in the short project period, they can remain uncertain about the feasibility of their solutions in practice. Many students perceived a gap between their outputs and real-world expectations, which contributed to doubts about their emerging professional competence and identity, as well as disappointment with their learning results. As mentioned by a student from Architecture:

"Sometimes, we feel frustrated, insecure, and fearful about what we can actually do. We are unsure about how our designs will be in real life."

DISCUSSION

Across all phases of project work, TU Delft students' experiences revealed that engaging with complex problems challenges their interpersonal skills, namely emotional resilience, collaborative skills, and tolerance for ambiguity. Students frequently struggled with the absence of clear problem definitions, the coexistence of multiple valid solutions, and the subjective nature of both decision-making and assessment. These difficulties were intensified by cross-disciplinary collaboration, shifting stakeholder expectations, and limited time for iteration. Emotional responses such as confusion, frustration, insecurity, and disappointment were common.

We also saw that curiosity, intrinsic motivation, and a supportive learning environment can help students engage more constructively with complexity. Educators play a crucial role in normalising ambiguity, guiding cross-disciplinary communication, and fostering psychological

safety. Ultimately, our study underscores that preparing engineering students for wicked problems requires deliberate attention to the development of reflective, adaptive, collaborative and emotional competencies. This requires explicit focus on strengthening interpersonal skills and teaching students to deal with the societal context.

It is not new that students need emotional competencies in addition to cognitive skills to tackle wicked problems (Lönngren et al., 2023). Several neuroscientific studies have shown that emotion and cognition are deeply intertwined in the human mind, and the division between them may be unrealistic. Both emotion and cognition influence human behaviours, including decision-making, and vice versa (Dolan, 2002; Pessoa, 2008); they guide behaviour by partially reactivating bodily and brain states from past experiences (Niedenthal, 2007). Some neuroscientists suggest that the brain's function during decision-making relies more on emotion than on intellect (De Martino et al., 2006).

How can we support students to deal with uncertainty and ambiguity?

While students and lecturers involved in challenge-based education must deal with various types and different levels of uncertainty, which inherently result in emotional responses, hardly any course developers make dealing with uncertainty and ambiguity explicit in their course design. At TU Delft, teachers expect students to take initiative and remain engaged even when facing ambiguity, and are often left to deal with uncertain and ambiguous situations on their own. Educators at higher universities, in general are not prepared to facilitate the development of emotional competencies (Tracey & Hutchinson, 2018). "*When facing challenging tasks, there is a need for a range of cognitive and emotional skills and other qualities that go beyond what most people normally learn in schools and higher education* (Ankrah et al., 2023)".

Insights from the literature review and interviews with TU Delft teachers and students informed the design of a game intended to support student teams working on complex project-based problems. **The Cards of Ambiguity** game aims to help students build confidence and autonomy in navigating ambiguous situations while reducing negative emotions such as anxiety and frustration (Tao, 2024). By discussing their experiences with uncertain project scenarios - an exercise aligned with intellectual candour (Lazarus et al., 2023) - students reflect on past responses, explore hypothetical challenges, and identify strategies suited to their team. It is building on educators' experience with confidence-building and reflective activities. Similar experiences were found with peer reflection by Bienkowska & Lovén (2017). The game thus fosters reflection, informal active learning, perspective-taking, empathy, and collaborative problem-solving, mostly belonging to interpersonal skills. Although team-oriented, the game incorporates a competitive element to appeal to players motivated by achievement (Heeter et al., 2011).

It includes 20 problem cards, 65 solution cards derived from both the research results and the literature, and erasable cards for students to add their own challenges and responses. Fig. 1 shows an example problem card, focusing on negative emotions emerging during the project (derived from the results), and an example solution card (suggested by an educator during the interview). During play, team members select and justify a solution card they believe best addresses the drawn problem card, then collectively choose the most suitable option. A typical session consists of five rounds plus a final reflective round, taking approximately 45 minutes. Additional time allows for the use of blank cards to tailor the activity to team-specific issues. All game materials - including instructions, cards, and packaging - are available for downloading and printing under the following link (Cards of Ambiguity).



Figure 1. The cover of the Cards of Ambiguity, an example of a problem and solution card

CONCLUSION

Challenge-based learning was shown to equip students with professional competencies, such as critical thinking, teamwork, self-direction, communication, and collaboration with societal stakeholders when compared to traditional educational methods (Klaassen & De Bruin, 2022, van Uum & Pepin 2020). Several studies have acknowledged that students and teachers experience uncertainty and ambiguity during challenge-based education (Bohm, 2024), while there was little attention paid to what challenges students experience, what kind of emotions these challenges trigger and how these affect their learning. This study first introduced a framework for ambiguity, based on Hillen et al (2017), listing sources, perception and responses to uncertainty in challenge-based learning. Then we listed the challenges students experienced per project phase and highlighted the emotions they reported to be related to the challenges. Although literature highlights that some learners experience ambiguity and uncertainty in a positive way, most emotions mentioned by teachers and students were negative. Educators, in general, thought that a positive and supportive learning environment is crucial in handling these emotions.

The results, namely the issues experienced by students and the copying mechanisms educators reported and found in literature, served as a basis for the game design. We wanted to create a tool that (1.) can be used by educators without extensive training, (2.) which incorporates theoretical and evidence-based elements about uncertainty and ambiguity, and finally (3.) stimulates informal collaborative learning, shaping how students perceive and respond to ambiguous challenges. Although previous versions of the game were tested in a project-based course by student teams, the testing mostly focused on playability and game mechanisms. The extent to which students learn from each other regarding how to respond to uncertainty and ambiguity in team projects, and whether the discussion helps to reduce negative emotions, needs to be evaluated in a classroom setup.

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BIOGRAPHICAL INFORMATION

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Yiwei Tao followed the Communication Design for Innovation MSc track at TU Delft. Her graduation project focused on tolerating ambiguity, and she created the first prototype for a serious game to support student teams in dealing with wicked problems.

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REDESIGNING FEEDBACK TO ENHANCE STUDENT DEVELOPMENT

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ABSTRACT

Feedback is fundamental to the educational development of engineering students. Students have often transitioned from a more supervised and directed style of learning in Further Education to becoming independent self-directed learners in Higher Education. As independent learners, feedback is of key importance as it offers both guidance and reassurance. A failure to engage with feedback could therefore have detrimental impacts on the learning experience. Arguably, feedback is most needed by those students who achieve lower grades. However, there exists a gap in current knowledge regarding which students access feedback, and if and how this feedback is then used. This original study aims to understand the types of students who engage with feedback and what this engagement looks like. The grades and feedback engagement records of 577 level 6 students in one module over 5 years were analysed, followed by interviews with 21 of the same students. Finally, 3 workshops each consisting of 4 students were undertaken. The results reveal that the higher a student's grades the more likely they are to access and utilise feedback. However, the students who are arguably most in need of the feedback due to receiving lower grades are the one of the groups least likely to access and action the feedback. There is a dichotomy between the type of feedback students want and the type they receive, and students across all grade boundaries believe feedback to be largely generic with little relevance to future module success. This research provides original insight into feedback actions and preferences of students and proposes solutions to redesign feedback to enhance student development.

KEYWORDS

Pedagogy, Curriculum Design, Collaboration, Learners, Standards:1

INTRODUCTION

The marking of work and provision of student feedback are some of the most commonly undertaken tasks within Higher Education (Winstone and Boud, 2022). Feedback itself is often considered crucial in both curriculum design and delivery (Scott and Fortune, 2013) and has been described as sitting hand in hand with the process of assessment (Chalmers et al., 2018). Feedback itself, however, is often considered of key importance for student development (Winstone et al., 2017). This is arguably critical for undergraduates who have often transitioned from a more directed and supervised way of learning to that of an independent learner. A failure to engage with and action feedback could lead to failing to fully understand a concept or learn from mistakes made. Ultimately this could then lead to graduates entering careers not fully capable to adequately perform the demands placed upon them.

This is arguably very problematic as Engineering and wider Built Environment students are often in high demand upon graduation (Higginbotham, 2025) and are therefore often required to 'hit the ground running' when commencing a new role. To ensure graduates are prepared to meet the needs industry presents, Higher Education Institutes need to suitably prepare students for such professional demands with appropriate knowledge, understanding, and critical thinking skills. Such preparation is achieved through the design and development of the Higher Education curriculum of which feedback is a core ingredient (Khan and Law, 2015; Hooda et al., 2022).

However, despite the importance of feedback being long understood and how it plays a crucial role in the Higher Education environment and in influencing its stakeholders (Hooda et al., 2022), there is a current gap in knowledge around the applicability and use of feedback by students, the types of students who access feedback, and why some students action feedback and others do not. The aim of this study is to understand which students engage with feedback, why, and what this engagement looks like. Addressing this gap in knowledge will help better inform Higher Education student feedback practices and prepare Engineering and Built Environment students for professional roles as leading industry practitioners' post-graduation. This is of international significance given the global nature of the roles available, and the often-common feedback practices adopted internationally throughout Higher Education. First, this paper outlines the importance of feedback before introducing the Engineering and wider Built Environment industries as the context in which this research takes place. The research methodology is then discussed before the findings analysed and the results presented. The significance of the study for current and future graduates, and the impacts the findings have upon graduate's respective future industries is then outlined. Recommendations from this original study are then stated for both the future agenda of feedback and curriculum design research and for how HEI's should look to structure their practices and processes going forward to maximise student learning and development.

This research links to the CDIO Standards 3.0, specifically Design-Implement engineering (Standard 5) in that this research focuses on student feedback and how this can advance learning as student's progress from basic to more advanced learning topics as part of broader curriculum design. This research also aligns with Active Learning (Standard 5.0) in that it supports student learning and development, helping motivate students and considers habits of lifelong learning. Finally, Program Evaluation (Standard 12.0) is also informed as this research is structured around better understanding student feedback perceptions, which can in turn be used to consider methods of continuous improvement across modules and programmes.

CURRICULUM DESIGN IN BUILT ENVIRONMENT EDUCATION

Graduates of Built Environment courses from Higher Education Institutes are increasingly in demand given the growth of the Built Environment over recent decades. This is due to an increased industry demand combining with a pipeline of fewer skilled professionals (Mackenzie et al., 2000). To help prepare graduates to meet this need, Higher Education Institutes provide a comprehensive and robust learning environment aimed at increasing a student's employability and general skills for life (Brint, 2018). Yet previous research has identified significant gaps in the level of knowledge gained by Higher Education students and the industry requirements they are faced with post-graduation (Azapagic et al., 2005).

To ensure such students are suitably prepared, Higher Education courses are designed with a robust curriculum in an attempt to ensure the progression of students from one level to the next (Khan and Law, 2015). Curriculum design has been described as crucial for Higher Education effectiveness (Barnett and Cole, 2005) and is one of the reasons there has been a significant increase in Higher Education curriculum research over the past two decades (Hicks, 2018). However, curriculum development research has been described as often disconnected, especially within Built Environment programmes (Posillico et al., 2022). This research goes further and finds that if curriculum design does not have a rigorous oversight process in place then the design of any curriculum will tend to favour lecturer skills rather than any requirements of the student (Posillico et al., 2022). Effective curriculum design should consist of clear content that is co-created amongst key stakeholders and is focused upon both the current skills students need within Higher Education and the skills they will need in future (Khan and Law, 2015). Although it is important to note that curriculum development alone is arguably not enough to support the development of student learning and that a diverse and comprehensive approach is required to maximise student knowledge and development (Doyle, 2023). For example, one often adopted assumption is that curriculum development occurs with feedback mechanisms embedded from the outset, with one study concluding this is often not the case (Molloy et al., 2020). Yet feedback is often considered a significant component of curriculum design, and is described as essential in every learner's journey (Scott and Fortune, 2013). Therefore, a core component of effective curriculum design is ensuring suitable feedback mechanisms are embedded into programmes and modules.

THE IMPORTANCE OF FEEDBACK

In a Higher Education environment, feedback can be defined as information given from lecturers to students to aid their understanding and help enhance the future work standards (Scott, 2014). The role of 'sustainable' feedback takes this concept further and introduces elements such as the feedback being a dialogue, with a focus both on immediate student improvement and of the ability of the student to 'self-regulate' performance on future tasks (Careless et al., 2011). One study claimed that feedback is said to be of the utmost importance in student development and learning (Gibbs and Simpson, 2005) as how feedback is understood and applied has long been understood to be crucial to student development and understanding (Timperley, 2007). This is arguably why lecturers' express frustration when students demonstrate limited engagement with feedback (Price et al., 2011).

Assessment feedback itself is often divided into two main categories. Formative is where feedback is provided throughout assessment and is intended for improvement purposes. Summative feedback is for evaluation purposes usually at the end of an assessment when it has been submitted, evaluated, and a mark awarded. Studies have shown that postgraduate students are more likely to question the validity of feedback and understand their own role in response to it, whereas undergraduate students saw the purpose of feedback in regards to

directing improvement (Smith, 2022). It has been argued that it is summative feedback that receives the most attention from lecturers (Onasanya and Ajamu, 2024).

Due to the importance of feedback, the practices, experiences, and expectations of Higher Education stakeholders has been explored from numerous perspectives in recent years. This includes the feedback delivery mode (Henderson and Phillips, 2019), the dialogue created through the use of effective feedback between students and lecturers (Winstone et al., 2017) and how student development can be enhanced through increasing the quality of feedback delivered (Dunworth and Sanchez, 2016). More recently (and perhaps unsurprisingly) feedback studies have focused on the interaction between feedback and Artificial Intelligence (AI). This includes the risks of implementing AI in marking student submissions as it was found AI provided higher grades and more generic and contradictory feedback on student submissions compared to lecturers (Usher, 2025). Another study found that the use of AI in creating and administering feedback, whilst having some variability, was found to be largely accurate and effective saving lecturer time in feedback creation and allowing greater numbers of students to receive feedback from fewer academic staff (Venter et al., 2024). However, the use of AI in assessment and feedback generally is still arguably a grey area and studies have shown how the acceptable line of usage by both staff and students is still being decided upon and agreed due to its relatively recent evolution and rapidly increasingly usage (Corbin et al., 2025).

A large-scale study conducted by Jansen et al. (2025) involving 1,709 secondary school students revealed a strong relationship between the way feedback is delivered and improvements in student academic performance. The findings highlight the critical role that well-structured, constructive feedback plays in supporting learning, particularly in the development of students' writing abilities. Rather than serving merely as an evaluative tool, feedback was shown to function as an instructional strategy that actively promotes student engagement and skill acquisition. The study found that if students receive feedback on their writing that identifies their knowledge gap and includes direction on how this gap can be closed, a rewarding intrinsically motivated experience is triggered by knowledge acquisition (Jansen et al., 2025). Feedback has also been viewed from the perspective of educators gathering feedback from learners in an attempt to enhance their own future performance (Mandouit, 2016). An earlier study also sought to understand how lecturers received and actioned feedback from students and found such reactions can be across a broad spectrum of shame, blame, tame, or reframe (Arthur, 2009).

Feedback can therefore serve a multitude of purposes for all stakeholders involved. However, feedback itself has been found to often be insufficient to aid development, delivered inconsistently, difficult to comprehend by the intended recipient, and even sometimes found to be discouraging towards improvement (Winstone et al., 2017). There have been growing calls that a collaborative approach between students and lecturers is required to improve the efficiency and effectiveness of feedback (Nash and Winstone, 2017). However, one criticism of the studies on feedback to date includes the fact they often presuppose both lecturers and students share the same understanding of what feedback essentially is (Molloy et al., 2020). This can be potentially problematic if perspectives are mismatched in that such a mismatch will prevent both effective feedback delivery and effective feedback receipt. Effectively delivering timely feedback has therefore been described as of crucial importance for student development (Khan and Law, 2015). However, there is a lack of research currently around which students access feedback, and if and how this feedback is then actioned.

RESEARCH METHODOLOGY

The identified research gap is investigated through three distinct research phases. The first research phase is inductive as the research data gathered is used to generate the theories and ideas to describe behaviours, rather than utilising existing theories that are then tested by the research process (Bell et al., 2022). The first adopts the ontological perspective of objectivism, a natural science approach where social phenomena exist independent of the actions of social actors (Robson and McCartan, 2017). This phase advocates for a positivist approach that ultimately determines the ontological and epistemological position is best understood via quantitative data (Clark et al., 2021). The data for this first research phase is anonymised records of student grades and whether or not summative feedback was accessed by each student. The data covers a total of 577 Level 6 Built Environment students over a 5-year period (20-21 – 24-25). The data was collated, compared, and analysed using Microsoft Excel. Trends and patterns are identified which then informed the development of the second research package.

A constructivist ontological position is adopted in the second research phase. Constructivism implies phenomena are socially constructed between, subject to change, and so are therefore best understood via an interpretivist epistemological approach (Clark et al., 2021). This approach is best suited to the collection of qualitative data. The research phase consisted of twenty-one semi-structured interviews. Purposive sampling was adopted. This is where participants who are able to best inform the research are approached for inclusion (Robson and McCartan, 2017). The questions asked resulted from the analysis of the first research phase, and the twenty-one semi-structured interview participants were from the cohort of 577 phase one students. The interview questions were structured using narrative analysis, a method by which questions are framed around the request for stories, with information then extracted, and is a technique that has been used increasingly in recent Built Environment research (Watts et al., 2023). Thematic analysis was then undertaken of the interview results, with themes of similarity and areas of differences identified across all the interview responses. Analysis of the interviews resulted in the development of the framework of feedback best practice that was then discussed in three workshops, each consisting of four different students as part of the third and final research phase. These workshops consisted of presentations of the overall research findings to those in attendance at each session. The proposed recommendations of the study were highlighted and ideas for improving the quality of feedback were discussed with feedback sough on the recommendations from the workshop participants. A process of thematic analysis was again undertaken with the feedback and comments from those in the workshop recorded, coded, and analysed.

FINDINGS AND DISCUSSION

Analysis of the data gathered across all three research phases revealed the following four main themes:

The students most and least likely to access feedback

Table 1 reveals the total number of students reviewed as part of the first research phase and illustrate which categories they fall within regarding both grade received and whether they accessed and engaged with feedback.

	Grades Achieved					Total Students
	70+	60-69	50-59	40-49	<39	
Students who accessed feedback (no):	101	75	34	8	7	**225**
As a %	55.80%	36.23%	35.42%	15.38%	17.07%	38.99%
Students who DID NOT access feedback (no):	80	132	62	44	34	**352**
As a %	44.20%	63.77%	64.58%	84.62%	82.93%	61.01%
Total students:	181	207	96	52	41	**577**

Table 1: Total student submissions in research package 1

Table 1.0 reveals that overall, across all grade brackets, 61% of students did not access feedback regarding their submission. If feedback is crucial for development as argued by Khan and Law (2015), then the initial barrier to overcome is arguably getting students to access the feedback in the first instance. Figure 1 analyses the data for patterns and trends by grade achieved and illustrates a curve that emerges within the data indicating that broadly, the lower grade a student receives, the less likely they are to access and engage with the associated lecturer feedback.

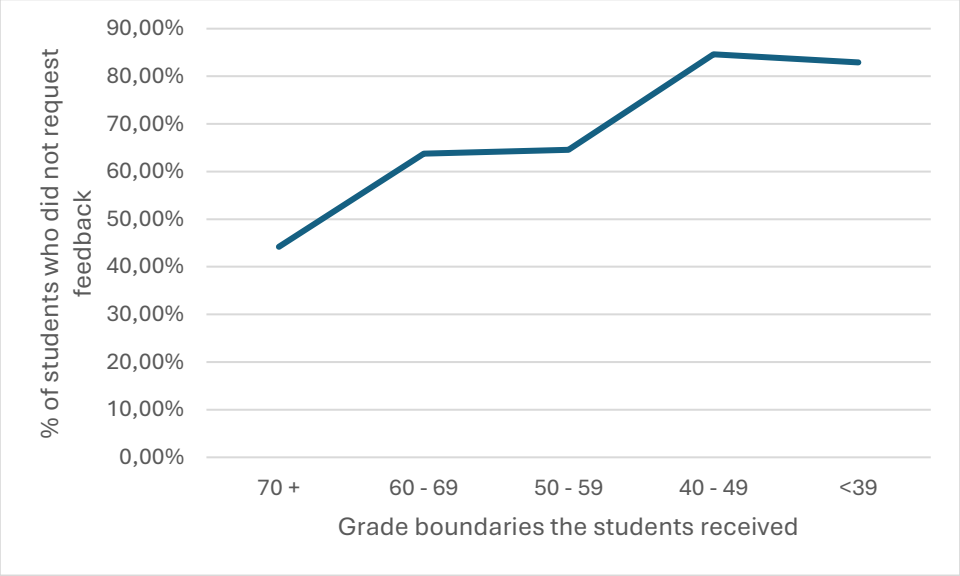


Figure 1: Students accessing feedback by grade received

This is arguably counter intuitive in that those students most in need of feedback (due to needing to improve their grades) are the ones least likely to access and engage with the feedback available. These results may not illustrate causation but there is a clear correlation that those who achieved the highest grades were the most likely to access feedback. These trends were also consistent across each of the five years analysed.

The dichotomy between the type of feedback students want and the type they receive.

When these results were explored within the interviews of the second research stage, one finding that emerged was the difference between the feedback students received and the feedback they actually wanted. Many participants who reported they did not access feedback themselves agreed in their reasons for not doing so, which can be summarised by one student who stated they:

"Every time feedback was mentioned [in class] … it was how we will get it within 15 days of submission"

In response to being specifically asked to describe feedback, one student stated:

"It is the information we get at the end of the module".

There was no discussion or awareness by this participant of formative feedback, and whilst they did not know the categories of feedback by name, summative feedback was the only type they were aware of and had any recollection of receiving.

A further student added:

"Lecturers do give feedback when we get our marks … but it's too late by then … I want to know what I can do better before I submit"

This was consistent across all those interviewed and revealed that the results largely aligned with those in the literature that summative feedback receives the most attention from lecturers (Onasanya and Ajamu, 2024) as this is what is primarily discussed by lecturers to students when they are discussing feedback. However, these findings go further and reveal that despite lecturers having a tendency to focus upon summative feedback, it is formative feedback that students most desire. This is confirmed by a final student who articulated well a belief shared by those participants who reported they did not access feedback:

"What's the point reading formative feedback…it's too late for that assignment"

Feedback is often too generic with little relevance to future module success.

Analysis and comparison of the results of all three research phases revealed that students also felt feedback was often too generic, one student confirmed:

"I find it really hard to see exactly which bits [of my assignment] the different feedback comments relate to"

This was expanded upon by a fellow student who confirmed:

"All assignment requirements are different…how will one feedback help another [assignment]".

One failure of feedback it appears, is that it often focuses upon what a student could have done differently in a past assignment, and has little focus on any transferable lessons that can be taken forward to future assignments and other modules.

However, interestingly, there was a difference in opinion amongst those interviewed between the students who did and those who did not report to have accessed and engaged with feedback. All those who reportedly do engage stated they understand the purpose and forms of feedback. Arguably, feedback helps all students improve, especially those most in need of improvement whose grades could be significantly enhanced, but the participants who did not regularly access feedback did not appear to agree. This builds on findings in the literature

regarding the understanding of feedback (Molloy et al., 2020) in that those who report a lack of understanding are those who don't fully engage with the feedback. However, all participants who stated they did regularly access feedback all espoused the benefits they experienced as a result. One student reported how feedback had helped them:

"Increase their grade" from one module to the next.

Other students reported that accessing and engaging with feedback avoided them making the same mistakes twice and they felt allowed them to gain higher grades in future modules.

Feedback as a monologue and not a dialogue

One key theme that arose in the final research package when best practice feedback frameworks were being discussed was the need for feedback to be delivered with the intention of a dialogue and not simply as a monologue. This theme has been mentioned in feedback literature for many years (see Careless et al., 2011; Winstone et al., 2017) but this research goes further and seeks to provide actionable solutions to dialogue creation.

The results of the workshops revealed that students heavily favoured a re-designed curriculum approach to feedback delivery that emphasized a focus on formative dialogues over summative monologies in order to enhance student development. Whist the importance of feedback is not perceived by some students, notably those who do not engage with feedback when available, this redesign will serve to both further develop the student who do engage with feedback, and get many of those students who currently do not engage with feedback to begin to do so. Arguably it is only through engagement with feedback that students can begin to truly develop their learning and understanding of concepts, and so overcoming the feedback engagement barriers some students typify is the first step of any successful student feedback delivery framework.

ONCLUSION

This study has demonstrated that feedback plays a critical role in supporting the transition of engineering and Built Environment students toward independent, self-directed learning. However, the findings reveal a persistent and concerning disparity in feedback engagement across performance groups. Students achieving higher grades were significantly more likely to access, interpret, and apply feedback, while those receiving lower grades, who arguably stand to benefit the most from feedback engagement, were among the least likely to engage. This highlights a systemic challenge within current feedback practices, whereby existing approaches may unintentionally reinforce achievement gaps rather than mitigate them.

The research identified a clear mismatch between the type of feedback students desire and the feedback they typically receive. Participants across all grade boundaries reported that feedback was often perceived as generic, lacking specificity and clear relevance to future assessments or module progression. This perception reduces its perceived value and contributes to disengagement, particularly among lower-performing students who may already lack confidence or clarity regarding academic expectations. These findings emphasise the need for a re-evaluation of feedback design and delivery within engineering education. The importance of feedback should be stressed to all students. Formative feedback should be provided to allow students to develop knowledge within a module and then summative feedback should be linked to transferable skills and knowledge for application in future learning. It is recommended that in pedagogical practice all feedback should be entered into by lecturers as a dialogue and students given the opportunity to respond and not simply delivered as a monologue as this can serve to hinder reflection and prevent the feedback being fully utilised. Recommendations for future research include a

focus on the development of best practice feedback models that span modules with multiple assessments, and cross different educational levels. Such framework models should then be tested beyond Built Environment students and once broadly established, should be rolled out as part of Higher Education lecturers ongoing learning and development. It is also recommended that feedback literacy be explored further from the perspective of academics, and so academic preferences and

Limitations of this research include that the students were all level 6, and broader perspectives of students from level 4, 5 and 7 would all be welcome to further illuminate the feedback processes and preferences at other stages of the educational journey. The study is also limited to students from within the Built Environment and understanding the feedback mechanisms from across discipline areas would be beneficial for gaining a greater appreciation of potential lessons to be shared across diverse student populations and teaching styles. Finally, whilst the sample size is significant, benefit would be gained from a much larger and more diverse sample size to allow for greater understanding and confidence in the datasets.

This research furthers knowledge around the CDIO Standard Design-Implement engineering (Standard 5) in that students progressing from level 6 to level 7 studies, there is potentially going to be a knowledge gap around how grades were achieved, and what aspects were good and which needed improving upon as for many students only the module grades were reviewed and not the detailed feedback. For Active Learning (Standard 5.0) this research reveals students are currently more concerned with the end result (grade) rather than the learning process. This is something that needs to be addressed in future curriculum and module design to encourage students to focus more on the process of learning as well as the end result. The findings of this research also contribute to Program Evaluation (Standard 12.0) as the perceptions of student feedback are explored and insights gained into how and why feedback is utilised by some students and why it is not by utilised others.

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Artificial intelligence usage declaration

Artificial Intelligence (AI) platforms were not used for any part of this research project and paper development.

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BEYOND THE CLASSROOM: RETROSPECTIVE EVIDENCE FROM A DECADE OF CHALLENGE-BASED LEARNING

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ABSTRACT

CDIO-aligned Challenge-Based Learning (CBL) programs are frequently credited as developing transversal competencies, yet evidence about whether these outcomes build and transfer into professional practice years later remains limited. This paper investigates the long-term impact of Fusion Point's Challenge-Based Innovation (CBI) program through a retrospective qualitative study of alumni experiences spanning approximately a decade of cohorts. We conducted 20 semi-structured interviews with former participants from business, design, and engineering backgrounds and analyzed the data using reflexive thematic analysis supported by Atlas.ti. Alumni consistently portray CBI as a uniquely memorable, "real-life" learning experience that differs from conventional coursework by combining authentic constraints, external stakeholders, and interdisciplinary teamwork. Four clusters of durable outcomes emerge: First, alumni report sustained innovation practices, including stakeholder-oriented problem framing, iterative development, and safely working with uncertainty. Second, they describe persistent interdisciplinary teamwork capabilities, such as translating across disciplinary "languages," aligning diverse perspectives, and negotiating trade-offs under time pressure. Third, alumni highlight leadership and influence as practiced through facilitation, sensemaking, and coordination rather than formal authority. Fourth, they emphasize identity-relevant personal development, including increased confidence, professional maturity, and long-lasting bonds that continue to support collaboration. Participants also describe career-related effects, including increased readiness for project-based, consulting, and tech and innovation-oriented roles and greater openness to social impact pathways. We discuss implications for CDIO-aligned program design, suggesting that interdisciplinary, challenge-driven learning environments can cultivate professional competencies and mindsets that alumni perceive as both transferable and durable years after participation.

KEYWORDS

Challenge-Based Learning, Engineering Education, Retrospective Alumni Study, Professional Identity, Interdisciplinary Teamwork, CDIO Standards: 2, 3, 5, 8

INTRODUCTION

Today's global challenges demand engineers who can combine high-level technical expertise with the ability to empathize with users and communities, understanding real human needs to frame problems well and design solutions that are both technically sound and genuinely impactful. Challenge-driven and CDIO-aligned programs are commonly reported to foster professional competencies such as teamwork, communication, problem solving, and stakeholder engagement (Bravo et al., 2025a, 2025b). However, much of the available evidence focuses on immediate or short-term outcomes, often measured at the end of a course or within the same academic year (Doulougeri et al., 2024; Gallagher & Savage, 2023; Olateju Temitope Akintayo et al., 2024) which fails to capture the sustainability of learning gains or the permanence of shifts in professional identity (Helker et al., 2025). This creates a gap in understanding whether the reported learnings are durable and whether it transfers into professional practice after graduation (Doulougeri et al., 2024; Van Den Beemt et al., 2023).

This paper addresses that gap through a retrospective perspective on Fusion Point's Challenge-Based Innovation (CBI) program, an interdisciplinary model delivered in collaboration with CERN IdeaSquare across eleven editions since 2014 (Hassi et al., 2016; Papageorgiou et al., 2021), grounded in Challenge-Based Learning pedagogies (Dikilitaş et al., 2025; Doulougeri et al., 2024; Gallagher & Savage, 2023). CBI engages students from business, design, and engineering in authentic, open-ended challenges demanding problem framing, stakeholder interaction, interdisciplinary teamwork, and iterative prototyping, aligning with CDIO principles of authentic context, integrated skills, and iterative development cycles (Charosky et al., 2018; Crawley et al., 2014; Malmqvist et al., 2015; Sierra & Di Stasi, 2024). Focusing on alumni provides a unique vantage point: graduates' retrospective evaluations of their university experience are a recognized measure of long-term educational value, and what alumni choose to remember and apply years after graduation serves as a strong indicator of perceived transfer and professional relevance (Egan, 2020; Garcia et al., 2024; Ritella et al., 2020; Tuononen & Parpala, 2019; Wood et al., 2015). Alumni perspectives have been used in the CDIO community as an instrument for program evaluation and competency benchmarking (Kovacs et al., 2023; Wiklund et al., 2005), yet longitudinal qualitative accounts of professional impact remain scarce in this literature.

The study specifically addresses these gaps through the following overarching research question: RQ: How does participation in an interdisciplinary challenge-based innovation program shape alumni's professional development and career trajectories over the long term? This is explored through three sub-questions:

- SQ1: What competencies and mindsets do alumni report using in professional practice years after participating in CBI?
- SQ2: How do alumni describe the long-term value of interdisciplinary teamwork, communication, and leadership experiences on their professional development?
- SQ3: How do alumni connect their CBI experience to career choices, opportunities, and professional identity formation?

THEORETICAL BACKGROUND

This research is grounded in 4 theoretical pillars: CBL as transformative pedagogy, its alignment with CDIO standards and epistemic fluency, the durability and transfer of learning, and leadership as distributed practice, presented as a conceptual framework (Figure 1).

CBL as Transformative Pedagogy

CBL is an active-learning pedagogy that uses authentic, real-world open-ended "challenges" as the primary driver of the curriculum (Doulougeri et al., 2024; Gallagher & Savage, 2023; Leijon et al., 2022; Perna et al., 2023). Grounded in Kolb's (1984) experiential learning theory, involves an iterative cycle of engaging with "Big Ideas," investigating through stakeholder research, and acting via prototyping (Bravo et al., 2025b; Perna et al., 2023; Van Den Beemt et al., 2023). Interdisciplinary teams imply the need to negotiate meanings and co-create knowledge with peers, teachers, and external stakeholders (Helker et al., 2025; Van Den Beemt et al., 2023). This process often triggers a "disorienting dilemma" forcing students to re-evaluate their professional identities through a period of peak frustration known as the "Groan Zone" (Feng et al., 2025; Kulturel-Konak et al., 2025; Mezirow, 1991).

CDIO Alignment and Epistemic Fluency

CBL aligns with multiple CDIO approach standards (Gunnarsson & Swartz, 2022; Kohn Rådberg et al., 2020). A core cognitive outcome of this radical interdisciplinarity is the development of epistemic fluency; the capacity to recognize and shift between different disciplinary ways of knowing. Engineering students, for instance, must learn to integrate the "human-centered" logic of design (which prioritizes empathy, user needs, and iterative problem-finding over purely technical solutions) with the "feasibility" logic of business (which focuses on technical constraints, economic viability, and implementation requirements) (Barnard et al., 2013; Charosky et al., 2018). Navigating the uncertainty of the "Groan Zone" (a period of peak frustration in the CBL process (Kaner, 2014), develops personal skills such as affective resilience and ambiguity tolerance; critical professional engineering competencies (Helker et al., 2025).

Durability and transfer of learnings

Durability is defined as the learning that remains cognitively and affectively long after the initial instructional intervention while transfer implies the mobilization of those resources in novel, complex professional contexts. In the CBI framework, durability is operationalized through the retrospective tracking of the "Innovation Mindset" with evidence suggesting that shifts in dimensions such as ambiguity tolerance and iterative prototyping habits persist at least three years into professional practice (Papageorgiou et al., 2021). This "learning residue" is often the result of transformative learning processes where students navigate "disorienting dilemmas" that reconfigure their problem-solving abilities (Feng et al., 2025; Kulturel-Konak et al., 2025) and a learner's frame of reference for their entire career (Martin & Bombaerts, 2024; Sluijs et al., 2024).

Professional identity and transversal skills

Professional identity is the integrated pattern of competences, performance, and recognition guiding career decision-making (Taconis & Bekker, 2023). CBL fosters this identity by functioning as a "social engine" where interdisciplinary friction forces students to negotiate professional boundaries, developing transversal skills: the 4C's (critical thinking, creative thinking, collaboration, communication) plus self-regulation, adaptability, and ethical reasoning (Haim & Aschauer, 2024; Helker et al., 2025; Ming et al., 2025). Acquired through the designed navigation of knowledge asymmetries within teams (Helker et al., 2025; Johnson et al., 2022; Nawawi et al., 2024; Papageorgiou et al., 2021). These gains are multidimensional, encompassing cognitive, metacognitive (self-regulation), affective (resilience), and socio-communicative components (Helker et al., 2025). By requiring collaboration with diverse

stakeholders under conditions that simulate workplace dynamics, CBL accelerates professional identity formation and instils a sense of agency toward societal issues (Bravo et al., 2025a; Martin & Bombaerts, 2024).

Leadership as practice in team-based innovation work

This study adopts a “leadership as practice” lens, understood as the situated ability to enable collaboration and facilitate sensemaking under high uncertainty (Hurst et al., 2016; Yang, 2021). Aligning with team-centric transformational leadership (TTFL): conceptualizing leadership as a distributed phenomenon where progress depends on managing diverse disciplinary perspectives and "epistemic friction" (the tension between different disciplinary approaches) within cooperation, psychological safety, and shared vision rather than top-down authority (Jiang & Chen, 2018; Klaic et al., 2020).

Figure 1 synthesizes these four theoretical pillars into a conceptual framework mapping the pathway from the CBI learning environment to the durable professional imprint.

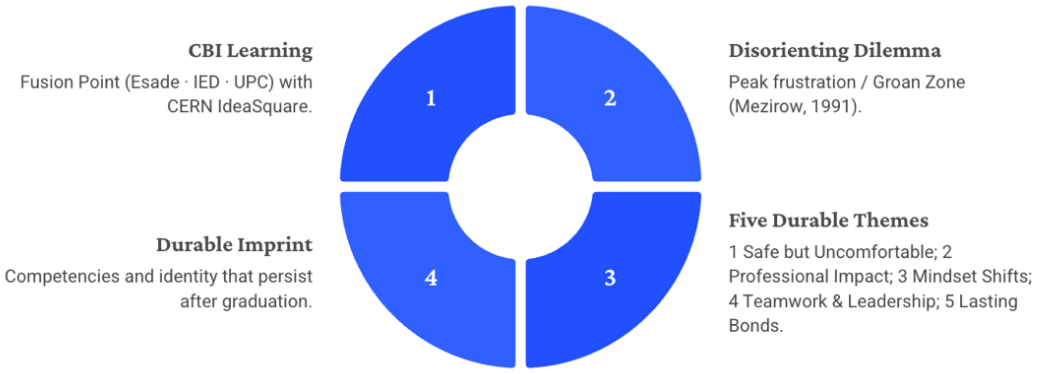


Figure 1. Conceptual framework: from CBI learning environment to durable professional imprint.

METHODS

This study employs a qualitative, retrospective research design targeting alumni who participated in the CBI program between 2014 and 2024, examining how experiences of "disorienting dilemmas" during the course have been metabolised into durable professional practices over the long term.

Research design and context

This study is a retrospective qualitative inquiry based on semi-structured alumni interviews. The institutional context is Fusion Point's CBI program: a four-month, in-person course running from September to December, which has engaged approximately 450 students to date (Hassi et al., 2016; Papageorgiou et al., 2021). It brings together MBA students from Esade Business School, design students from IED Barcelona, and engineering students from UPC (disciplines with varying levels of prior professional experience) working in interdisciplinary teams on challenges aligned with the Sustainable Development Goals, drawing on CERN IdeaSquare's pedagogies to translate science into societal applications (Charosky et al., 2022; Sierra & Di Stasi, 2024; Vignoli et al., 2021). Teams progress through problem exploration, ideation, iterative prototyping, and milestone presentations with stakeholder feedback, producing a written report, a public pitch, and a solution prototype. Assessment is conducted by an

interdisciplinary coaching team (at least one coach per institution) who reach consensus in a joint grading meeting; peer assessment contributes 15% of the final grade (Dikilitaş et al., 2025). Feedback is embedded throughout from faculty, stakeholders, users, and peers, and is central to how the program progressively cultivates professional competencies.

Sample and recruitment

This study is focused on alumni that participated in the program from 2014 to 2024. Participants were contacted through multiple channels: snowball referrals, direct outreach via LinkedIn, and a dedicated invitation distributed for the program's 10th anniversary event. This multi-channel approach aimed to reach a diverse range of cohorts and disciplines, and the research seeks to move beyond immediate course satisfaction to understand the long-term "professional imprint" left by this pedagogical model.

It received formal approval from the Esade Research Ethics Committee (No. 027/2025). Following GDPR, all participants provided written informed consent prior to the interviews. Data is stored securely on a university SharePoint platform, and all records were fully anonymized with unique identification codes to ensure participant confidentiality.

At the time of writing, 20 interviews had been fully coded, the remaining interviews were transcribed and scheduled for integration in the next cycle. Of the 20 coded participants, 7 came from Esade (business), 5 from IED Barcelona (design), and 8 from UPC (engineering); 9 were female and 11 males. Fourteen participants had attended editions prior to COVID-19 (2014–2019) and six had attended post-COVID editions (2020–2024). No systematic thematic differences were identified between pre- and post-COVID cohorts in the coded set. Participants represented diverse disciplinary backgrounds and a range of graduation years, enabling exploration of perceived impacts at different time distances from the course.

Data collection

Interviews lasted around 45–75 minutes following a semi-structured guide designed to identify concrete episodes and reflections on long-term impact through the critical incident technique (FitzGerald et al., 2008). The core questions included:

- “What do you remember most vividly from CBI, and why?”
- “Can you describe a situation at work where you used something you learned in CBI?”
- “What was it like to work across disciplines, and how has that mattered later?”
- “Did CBI influence your career choices or professional identity? How?”

All interviews were conducted in English. Most participants, as well as interviewers, are non-native English speakers; the verbatim excerpts reported in the findings reflect authentic multilingual expression and are presented without linguistic correction to preserve meaning.

Analysis

Analysis followed a reflexive thematic approach (Braun & Clarke, 2019) using ATLAS.ti software, involving iterative coding and clustering. Coding was conducted by two researchers. Starting from an initial sensitizing list of topics grounded in the interview guide, both coders independently coded a subset of transcripts; these were then compared and discussed, to refine and expand the coding where new categories emerged. A final consistency review was conducted across a sample of fully coded transcripts to confirm category stability before proceeding to theme development. Analysis proceeded in four steps: (1) familiarisation (2)

inductive coding (3) theme development through iterative clustering and refinement, and (4) theme validation through negative case checks and consistency review across transcripts. The table below summarizes the themes meanings and codes 'groundedness' (frequency across quotations) as an indicator of the number of coded quotations linked to each code.

Table 1. Themes, transfer to professional practice, and groundedness

Theme	Core meaning	Examples of transfer into professional practice	Groundedness (supporting codes)
1. A 'Safe but uncomfortable' learning space	Supportive but demanding environment (ambiguity, time pressure, real constraints) that stretches students	Tolerating uncertainty; persisting through setbacks; higher confidence in unstructured work; taking initiative without perfect instructions	Course (overall) (58); Experiences (55); Real-life experience (29); Time/Pressure (6)
2. Professional impact and workplace readiness	CBI as preparation for professional project dynamics	Handling open-ended briefs; structuring work under deadlines; presenting to external audiences; using CBI as a career narrative	Professional life (104); Project (63); Professional career impact (58); PM skills (25); Public speaking (13)
3. Mindset shifts toward user-centricity and systems thinking	Durable orientation toward people, context, systems, and trade-offs	Empathy/perspective-taking; reframing problems; considering constraints and consequences; integrating sustainability considerations	Empathy (38); DT process (36); User centric (24); Think big (23); Sustainability (15)
4. Interdisciplinary teamwork, communication, and leadership-as-practice across differences	Learning to collaborate across disciplinary 'territories' and assumptions, including coordination, influence, and facilitation under ambiguity	Translating between disciplines; negotiating priorities; coordinating cross-functional teams; managing conflict constructively; facilitating alignment and decision-making without formal authority	Team dynamics (82); Disciplinary diversity (81); Cultural differences (33); Soft skills (21); Management/Project skills (25); Public speaking (13)
5. Long-lasting social and affective bonds	Relationships and sense of belonging formed through intense collaboration that persist over time and continue to shape professional networks	Maintaining alumni connections; leveraging trusted relationships for collaboration, referrals, or advice; increased confidence through belonging to a strong peer community	Bonds created (44); Experiences (55); (optional context) Course (overall) (58)

FINDINGS

The thematic analysis of the 20 interviews reveals a consistent narrative of transformation, which we term a "durable professional imprint" characterized by five distinct thematic clusters that bridge the gap between the academic experience and professional practice.

Theme 1: A "Safe but Uncomfortable" learning space

Alumni identify CBI as a "life-changing" experiential anchor (Ojasalo & Kaartti, 2021; Papageorgiou et al., 2021). The 'Real-life experience' code (n=29) captures how the CERN environment anchors this memorability (the physical presence, the scientists, the "license to dream") as a uniquely authentic setting distinct from campus-based coursework (Vignoli et al., 2021).

"I think it wouldn't have been as memorable if we didn't go to CERN and we're physically there and talk to certain professors. And that, I think, is very, very, very important. Maybe the equivalent would be like doing a semester in another country and being able to meet people from different countries." (UPC student, 2017)

The 'Experiences' (n=55) and 'Time/Pressure' (n=6) codes capture how this intensity functions as a "stretching", the program provided a "safe space" to navigate the uncertainty inherent in real-world innovation. Alumni describe the discomfort not as a problem but as a necessary condition for growth, distinct from the predictable structure of traditional courses.

"It stretches you physically, even more mentally... it makes you be at the limit every time, every day during the project. So, at the end you realize some things that could happen in a very extreme level... I'm sure that I won't learn that in the same way [in a normal course]." (business student, 2015)

"It gives you an interdisciplinary experience, which is super important after uni, and gives you an uncomfortable setting, but in a safe space […] it's a really nice environment to feel challenged and to feel that you can achieve something that out of it seems crazy." (engineering student, 2019)

Theme 2: Professional impact and workplace readiness

The "Professional Life" code captures how CBI influenced career moves and self-efficacy. Alumni credited the program with providing the "real-life readiness" needed for leadership roles, often supporting earlier readiness for career advancements (Bravo et al., 2025a; Colombelli et al., 2022). The experience bridged the gap between student insecurity and professional confidence:

"When I finished my degree, I went directly to work to consulting. And I think that CBI probably was one of the main reasons. Because consulting is about a client giving you a problem and you need to find a solution. And not be that focused on the technology that we want to use... It's not that we want to use a technology, it's that we want to solve a problem" (business student, 2018)

The 'Professional career impact' code (n=58) also surfaces in how the exposure to both academic research (at CERN) and industry application helped alumni make informed career choices, with some explicitly citing CBI as the catalyst for deciding between a PhD track or an industry career:

"After CBI, inspired by CERN I've started a PhD, now I'm about to finish and I have to decide whether If I want to go for academia or for industry […] I feel it helped me to be able to make a more informed decision of what's best to do." (engineering student, 2016)

Theme 3: Mindset shifts toward user-centricity and systems thinking

A significant outcome is the permanent shift from "technology-push" to "problem-first" reasoning (Charosky et al., 2018). The 'DT process' (n=36) and 'User centric' (n=24) codes are the primary anchors here: engineering alumni specifically noted that CBI was the first time they were forced to "think about the problem" rather than focus solely on the technology (Charosky et al., 2018; Helker et al., 2025), describing this not just as a method but as a fundamental change in professional orientation:

"It was the first time that we were... thinking about the problem and then solve it. And not be that focused on the technology that we want to use." (engineering student, 2018)

"I would say that the main learning for me was the application of design thinking process solving the problem. I think finally this is the main learning" (business student 2014)

The 'Empathy' code (n=38) (the highest-groundedness code in this theme) captures a deeper shift: from analytical detachment to what one participant describes as a "warm point of view," understanding the user as a living part of a community:

"I always start with a very warm point of view... thinking a lot in the user, not only as a person... but as a part of society... This kind of project makes me think and design a lot in terms of warmness." (design student, 2016)

Theme 4: Interdisciplinary teamwork, communication, and leadership-as-practice across epistemic differences

The highest-ranking learning codes: 'Team Dynamics' (n=82) and 'Disciplinary Diversity' (n=81), reveal that learning occurred most intensely at the intersection of disciplines. Initial difficulty of communicating across disciplines generating a common "language" is described as becoming a core professional asset (Ming et al., 2025) later on.

*“She told me like” when you explain what's happening in your head, be conscious that we are not designers, so try to explain it clear and well defined. If you need more time, it's OK. If you need to spend 15 minutes to explain an idea that should be in five, it's OK. But it would help us to understand what's your point and she was right. […] this was a special an example of the communication between the teammates.” (*design student 2016)

"If you're building a product as an engineer... [clients] don't have this technical perspective, so you have to also be able to transmit this idea... being able to transform a product into something that people without a background can understand is a common exercise that you're doing continuously at CBI." (engineering student, 2021)

This "epistemic friction" was scaffolded by supporting on how to negotiate and lead in mixed environments, a skill they found rare among peers who had not participated in such programs.

Theme 5: Long-Lasting Social and Affective Bonds

Beyond technical skills, alumni consistently describe the affective and relational dimensions of CBI as among its most durable outcomes. The 'Bonds created' code (n=44) is the primary evidence base here: the intensity of collaborative challenge-work under real constraints created interpersonal bonds that many alumni continue to maintain professionally years after graduating, a phenomenon rooted in shared vulnerability and mutual reliance (Bravo et al., 2025b; Ojasalo & Kaartti, 2021). These bonds are not peripheral; peer networks built during CBI persist as professional support systems, referral channels, and collaboration opportunities.

"I still keep in touch with the people from my team in CBI. So, I guess that it shows you how we actually bonded a lot during the course, and we stayed friends still today." (UPC student, 2017)

"I made super, super good friends... every single time we've gotten back together we were like 'oh, if we would have to do one perfect team we would know how to choose perfectly and we would love to do it again'." (Interview 3, Business)

This suggests that the "imprint" of the program is not merely cognitive, it is social and affective, manifesting as a lasting professional community that increases confidence, enables future collaboration, and supports continued learning long after the course ends.

Mapping themes to CDIO standards

Table 2 provides a thematic map that synthesizes the qualitative findings and makes explicit how the durable outcomes of each theme can be interpreted through relevant CDIO Standard highlighting the mechanisms that alumni narratives suggest help these learnings to persist and transfer into professional practice years after participation.

Table 2. Themes and transfer mechanisms mapped to CDIO Standards

Theme	CDIO Standard / Syllabus (2, 3, 5, 8)	Durable Outcome / Mechanism (why it 'sticks' for years)
1. A 'safe but uncomfortable' learning space	S8 Active Learning: student-centred active and experiential learning; S5 Design–Implement Experiences: iterating and making under constraints; S2 Learning Outcomes: confidence, resilience, teamwork-related competences	Mechanism: repeated exposure to authentic ambiguity and time pressure creates productive discomfort that builds tolerance for uncertainty and iteration. Because students must act (not just discuss), they develop procedural know-how and self-efficacy that alumni later recognise and reuse when facing ill-structured workplace problems.
2. Professional impact and workplace readiness	S2 Learning Outcomes: professional skills (communication, project management, stakeholder interaction); S5 Design–Implement Experiences: delivery cycles with constraints; S8 Active Learning: student responsibility for decisions and outputs	Mechanism: authenticity generates performance-relevant rehearsal of professional practice (open-ended briefs, external audiences, delivery deadlines). This enables near and far transfer because alumni encode not only 'what' they learned but 'how' to behave in project-based work (structuring, communicating, presenting, prioritising).
3. Mindset shifts toward user-centricity and systems thinking	S2 Learning Outcomes: systems thinking, ethics and sustainability, societal/stakeholder awareness; S5 Design-Implement Experiences: challenges requiring stakeholders to be integrated into the design and reasoning process. S8 Active Learning: learners construct meaning through engagement and reflection; S3 Integrated Curriculum: reinforcement of professional mindsets across activities	Mechanism: repeated stakeholder-oriented reframing produces an identity-relevant shift from technology-push to problem-first inquiry. The mindset 'sticks' because it is tied to concrete episodes of seeing consequences, negotiating trade-offs, and making decisions that combine human needs, technical feasibility, and sustainability.
4. Interdisciplinary teamwork, communication, and leadership-as-practice across epistemic differences	S2 Learning Outcomes: teamwork, communication, leadership, collaboration; S3 Integrated Curriculum: mindset development reinforced by coordinated multidisciplinary curriculum design; S5 Design-Implement Experiences: teamwork and leadership practised within authentic project delivery; S8 Active Learning: negotiation, decision-making, and coordination in action	Mechanism: epistemic friction (different disciplinary 'languages' and assumptions) forces ongoing translation, negotiation, and alignment. Alumni learn to exercise informal leadership (facilitation, influence without authority) because progress depends on coordinating perspectives under ambiguity, making it transferable to cross-functional professional contexts.
5. Long-lasting social and affective bonds	S8 Active Learning: intense shared doing strengthens cohesion; S2 Learning Outcomes: interpersonal competence, collaboration; S3 Integrated Curriculum: sustained teamwork across course structures	Mechanism: high-intensity collaboration under challenge conditions creates social and emotional anchoring (shared struggle, mutual support, collective pride). These affective bonds persist as durable professional networks, increasing confidence, enabling future collaboration, and sustaining continued learning through peer exchange long after the course ends.

DISCUSSION

The alumni narratives collected across a decade of Fusion Point's CBI program suggest that challenge-driven, interdisciplinary immersion leaves a significant "learning residue" that remains salient long after graduation. The most practically significant dimension of this imprint (and the one with the most direct implications for CDIO program designers) is its career-shaping effect: alumni report concrete changes in occupational trajectories, informed transitions between academia and industry, and accelerated professional readiness that they trace directly to their CBI participation. This discussion interprets these findings through the theoretical lenses of transformative learning, epistemic fluency, and leadership as practice.

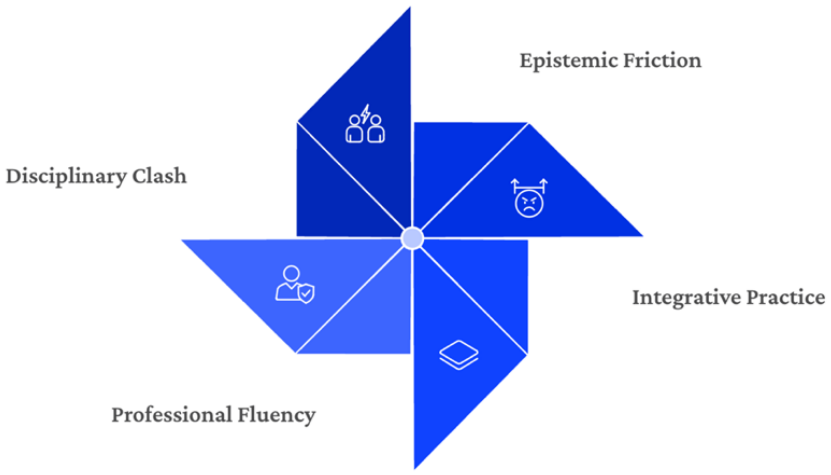


Figure 2. From Disciplinary Clash to Professional Fluency: The Epistemic Friction Mechanism

The Durability of Transformative "Learning Residue"

The most striking finding is the decade-long durability of mindset shifts, particularly the transition from "technology-push" to "problem-first" reasoning. While traditional engineering curricula often prioritize linear problem-solving (Dikilitaş et al., 2025), CBI alumni describe a permanent reconfiguration of their professional identity centered on user-centricity and empathy. This aligns with the "subjectification" function of learning, where students do not merely acquire skills but are transformed as individuals. The reported "Safe but Uncomfortable" environment acts as a catalyst for this transformation; by navigating the "Groan Zone", students develop affective resilience and a high tolerance for ambiguity (Huesca et al., 2024). These gains but represent what Mezirow (1991) defined as a shift in "meaning perspective"; a durable lens through which alumni continue to interpret complex professional challenges (Feng et al., 2025; Sundman et al., 2025).

Epistemic Friction as a Mechanism for Epistemic Fluency

The high groundedness of the "Team Dynamics" and "Disciplinary Diversity" codes indicates that the most significant learning occurs at the point of epistemic friction; the tension generated when diverse disciplinary ways of knowing collide (Dikilitaş et al., 2025). In contrast to "divide-and-conquer" strategies common in traditional group work, CBI forces a genuine integration of engineering feasibility, design desirability, and business viability (Charosky et al., 2018; Van Den Beemt et al., 2020, 2023). This process cultivates epistemic fluency, enabling graduates to act as "translators" across disciplinary and organizational silos (Kans & Gustafsson, 2016; Visscher et al., 2022). This ability to communicate complex ideas to non-experts is reported as a "core professional asset" (Dikilitaş et al., 2025). Confirming that interdisciplinary friction, while a source of peak frustration during the program, is the primary driver of the sophisticated communication and collaboration skills required in Industry 4.0 environments (Van Den Beemt et al., 2023). Figure 2 illustrates this mechanism.

Leadership as Distributed Practice and Collective Sensemaking

Rather than identifying a single "hero" leader, alumni narratives describe leadership as a distributed practice of enabling collaboration and facilitating sensemaking under uncertainty (McCrory et al., 2021). This enactment of leadership aligns with team-centric transformational leadership, where the focus shifts from top-down authority to the cultivation of cooperative norms and psychological safety (Jiang & Chen, 2018; Klaic et al., 2020). Graduates credit CBI with providing "real-life readiness" (Vilalta-Perdomo et al., 2022), reporting that the experience of managing a network of experts and stakeholders accelerated their seniority in leadership and consulting roles (Dikilitaş et al., 2025). This suggests that CBI functions as a "leadership laboratory" where the mastery of relational dynamics; such as conflict management and shared decision-making, predicts long-term professional success more effectively than technical mastery alone (Klaic et al., 2020).

The "Social Engine" of Innovation and Professional Networks

Finally, durable social bonds highlight that innovation is social as well as technical (Dikilitaş et al., 2025). The shared intensity of CBI creates lasting professional networks, a form of "social capital" that improves graduates' confidence and self-efficacy long after the program ends (Bravo et al., 2025a; Helker et al., 2025; Ojasalo & Kaartti, 2021). For engineering education, this underscores the importance of designing "memorable educational experiences" (Lara-Prieto et al., 2023) that leverage the "Human Dimension" of learning building not just

engineers, but a connected community of change-makers (Ojasalo & Kaartti, 2021; Papageorgiou et al., 2021)

IMPLICATIONS FOR CDIO-ALIGNED COURSE DESIGN

The retrospective evidence suggests that the durability of competence is not driven by content knowledge, but by the intensity of the learning environment. For institutions aiming to replicate these long-term outcomes, we propose four design principles anchored in the CDIO Standards:

Table 3. Design principles for CDIO-aligned programs producing durable professional competencies.

Design Principle	CDIO Standard	Evidence from Alumni
Operationalise Epistemic Friction — intentionally form teams with maximum disciplinary distance	Standard 3 — Integrated Curriculum	Alumni attribute cross-disciplinary communication and negotiation skills to the friction of working across engineering, design, and business
Embrace the Pedagogy of Discomfort — avoid over-scaffolding; ambiguity is a feature, not a bug	Standard 5 — Design–Implement Experiences	The 'uncomfortable' open-ended challenge is the primary anchor for memory and professional confidence a decade later
Ensure Authenticity through External Stakeholders — feedback based on value and feasibility, not academic compliance	Standard 7 — Integrated Learning Experiences	Alumni credit accountability to real stakeholders — not grades — as the driver of user-centric mindset shifts
Structure Reflection as an Identity Mechanism — require students to articulate how they navigated conflict and ambiguity	Standard 8 — Active Learning	The 'Groan Zone' is only transformative when followed by structured reflection that cements the experience into professional identity

Table 3 synthesizes these principles as actionable guidelines grounded in alumni evidence. Two of the four principles map to Standard 5 (Design-Implement Experiences), reflecting distinct but complementary facets: the productive value of ambiguity in challenge design, and the accountability generated by genuine external stakeholders. Standard 3 (Integrated Curriculum) addresses team composition as a curricular design decision (De Fouw et al., 2020); Standard 8 (Active Learning) addresses the reflective practices that consolidate experiential learning into professional identity.

CONCLUSIONS AND NEXT STEPS

A decade of retrospective alumni evidence confirms that intensive, interdisciplinary, challenge-driven immersion leaves a "learning residue" that is cognitively and affectively salient long after graduation: a permanent shift from "technology-push" to user-centric reasoning that alumni trace directly to their CBI participation (Charosky et al., 2022; Ojasalo & Kaartti, 2021; Papageorgiou et al., 2021). Epistemic friction (navigated through the "Groan Zone") is the primary mechanism for this maturation (Sluijs et al., 2024): it produces the epistemic fluency required to act as a "translator" across disciplinary silos and the leadership-as-practice capability to facilitate collective sensemaking in mixed professional environments (Balboni et al., 2021; Van Den Beemt et al., 2023). This transformation is characterized by the far-transfer

of core innovation skills such as ambiguity tolerance and iterative prototyping into diverse professional domains. As students navigate the “Safe but Uncomfortable” program environment, undergo through a “permanent reconfiguration of how they approach any complex problem” illustrating that challenge-based pedagogy acts as a “social engine” that fundamentally re-authors professional identity and fosters “Significant Learning” (Ojasalo & Kaartti, 2021).

These findings provide much-needed evidence to the CDIO community that epistemic friction is not merely a pedagogical abstraction, but the primary mechanism for professional maturation (Sluijs et al., 2024). By persisting through the frustration of the “Groan Zone” students develop the epistemic fluency required to act as “translators” across disciplinary silos (Balboni et al., 2021). It allows them to master leadership as practice, conceptualized as the situated ability to facilitate collective sensemaking and build alignment in mixed environments (Van Den Beemt et al., 2023). The ability to “break outside your disciplinary box” becomes a "core professional” (Figueiredo et al., 2022), shaping their careers in leadership and consulting roles (Colombelli et al., 2022; Pan et al., 2021).

Returning to the overarching research question and its sub-questions, the findings offer the following answers. Addressing SQ1, alumni consistently report using stakeholder-oriented problem framing, iterative development habits, ambiguity tolerance, and cross-functional communication as durable professional practices, competencies that they trace directly to their CBI participation. Addressing SQ2, the long-term value of interdisciplinary teamwork, communication, and leadership is most strongly attributed to the productive friction of working across disciplinary "languages"; alumni describe this experience as the origin of facilitation and sensemaking capabilities that distinguish them in professional settings. Addressing SQ3 (and responding to the overarching RQ) alumni describe CBI as the most career-shaping educational experience of their training: influencing entry into consulting, innovation, and project-based roles; informing consequential decisions between academic and industry pathways; and contributing to a lasting professional identity grounded in user-centricity, social impact, and collaborative agency. That alumni from business, design, and engineering backgrounds consistently converge on this career-level impact, despite arriving with very different prior experience and professional expectations, suggests that the programs interdisciplinary design generates effects that transcend any single discipline.

Despite these robust qualitative insights, the study’s reliance on retrospective self-report introduces potential recall bias and self-selection, (as those with more positive experiences may be more likely to participate), and social desirability bias; the tendency of respondents to present their experiences in alignment with perceived social norms or positive expectations rather than reflecting their true experience. The analysis focuses on perceived transfer rather than establishing direct causal links between specific course features and long-term career outcomes. To address these gaps, future research will implement a triangulation strategy by mapping interview themes against archival course artifacts, interdisciplinary grading rubrics, and process-tracking logs. By comparing longitudinal alumni accounts with nearer-term student data using advanced statistical models, we aim to further elucidate the specific “scaffolding mechanisms” (Gallagher & Savage, 2023) that ensure the persistence of innovation capabilities throughout the professional lifecycle (Ming et al., 2025).

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UPC, and our partners at CERN's IdeaSquare; your unwavering passion and drive have been the heartbeat of this initiative. Most importantly, we are deeply grateful to the hundreds of students who stepped into the 'uncomfortable' space of innovation with us. This paper belongs to you; thank you for sharing your stories and for proving that the bonds we created are just as durable as the skills you learned.

AI usage declaration

The authors utilized large language model (LLM) tools (Claude AI, ChatGPT and Gamma AI) during the preparation of this manuscript to assist with text structuring, grammatical refinement, the synthesis of qualitative coding data and figures and tables, The core research design, qualitative analysis, and final interpretation of findings were conducted entirely by the authors.

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