

Towards a New Model for First-Year Introductory Courses in Engineering Education Programmes

Göran Gustafsson

Johan Malmqvist

Dava J. Newman

Sven Stafström

Hans Peter Wallin

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Abstract

An important and common component of engineering programmes is a first-year course aimed at introducing various subjects as well as motivating the students and introducing them to the engineering profession. This paper compares four such courses at Chalmers University of Technology (Chalmers), The Royal Institute of Technology (KTH) and Linköping University (LiU), all in Sweden, and Massachusetts Institute of Technology (MIT), Massachusetts, USA. Discriminators showing details of each course are displayed and possible course development is discussed.

The presented study is a part of the ongoing Conceive, Design, Implement, and Operate (CDIO) Program for Engineering Education Reform, which is run by the abovementioned universities and supported by the Swedish Knut and Alice Wallenberg Foundation. The CDIO Program aims at developing a new model for engineering education, focusing on Conceive, Design, Implement and Operate skills. The concept is characterized by a curriculum organized around the various disciplines while emphasizing that engineering is about conceiving – designing – implementing and operating products and systems, a multitude of student projects, a pedagogic model that supports active, experiential and group learning, a varied learning environment with classrooms, workshops and the outside world as well as a continuous improvement process.

1 Introduction

Historically, elements of hands-on practice and scientific fundamentals have been well balanced in academic engineering education. Most teachers were practicing engineers themselves who focused on solving concrete problems, and their students learned to conceptualise and design products and systems. However, after the Second World War, the rapid expansion of scientific and technical knowledge saw engineering education evolve into the teaching of engineering science with less emphasis on actual engineering practice. This has led to an increased concern that graduating students, while technically adept, lack many skills needed in real world situations. Industry and related organisations have reacted by

creating various requirements of attributes vital for graduating engineers, and in the late 1990s a group of university engineering educators started to examine the issue. Their work has resulted in a new approach to engineering education, the aim of which can be stated: *Graduating engineers should be able to **Conceive, Design, Implement and Operate** complex value-added engineering systems in a modern, team-based environment.*

The acronym CDIO has become the trademark of this approach and a detailed educational syllabus has been developed [3], which is displayed in condensed form in Table 1. The vision of the CDIO is to provide students with an education that stresses fundamental engineering methods, systems and products. This is essential to sustaining productivity, innovation and excellence in a future that is increasingly based on technologically complex systems. The CDIO is an open architecture endeavour that is specifically designed for, and offered to, all university engineering programs to customize and adapt to their specific needs.

The new educational model is integrated, with mutually supporting disciplines and a multitude of projects. Students learn experientially about system building through team-based design-build-operate projects and develop a deep working knowledge of the fundamentals. This is particularly important nowadays, when students no longer arrive at the universities armed with the hands-on experiences of earlier generations from tinkering with mopeds and building radios. We cannot, as we used to, expect that the students have the necessary foundation upon which to base the forming and testing of hypotheses in an abstract fashion. To address this and other learning needs, the CDIO program prescribes changes/improvements in four basic areas: increasing hands-on learning, emphasizing problem formulation, increasing active learning, and enhancing feedback mechanisms. In order to succeed with the CDIO approach it is necessary to find innovative ways to simultaneously teach fundamental skills and CDIO skills by focusing on more creative and open-ended problems and devoting more time to activities in workshops and laboratories.

Chalmers University of Technology, The Royal Institute of Technology (KTH), Linköping University (LiU) and the Massachusetts Institute of Technology (MIT) are presently running a joint project aimed at developing an engineering curriculum in accordance with the CDIO syllabus, and to implement it in their own education. The project, supported by the Swedish Knut and Alice Wallenberg foundation, is now into its second year of the total four. This paper presents and compares first-year engineering introductory courses at these universities from the CDIO perspective.

2 First-year introductory courses

First-year introductory courses in engineering programmes are an ideal testing ground for the CDIO approach, where the new ideas can be tried, developed and assessed to support the learning of CDIO skills, numbered 2-4 in Table 1. It is assumed that all core subjects have as an educational goal to teach CDIO technical knowledge and reasoning (skill number 1 in Table 1). Four first-year courses, one from each university, is discussed below. They are:

- Introduction to Mechanical Engineering (Chalmers)
- Perspective of Vehicle Engineering (KTH)
- Introduction to Applied Physics and Electrical Engineering (LiU)
- Introduction to Aerospace Engineering and Design (MIT)

All four courses are part of an engineering programme first-year curriculum at the respective university. The different courses content with respect to the CDIO Syllabus are presented in Table 2, which is a condensed version of a more extensive description [1]. The objective of the courses is to introduce and attract students to engineering and to motivate them for their studies. The intention is to do that by introducing the students to the disciplines that will follow, giving them some confidence in handling basic tools and theories and providing a motivational link for their chosen academic careers.

Four different areas of engineering are represented among the courses, and each course naturally contains elements that are specific to its particular area. The limited space available here does not permit an extensive comparison of the courses, and subject-specific differences are outside the scope of the paper. Below a few aspects of the structure of the first-year courses and their general contents will be discussed from a CDIO perspective.

2.1 Basic course facts

The LiU course will run for the first time during the academic year 2002-2003. At the time of writing this paper the available data on it is incomplete, but sufficient for the analysis that will follow. An earlier version of the present Chalmers course is extensively described in a paper by one of the present authors [7]. Although some of the content of the course have been successively developed, changed or replaced during the five years that have passed since the writing of that paper, the basic structure of the course and the majority of its elements remain the same today. The CDIO version of the MIT course has been taught with continuous improvements for eight years and is detailed in [8].

At MIT the students spend 140 hours on their first-year course. At Chalmers and LiU the corresponding time is 160 hours, and at KTH it is 240 hours. These numbers are roughly equal to 2-3 % of the respective engineering programme curriculum. The three Swedish courses have up to about three times as many students (150-170) as the MIT course (60), while the latter has a notably greater fraction of female students (33% versus 10-20%).

The courses all contain 1-4 student projects of some kind, and in total the students devote at least 50% of the total first-year course time to these projects. In all courses there is at least one design-build type project. The Chalmers project concentrates on the first steps in the product development process, while the MIT and some LiU projects extend all the way from designing up to and including the building phase. (Other LiU projects are about mathematics and software.) The KTH project ends in a virtual design. At Chalmers and LiU the project teams choose their individual project topics from a catalogue of ideas, while at KTH the teams get their individual tasks from supervisors and at MIT all teams work on the same given task. Most projects are thus pre-planned, although Chalmers has a self-planning option for those teams that propose and get approval for a project of their own, which is actually recommended. The three KTH projects also contain various elements of self-planning. The Swedish universities rotate, alternate or replace projects every year to successively renew their project catalogues, while MIT runs the same major course project every year, having students design, build and operate a lighter-than-air vehicle [9]. One of the KTH projects is performed individually, while the sizes of the project teams in the other projects at all four

1	TECHNICAL KNOWLEDGE AND REASONING		3.2 COMMUNICATIONS 3.2.1 Communications Strategy 3.2.2 Communications Structure 3.2.3 Written Communication 3.2.4 Electronic/Multimedia Communication 3.2.5 Graphical Communication 3.2.6 Oral Presentation and Inter-Personal Communications
	1.1	KNOWLEDGE OF UNDERLYING SCIENCES	
	1.2	CORE ENGINEERING FUNDAMENTAL KNOWLEDGE	
	1.3	ADVANCED ENGINEERING FUNDAMENTAL KNOWLEDGE	
2	PERSONAL AND PROFESSIONAL SKILLS AND ATTRIBUTES		3.3 COMMUNICATION IN FOREIGN LANGUAGES 3.3.1 Communication in English 3.3.2 Communication in Intra-EU Languages 3.3.3 Communication in Extra-EU Languages
	2.1	ENGINEERING REASONING AND PROBLEM SOLVING 2.1.1 Problem Identification and Formulation 2.1.2 Modeling 2.1.3 Estimation and Qualitative Analysis 2.1.4 Analysis With Uncertainty 2.1.5 Solution and Recommendation	
	2.2	EXPERIMENTATION AND KNOWLEDGE DISCOVERY 2.2.1 Hypothesis Formulation 2.2.2 Survey of Print and Electronic Literature 2.2.3 Experimental Inquiry 2.2.4 Hypothesis Test and Defense	4 CONCEIVING, DESIGNING, IMPLEMENTING AND OPERATING SYSTEMS IN THE ENTERPRISE AND SOCIETAL CONTEXT
	2.3	SYSTEM THINKING 2.3.1 Thinking Holistically 2.3.2 Emergence and Interactions in Systems 2.3.3 Prioritization and Focus 2.3.4 Trade-offs, Judgment and Balance in Resolution	
	2.4	PERSONAL SKILLS AND ATTRIBUTES 2.4.1 Initiative and Willingness to Take Risks 2.4.2 Perseverance and Flexibility 2.4.3 Creative Thinking 2.4.4 Critical Thinking 2.4.5 Awareness of One's Personal Knowledge, Skills and Attitudes 2.4.6 Curiosity and Lifelong Learning 2.4.7 Time and Resource Management	
	2.5	PROFESSIONAL SKILLS AND ATTITUDES 2.5.1 Professional Ethics, Integrity, Responsibility and Accountability 2.5.2 Professional Behavior 2.5.3 Proactively Planning for One's Career 2.5.4 Staying Current on World of Engineering	
3	INTERPERSONAL SKILLS: TEAMWORK AND COMMUNICATION		4.1 EXTERNAL AND SOCIETAL CONTEXT 4.1.1 Roles and Responsibility of Engineers 4.1.2 The Impact of Engineering on Society 4.1.3 Society's Regulation of Engineering 4.1.4 The Historical and Cultural Context 4.1.5 Contemporary Issues and Values 4.1.6 Developing a Global Perspective
	3.1	TEAMWORK 3.1.1 Forming Effective Teams 3.1.2 Team Operation 3.1.3 Team Growth and Evolution 3.1.4 Leadership 3.1.5 Technical Teaming	4.2 ENTERPRISE AND BUSINESS CONTEXT 4.2.1 Appreciating Different Enterprise Cultures 4.2.2 Enterprise Strategy, Goals and Planning 4.2.3 Technical Entrepreneurship 4.2.4 Working Successfully in Organizations
			4.3 CONCEIVING AND ENGINEERING SYSTEMS 4.3.1 Setting System Goals and Requirements 4.3.2 Defining Function, Concept and Architecture 4.3.3 Modeling of System and Insuring Goals Can Be Met 4.3.4 Development Project Management
			4.4 DESIGNING 4.4.1 The Design Process 4.4.2 The Design Process Phasing and Approaches 4.4.3 Utilization of Knowledge in Design 4.4.4 Disciplinary Design 4.4.5 Multidisciplinary Design 4.4.6 Multi-Objective Design (DFX)
			4.5 IMPLEMENTING 4.5.1 Designing the Implementation Process 4.5.2 Hardware Manufacturing Process 4.5.3 Software Implementing Process 4.5.4 Hardware Software Integration 4.5.5 Test, Verification, Validation and Certification 4.5.6 Implementation Management
			4.6 OPERATING 4.6.1 Designing and Optimizing Operations 4.6.2 Training and Operations 4.6.3 Supporting the System Lifecycle 4.6.4 System Improvement and Evolution 4.6.5 Disposal and Life-End Issues 4.6.6 Operations Management

Table 1. Condensed CDIO Syllabus, showing three levels of content detail [3].

CDIO SYLLABUS ITEM	FIRST-YEAR COURSE	INTRODUCE/TEACH/UTILIZE	EMPHASIZED SUBTOPICS IN CDIO SYLLABUS
2.1 Engineering Reasoning & Problem Solving	Chalmers KTH LiU MIT	T T T T	2.1.1, 2.1.5 2.1.1-5 2.1.1-5 2.1.1-3
2.2 Experimentation & Knowledge Discovery	Chalmers KTH LiU MIT	T, U T, U T I	2.2.2 2.2.1-2, 2.2.4 2.2.4 2.2.3
2.3 System Thinking	Chalmers KTH LiU MIT	I T T T	2.3.1, 2.3.4 2.3.1, 2.3.3-4 2.3.2 2.3.2-4
2.4 Personal Skills & Attitudes	Chalmers KTH LiU MIT	I I T T	2.4.3-4, 2.4.6-7 2.4.3-4, 2.4.6 2.4.3-4, 2.4.7 2.4.4-5
2.5 Professional Skills & Attitudes	Chalmers KTH LiU MIT	I I I	2.5.4 2.5.1-2
3.1 Teamwork	Chalmers KTH LiU MIT	T, U I, U T, U T, U	3.1.2 3.1.2 3.1.2-5 3.1.2-5
3.2 Communications	Chalmers KTH LiU MIT	T, U T, U T, U T, U	3.2.3, 3.2.5-6 3.2.3, 3.2.5-6 3.2.3, 3.2.6 3.2.4, 3.2.6
4.1 Societal & External Context	Chalmers KTH LiU MIT	T T I I	4.1.1-2, 4.1.4-6 4.1.1-6 4.1.1-6 4.1.1-6
4.2 Enterprise & Business Context	Chalmers KTH LiU MIT	I I	4.2.2 4.2.4
4.3 Conceiving & Engineering Systems	Chalmers KTH LiU MIT	T, U I T T	4.3.1-2 4.3.1, 4.3.4 4.3.2
4.4 Designing	Chalmers KTH LiU MIT	T, U I I T, U	4.4.1-2 4.4.1-5
4.5 Implementing	Chalmers KTH LiU MIT	I I	4.5.2, 4.5.5
4.6 Operating	Chalmers KTH LiU MIT	I T,U	4.6.1-2

Table 2. Contents of first-year courses.

universities range from 2-3 up to 5-6 students depending on the project.

The teams are either randomly composed or self-selected by the students. In this process LiU and MIT intervenes by taking account of student experience and diversity, and these two universities also strive to create a gender balance in their project teams.

In all of the first-year courses industry and other external actors are involved as invited speakers or lecturers, or they host company visits for the students. LiU also develops its' course jointly with industrial companies. A students' final course grade depends on his/her performance with respect to several different requirements and course elements.

2.2 Some differences and similarities

In Table 2 we distinguish between the three levels Introduce (I), Teach (T) and Utilize (U) to describe the detail of treatment of each CDIO Syllabus subtopic in our first-year courses. The level Teach presupposes the level Introduce, and in short the teaching goals and differences between the three levels can be described as follows [4]:

Introduce: Briefly touch on or expose the students to. Less than one hour of course time dedicated to the topic, and no specific learning objective or knowledge retention linked to it.
Example: Without treatment of ethics in general, present an ethical problem to the students to set the context for a lecture on the subject.

Teach: Try to make the students learn the material. At least one hour of course time dedicated to the topic, with the objective to advance the students' learning at least one cognitive level.
Example: Explicit presentation of the methodology and tools of product design, which is then practised by the students in assignments.

Utilize: Assumes some knowledge of the topic, but no course time is explicitly allotted to teaching it. No specific learning objective, but use of the topic to reach other learning objectives.
Example: In lab work students are expected to utilize their skills in experimentation, but no explicit instruction on the subject is given.

Table 2 shows that the four first-year courses treat many of the CDIO Syllabus topics. Three of the four top-level items of the syllabus, i.e. items 2-4, are addressed, and at the next lower level the only item that is not explicitly treated in any of the courses is 3.3, Communication in Foreign Languages. One subtopic, 3.1, Teamwork, is taught in three of the four courses and utilized in all of them.

2.2.1 Analysis and experiments

Analysis and experiments are mainly covered by CDIO Syllabus topics 2.1 and 2.2. All four first-year courses include engineering reasoning & problem solving. The KTH and LiU courses treat all aspects of it, while the Chalmers and MIT courses are concentrated on the identification and formulation of problems. The Chalmers course then proceeds to the formal solution of these while the MIT course more discusses how to estimate and find approximate solutions. In the KTH course hypothesis formulation as well as hypothesis test and defence are taught, while in the LiU course only the latter is treated. The MIT course is the only one of the four that includes an introductory session on experimental inquiry, but all courses except

the one at Chalmers include elements of experimentation. As had been said earlier, hands-on experience and experiential learning has now become more important than ever in our curricula, and with the completion of its new student laboratory Chalmers will be able to follow suit. The other three universities have newly constructed classrooms and laboratories to facilitate design projects and active learning methods.

2.2.2 Designing and building

Designing and building skills fall under the CDIO Syllabus items 4.3 - 4.6. Table 2 shows that all four courses contain elements that are categorised as such. In the Chalmers course emphasis is put on teaching the design process, how to set requirements and goals and how to create solutions that meet them. The students utilize their new knowledge in a project that leads to a 'paper design' in the form of simple drawings and sketches. The KTH course introduces the same subjects, but its project is directed towards the application of experimental methodology rather than the design of something. In the LiU course goal setting and project management are taught, while design, implementation and operation are only introduced. The MIT course covers all the steps in the development process, with emphasis on design and operation, but has a different approach compared to the Chalmers course. While Chalmers applies systematic design methods like e.g. brainstorming and functional analysis, MIT emphasizes design reviews, systems engineering methods and individual student design portfolios all of which enable a team vehicle design project.

However, West [10] has argued that design projects with the ultimate goal of producing a 'paper design' are fundamentally limited in the sense that students are unable to verify their solutions themselves. It is important for increased student motivation and confidence that at the end of a project something will 'fly' or 'work'. At present the MIT course is the only one of the four that carries a student project into the building phase. This course is probably also the one where this is most easily done, since Aerospace Engineering is a rewarding subject for making operational prototypes. In the Chalmers and KTH courses it would also be possible to design and build real objects that will if not fly so at least move on the ground, but the Chalmers course has not yet been developed to that stage and the KTH course more aims at virtual designs. Chalmers is now about to equip a student laboratory that will permit prototype building to be included in its first-year course, but together with KTH shares a further complication: At the time when they take the first-year course, the students have not yet chosen which curriculum stream to follow. The object that they design and build may therefore not be representative of the topics that they will later specialize in. (However, this disadvantage might of course be an advantage for multidisciplinary engineering education.)

It is relatively more difficult to arrive at moving prototypes in the LiU course, but here too the intention is by time to allow the students to extend their ideas into something operational. Simple devices can be built to illustrate basic physical principles. As an example, a popular concept in engineering education has for a long time been to arrange races between student-built vehicles that are propelled by the energy stored in the spring of a mousetrap or an elevated weight, see e.g. [6]. The MIT lighter-than-air vehicle design project culminates in a friendly competition with blimps flying around the gymnasium [9].

2.2.3 Assessment and grades

Students are assessed individually as well as in teams in all courses but the one at LiU, where only teams are assessed. Individual assessment is in the form of written exams, at Chalmers

and KTH, or written assignments, at MIT. KTH has an additional individual oral presentation and exam in its course, and MIT also uses portfolios and peer instruction and evaluation assessments. All four courses assess teams by written reports and oral presentations. In the three Swedish universities all team members get the same grade, although in the Chalmers and KTH courses individual adjustments can be made due to good performance. In the MIT course 50% of the grade is based on team performance and 50% depends on the individual achievement. In all the four courses a student's final grade depends on how well he/she has performed overall. Except for LiU, which has only pass/fail grades, all courses award differentiated pass grades. Chalmers and KTH have three pass grades and MIT has four.

The use of differentiated grades is a topic of discussion in the CDIO project. Chalmers started out with only pass/fail grades in its first-year course, but has later introduced differentiated pass grades with the aim to increase student interest in the course by rewarding those who perform better than just acceptable. LiU, in its new course, has like Chalmers at the outset chosen to use only pass/fail. Here there is rather a fear of the opposite, i.e., that with differentiated pass grades the students would spend too much of their available time on the first-year course at the expense of other courses. MIT has had a long-standing policy that all first year courses are graded, but on the students' official transcript only Pass/No Pass are shown. This policy has recently been amended and in 2003 will change so that only Pass/No Pass is recorded during the first semester, but individual grades are shown during the second semester. The real effects of these different ways of rewarding our students are largely unknown though.

3 Conclusion

First-year introductory courses should prepare and pave the way for continued learning, by providing the basic knowledge that the students need later on. Table 2 shows that the four courses address a large fraction of the CDIO Syllabus items in Table 1. All of them treat items 2.1 – 2.4, 3.1 – 3.2 and 4.1. Of the CDIO 'core' skills, items 4.3 – 4.6, the first stages of the design-build process are overall more emphasized than the latter stages. With the exception of the MIT course, Implementing and Operating are either only introduced (at LiU) or absent (at Chalmers and KTH). From the previous comparisons it can be concluded that these topics, as well as experimentation, ought to be introduced in those courses where they are now absent, and perhaps further strengthened where they exist. Assessment of the MIT course shows that students clearly improved their comfort level working on technical problems with no clear answers; their grasp of how to design and build a device from an assortment of parts also significantly increased (statistical significance determined by the McNemar Test [2] and detailed in [8]).

Altogether absent in all the four courses is an explicit treatment of the CDIO Syllabus item 3.3, Communication in foreign languages. However, it should then be clear that it is very common in Swedish universities to use English as a second language. Textbooks in English and English software are not uncommon in undergraduate courses, and the students are generally expected to be able to find, access and handle information in English. This means that the students may improve their English in many of the courses they take although the topic itself is not explicitly addressed.

Teamwork has in all first-year courses been identified as an important subject, and our four

courses will be compared from this perspective in a future paper, [5]. In the MIT course, students' outlook toward teamwork has been assessed and documented changes are noted as well as comments revealing that students had great fun and satisfaction designing and building the blimps [8]. Chalmers will also devote more time to teamwork during the next run of its' first-year course, and in the CDIO Program there are discussions on how to strengthen this subject in all four courses through a 'learning module' to be developed for use by all. There are also suggestions for 'learning modules' in other subjects that could be jointly developed by the four partners.

During the remainder of the CDIO project the four universities will also proceed to compare more in detail different elements of their respective first-year courses and attempt to assess the student learning progress and efficiency. Central to the CDIO program are new ways of obtaining feedback as part of a continuous improvement process, and a subject of further work is how to assess student motivation. Data from the four universities on how the students have performed in the first-year courses as well as following courses over the years provides rich material from which it ought to be possible to extract knowledge on how the students' learning is affected by various ways of assessing and grading them. This can help to further improve the learning if we attempt to use those systems and techniques that seem to best support student learning and help us reach the educational goals. When changing the ways of rewarding the students for their work, it is important that we observe the effects so that we always maintain a reasonable balance between the efforts spent by the students on different courses.

Our intention is not to arrive at a 'standard' first-year course curriculum to be applied by all, but rather to learn from each other's good examples to improve all courses at the same time as preserving necessary individual characteristics of each. No single engineering course can, or probably ought not even try to, cover all items in the CDIO Syllabus, but a complete engineering education programme should of course cover them all. The CDIO Syllabus provides a basis for a discussion of where in the engineering curriculum particular skills are best taught. The challenges are to find out which items that should be focused in a specific course, in our case a first-year course, how to best teach them, and how to link them to other courses to support and optimise the students' learning.

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Göran Gustafsson
 Engineering and Industrial Design
 Product and Production Development
 Chalmers University of Technology
 SE-412 96 Göteborg
 Sweden

Phone: +46 31 772 1357
 Fax: +46 31 772 1375
 Email: goran.gustafsson@me.chalmers.se

Johan Malmqvist
 Engineering and Industrial design
 Product and Production Development
 Chalmers University of Technology
 SE-412 96 Göteborg
 Sweden

Phone: +46 31 772 1382
 Fax: +46 31 772 1375
 Email: johan.malmqvist@me.chalmers.se

Dava J. Newman
 Dept of Aeronautics and Astronautics
 Massachusetts Institute of Technology
 77 Massachusetts Avenue
 Cambridge, MA 02139-4307
 USA

Phone: +1 (617) 258-8799
 Email: dnewman@MIT.EDU

Sven Stafström
 Dept of Physics
 Linköping University
 SE-581 83 Linköping
 Sweden

Phone: +46 13 28 1352
 Fax: +46 13 13 7568
 Email: sst@ifm.liu.se

Hans Peter Wallin
Dept of Vehicle Engineering
Royal Institute of Technology
SE-100 44 Stockholm
Sweden

Phone: +46 8 790 7942

Fax: +46 8 790 6122

Email: hp@fkt.kth.se