USING IMMERSIVE VIRTUAL EXPERIMENT TO DEVELOP SAFETY MINDSET AND PROCESS OPERATION SKILLS

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ABSTRACT

The Diploma in Chemical Engineering (DCHE) implemented a suite of skills-based modules in its spiral curriculum to develop in students a safety mindset alongside the technical competencies required by process technicians in chemical processing industries according to the Singapore Skills Framework. Work shared here is from the third skills-based module, *Process Operations Skills 1* (*POS1*) where students will attain process operation skills and safety mindset specifically to prepare process equipment for maintenance. Preparing equipment to render it safe for maintenance requires the application of Workplace Safety and Health (WSH) by identifying hazards and the control measures to take, and applying Safe System of Work (SSoW) framework and Standard Operating Procedure (SOP) based on the process where the equipment is used. In *POS1*, they will extend the WSH knowledge learnt earlier and apply SSoW framework for the first time. Since students were new to mechanical work and have few chances to practice the skills due to limited actual equipment available, DCHE incorporated immersive technology in form of an immersive virtual experiment (IVE) into a learning activity to develop students' competency using control valve isolation as a basis. Thereafter, students had to demonstrate the competency by isolating a pump on an actual test skid. Survey findings showed the IVE was effective as students could better visualise and understand the rationale behind the steps to isolate a control valve. Most felt more prepared to demonstrate knowledge transfer to prepare an equipment for maintenance. Reflections of students' learning experiences using the IVE and subsequent application of learning on the test skid suggested they had acquired skills needed to develop competency in preparing process equipment for maintenance work with a safety mindset. Finally, plans to continue developing safety mindset and technical competences using immersive technology into other skills-based modules are shared.

KEYWORDS

Safety Mindset, Process Operation Skills, Chemical Engineering, Immersive Technology, Standards: 3, 6, 7.

INTRODUCTION

The Diploma in Chemical Engineering (DCHE) at Singapore Polytechnic (SP) trains students to work as process technicians in many industries, including the chemical processing industry. Having a safety mindset is of utmost importance in the chemical processing industry where processes operate at elevated temperatures and pressures using materials that are often hazardous, such as being toxic and flammable. Exercising caution is also needed when carrying out process operating tasks such as starting up a processing plant from ambient condition and preparing equipment for mechanical work due to the hazards present. This paper will focus on the training of students to work as process technicians in the chemical processing industry, specifically to develop the process operation skills alongside a safety mindset needed to perform the task of preparing equipment for maintenance (mechanical work) or after a shutdown.

DEVELOPING SAFETY MINDSET WITH PROCESS OPERATION SKILLS USING CDIO FRAMEWORK

Based on the hierarchy of Info-Communication Technologies (ICT) utilisation suggested by Anderson (2010), this paper adapted the work of Yang & Cheah (2020) to show how safety mindset and process operation skills can be progressively developed with digital technology using the CDIO Framework (Figure 1).

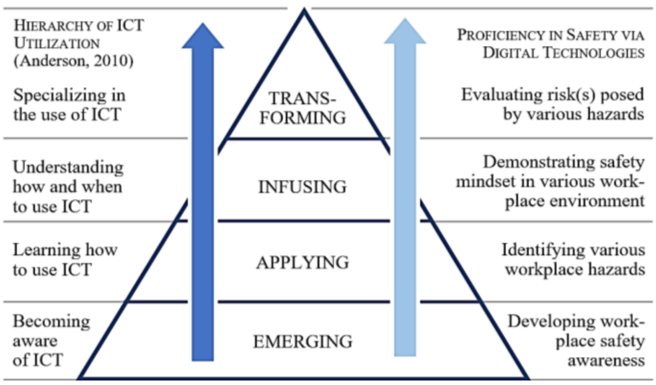

Figure 1. Progressive development of safety mindset using digital technologies

CDIO is an innovative framework for redesigning engineering curriculum that had been used by DCHE since 2007. The CDIO Framework comprises the CDIO Syllabus which guides the writing of learning outcomes and a set of 12 CDIO Core Standards which guides the curriculum redesign process. According to the Job Role Description for Process Technicians referenced from the Singapore Skills Framework (SSF) for the Energy & Chemicals (E&C) Sector (SkillsFuture Singapore, 2017), process technicians perform process operating tasks in the chemical processing industry such as to

- Apply Standard Operating Procedures (SOPs) for process operations
- Perform start-up, monitoring and shutdown of process units and utilities at plant sites
- Prepare process equipment and work areas for mechanical, maintenance and turnaround works
- Support troubleshooting during all modes of operation, including process upset conditions

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and require technical competencies such as (1) Standard Operating Procedure (SOP) Development and Implementation, (2) Process Operations Troubleshooting, and (3) Process Equipment Preparation for Mechanical Work at a proficiency level of 2. They will also need to have some of the following technical competencies, such as (4) Workplace Safety and Health Development and Implementation, (5) Workplace Safety and Health Hazard Identification and Risk Control Management, and (6) Safe System of Work (SSoW) Development and Implementation to apply SSoW procedures and comply with Workplace Safety and Health (WSH) systems to perform these tasks safely. Besides these technical competencies, process technicians also require generic competencies such as Teamwork, Communication, and Problem Solving (SkillsFuture Singapore, 2017).

By referencing the above mentioned technical and generic competencies, DCHE used its spiral curriculum, designed using CDIO Standard 3: Integrated Curriculum (Cheah & Yang, 2018) (Figure 2), to develop safety mindset with process operation skills in students through four of its skills-based modules over two years as these modules provide the best context for learning about the job role and responsibilities of process technicians: *Laboratory & Process Skills 1 (LPS1)* and *Laboratory & Process Skills 2 (LPS2)* in Year 1, and *Process Operation Skills 1 (POS1)* and *Process Operation Skills 2 (POS2)* in Year 2.

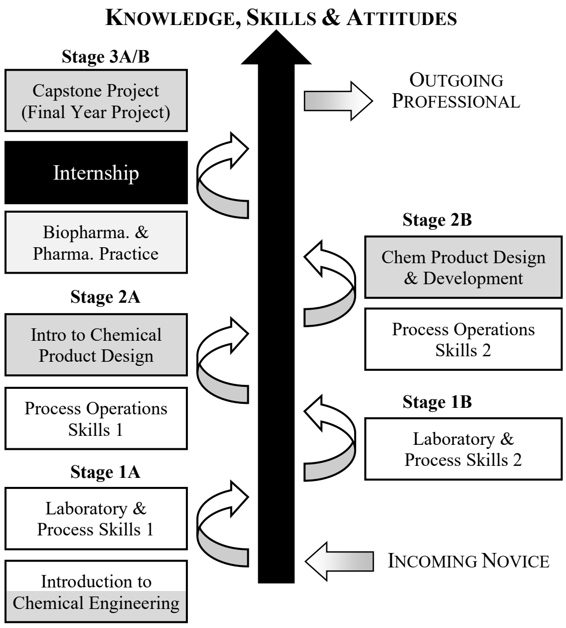

Figure 2. The DCHE Spiral Curriculum

The work shared here will be that done in *POS1*, taken by DCHE students in Year 2, Semester 1, and is a continuation of earlier effort to instill safety mindset in DCHE students, starting in *LPS1* where general workplace safety awareness is cultivated using Augmented Reality/ Virtual Reality training (Yang & Cheah, 2020) and laboratory safety was taught using Job Safety Analysis. In *LPS2*, students applied Job Safety Analysis and were exposed to Process Hazard Analysis when operating simple pilot plants. Such training comprises a blend of physical plants as well as virtual ones (Cheah, 2022; Cheah, 2021), designed based on CDIO Standard 7: Integrated Learning Experiences, where technical knowledge, skills and attitudes are all developed simultaneously using scenarios that mimic real-world work environment. Constructive alignment was used to check for attainment of learning outcomes using both formative and summative assessments.

Integrated Learning Experiences in POS1

POS1 has nine learning activities designed to provide students with a range of simulated real-world working environment of what process technicians do in their stipulated job role. Six of these learning activities will gradually develop students' abovementioned key competencies for process technicians as stipulated in the SSF for E&C Sector (Figure 3). The work shared here is carried out in Week 4 and is intended to support the later activity of preparing an equipment for maintenance in Week 6.

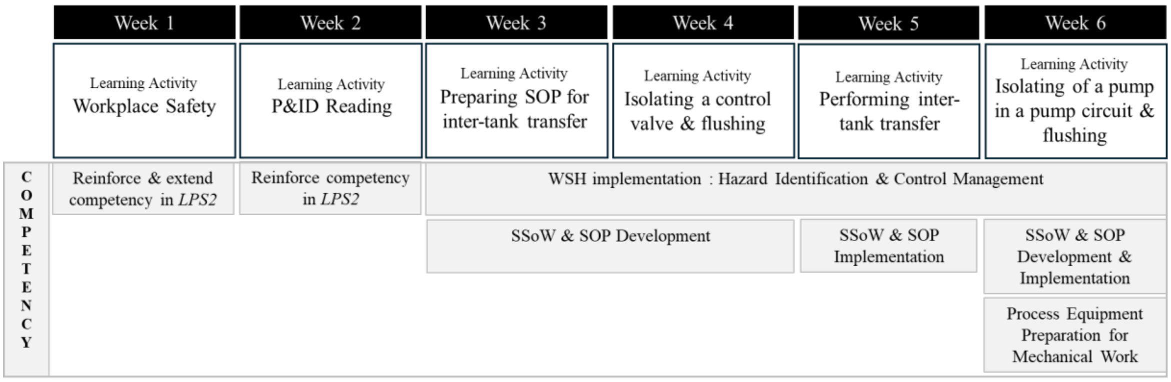

Figure 3. Selected Learning Activities in *POS1*

Since DCHE students do not have any real-world experience working in the chemical processing industry, learning activities to implement WSH and SSoW plans had to be slowly scaffolded into the module. Students' knowledge in *LPS2* from the previous semester on WSH awareness and Process Hazard Analysis were leveraged upon to progressively engaging them in activities with increasing complexity in *POS1*. In Week 4, isolation of a control valve and flushing of its associated piping were used as the basis to develop students' competency in preparing an equipment for maintenance. Choice of control valve was deliberate as it is commonly found in industry, and students had prior experience operating control valves in *LPS2*. Subsequently in Week 6, students had to demonstrate their ability to transfer the learning from control valve isolation to the preparation of a process equipment – in this case isolating a pump and its associated components (strainer, check valve and pipes), for flushing to remove any remnant chemicals in the pipes using an actual test skid in the workshop. Finally, students will submit a group report on their work done and a reflection journal of their learning experiences of the activities in Weeks 4 and 6.

To address the challenge of the large student cohort size (100-120 students per semester) which made it impractical to have many test skids in the limited workshop space which in turn reduces the number of hands-on practice students could have on the actual equipment, DCHE leveraged on technology and incorporated an Immersive Virtual Experiment (IVE) into the learning activity for Week 4. This approach is similar to that taken by Zhao *et al*. (2019) who used a virtual manufacturing shopfloor identical to the physical setup to overcome equipment and instructional hours limitations to teach safety, manufacturing equipment selection and operation.

Immersive Technology for Control Valve Isolation

The IVE is a digital learning package designed and developed in-house by SP. Since immersive technology provides a sense of immersion (Fracaro *et al.,* 2022; Lee *et al.,* 2013;

Lee *et al.,* 2012), when the technology is modelled after an actual site or equipment, users can gain familiarity through repeated virtual exploration of the site or equipment. This helps scaffold learning and allows faster transition to on-site work, or actual equipment operation (Fleury & Bondesan, 2024; Millard *et al.,* 2007; Zhao *et al.,* 2019). The IVE was therefore modelled after an actual control valve station commonly found in the chemical processing industry and on the actual test skid students will work on in Week 6 to provide familiarity and facilitate transition due to their lack of prior experience in carrying out mechanical work and difficulty in visualising the steps needed to plan and perform the work.

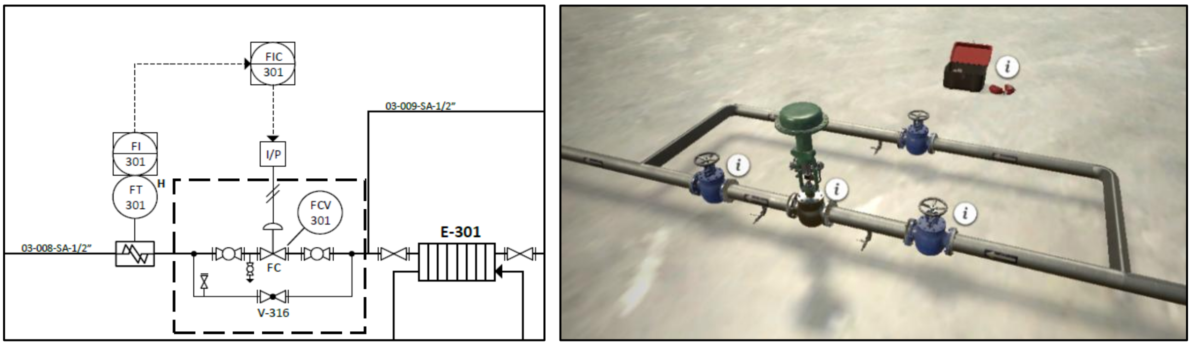

Figure 4. Schematic diagram of a typical control valve station enclosed in a rectangle (left) and the virtual control valve in the IVE (right)

The IVE consists of a 3D virtual representation of a control valve drawn to scale and offers active interaction between students and a section of the skid (Figure 4). It uses simple animations to allow students to interact with items within the environment and engage them in learning the content. Various hazardous scenarios were created to show consequences to students' actions using animations that would otherwise be impossible to replicate in real-life without serious consequences to safety. This enables experiential learning where students can better appreciate consequences of their actions, such as failure to undertake proper safe work practices, or overlooking a hazard during the risk assessment process, in a safe setting (Addison *et al.,* 2013; Fracaro *et al.,* 2022) thus increasing situational visualisation and awareness compared to traditional settings (Nakai, 2015; Nazir & Manca, 2015), all of which are useful when learning about health and safety (Millard *et al.,* 2007; Yang & Cheah, 2020) and operations (Norton *et al.,* 2008; Zhao *et al.,* 2019).

The prototype IVE was tested with 8 student volunteers from an earlier cohort who had completed *POS1*, and their input helped to refine the software package. The IVE was subsequently rolled out in Semester 1 Academic Year 2023/2024 to all six classes of students in the cohort reading *POS1*. Students will need to complete some of the following tasks in the IVE to demonstrate attainment of the desired learning outcomes:

- WSH Development and Implementation, Hazard Identification and Risk Control Management:
    1. Identify proper safety permits to use
    2. Barricade work area for restricted access
    3. Appropriate signage to warn of hazards present
    4. Select appropriate tools for the task on hand
- Process Equipment Preparation for Mechanical Work:
    1. Arrange steps in correct sequence according to the given SOP
    2. Identify suitable location to break flange

3. Coordination with Boardman in Control Room
4. Provision of secondary containment to reduce contamination of environment by residual process liquid during dismantling of piping

EVALUATION OF STUDENTS' LEARNING EXPERIENCE

A mixed-method survey was designed to evaluate the students' learning experience using the IVE in Week 4, and its effectiveness in helping them prepare for the activity in Week 6. A 5-point Likert-Scale was used where students were required to rate from "Strongly Disagree" to "Strongly Agree" on the following five questions:

1. The amount of content covered in the IVE was just nice.
2. I felt engaged (committed and motivated) when going through the IVE.
3. The simulations in the IVE have enabled me to better visualise the task at hand.
4. The knowledge checks in the IVE helped to check my understanding.
5. After doing the IVE, I feel more prepared to perform the practical on maintenance work in W319 (the workshop).

Students were then asked to estimate the amount of time they spent on the IVE, and finally to answer the following two open-ended questions:

6. Based on your response to Question 5, elaborate on your choice.
7. Suggest other ways(s) in which the IVE can help you be more prepared to perform the practical on maintenance work in W319 (the workshop).

The survey was administered to all students in the cohort reading *POS1*, and 88 students (83% of cohort) voluntarily completed the survey.

Discussion on the effectiveness of the IVE

87.5% of the respondents found the IVE content coverage sufficient for their learning of hazard identification and implementation of WSH and SSoW, and control valve isolation (Figure 5, left), with 92.0% of them completing it in 30 minutes or less (results not shown). Students felt that the timeframe was just right for them to remain engaged throughout to learn the content (87.5%; Figure 5, left). This suggests that even though use of immersive technology can enhance learning experiences and student engagement as reported by others (Colombo & Golzio, 2016; Huang *et al.,* 2016; Huang *et al.,* 2010), it is important to balance the duration of time needed and amount of effort needed to learn content using such technology. When students feel that they need to spend too much time to learn the content or too much effort to learn the content using the technology compared to traditional, which is often regarded as 'easier' due to familiarity, methods of, e.g. reading from notes or attending lectures, they may become disengaged or even surface undesirable behaviour such as introjected regulatory behaviour (Tan *et al.,* 2009). It is also important for students to be given explicit instructions on how to use the technology and/ or time to explore especially if the technology is unfamiliar to them.

Majority of students surveyed strongly agree or agree that the IVE was effective in preparing them to transfer what they learnt from the IVE in Week 4 and demonstrate it in another context - the activity carried out in Week 6 where they had to prepare a process equipment (a pump) in the workshop (W319) for maintenance (87.5%; Figure 5, right). This was attributed to the interactivity and clarity of each step in the IVE as shared by one student: *"The IVE made it clear on what key tasks were involved in the maintenance work and how to perform the tasks"*.

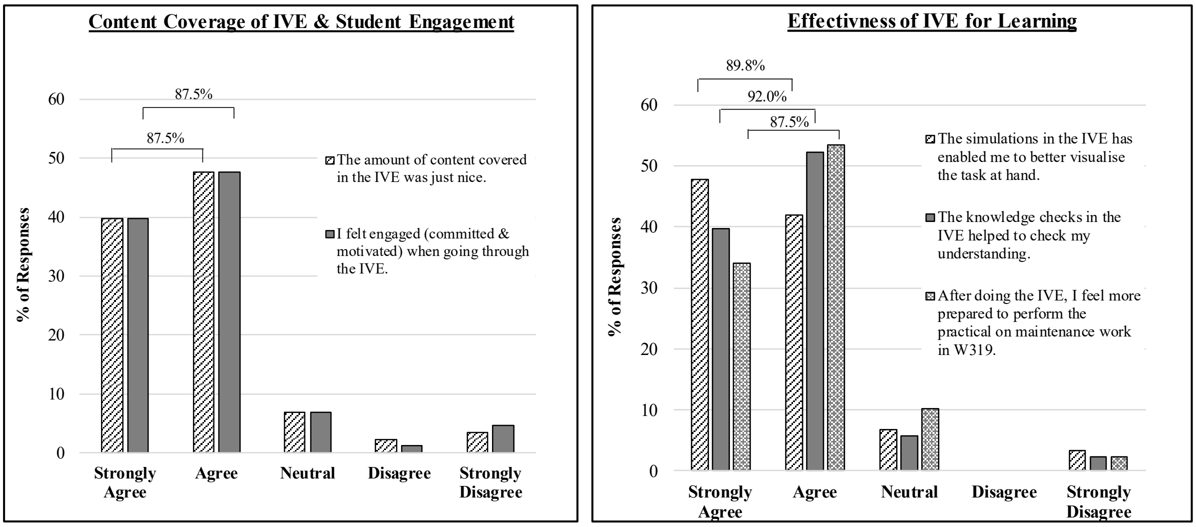

Figure 5. Content coverage of IVE and student engagement when using IVE (left) and effectiveness of IVE for learning (right)

A student opined that the IVE *"allowed me to know the different permits needed"* which is a key requirement when preparing equipment for maintenance based on the SSoW framework that students had to carry out in Week 6. Nonetheless, a few students had some reservations (2.3% disagree or strongly disagree; Figure 5, right) on their preparedness to demonstrate transfer and application of knowledge on the actual equipment in Week 6. This lack of confidence was not surprising as this was the first instance students had to perform mechanical work. One student shared: *"I felt mostly prepared to perform isolation, but not fully since there are differences in doing isolation for a control valve and a pump"*, suggesting the different context that he/she had to apply the knowledge led to the reservation and not the insufficient knowledge of how to go about doing so.

The overall positive sentiments on the effectiveness of IVE for learning, and engagement that students felt when using the IVE can be attributed to three factors: the knowledge checks, the interactivity and the realistic visuals/ animations. 92.0% of students strongly agreed or agreed that the knowledge checks provided insights to how well they understood the IVE content and the specific section(s) they may need to re-visit (Figure 5, right) to meet the learning outcomes. Through the interactivity and realism provided in the IVE, 89.8% of students strongly agree or agree they were able to better visualise the planning and execution processes needed to prepare an equipment for maintenance and developing simultaneously the safety mindset needed (Figure 5, right) even though they had no prior experience in carrying out such mechanical work. They were able to identify the hazards and measures needed to mitigate or control these hazards. This was followed by identifying the permits needed in the SSoW and finally sequencing the steps that will lead to the isolation of the control valve into an SOP. Consequences were also shown if the SOP was not followed and/ or students choose to take an action that will result in an unsafe or hazardous condition. These were succinctly articulated by two students: *"The IVE gave me a better idea on how to perform practical 6 as it is visually enriching, and it helped to guide me through the different steps that needed to be taken during* *the isolation and preparation of the equipment for maintenance.", and "It helped me to visualise what I have to do with my team for maintenance work. For example, which isolation valves to close first."*

These positive survey findings show that the IVE was useful to develop in students the desired safety mindset alongside the key competencies required by Process Technicians as stipulated in the SSF for E&C sector (Figure 3) similar to that reported by Colombo & Golzio (2016) who found that immersive technology when used for training in the process industry enabled more learning compared to traditional didactic training.

Discussion on students' reflections on learning to prepare process equipment for maintenance and safety mindset

In students' reflection journals submitted after both learning activities in Weeks 4 and 6 were completed, the most frequently cited skills that were acquired were (1) construction of utility tie-in lines which are needed for flushing after equipment isolation, (2) application of the correct procedures (Lock Out, Tag Out; LOTO) to ensure that equipment was properly isolated before maintenance, (3) proper handling and usage of tools needed for equipment isolation and (4) selection of correct location and steps needed to break flanges safely when isolating equipment (Figure 6). These technical skills are necessary to develop competency in preparing process equipment for maintenance work alongside with a safety mindset. Students also cited top non-generic skills that they acquired and were highly important to ensure safety and work efficiency such as (1) planning of work and preparation of required documentations such as SOP, permits etc, (2) communication and teamwork, (3) leadership, and (4) adaptability and problem-solving ability. In one entry, a student reflected that: *"…, I learnt that the planning stage is crucial in the context of preparing equipment or a system for shutdown for several reasons. Firstly, the biggest point of concern during any plant activity: safety. Proper planning allows for a comprehensive assessment of potential risks, identification of safety procedures, and implementation of necessary precautions. This includes ensuring that appropriate isolation procedures are followed, hazardous materials are handled safely, and potential safety hazards are mitigated."*

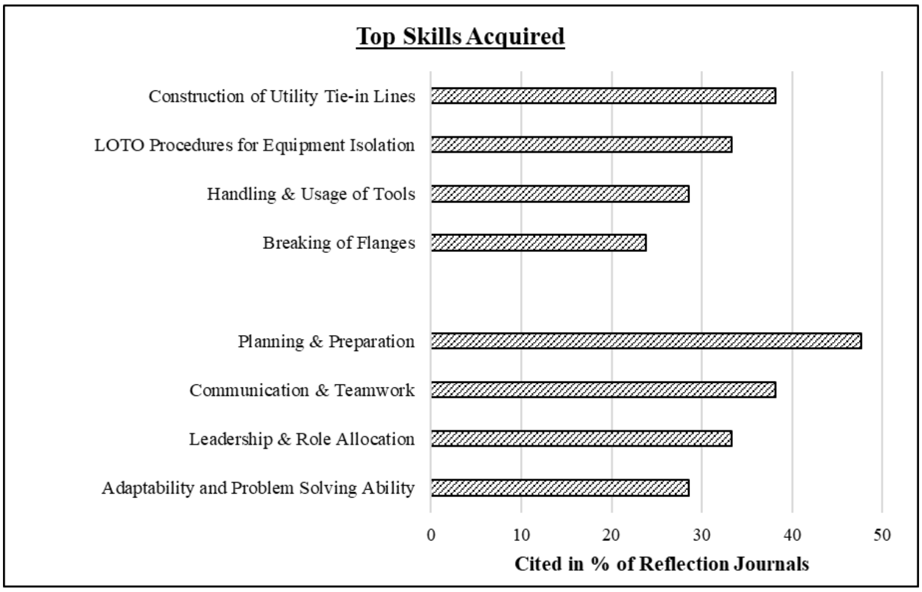

Figure 6. Top skills acquired from learning activities in Weeks 4 and 6

During the actual hands-on activity where students performed pump isolation in Week 6, all students experienced leakages (of various magnitudes) of the residual process liquid during flushing due to poor tightening of flanges and fittings. Many students were caught off-guard as leakages during flushing were not modelled in the IVE, and they did not realise the importance of proper flange tightening techniques and the resultant consequences even though the lecturer had gone through a briefing prior to the start of the activity. Although the process liquid was only water, it can be a hazardous liquid in real-life industry and consequences will be far more severe. Students also had to adapt to the unexpected unsafe situation that had developed and perform problem solving on the spot to resolve the leakages and continue with the learning activity. As such, this incident left a lasting impression on many students (hence, relatively high number of journal entries – 42.9% cited leakage prevention as important), and helped reinforced the need to perform thorough hazard identification and risk control management. In their reflection journals, students were able to highlight the importance of on-site verification in ensuring safety and adherence to SSoW and WSH systems as it allows checking of the accuracy of SOP developed, identification of hazards that may otherwise been missed out during planning stages and also inspection of any non-compliance to regulatory and procedural requirements. These reflections suggest that students had acquired the key competencies needed to prepare process equipment for mechanical works safely as required by the SSF for the E&C sector for process technicians.

CONCLUSION

The experience of using an IVE to facilitate training of students to prepare equipment for maintenance with a safety mindset, which are key competencies for process technicians in the E&C sector, was shared here. Survey findings and reflection journal entries from the students' experiences in using the IVE to learn WSH, and SSoW and SOP implementation for control valve isolation, and subsequently to transfer this learning to that of pump isolation and maintenance was positive. The benefits of the IVE in teaching and learning of these skills can be clearly summarised by one student's sharing *"It helped visualise an otherwise difficult area of study to imagine without seeing firsthand examples and thus assisted in understanding of the process as well as the tasks we are supposed to do".*

This is very encouraging, given that the realism of the visuals and interactivity to actual operations in immersive digital technology (Nazir & Manca, 2015) and the ability to allow for repeated practice make such technology a natural fit for teaching and learning of knowledge and skills for industries such as chemical process when there is a need to transfer the acquired knowledge or skills readily to actual equipment or processes or to replicate conditions for training that would otherwise be unsafe or impossible to carry out in real life (Addison *et al.,* 2013; Fracaro *et al.,* 2022; Koskela *et al.,* 2005; Millard *et al.,* 2007; Norton *et al.,* 2008; Zhao *et al.,* 2019). DCHE is reviewing and purposefully designing more activities with greater complexity that leverage on similar technology such as to make use of a digital twin of an actual pilot plant to let students operate a pilot plant under different scenarios such as a sudden plant upset and learn how to respond in these situations with a safety mindset. These activities will facilitate further development of key competencies alongside with the safety mindset to the desired proficiency level as required by process technicians in the E&C sector.

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