DESIGNING A DIGITAL TWIN VIRTUAL LAB FOR PLC APPLICATIONS

Chew-Lin CHIA and Rick CHUA

School of Electrical & Electronic Engineering, Singapore Polytechnic

ABSTRACT

This study evaluates the integration of a Digital Twin (DT) virtual model into the *ET0917 Programmable Logic Controller (PLC) Applications* module, assessing its impact on enhancing learning by simulating car park scenarios beyond the constraints of the physical lab. Aligned with CDIO principles, all labs in ET0917 are designed to bridge theory and practice, equipping students with essential skills in ladder logic programming, I/O device configuration, and automated control system development. The DT virtual lab extends these learning opportunities by providing a dynamic, interactive environment that overcomes the limitations of the standard lab setup. The DT virtual lab was designed incorporating the principles of Self-Determination Theory and Cognitive Load Theory to strategically reduce extraneous cognitive load while deepening student engagement. Survey and interview feedback from students and staff indicated positive responses, with students reporting improved visualization and a stronger grasp of problem-solving concepts. Building on this success, future developments will expand DT technology to incorporate additional scenarios beyond the standard lab setup. This will broaden the scope of learning and application, particularly by simulating future scenarios that are not physically possible. This approach aims to nurture students' futures thinking competency, preparing them to anticipate and address emerging engineering challenges while strengthening their ability to conceive, design, implement, and operate solutions within the CDIO framework.

KEYWORDS

Digital Twins, Visualization, Self-determination Theory, Extraneous cognitive load, CDIO Syllabus, CDIO Standards 1, 6, 7 and 8.

NOTE: Singapore Polytechnic uses the word 'courses' to describe its education 'programs'. A 'course' in the Diploma in Chemical Engineering consists of many subjects that are termed 'modules'; which in the universities' contexts are often called 'courses'. A teaching academic is known as a 'lecturer', which is often referred to a as 'faculty' in the universities.

DESIGNING EFFECTIVE MULTIMEDIA LEARNING: A BLEND OF MOTIVATION AND COGNITIVE LOAD PRINCIPLES

The accelerated digitalization in the manufacturing sector has necessitated updates to our engineering curricula to prepare students for Industry 4.0 and Smart Manufacturing. Among the emerging technologies, Digital Twin (DT) has gained significant importance. DT technology is a virtual representation of physical objects, systems, or processes. With its capability to mimics the characteristics, behaviors, and functionalities of its real-world counterpart, it offers solutions for creating learning tasks that are not feasible in physical labs.

However, research shows that adopting technology alone does not inherently improve learning outcomes. For example, Madden *et al.* (2019) found no significant differences in learning outcomes after comparing different teaching methods including hands-on activities, virtual reality, and desktop simulations. Similarly, a meta-analysis conducted by Karich *et al.* (2014) concluded that learner control in multimedia environments had negligible overall effects on outcomes. To enhance learning outcomes, Rey *et al.* (2019) suggested presenting the multimedia instruction in meaningful, progressive stages that support human cognitive processes. Progressive and meaningful implementation of DT technology can resolve these issues by providing structured, interactive, and realistic simulated environments that enhance learning and motivation. DT technology offers immediate feedback mechanisms, which build competence by providing clarity and reinforcing progress (Hattie & Timperley, 2007). Additionally, the interactive features of the DT model promote autonomy by enabling students to choose their problem-solving methods, while carefully managing cognitive load to avoid overload (de Brabander & Martens, 2014).

This paper explores the use of DT for students from the School of Electrical and Electronics Engineering (SEEE) in Singapore Polytechnic (SP). The goals are twofold: firstly, to leverage the advantages of DT to simulate scenarios not feasible to create in physical labs; and secondly, to help students appreciate the impact of digitalization in the manufacturing industry. This initiative aligns with Standard 6, which recently added digital workplaces into education, and CDIO Syllabus (2.4.5) Staying Current on the World of Engineering. To achieve these goals and address the challenges, we draw on Self-Determination Theory (SDT) and Cognitive Load Theory (CLT) to offer guiding principles for achieving this balance. As proposed by Ryan and Deci (2000), SDT identifies three innate psychological needs namely autonomy (control over one's actions), competence (feeling capable and effective), and relatedness (feeling connected to others) which are essential for fostering intrinsic motivation, deeper engagement, and active participation. At the same time, CLT, introduced by Sweller (1998), highlights the importance of managing cognitive demands by minimizing extraneous load.

OVERVIEW OF THE MODULE: ET0917 PLC APPLICATIONS

In the SEEE, all second-year students from the Diploma of Electrical and Electronics (DEEE) are required to take the module *ET0917: Programmable Logic Controller (PLC) Applications.* This module is designed to provide hands-on, experiential learning that connects theory with practice in the context of manufacturing and process automation. It adopts an active and integrated learning approach, in line with Standards 7 and 8, to foster meaningful engagement and practical application. The module spans 15 weeks, with 5 hours per week, including 3 hours in a laboratory setting. The lab activities are centered around authentic, real-world tasks (Standard 1) and are sequenced progressively from simple practical exercises to more complex industry challenges. This progression enables students to appreciate and reflect on the *Roles and Responsibilities of Engineers (4.1.1)* and the importance of *Training and Operations (4.6.2).*

Through this module, students gain proficiency in essential PLC skills, including ladder logic programming, configuring INPUT/OUTPUT (I/O) devices, integrating human-machine interfaces, and developing automated control systems. These skills are fundamental for designing, programming, and maintaining industrial automation systems used in manufacturing and process industries. In the lab, students engage in hands-on learning activities such as developing ladder logic programs, configuring hardware, and troubleshooting systems. These activities foster *systems thinking (2.3)* as students analyze the relationships, interactions, and interfaces among I/O devices. The module also emphasizes *Experimentation, Investigation, and Knowledge Discovery (2.2)*, encouraging students to engage in *self-awareness, self-reflection, and metacognition (2.4.6)* as they assess their skills, strengths, and areas for improvement.

Additionally, the module develops *interpersonal skills (3.0)*, *adaptability and flexibility (2.4.3)*, and CDIO skills, which include systems thinking, implementation, and integrated problem-solving competencies *(4.3) – (4.6).* These competencies are further enhanced through structured practical exercises (Standard 7) and a capstone CDIO project (Standard 5). This integration of attitudes and technical skills ensures a holistic learning experience, equipping students for the complexities of both the industry and society.

DESIGNING THE LEARNING TASK INCORPORATED WITH DT TECHNOLOGY

Incorporating DT technology into learning tasks requires a timely and structured approach to prevent increasing cognitive load that hinders learning. Table 1 outlines the PLC module's three-week schedule, which helps illustrate the rationale for introducing the DT lab in Week 3.

Week 1: Students are introduced to the fundamental concepts of PLC programming, basic functions, and applications during lectures. In the lab, they familiarize themselves with the hardware layout, identify parts and their functions, install PLC software tools, and get accustomed to the programming environment.

Week 2: Students learn about basic I/O devices and develop simple ladder logic programs during lectures. In the lab, they apply this knowledge through mini learning tasks, gaining hands-on practice in constructing ladder logic programs and working with I/O devices. They also build timing applications by incorporating timers into their programs.

Table 1. Overview of 3 Weeks Learning Schedule for *ET0917: PLC Applications*

Week	**Week 1**	**Week 2**	**Week 3** ***DT Implementation**
Learning outcomes	PLC hardware architecture and components	Interface common hardware components to PLC	
Lecture (2 hrs/wk)	PLC hardware architecture of a PLC system.	Commonly used hardware used in PLC systems	
Lab (3 hrs/wk)	Familiarization of the whole system Assemble and prepare PLC system for operation	Basic Programming Simple wiring and I/O devices	Introduction to timers and counters applications.

Week 3: By this time, students are expected to understand the basic operations of PLC systems, including hardware architecture, such as the CPU, input/output peripherals, and power supply. They should be able to identify and connect common industrial sensors and

hardware components, address safety considerations using interlocks and overload protection, and understand the IEC 61131-3 standard, including different PLC programming languages like Ladder Logic, Function Block, and Structured Text, as well as variable declarations and addressing modes. This foundational knowledge prepares them to work effectively with simple PLC systems.

Students then progress to learn about Up, Down, and Up/Down counters by creating and testing programs involving these types. To reinforce what is learned, students work on tasks that apply counters in real-world scenarios. However, the primary setup in the lab consists only of a conveyor belt system with standard I/O devices (Figure 1). When tasks involve scenarios beyond the physical setup, students visualize these scenarios using the existing equipment. For example, one learning task requires students to program a car park system with 20 parking lots. Before solving this, students need to first imagine the conveyor belt functioning as a car park, using sensors attached to it (simulated with hand movements) to detect cars entering and exiting (Figure 1). When the car park is full, an LED light on the board indicates its status. This task challenges students to program an Up/Down counter, encouraging them to apply their technical skills while fostering problem-solving abilities when real-world setups cannot be directly replicated.

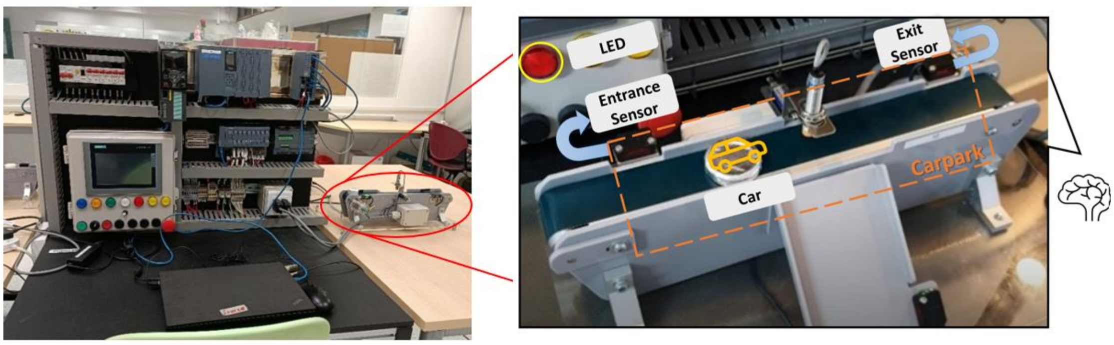

Figure 1. A complete training station meant for 1 to 2 students and how students visualize the carpark scenario in one of the learning tasks in the PLC laboratory.

With prior experience using the basic PLC setup and operations, students are prepared to work with the DT model without the frustration of figuring out basic PLC operations (Sweller, 1988). The introduction of a DT-simulated model of the car park may enhances their ability to visualize operations effectively. Such virtual simulation fosters visual-spatial skills, enhancing problem comprehension, futures thinking, and problem-solving abilities. Gagnon and Landry (2023) demonstrated that visual aids improve spatial knowledge and facilitate navigation in complex environments, supporting the use of simulations in learning contexts. Similarly, Duffy (2016) highlighted that visual spatial thinking is pivotal in problem-solving, aiding the understanding of interactions among system components. Incorporating such simulations into the learning process develops essential visual-spatial skills and encourages anticipatory reasoning and systems analysis, core to futures thinking competency.

Before using the DT virtual model, students follow a series of steps and settings to ensure the physical setup interacts with it. This process requires basic IT technical proficiency and attention to detail. To minimize extraneous cognitive load, strategies such as providing clear, concise, and organized instructions are employed. Techniques like numbering steps and using "red box" emphasize critical actions that need to be followed, as Jamet (2014) demonstrated that visual cues improve learning by directing attention to essential elements. Figure 2 illustrates the application of these methods in the instructions for running the DT virtual model on students' computers.

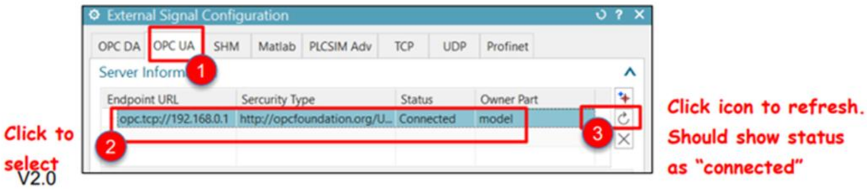

Figure 2. A snapshot of the Instructions for students to prepare for the DT lab.

Once students link the DT virtual model to the physical PLC system at their workstations (Figure 3), they can interact with the virtual models via physical sensors (Figure 1) to develop and test their PLC programs. This integration fosters autonomy by allowing students to explore various programming approaches, enhancing their systems and logical thinking skills.

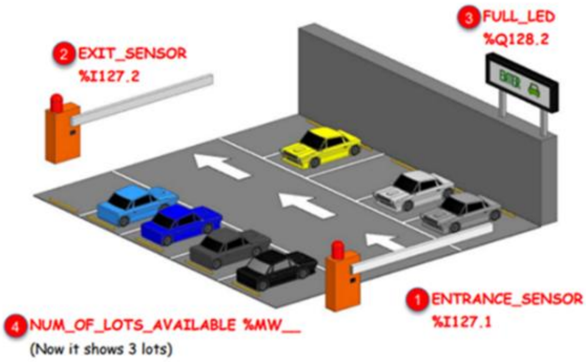

Figure 3. the DT virtual model of the car park task linked to the physical PLC system.

FINDINGS AND DISCUSSIONS

Participants & Instruments Used

The study was conducted with all six classes of second-year DEEE students, totaling 103 participants taking the module in the second semester of the Academic Year 2023/2024. To support the teaching staff and students during the DT lab implementation, two in-house interns who had worked on the DT model were tasked with assisting in the sessions. A mixed-methods approach integrating both quantitative and qualitative data collection methods, including questionnaires, interviews, and observations was adopted to provide a comprehensive understanding of the study outcomes. This approach allowed for a more holistic analysis, capturing not only numerical trends but also deeper insights into student experiences. The questionnaire was conducted using Microsoft Form at the end of the DT lab session, receiving 96 responses (95%). It consisted of twelve 7-point Likert scale items (1 = not true at all to 7 = extremely true), covering four subcategories, as shown in Table 2. Items 1 to 6, adapted from the Intrinsic Motivation Inventory (IMI; http://selfdeterminationtheory.org/), assessed student attitudes. The rest of the items were adapted from Hwang et al. (2013), focusing on the "Perceived Usefulness" and "Perceived Ease of Use" of the technology.

Table 2. Question items and its corresponding subscale.

Item no.	Item content	Subscale	Negative |	Neutral | Positive n=96	
1.	I have some choice on how I want to program to complete this task.	Perceived autonomy	5%	22%	72%
2.	I enjoyed the human-Digital Twin interaction experience in this task.	Interest/ Enjoyment	7%	17%	76%
3	I enjoyed working on this task.		8%	13%	79%
4.	Compared to working on the learning task in the traditional setup, the use of Digital Twin increased my motivation for learning.		11%	20%	68%
5.	After working at this task for awhile, I felt pretty competent.	Perceived Competence	12%	26%	62%
6.	I feel I can make sense of the response feedback from the Digital Twin System and correct my program accordingly to make it work as expected.		10%	20%	69%
7.	Using Digital Twin in this task had made my learning easier.	Technology Acceptance	13%	19%	67%
8.	I find it important to keep myself up to date by learning the latest technology such as Digital Twin.		9%	22%	68%
9.	I prefer to use Digital Twin compared to the traditional setup in the lab.		11%	22%	66%
10.	It is not difficult for me to learn to setup the Digital Twin.		12%	27%	61%
11.	I look forward to using Digital Twin in my practical lessons.		13%	20%	66%
12.	I feel I learned better using Digital Twin.		13%	23%	63%

Survey Analysis

For better visualization, a diverging stacked bar chart as seen in Figures 4 and 5 was used to visualize the overall sentiment towards the DT lab.

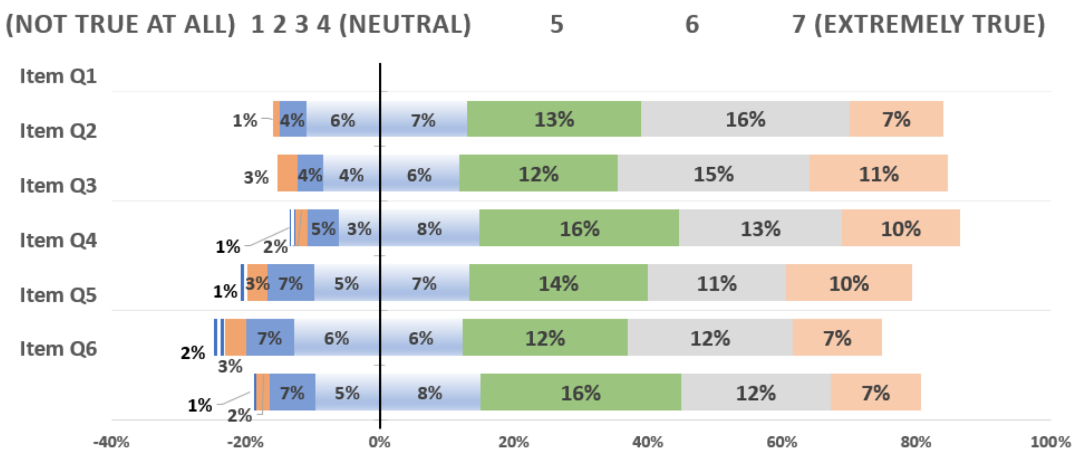

Figure 4. Students' response for Q1 to Q6

As seen, each bar is divided into 8 segments representing all the Likert responses, with a neutral line at zero. Segments to the right indicate positive responses (Likert scale 5, 6, and 7, plus half of the neutral responses), while those to the left represent negative responses (Likert scale 1, 2, and 3, plus half of the neutral responses). For all items 1 to 6, the bars extend more to the right (62-79% of 96 respondents), suggesting high satisfaction. Students generally found the DT technology motivating, valuable, and useful, feeling they had a choice in their learning. This aligns with lab observations. Figure 5 shows that 61-68% of students were positive about DT use in the lab, indicating that DT technology made learning easier, helped them stay updated with industry trends, and should be used more in future lab sessions. Notably, for some items, no respondents selected rating 1, further reinforcing the absence of strong negative perceptions.

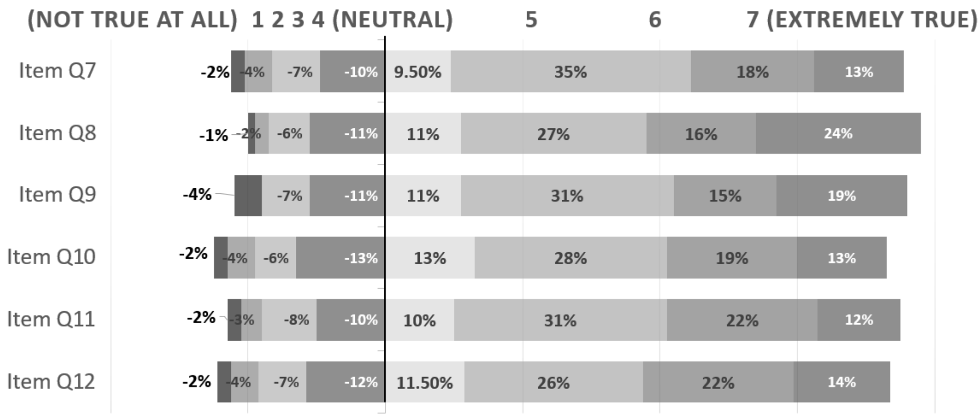

Figure 5. Students' responses for Questions under the subscale of Technology Acceptance.

For greater insight, students were asked to share their personal experiences with the DT lab at the end of the survey. Table 3 presents representative comments categorized by sentiment, based on an intuitive assessment of content and tone. Representative quotes were selected to illustrate each sentiment group. All student responses were reviewed, and examples were chosen to reflect common themes within each category, ensuring a balanced representation of views across positive, neutral, and negative feedback. Out of 96 respondents, 34.7% provided positive feedback, highlighting the ease of visualization and interactive learning benefits. The majority (58.1%) were neutral, possibly indicating indifference or general satisfaction with previous questions. A small portion (5.1%) expressed negative sentiments, citing challenges related to the clarity of the instructions and the usability of the DT.

Table 3. Students' responses to the question – Share your experience with us if you find Digital Twin has impacted your learning in this lab.

Sentiment	No. of student responses	Selected representative comments from students' responses in each sentiment response category.
Positive	34	*"It was fun and interactive".* *"It has made me see it virtually which enhances the learning."* *"It is good that we can keep up with latest technology in school."*
Neutral/Mixed	7	*" With the Digital Twin, it makes understanding of the code easier as it is able to simulate it. However, the connection between the TIA Portal and Digital Twin is unclear as there is no clear sign showing it is connected unlike the TIA portal."* *" I don't think it made much difference but it did make learning and visualising easier."*
Negative	5	*" I find that it's a little harder to learn because I can't see the physical connections so I get confused how or why something gets turned on or off."* *" I didn't quite understand how to use it."*

Face-to-Face Focus Group

Shortly after the survey, a face-to-face focus group discussion with six students was conducted to gain qualitative insights into their experiences with the DT lab. All students shared specific examples of how they enjoyed interacting with the DT technology and how it enhanced their learning. Some examples are shown below:

“Interesting, it is my first time encounter a 3d model that I can use to interact with the actual sensors in the lab”.

“It is helpful for my learning as it helps me to see what the PLC is capable of. I can see the actual application in action just like the carpark example.”

“It was fun. It was interesting. I have a clear indication of what is going wrong, see the problem and solve it.”

To summarize, students appreciated the interactive nature of the DT technology, citing improved understanding of PLC capabilities and enhanced problem-solving through realistic simulations. They recommended more frequent DT labs, additional practical applications, and using DT in short courses to gather industry feedback.

Staff feedback

Immediately following the week when the DT labs were conducted, an online survey were sent to all the four teaching staff members to gather their feedback on the DT lab. The survey included the following four items rated on a 7-point Likert scale (1 = strongly disagree to 7 = strongly agree) as shown in Figure 6.

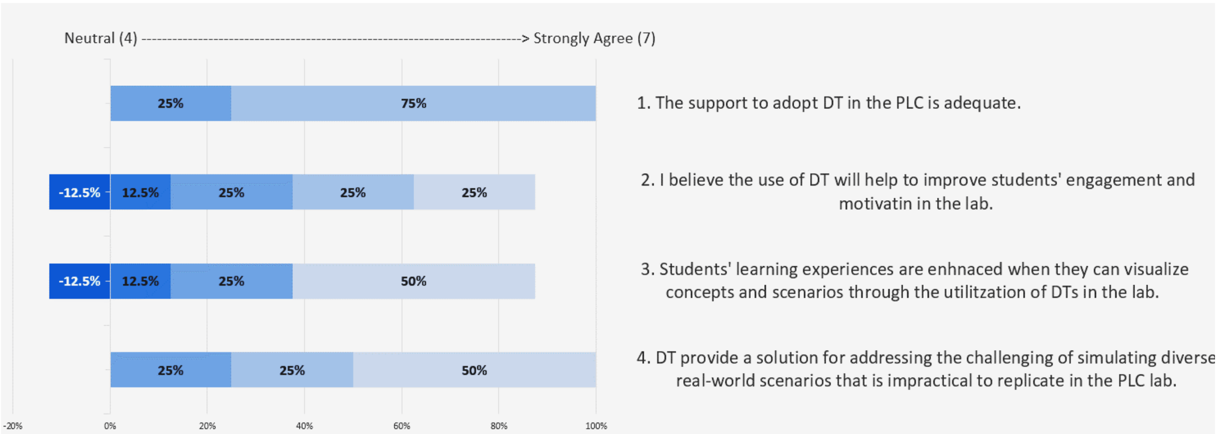

Figure 6. Teaching staff’ responses for Questions under the subscale of Technology Acceptance

The bar chart in Figure 6 shows uniformly positive responses from all teaching staff, ranging from neutral to strong agreement, indicating an overall support for DT integration and recognizing its benefits for student learning, engagement, and future potential. Constructive feedback for future improvements were also given. They included students' unfamiliarity with NX software made troubleshooting connectivity with TIA Portal more challenging, first-time DT users required additional time to adapt, and time constraints in the lab posed difficulties.

Addressing Challenges and Future Directions

The main challenge identified from the findings was connectivity issues between the TIA Portal and NX software, which left some students feeling lost and hindered their ability to fully appreciate the benefits of DT activities. Addressing these technical challenges is crucial to enhancing the effectiveness of the DT lab and ensuring all students can fully benefit from DT technology. Since all students were first-time users, providing clear, comprehensive instructions, including troubleshooting tips, can help them resolve issues independently.

Building on the successful implementation of a DT lab activity, the next step is to expand its use by developing additional scenarios beyond the current lab setup. Since DT simulations allow for the creation of scenarios beyond the limitations of traditional physical setups, activities can be designed to equip students with forward-thinking problem-solving skills. For example, while students currently optimize conventional car park designs, DT models could be used to explore future challenges such as integrating EV charging stations or designing vertical car parks to address urban land constraints. These exercises shift the focus from immediate operational issues to innovative, sustainable solutions, reinforcing a precautionary mindset, an essential aspect of futures thinking. This can help to nurture students' futures thinking competency, preparing them to anticipate and address emerging engineering challenges while strengthening their ability to conceive, design, implement, and operate solutions within the CDIO framework. To ensure meaningful integration, lab activities will align with the module's intended learning outcomes, guided by CDIO Standard 2, while assessments based on CDIO Standard 11 will evaluate learning gains and competency development. By embedding these competencies within DT simulations, students develop the ability to anticipate risks, balance innovation with sustainability, and navigate uncertainties. This aligns with the goals of Education for Sustainable Development (ESD), as highlighted by UNESCO (2017). Further studies will be conducted to assess the long-term benefits of this approach.

CONCLUSION

An in-house Digital Twin (DT) model was developed to simulate a car park scenario in the ET0917 PLC Applications module, enhancing student learning beyond the physical lab's limitations. This DT model was designed with principles from Self-Determination Theory and Cognitive Load Theory to help reduce cognitive load and improve visualization, contributing to more effective learning experiences. Findings from surveys and interviews revealed positive feedback from students and staff, with most students highlighting DT's role in improving visualization and learning. Importantly, this development serves as a targeted educational tool aimed not only at improving students' understanding of current scenarios but also at fostering critical thinking about potential future challenges in engineering. By simulating scenarios that extend beyond the physical lab setup, students can practice anticipating issues and developing solutions, preparing them for the evolving demands of the field. The DT model, while linked to the fixed physical setup in the lab, allows for the inclusion of various scenarios that cannot be physically replicated, thereby broadening the scope of learning and application.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to Cheah Sin Moh for his invaluable assistance and generous time in reviewing this paper. His thoughtful feedback and insightful suggestions have greatly improved the quality and clarity of this work. The authors affirm that this research was conducted without any financial support or funding.

REFERENCES

De Brabander, C. J., & Martens, R. L. (2014). Towards a unified theory of task-specific motivation. *Educational Research Review, 11*, 27–44.

Gagnon, J., & Landry, F. (2023). Visual aids and spatial knowledge: Enhancing learning in simulation-based education. *Journal of Educational Technology, 12*(4), 567–580.

Hattie, J., & Timperley, H. (2007). The power of feedback. *Review of Educational Research, 77*(1), 81–112.

Duffy, G., Sorby, S., Nozaki, S., & Bowe, B. (2016). Exploring the role of spatial cognition in problem-solving. In *Proceedings of the 46th Annual Frontiers in Education Conference* (pp. 1–4). https://doi.org/10.1109/FIE.2016.7757593

Hwang, G. J., Yang, L. H., & Wang, S. Y. (2013). A concept map-embedded educational computer game for improving students' learning performance in natural science courses. *Computers & Education, 69*, 121–130.

Jamet, É. (2014). An eye-tracking study of cueing effects in multimedia learning. *Learning and Instruction, 32*, 48–57.

Karich, A. C., Burns, M. K., & Maki, K. E. (2014). Updated meta-analysis of learner control within educational technology. *Review of Educational Research, 84*(3), 392–410.

Madden, J., Pandita, S., Schuldt, J., Kim, B., Won, A., & Holmes, N. (2020). Ready student one: Exploring the predictors of student learning in virtual reality. *PLOS ONE, 15*, e0229788. https://doi.org/10.1371/journal.pone.0229788

Rey, G. D., Beege, M., Nebel, S., Wirzberger, M., Schmitt, T., & Schneider, S. (2019). A review of the effects of segmentation on learning outcomes in multimedia learning. *Educational Psychology Review, 31*(2), 389–414.

Ryan, E. D. R. (1980). The empirical exploration of intrinsic motivation processes. In L. Berkowitz (Ed.), *Advances in experimental social psychology* (Vol. 13, pp. 39–80). Academic Press.

Schminder, J., Nilsson, F., Lundberg, P., Nguyen, N.-A., Hag, C., & Najafabadi, H. (2019). An IVR engineering educational laboratory accommodating CDIO standards. In *Proceedings of the 19th International Conference on the Engineering of Computer-Based Systems* (pp. 1–6). https://doi.org/10.1109/ECBS.2019.00015

Sweller, J., van Merriënboer, J. J., & Paas, F. G. (1998). Cognitive architecture and instructional design. *Educational Psychology Review, 10*(3), 251–296.

Fleury, S., Baudouin, C., & Bondesan, P. (2024, June 11). Immersive digital twins of an industrial forge in engineering education. In *Proceedings of the 20th International CDIO Conference, Tunisia*.

UNESCO. (2017). *Education for sustainable development goals: Learning objectives*. United Nations Educational, Scientific and Cultural Organization.

BIOGRAPHICAL INFORMATION

Chia Chew Lin is the T & L Mentor at the School of Electrical and Electronic Engineering in Singapore Polytechnic. She currently explores teaching approaches that embed sustainability competencies. She aims to create psychology-driven/evidence-based strategies that are easily implemented by other educators for long-term impact in sustainable education.

Rick Chua is an educator with more than 15 years of experience. He is currently a senior lecturer in the School of Electrical and Electronic Engineering at Singapore Polytechnic. He holds a degree in electrical engineering and a post graduate diploma in education. His areas of interests include automation and digital twin.

Corresponding author

Dr Chia Chew Lin

School of Electrical and Electronics Engineering Singapore Polytechnic 500 Dover Road, Singapore S139651 65-68708244 chia_chew_lin@sp.edu.sg