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Developing a Skilled Workforce for Future Industry Demand: The Potential of Digital Twin-Based Teaching and Learning Practices in Engineering Education

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Abstract: Engineering education providers should foresee the potential of digital transformation of teaching and skill-developing activities so that graduating engineers can find themselves highly aligned with the demands and attributes needed by prospective industrial employers. The advancement of industrial revolutions towards hybridisation of the enabling technologies recognised by Industry 4.0, Society 5.0, and Industry 5.0 have transformed the components of the engineering higher education system remarkably. Future workforce requirements will demand an employee's multidisciplinary skill mix and other professional qualities. Implementing human-centric decision-making based on insights from the Digital Twin (DT) systems, sustainability, and lean systems is necessary for further economic growth. Recent barriers identified by the Australian Council of Engineering Deans, the development of teaching capabilities, and affordable and digitally transformed learning facilities by education providers were all considered. This paper explores the role of Digital Twins (DTs) in enhancing engineering higher education by incorporating Industry 4.0 components and other industrial advances. By reviewing curricula, pedagogy, and the evolving skill requirements for engineering graduates, this study identifies key benefits of DTs, such as cost-effectiveness, resource management, and immersive learning experiences. This paper also outlines challenges in implementing DT-based labs, including IT infrastructure, data quality, privacy, and security issues. The findings indicate that engineering education should embrace DTs to foster multidisciplinary skills and human-centric decision-making to meet future workforce demands. Collaboration with industry is highlighted as a crucial factor in the successful transformation of teaching practices and in offering real-world experiences. The COVID-19 pandemic has expedited the adoption of DT technologies, demonstrating their utility in minimising educational disruptions. While this paper acknowledges the high potential of DTs to prepare engineering students for future industry demands, it also emphasises the need for professional development among educators to ensure effective and balanced implementation.

Keywords: learning and teaching methods; digital twin; engineering education; future development of teaching; digital transformation

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1. Introduction

Intelligent and digital technologies have helped transform teaching and learning activities for quality and sustainable primary, secondary, and tertiary education. The rapid emergence and institutionalisation of various digital technologies could occur due to the recent global COVID-19 pandemic-led lockdown and quarantine activities [1]. The modern educational system is hybrid and flexible to meet the enrolled students' goals in their desired programs [2]. The recent pandemic helped validate the necessity of interactive digital technologies. Technology-assisted demonstrative and interactive learning facilities have elevated student engagement in modern classrooms and online-based teaching. With digital learning facilities, students can access more resources to improve their core competency skills in problem solving and innovation through creative thinking, organising, analysis, and decision making [1,2]. The rapid progression of the diversity of professional engineering services in the industries makes engineering graduates expected to be skilled in dealing with creative, collaborative, complex, and multidisciplinary expertise to solve issues through their educational journey to avoid loss of investment and time to train them [3,4]. Highly competent teaching instructors can use modern technologies to teach and train engineering students in innovative and collaborative trial-and-error-based analysis methods incorporating real-world systems to explore their respective engineering disciplines.

Digital Twins (DTs), with the help of components from Industry 4.0 (I4.0) and beyond, have the potential to offer a platform where engineering students can train themselves with a virtual model that represents a real-world physical model from any industry. Students can apply their engineering knowledge to understand the product life cycle (i.e., operational outputs, performance optimisation, predictive maintenance, and product development requirements), thus creating more accessibility to affordable engineering education with minimum cost [5–7]. Educational systems must undergo purposive transformation to harness knowledge and skills to minimise the gap between the periods (Figure 1) of social pain and prosperity.

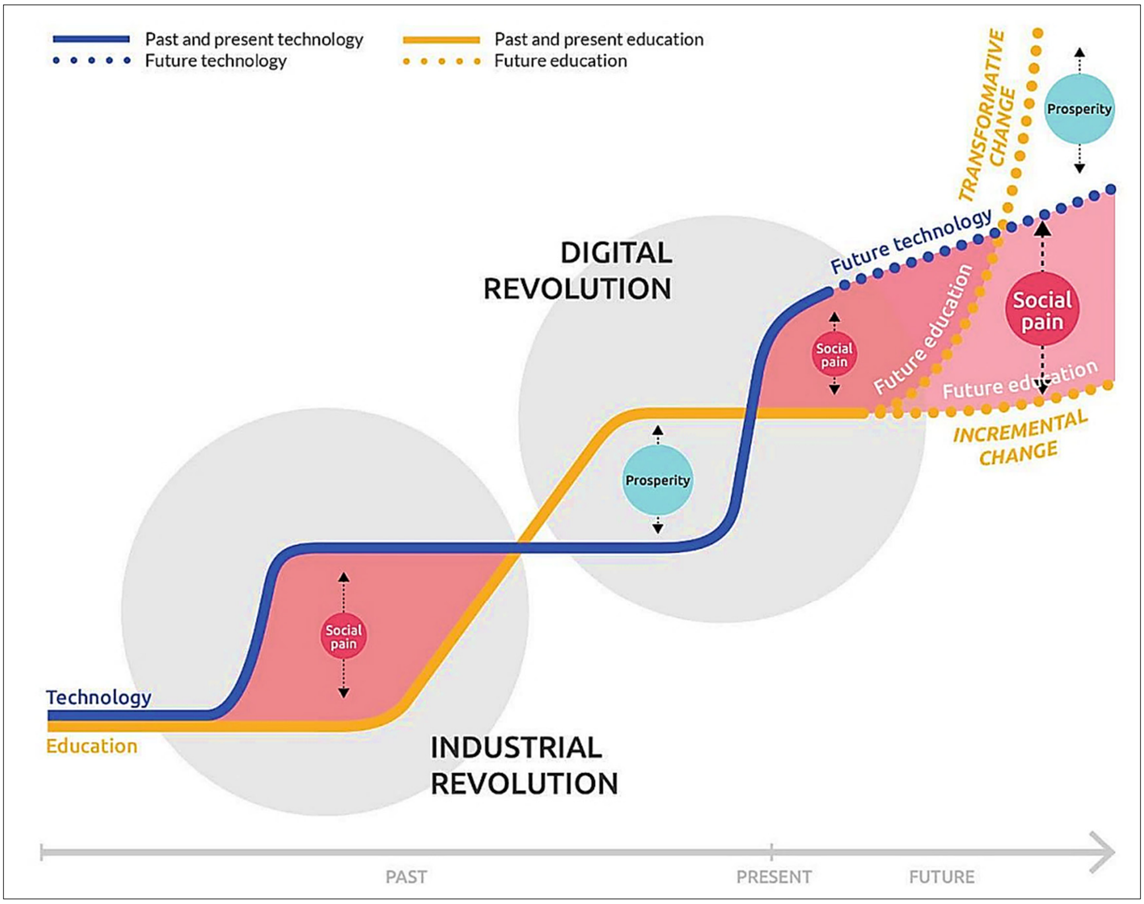

Figure 1. Social pain and prosperity with the industrial and digital revolutions (adapted from OECD [4], which was inspired by Goldin and Katz [8]; license: CC BY-NCSA 3.0 IGO [9]).

Transformations must shape the ability of educators to deliver a competitive learning and teaching experience that will produce graduates meeting the future engineering skills demand [3,4,8]. The Australian Council of Engineering Deans (ACED) has conducted studies identifying the necessity of shaping Australian engineering educational content. They postulate systematic active learning integrating inter-disciplinary competencies to produce future professional engineers capable of harnessing the necessary skills to meet the demand caused by recent seismic shifts of industrial practices in the world [3,10,11].

This study has comprehensively reviewed and analysed recent peer-reviewed and grey literature works to identify the critical knowledge gaps and issues that need more attention to develop efficient DT models for engineering higher education. Also, this study examined how the rollout of DT-based education programs can be integrated with the I4.0 components and other subsequent industrial and societal advances. Additionally, this study reviewed the technical barriers and limitations to determine the potential for DT technology to reduce resource costs and enhance flexibility in engineering teaching for education providers. Key findings from this critically and constructively reviewed article have been provided along with recommendations in the future directions section. This study's findings can potentially shape the future of engineering educational frameworks in Australia and other countries that are seeking efficient and productive learning and teaching tools for effective workforce development for future industries.

2. Evolution of the Modern Education System with Technologies

Since the beginning of human activities on earth, there has always been a demand for learning facilities to develop skills to survive and continue social activities. Education is essential to develop generations within the respective societies, and the learning contents have continually evolved to satisfy the requirements of the societal establishment with traces of substantial impacts through learning outputs [2]. A unanimously accepted theme over the ages, "It takes a school to prosper", indicates the evolution of formal learning facilities for a long time. The societal necessities and the industrial development histories also reflect the necessity of specially trained and educated people for economic growth and further technological innovations [2,4,12].

The specific psychological and intellectual attributes of creativity, initiative, and self-regulation help develop intellectual self-realization capabilities in individuals with higher cognitive capabilities and knowledge in business, engineering, and scientific research [13]. In addition, many countries have gained economic and social prospects in the regional and urban areas through progressive industrialization due to planned access to the knowledge-acquiring system designed through primary, secondary [14], and tertiary education [15].

Technological evolution has undoubtedly changed teaching and learning systems, e.g., from wooden paddles during the colonial era to artificial intelligence like ChatGPT [16]. The technology evolution also included the radio, overhead projector, ballpoint pen, headphones, videotapes, Skinner teaching machine, photocopier, scantron system of testing, computer systems, Internet, laptop, E-book, and PDA in only the previous century. The rapid progress of numerous technologies during the current century has made the educational system a hotbed for research, innovation, and commercialization of more advanced technologies [17]. Therefore, educators must develop their teaching skills and learning content through innovativeness and engagement to maintain the continuous growth of society and keep pace with technologies [2].

Engineering higher education techniques are constantly evolving due to the focus on making them more engaging, student-centred, and able to develop the students from inexperienced people to meeting future professional challenges, including promoting sustainability, developing complex automation systems, and cultivating future-proof employability [18]. Advanced multimedia technologies (AMT) [19], interactive learning methods [20], digital game-based learning methods [21], and personalized adaptive learning [22] are a few of the continuously developing efforts used for making the engineering education system more fruitful and engaging to budding engineering minds. Winberg et al. [23]

stressed that engineering graduates should strongly discern engineering principles across contexts and be capable of dealing with other professional skills (Figure 2). This systematic review concentrated on curricular contents, pedagogical frameworks, and the work-readiness of engineering graduates for the twenty-first century's dynamic skill set. Therefore, modern education facilities should adopt teaching and learning arrangements to instil these attributes in students.

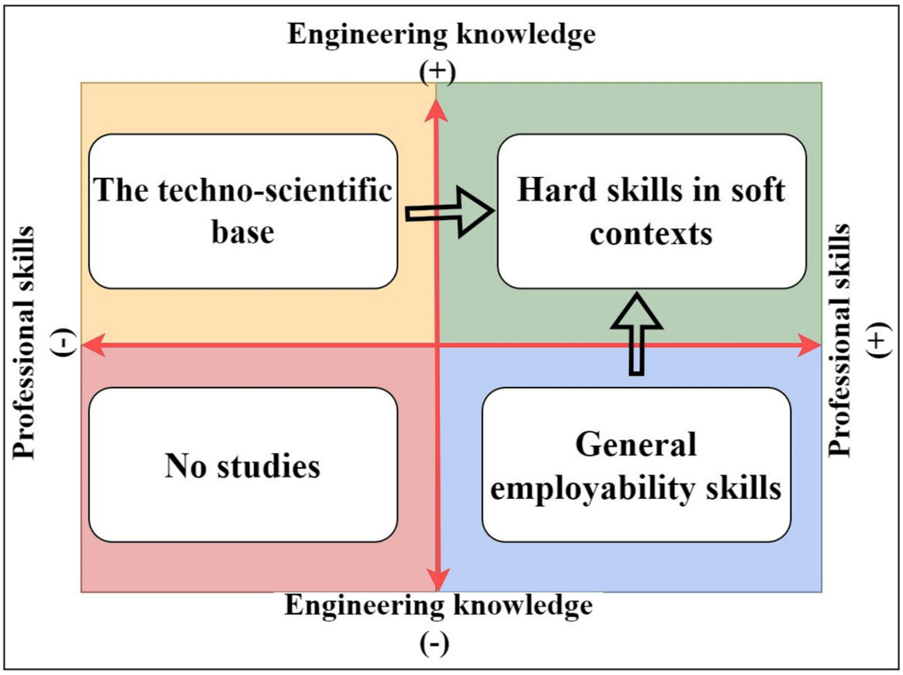

Figure 2. Employability development strategy in engineering education programs (adapted from [23]).

3. Australian Engineering Higher Education System

The role of engineering education, training, and application is significant in strengthening the national economy and sustaining global economic growth [11]. Regarding the value added to career and economic development, Australian engineering educational outcomes ranked seventh among 99 countries in 2016. There was approximately a 65% increase in engineering professionals between 2006 and 2016, which indicated more significant growth in this stream than in other skilled professionals. Though migration had a significant impact on increasing the professional engineering workforce, the trends have been declining. On the other hand, despite growth and substantial contribution towards economic development, the Australian workforce only contains about 2.9% of qualified professional engineers. This number is alarming as it is lower than most developed economies globally.

Moreover, the portion of enrolled women undergraduate engineers, hence prospective professionals, was low in Australia at 18% in 2020, although marginally improving from 16% in 2016 [24]. Australian higher education providers are mainly public universities (36 out of 43), private universities, and registered colleges [25]. Australia's professional engineering education programs comprise 269 Bachelor (honours)-level and 121 Master's-level engineering courses, focusing on meeting the demand for future workforce resources for various industries [11]. However, the typical engineering curriculum in Australian higher education systems has faced barriers to expanding specialised engineering graduate development to make them fit for the rapidly progressing high-tech interdisciplinary technical industries [11,26]. A few identified barriers comprise the cost of upscaling existing specialised programs designed with hands-on practice-based education and the educators' capability and institutional ability to provide resources and support. With the progress of industrial revolutions and diversity in engineering applications, it is necessary to develop engineering graduates who offer the skills required by future industries [3,11,27]. The elementary barriers to overcoming and producing the required skilled graduates in Australia are the development of teaching capabilities and affordable learning facilities provided by educational institutes. The ACED identifies seven categories [11,28] of academic teaching capability to deliver future graduate expectations (Figure 3).

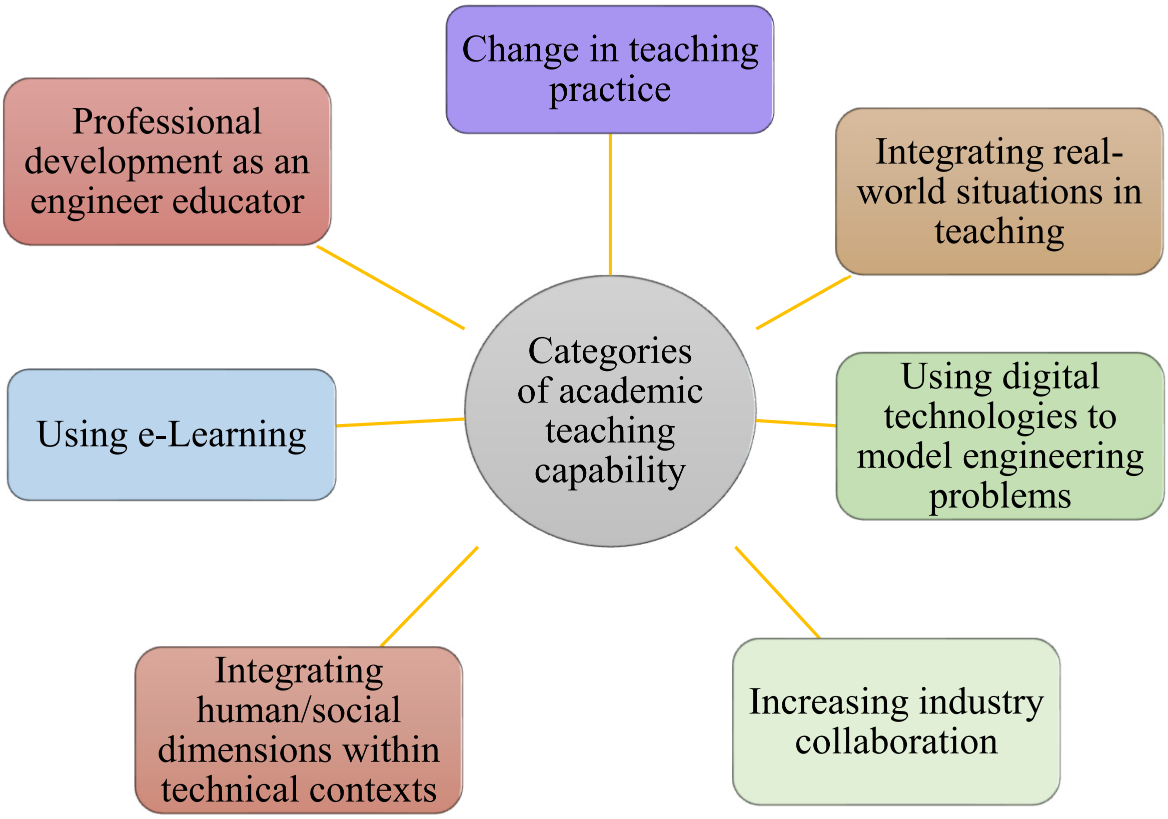

Figure 3. Categories of academic teaching capability required to deliver future capable engineering graduates (developed from [11,28]).

4. Digital Twin (DT) Technology

DT [29], a prevailing I4.0 manufacturing technology, is often regarded as a "high fidelity virtual replica of the physical asset with real-time bidirectional communication for simulation purposes and decision-aiding features for product service enhancement". DT was first used and engendered from product lifecycle management (PLM). Initially, DT was referred to as the Conceptual Ideal for PLM in 2002, then as the Mirrored Spaces Model in 2003, and Information Mirroring Model in 2006, respectively, by Michael Grieves [30–32] based on lean thinking for product management throughout its life stages of creation, production, operations, and disposal for better productivity. Based on these, the functional model of the PLM consisted primarily of the plan, design, build, support and dispose categories, along with a centralized information core that collects, analyses, and disseminates the information within these categories [30]. The information mirroring model (IMM) consisted of four key components: the real or physical space, virtual space, linkage (data linkage and information processing linkage) between the real or physical and virtual spaces, and the virtual simulation spaces (Figure 4) [32]. Finally, M. Grieves at the University of Michigan and J. Vickers from NASA conceived the DT backbone from the IMM concept in 2010 [32–34].

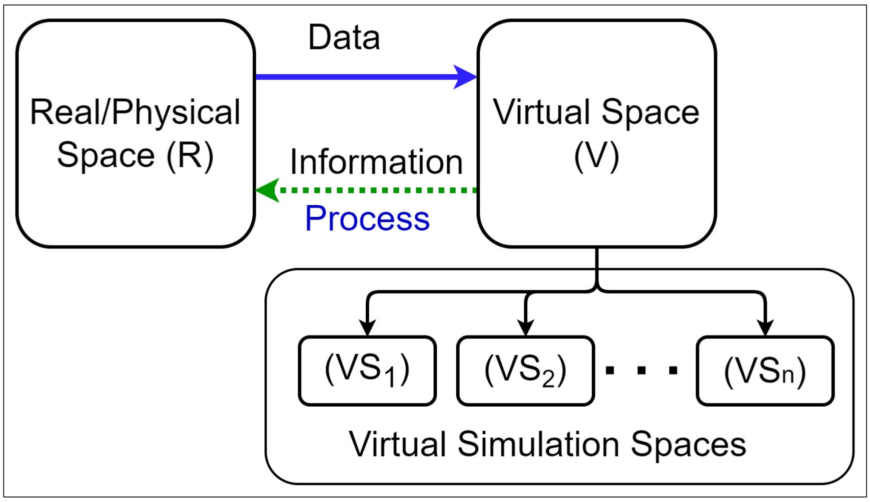

Figure 4. Conceptual ideal components of IMM for PLM (adapted from [32]).

Hence, the DT technology framework is a virtual representation, replica, or twin of a real physical model or potentially future version of a real physical model or model concept [6,32,34,35]. The virtual space runs desired simulations based on the real-time data input, and it delivers decision-making information for the users to perform changes in the operations of the physical object. In more sophisticated systems, the physical object can also be controlled autonomously by the inputs from the virtual space. Virtual products are typically from the micro-atomic or macro-geometric level; therefore, DT technology can deliver any information related to the product that a user would like to obtain from a physical asset [32–35]. The standard simulation-based product development activities, i.e., using geometries to simulate and validate with input data, differ from the virtual simulation (VS) within the DT in terms of the sale of the geometric models, number of processes, the state of the data input requirements, and the insight-developing capability from the simulation results [33,35]. Indeed, the insights from the virtual space can be used as a powerhouse for innovation and uncover significant opportunities. Specifically, DT systems can extend the lifespan, performance enhancement, and cost-effectiveness in the virtual space, which are applied to the physical world to develop skills and knowledge for efficiently transforming the relevant business [36].

Grieves and Vickers [32] have categorized DT into DT Prototypes (DTP) and DT Instances (DTI). The DT Environment (DTE) performs various operations on a digital space developed by integrating multi-physics applications. The subcategories of the DTE are Predictive and Interrogative, used by the DTP and DTI, respectively.

The DTP imports or collects detailed data into the virtual environments (i.e., virtual or virtual simulation space) to replicate the physical model without connection to the physical model, therefore serving as an experimental twin or prototype of the physical artifact [32,37]. Indeed, a DTP helps comprehension of the physical model and significantly reduces the time and costs related to testing and validation with physical prototypes. The DTP advantages apply to quality control, product lifecycle prediction, material specifications with an optimized bill of materials (BOM), bill of processes (BOP), bill of services (BOS), and bill of disposals (BOD) [32].

In contrast, the DTI describes the system where a virtual environment connects a physical model to analyse and improve the activities throughout its lifecycle [32]. Objectives for the DTI are delivered through the DT system importing 3D geometry (fully annotated) with detailed geometric dimensioning and tolerance (GD&T); development activities and effects; all the past and present records related to the bills (i.e., BOM, BOP, BOS, BOD), tests, operations, component replacements, maintenance, and past; as well as present real-time data collected through sensors [32]. Furthermore, with the advent and matured capabilities of the cyber–physical system (CPS) through enabling I4.0 technologies and beyond [38–41], the DT system can efficiently analyse those collective data and information to provide reliable insight into the respective industries to gain the best outcomes possible from the physical artifact [32,38].

Notably, the DT system should not be confused with other terms like digital modelling and digital shadow, which are different based on interactions with data, modelling, and the level of implementation for the physical models [7,42]. Moreover, different DT systems could be present based on the application areas of the systems or processes (e.g., component/parts twins, asset twins, systems/unit twins, and process twins) [35]. Furthermore, these systems could co-exist within them due to the advantages sought after by many industries, including the power-generation/energy sector [38,43,44], structural engineering [45,46], manufacturing [47,48], logistics and operations [45,49], healthcare [50,51], automotive and aerospace [52,53], urban planning [54,55], and other prospective applications [55–58]. With the progressive potential of technological innovations through DT, markets predict this technology will grow from USD 6.9 billion to USD 73.5 billion from 2022 to 2027 [59].

5. Infrastructure to Apply DT Technology in Engineering Education

The recent uptake of DT systems in the industry for applications, research, and development is now broadly permeating academia. With DT systems being an industrial development accelerator, they also become an effective tool for demonstrations and motivating students to explore their skill-developing and future-thinking abilities. With the aid of DTs, students may virtually explore and comprehend the dynamics and behaviour of intricate systems in engineering and many other program areas. Educators may also design interactive and realistic situations that simulate real-world, complex, and interdisciplinary technical cases [60]. Therefore, when education institutes incorporate DT systems through inputs from industry partners, the most praised teaching pedagogy of problem-based learning (PBL) can efficiently be transformed into practice-based education (PBE) [61]. Moreover, DT efficiently enables students to experience rich learning in the same procedures, experiments, computations, validation, quality control, life cycle, and cost analysis as practised in a real-world scenario.

Key benefits envisioned in establishing a DT-based laboratory include increased affordability, space efficiency, resource management, and learning diversity and depth compared to physical model-based laboratories [62]. Furthermore, by giving students dynamic visuals, often linked to real physical systems in operation, DT will likely motivate students, creating heightened immersive learning. However, transforming conventional teaching frameworks into a DT technology-integrated and smart learning environment [22] for engineering education will require pedagogical changes that present opportunities for curricular reform. In this way, DT technology can significantly progress the ACEDs model for engineering education of the future while following established objectives for engineering laboratories [63]. However, observing how efficient the technologies are as educational tools to develop a new teaching framework for a specific application is essential.

The critical challenges for establishing an effective DT system include the capability of information technology infrastructure, quality of collected data from the data acquisition systems, privacy, trust, and security concerns with using and sharing data and access to active systems. Additional concerns include the use of similar types of equipment from various places, expectations in setting up a DT system, lack of common standards for modelling techniques, multidisciplinary capabilities introducing complexity, and establishing a compatible domain across stages of the implementation of enabling technologies (e.g., Internet of things (IoT) and data analytics) [37,64].

Reviews of the educational framework and enabling technologies are needed to determine the capability of employing DT-based learning methods for engineering education. The following discussion makes progress.

5.1. Industry 4.0 (I4.0)

The term I4.0 is used interchangeably with the fourth industrial revolution and represents a new stage in the organization and control of the industrial value chain [65]. The relatively well-known I4.0 design principles [65,66] are (i) interoperability, (ii) information transparency, (iii) decentralization, (iv) real-time capability, (v) technical assistance and service orientation, and (vi) modularity. Furthermore, I4.0 is pushing toward further innovations by adopting automation, data-driven analysis, and decision-making facilities for increased industry outputs. Additionally, I4.0 has matured to establish industrial economies by incorporating applications of sustainably developed methodologies for increased profitability, lowering risks in exploring further development activities and increasing resilience to any uneven consequences [67].

I4.0 refers to the convergence and application of nine digital industrial technologies [67–69] comprising (i) advanced autonomous robotics, (ii) additive manufacturing, (iii) augmented reality, (iv) simulation and modelling, (v) horizontal and vertical integration, (vi) Internet of things (IoT) or industrial IoT, (vii) the cloud, (viii) cybersecurity, and (ix) big data and analytics. Besides these, Butt [66] has mentioned that cyber manufacturing and cyber–physical systems (CPS) are also the enabling technologies for I4.0. DTs inherently employ all such enabling technologies [70] to achieve set objectives (i.e., maximize revenue growth and quality and minimise warranty and operational costs, new product development lead time, supply chain lead times, and digital recording and tracking) [71]. The Reference Architectural Model Industry 4.0 (RAMI 4.0) [65,72,73] provides the key concepts, characteristics, and interdependencies of the I4.0-enabling technologies and structured information for the stakeholders through three-dimensional mapping. Cañas et al. [74] demonstrated how the I4.0 context could develop a conceptual framework for smart production planning and control, termed SPPC4.0, using the RAMI4.0 matrix.

The genuine opportunities of I4.0 reside in identifying and implementing new business models. Businesses worldwide continuously develop integrated process-management frameworks for implementing and transition to I4.0, enabling technologies for efficient outputs [66,69]. Hence, engineering professionals require knowledge and skills to identify the associations and interdependencies of respective business and engineering processes. A restructured educational framework (e.g., curriculum, laboratory, and student club under open innovation [75]) can help identify the requirements and develop the framework to instil basic capabilities in the graduates very efficiently [27,66,67]. In addition, a recent report by Viljoen and Viljoen [27] identified that enterprise and soft skill sets (i.e., communication, higher-order thinking, teamwork and collaboration, leadership and management, ethical competency, and customer-focused services) are also required to enter the engineering workforces.

Furthermore, the Australian Qualifications Framework (AQF) for engineering and technical education and training provides an integrated matrix of the required skills for future work, aligning with fields incorporating I4.0. The key challenge for higher education providers is to produce new-age skills through more adaptive, personalized, hands-on work-integrated-learning facilities to become participants in industrial revolutions like I4.0 and beyond. However, no single explicit pathway exists to achieve this complex goal [11,22,23,75,76].

Due to continuous development trends, the objectives and the requirements of the works performed by the DT system have accelerated the transition of I4.0 to Industry 5.0 [77] and Society 5.0 [78] to facilitate sustainability and circular economic solutions by integrating with human capabilities, as well as the advancement of Industry 4.0-enabling technologies, and lean-smart society [42,64,79,80]. Indeed, the enabling technologies of Industry 5.0 (i.e., human–machine interaction; bio-inspired technologies and smart materials; digital twin and simulation model development of an entire system; more mature technologies for data transmission, storage, and analysis; evolved artificial intelligence; and the technologies for energy efficiency, renewable energy production, energy storage, and autonomy) have been identified as the intersection between physical and virtual worlds [77]. Besides, the inclusiveness of economy, sustainability, and human-centric interactions with these Industry 4.0 and Industry 5.0 technologies to develop a balanced economic development for people have encouraged the evolution of Society 5.0 [78,81]. As a result, DT technology implementation is one of the critical enablers, along with human–machine interaction, for the progression of Industry 5.0. Indeed, the scalability of DTs can leverage an integrated co-existence and synthesis with technology-driven I4.0 capabilities, value-driven Industry 5.0 enablers, and lean-based Society 5.0 components. The synthesis is achieved sustainably by improving the efficiency of policies (agility, inter-relations, and systematic), increasing economic values (profitable, scalable, and business model), minimising ecological disturbances (emission reduction and circular economy) and maximising societal outcomes (solving societal challenges and human-centred and empathetic development) [70,73,78,80,82].

5.2. Education 4.0

The predominant components of Education 4.0 are teaching methods and techniques [83]. For engineering education, Education 4.0 presents critical guidelines to educators and institutions to produce a skilled workforce by leveraging the digital teaching facilities that would meet the requirement engendered through the I4.0 workforce demand [76,83]. Miranda et al. [84] proposed a detailed concept-based definition of Education 4.0 in the higher education sector: "Education 4.0 is the current period in which Higher Education institutions apply new learning methods, innovative didactic and management tools, and smart and sustainable infrastructure mainly complemented by new and emerging ICTs to improve knowledge generation and information transfer processes. Combining these resources during teaching-learning processes will support the training and development of desirable critical competencies in today's students." As presented in Figure 5, the authors [84], have proposed four core components: (i) Competencies, (ii) Learning Methods, (iii) Information and Communication Technologies (ICTs), and (iv) Infrastructure.

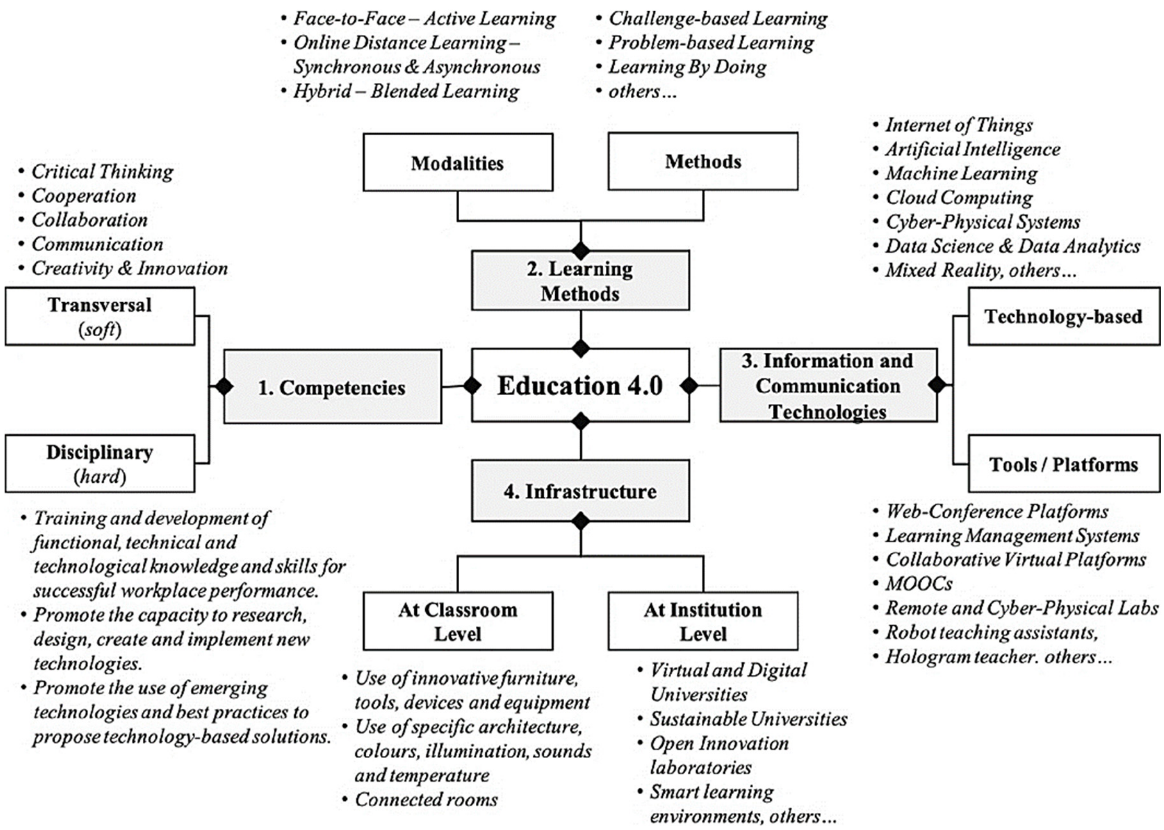

Figure 5. Core components of the Education 4.0 framework (adapted from [84]; license: CC BY-NC-ND 4.0 [85]).

The challenges arising due to the recent pandemic (COVID-19) excelled the digitization process of the teaching systems through an emergency transition to remote teaching (ERT) incorporating adaptation of the enabling technologies to meet the teaching and learning requirements in schools [86] and universities [87,88]. Ramírez et al. [89] and Ripoll et al. [88] demonstrated teaching and learning experiences of chemical and biochemical engineering and chemical reaction experiments through remote and virtual learning facilities aided by industry-developed software. A recent article presented a redesigned course curriculum for chemical engineering by mixing the flipped classroom, problem-oriented project-based learning (PO-PBL), and e-learning pedagogies through ICT facilities and demonstrated achievement of evidence-based skill development in technical and people-related activities [90]. While the world is returning to normality or traditional teaching facilities, the standardization and integration of digital teaching facilities in the Education 4.0 framework can notably enhance skill development for graduates facing I4.0 [76,83]. "Though such changes are still not wholly occurring in the DT environments, the building blocks for the transformation of DT system-based learning and teaching with the correct use of technologies and ICT platforms are emerging (Figure 5), thus creating pedagogy dynamics for future industrial progress".

Miranda et al. [84] presented a case study on combining multiple disciplinary skills (computing intelligence, mechatronics, and bio design) by developing a long-term project development at the School of Engineering and Sciences, Tecnologico de Monterrey, Mexico. The students used the tools (MOOCs, LMS, research databases, e-learning tools, and virtual collaboration) and technology-based tools (IoT, robotics, AI tools, and simulators) of the ICT component of Education 4.0. While completing their project, they also demonstrated other components of the Education 4.0 framework (i.e., competencies, infrastructures, and learning methods). As a result, the project helped acquire new knowledge sets, collaboration and networking, openness in deriving solutions for innovative works, and use of resources to accomplish the goals, which are highly sought-after skills for future workforces for the deployment and advancement of enablers of I4.0 and beyond.

6. DT Technology in Engineering Education

Engineering educators have a significant role in producing graduates with skills and experience to implement sustainably and progress the visions of the industrial revolutions. Tao et al. [91] reviewed publications on disciplinary interests in employing DT technology. The results indicated that various science and technology fields, as well as interdisciplinary modelling (e.g., integration of electro-mechanical-hydraulic systems for precision machining purposes or intelligent fluid dynamic industrial applications), are required to meet the purpose of the applications. Manufacturing and mechanical engineering applications will gain significantly from deploying DT technology, like the design and continuous development of automated production lines. More importantly, DT technology can provide widespread advantages in teaching product lifecycle management through predictive maintenance, remote diagnosis, and remote operations. A case study on a Siemens initiative for collaboration on DT capabilities demonstrated more freedom to develop new design ideas and conduct trial operations with the DT models, creating open innovativeness and formal interactive learning and skill development for engineering students [5].

6.1. Benefits of DT Technology in Engineering Education

This study thus presents the following identified and summarised benefits of applying DT technologies in engineering higher education programs.

6.1.1. Better Understanding of Complex Systems

Engineers often deal with complicated designs and complexities of multifaced systems. Students may better comprehend complex systems by creating virtual duplicates using DT technology. DTs are virtual representations of real-world systems, processes, and objects. Letting students investigate and engage with complicated systems in a virtual setting may provide highly immersive learning experiences and the discovery of salient factors and interconnections to focus knowledge development. For instance, a student may investigate the DT of a turbine to learn about its many parts and how they cooperate to generate electricity. The learner may experiment with various circumstances using the DT to learn how the turbine might be improved and which design factors have greater significance. Students can better apply their knowledge of complex systems to real-world situations and develop a deeper comprehension of them by employing DTs [92].

6.1.2. Improved Interdisciplinary Collaboration and Teamwork Skills

Successful teamwork and collaboration are essential skills for functioning in the engineering industry. Students and instructors may collaborate more effectively using DTs, allowing for a greater flow of ideas and information. As DTs are digital versions of real-world systems, processes, and things, they may encourage cooperation between students and teachers and replicate and track the functioning of a real thing or system involving hierarchical operations. Students and teachers may easily communicate thoughts and information and work together by building a DT. The hierarchical approach makes it possible to mirror task and project management more skilfully with the real world and to share ideas and expertise more effectively. DTs can also enable monitoring of the performance of a physical object or system to ensure peak operating efficiency across multiple levels of the business model, which may present competing objectives. Students and instructors working on research projects or challenging assignments may find exploring system optimisation incredibly insightful.

6.1.3. Enhanced Learning Experiences and Improved Learning Outcomes

DTs may provide immersive learning experiences that let students engage with and investigate complicated systems virtually. Engineering education may benefit significantly from employing DT technologies to enhance learning results. Building a virtual version of a real system enables students to comprehend complicated engineering ideas more easily. With the help of this virtual system, students may test their ideas and better comprehend the subject matter by simulating real-world situations. Students will identify knowledge misconceptions, verify what they have learnt correctly, and expand theories with practical experience and confidence through performance feedback. Students may also have the opportunity to learn through play by being free to explore the system operation space, hence engaging in self-directed and self-regulated learning. Using DT technology may also provide pupils with insights into their areas of weakness and methods to monitor their development.

6.1.4. Greater Resource Efficiency

Automating certain operations using DT technology may improve efficiency and save costs. DTs also facilitate remote connection to physical objects, which may be impossible to locate with the students or staff. It may also help to learn more about physical systems, which leads to improved decision-making performance. Additionally, simulating anticipated events enables businesses to see potential hazards or growth opportunities in advance. As establishing a DT creates a digital copy of an actual object, more precise simulations and data-processing tasks can be performed with the generated knowledge. Because DTs provide an immersive learning experience that enables students to comprehend engineering topics on a deeper level, DTs have an increasingly significant role in engineering education. Learning may be more immersive and exciting by allowing students to explore and experiment with various design situations using DTs. Creating a more engaging learning space can increase the effectiveness of engineering education by giving students a specialised but highly suitable learning environment, enabling them to comprehend the material on a deeper level. DTs also allow students to practice with cutting-edge tools, enhancing their technical knowledge and preparing them for the future.

6.1.5. Informed Decision Making

Through the provision of real-time data to assess and optimise operations, DTs have the potential to enhance decision making. This information may pinpoint issues and chances, forecast possible outcomes, and improve procedures. In addition to learning from the data they gather, DTs may also deliver more precise forecasts and insights. Organizations may make better judgments thanks to this enhanced decisionmaking to increase operational effectiveness, decrease downtime, and boost overall performance. DTs may help students make better decisions in engineering classes by giving them immediate, interactive feedback. Students can rapidly determine what works and what does not by being able to trial ideas in a virtual environment. They may change their designs and learn more about engineering processes and theories. Students may utilize DTs to forecast system performance, enabling them to design with more knowledge and confidence. DTs may also provide teachers with insightful information on students' progress and where students need to improve, enabling a personalised approach to their lessons with more focused feedback.

6.1.6. Enhanced Problem-Solving Skills

DTs can help improve students' problem-solving abilities; a central skill developed in engineering education. As DTs are virtual copies of real-world systems or items, they help engineers see issues more clearly and find solutions because they give them a firmer grasp of the interaction of system components. Students may study the fundamental workings of a system, how it evolves, and how various components interact by employing DTs, honing their problem-solving abilities. Additionally, DTs provide students with a simulation platform, enabling practice and self-assessment of skills and knowledge in a secure setting. Through simulation, students may experiment with many situations and investigate various solutions, allowing them to comprehend how various decisions might impact a system without restrictions imposed by physical testing. By encouraging students to think critically and obtain a deeper grasp of a system's guiding principles, this kind of study may aid in developing their problem-solving abilities. Using DTs may significantly improve students' problem-solving ability while studying engineering. They provide students with the chance to learn about the fundamental mechanics of a system and consider various solutions rapidly by providing a platform for simulation and investigation that drives authentic problem-solving.

6.2. Challenges of DT Technology in Engineering Education

A high-fidelity and efficient DT model requires a sophisticated virtual model. The DT must accurately mirror the physical model with real-time data collection and transmission; employ a full-scale virtual environment with simulation and data analysis, validation, and optimization capability; and integrate user insights to execute decisions on the physical system. Thus, there are several challenges to enabling technologies and the DT development framework [70,93,94]. Besides the technical capabilities of the functioning physical system, DTs have several other challenging issues. For example, physical security concerns exist at integration endpoints that create potential unauthorised system access, and cloud-based data sharing depends on cybersecurity. The accuracy of automation development with big data acquisition and handling systems depends on complex data-processing systems. There is a need for conflict mitigation while implementing changes based on insights developed, which could involve extensive and new operational procedures. Maintaining seamless collaboration among the technology enablers working for the DT system presents language and cultural challenges. Common regulations and standards for DT technology implementation are currently lacking, creating unforeseen compatibility issues. The cost of implementation is also high, as with most developing technologies. Also, the scalability handling capacity of the current modelling, simulation, and data analysis technologies is trailing advanced DT developments. Finally, workforce training presents many challenges across the breadth of the DT development space [37,64,70,93–96].

DT technology in engineering education is very effective [60,97]. It enables students to comprehend how intricate systems function in practical settings and to visualise them. DT technology can transform engineering education by modelling real-world issues in an engaging digital setting. However, institutions must resolve various issues for DT technology to be effective in engineering education. The expense of creating DT technology is one of the main obstacles. Hiring people, buying technology, and developing software to create DTs can often become cost-prohibitive. In addition, high expenses deter engineering schools that cannot produce many DT technology components.

Furthermore, DTs require high data intensity to function well. The DTs must obtain and process data quickly to correctly imitate the real-world environment, which can easily become costly and time-consuming. The lack of knowledge required to build and manage DTs is another difficulty. Professionals with particular expertise and abilities are needed to construct and manage DTs efficiently. Some engineering colleges may find it challenging to locate and costly to employ key personnel.

DTs also need frequent upkeep and upgrades to keep them accurate and current. It might be difficult for specific engineering schools that lack the staff or resources necessary to perform this work. The absence of DT standards might also be a problem. Since each DT is different, no one method is universal. Engineering schools may find it challenging to compare and assess various DTs. A lack of standards will likely make adopting DTs in engineering education unclear and inconsistent. DT technology has the potential to transform engineering education despite these obstacles. DTs may provide students with a valuable tool for comprehending complicated systems and real-world applications with adequate resources and knowledge. These problems with DT technology will inhibit the needed evolution of engineering education.

6.3. Case Studies of DT Applications in Engineering Education

6.3.1. DT Modelling to Train the Students in the Master's Program at the Darmstadt University of Applied Sciences, Germany

The students in the Master's program at the Darmstadt University of Applied Sciences in Germany were taught automation and industrial plant process control technologies with DT modelling (Figure 6) [98]. The learning process consisted of converting the mathematical models of the industrial plant processes into hardware models to replicate the real system. First, students manipulated these hardware models (HWM) with real programmable logic controllers (PLCs), a process called controller-in-the-loop (CIL). Then, these HWM and CIL were converted into software models within a host computer, named model-in-the-loop (MIL). Finally, students simulated the reactors with the acquired code from the logic controller, which could be transferred to the microcontroller of the real plant system to run a rapid control prototyping (RCP) test to improve the plant operation processes if needed.

On the other hand, the software model of the real plant could be connected to the laboratory's real controller to test the capabilities of the laboratory control logic without necessitating the connection to the real plant processes, which is called a hardware-in-the-loop (HWL). In these cases, if the same host computer executes the laboratory's control logic code in the software model of the real plant, the entire process is termed software-in-the-loop (SIL). However, if the host connects its software model with the external controller like a microcontroller, the process is termed processor-in-the-loop (PIL).

This transition to the DT system indicated better cost and time savings in establishing the laboratory with physical systems spread over multiple work locations. The DT-based laboratory system provided improved training and upskilling opportunities from one place with one operator but also facilitated interactive learning for multiple students simultaneously. Key challenging features of the DT system development reported by the authors were the design model development and the cost of the design software. However, they reported the overall cost-effectiveness of the DT system in comparison to the establishment of a physical system. The DT system in this program did not use a live connection to the physical plant but instead used a software model to investigate the effect of the control logic in the model plant system.

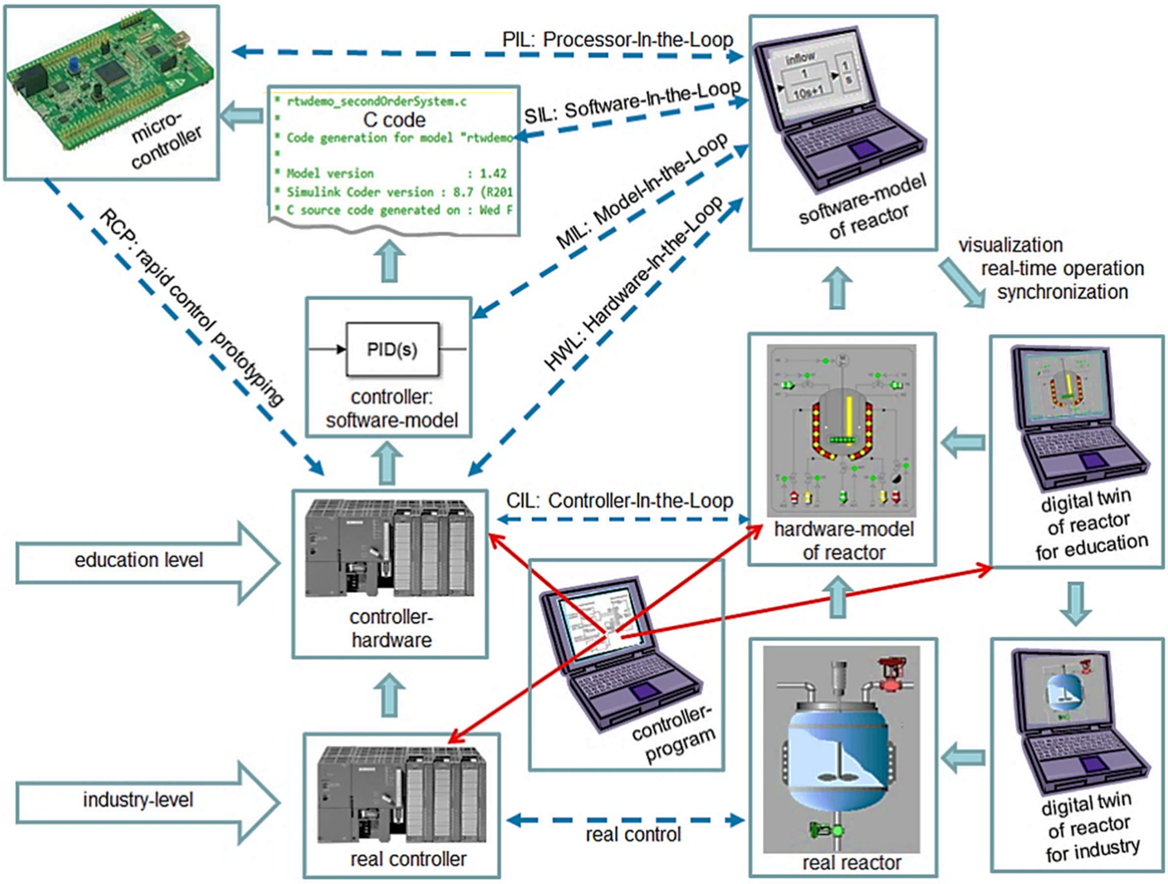

Figure 6. DT modelling for education and industry levels using various models (adapted from [98]; license: CC BY-NC-SA 4.0 [99]).

6.3.2. Practical Course: Design and Development of DTs at the Technical University of Munich (TUM), Germany

A product development laboratory course was designed at the Technical University of Munich (TUM) to teach students about product development using DT technologies [100]. One of the critical attributes of this course was to develop interdisciplinary student teams from mechanical engineering, industrial engineering, and computer science disciplines to demonstrate their capabilities within a team and learn how to conduct a modern industrial project by mixing different knowledge sectors.

6.3.3. Laboratory Teaching for Students to Master Complex Engineering Tasks Using a DT at Aalto University, Finland

Aalto University has arranged an interdisciplinary student learning facility with DT modelling [101] to learn virtually real industrial operations, predictive maintenance, and production systems. The DT environment incorporated various design, simulation, and PLM software for 3D design, modelling, and other services from Siemens Digital Industries Software solutions. With the availability of leading-edge tools and the collection of real-time data from industrial collaboration to learn project-based problem-solving skills, engineering students gain teamwork experience and apply innovative ideas to improve an industrial component and conduct predictive maintenance as plant production process management. Autiosalo [102] has presented different case studies (i.e., high accuracy lifting innovation, user identification, mixed reality-based visualization and controlling, and applying product designing methodology) of using DT technology for an industrial crane conducted by undergraduate and postgraduate students at this laboratory facility. These works have demonstrated IoT, cyber–physical systems, and other digital technologies to establish a DT environment as per the case studies required. Thus, the DT technology helped the students learn from working with industry-collaborated equipment and gain skills required by modern industries.

6.3.4. Online (Remote) Laboratory-Based Class Teaching with DT (Lucerne University of Applied Sciences (HSLU) in Switzerland during the COVID-19 Pandemic

Due to the COVID-19 pandemic, a transformation of laboratories into remotely controllable web-based DT environments was necessary for undergraduate courses in fluid mechanics, thermodynamics, turbomachinery, energy efficiency, and mass and energy flow balances [103]. The experiments included potential vortex, linear momentum equation, diffuser flow, radial and piston compressor, fuel cell, and pump test. Though the conversion encountered a few complexities in adapting the overall experience of online teaching and learning compared to conducting laboratory experiments by the students, it eventually met the expected outputs per learning objectives. Furthermore, the scenario demonstrated that achieving learning objectives is possible in disruptive environments where quick migration to DT prototype systems to teach the essentially interactive engineering laboratory courses is possible.

6.3.5. University-Level Taught Courses on DT Technologies

A doctoral-level course (VB8005—DT for sustainable manufacturing) was designed and offered [104] at the Department of Manufacturing and Civil Engineering in the NTNU, Norway, to allow students to gain comprehensive knowledge and applications of DT systems in manufacturing. The course intended to teach relevant content like predictive maintenance, enabling technologies to implement industry standard cyber–physical systems, digital communication, and IoT in sustainable manufacturing principles, along with data analysis and insight development. Furthermore, the project adopted CIRUS's DT software to train students to handle DT systems. As a result, the course expects the students to gain critical, analytical, and decision-making capabilities to approach sustainability in manufacturing process engineering activities using cyber–physical systems. Indeed, the DT system can ensure secure and efficient manufacturing [63]. Therefore, such a higher-level course introduction to engineering students can help develop strong skill sets for ongoing and future industrial requirements.

Furthermore, the Department of Marine Technology (IMT) of the NTNU conducted a prospect of using DT applications in various courses of the 5-year Master of Science program during the summer–fall sessions of 2018 [105]. They have inspected and proposed a DT transformation of the research vessel R/V Gunnerus applied in about 13 different courses at different levels of the study program. Such a study plan indicates that engineering students can gain insight into their applied studies throughout their program from a single DT system.

Schleich et al. [106] developed an undergraduate engineering unit to develop critical capabilities in managing the variations of geometrical measurements more efficiently by applying DT technology with the Department of Mechanical Engineering in the Friedrich–Alexander–Universität Erlangen–Nürnberg (FAU), Germany. The example model was developed by incorporating DT in this course to introduce vital learning content for product lifecycle management, additive manufacturing, and product-assembly applications in modern industries (Figure 7). Though COVID-19 restrictions to conduct physical model assembly validation by the students hampered the teaching activities, a doctoral student validated a similar task, indicating a positive initiation of the DT system in managing geometrical variations.

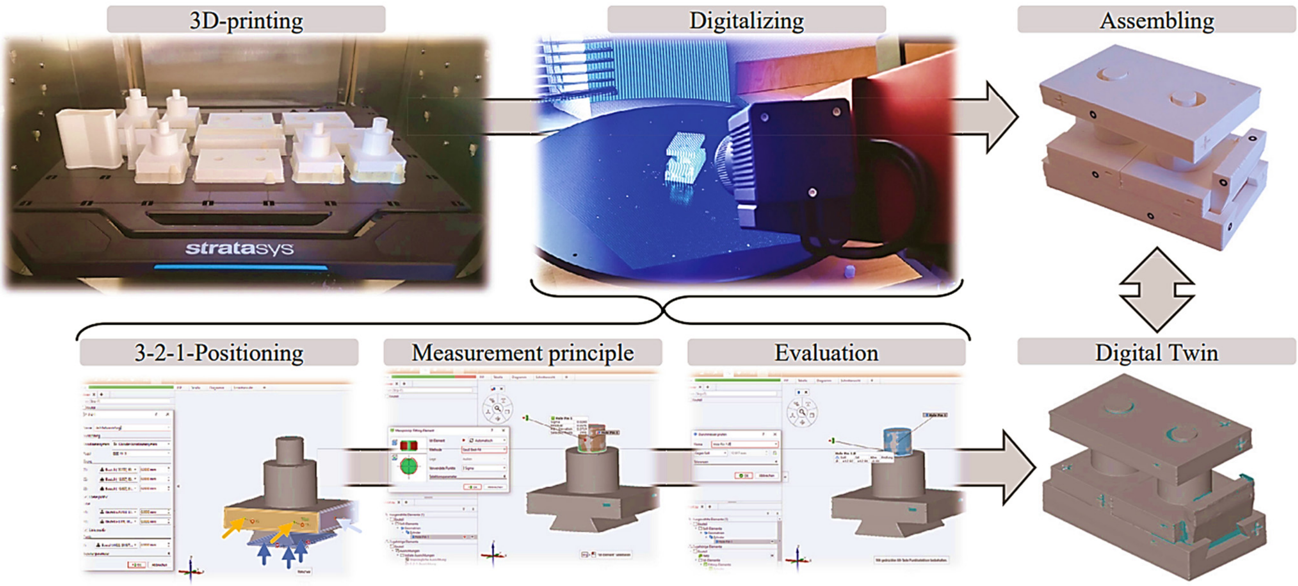

Figure 7. Use of DT technology to teach about managing geometrical measurement variations in design and manufacturing (adapted from [106]; license: CC BY-NC-ND [85]).

6.3.6. Use of Digital Technologies (i.e., Simulation, DT, Internet of Things (IoT), and Augmented Reality (AR)) at Monash University, Australia

To introduce digital technologies to the engineering students at Monash University, the Monash Student Pilot Plant developed AR-based DT technologies as an educational tool in various engineering applications [107]. The university expects to resolve project limitations, such as the scalability of laboratory equipment, remote accessibility issues, and the simultaneous working capacity with many students when enabling I4.0 technologies and implementing the DT. These activities will create automation and operational capabilities of various processes that will attract enhanced industrial collaboration and create learning and research facilities for the students and researchers. Through the partnership of Monash University with the PTC and LEAP Australia, it is expecting to use the Vuforia Studio for digital visualization of plants and equipment before being brought into reality. Meanwhile, the ThingWorx IoT/DT platform and Ansys simulation facilitate the creation of human–machine interfaces so that the cyber–physical accessibility to the plant equipment can be created and visualized in the DT system remotely. Therefore, incorporating a more extensive suite of industry-standard collaboration projects into a DT and AR will help students from different disciplines to work and learn as per their capability.

6.3.7. DT Development Projects at the Centre for Spatial Data Infrastructures and Land Administration (CSDILA), University of Melbourne, Australia

The CSDILA team at the University of Melbourne has developed a high-level DT platform by collaborating with industrial and government-level stakeholders. This indicates the result-driven capability of the research centre, thereby creating postgraduate-level research and educational facilities within it. A few of the DT projects include (i) the development of a decision-support tool in the DT environment to understand the capacity of stormwater of proposed road networks; (ii) Fisherman's Bend DT, a partnership with the Victorian Government Land Use Victoria Department of Environment, Land, Water and Planning to produce urban renewal and precinct planning activities in the Fisherman's Bend precinct; (iii) a coastal flood platform project from multidisciplinary collaboration; (iv) collaboration with the campus planning and design team of the University of Melbourne to develop an urban planning tool with an envelope based on planning controls; (v) a surge capacity analysis and visualisation tool for the Fire Incident Report System, a spatially enabled decision support tool to visualise volunteer firefighting capacity across

Victoria; and (vi) development of PedDesign tool in collaboration with ARUP to analyse pedestrian movements.

6.3.8. Remote Design Studio, Central Queensland University, Australia

Sharma et al. [108] developed a remote design studio (RDS) at Central Queensland University, Australia, where a DT prototype replaced the traditional instructional laboratory work in a Hydraulics and Hydrology course. The students created the DT prototype model using HE-RAS software (version 6.1) which they calibrated and validated with data from the physical model after obtaining the preliminary and final simulation results. Students further evaluated the DT prototype by conducting a sensitivity analysis to realise the effect of varying design parameters. The students worked remotely and collaborated with their team members and course officials through Zoom. The RDS helped students to gain a more detailed insight into their theoretical knowledge applied through modelling and simulation while overcoming the necessity to visit the campus for physical laboratory experiments due to accessibility issues like the COVID-19 lockdown or distances from the campus. The RDS and DT prototypes also focused on promoting the adoption of new technologies, sustainability, and equitability for students while learning and gaining experiences for engineering applications and tools and engaging students effectively.

Furthermore, an assessment was conducted based on the objectives of the engineering laboratory courses aligning with the Engineers Australia (EA) stage 1 competencies (cognitive domain: instrumentation, models, experiment, data analysis, design, new technology, and sustainable development; psychomotor domain: psychomotor, sensory awareness, and accessibility; and affective domain: learning from failure, creativity, safety, communication, teamwork, ethics in the laboratory, engagement, and learning) [109]. Feedback from survey assessments indicated a positive effect from the initial trial of an RDS (3.1 out of 5.0) on learning and teaching compared to the traditional laboratory approach (2.6 out of 5.0). The university expects that these positive effects will influence other laboratory courses to transform into DT-based RDS facilities.

6.4. Prospective Transformation of an Existing Project-Based Learning Course into a DT Prototype-Based Learning Program, Central Queensland University, Australia

In response to developing the RDS at Central Queensland University, another engineering project-based course within the School of Engineering and Technology was identified for a DT prototype model transformation (*ENEM14014: Capstone Thermofluid Engineering*). The key project objective in this course is to assess high-voltage air conditioning (HVAC) energy performance and retrofit a multi-storied office building for improved thermal management.

This project will exercise the theoretical thermo-fluid knowledge and skills in a practical application of building HVAC systems. Currently, instructors introduce students to the detailed theoretical background on energy-management strategies (EMS); energy-conservation measures (ECM); relevant Australian Standards and Commercial Buildings Energy Codes for heating, ventilating and air conditioning; HVAC system design parameters for residential and commercial buildings; and weather-related database (Australian Bureau of Meteorology) through course lectures, static resources, and other project materials. Then, the students are grouped into different teams to conduct their project on one of the reference buildings for the given weather locations throughout Central Queensland. The Moodle learning management system contains detailed information on the reference multi-storied office buildings. Instructors also strongly recommend that student teams use reference materials from the library and any other scholarly sources and product suppliers. Next, students create a detailed building energy management system (BMS) through computational fluid dynamic analysis using the DesignBuilder building energy performance simulation software for the existing HVAC installed in the reference structure while following the thermal conditions and energy consumption data supplied to them. Once the teams build and validate their DT prototype model of the existing building, they explore alternatives and create an improved HVAC system. The DT Prototype model also produces detailed ECM from the simulation environment to quantify the reduced energy use intensity (EUI) (i.e., annual kWh/m^2) of the advanced system in the building.

In this project, the students work with a full-scale building model and acquire real energy use data for a given period. Furthermore, it requires real data input from the seasonal weather records to conduct a detailed economic and efficient energy-management plan for the HVAC system. As a result, engineering students learn how to handle multidisciplinary data to achieve targeted work outputs. For example, one of the student projects based on the reference multi-storied building in the climatic condition of Cairns, Australia, demonstrated a potential reduction of total energy consumption by 33.9% per year, saving around AUD 77,806 through their proposed modification of the existing HVAC system. This information can help the operation team to modify the physical system and achieve these expected outputs.

Converting the HVAC system into a DT prototype model offers more significant benefits. Creating a DT model enables consideration of the dynamic non-linear characteristics of HVAC systems [110–112]. Furthermore, opportunities exist to incorporate additional analyses on fault detection and diagnosis of the HVAC control systems [111] to achieve the dynamic asset management objectives through efficient thermal, air quality, and energy management [112,113].

Mohseni et al. [112] adopted the proximal policy optimization (PPO) algorithm based on model-independent non-singular-terminal sliding-mode control (MINTSMC) methodology that worked efficiently in proposing the regulating parameters for the HVAC system. The DT model also included the software-in-loop (SIL) model interface and functional mock-up interfacing (FMI) with the hardware-in-loop (HIL) model of the real HVAC system. Developing the HIL model [98] helped avoid complex interactions with real assets like building automation systems. Thus, the DT generated realistic insights from data analysis and simulations. As a result, this activity plan of the DT system produced highly reliable outputs, and there was an insignificant difference compared to the real HVAC system.

However, Xie et al. [111] developed DT for building HVAC systems to demonstrate dynamic asset management through fault detection and diagnosis (FDD). The model consisted of multiple zones and different setpoints for air temperature in the unoccupied and occupied zones in different seasons. Their proposed methodology used AI techniques for data analysis and filtration to develop an intelligent building management system with HVAC. On the other hand, Chen et al. [110] developed an entire life-cycle-based DT framework to derive energy efficiency from HVAC systems. The IoT collects data from the PLC of the real HVAC system. Then, the data are transmitted through the Internet and cloud facilities, and the cyber or virtual space conducts big data analysis and employs AI technologies through a broad learning system (BLS) for further modelling and simulation. Therefore, the model and algorithm could solve the issues of real asset systems. BLS-based HVAC models have prospects for real-time operation optimisation, fault detection and diagnosis, and smart lifecycle management of HVAC equipment.

The study conducted by Arsiwala et al. [113] can help develop a first-stage migration to a laboratory for building air quality monitoring incorporating DT systems for engineering students. The researchers integrated I4.0 technologies, like IoT, cloud, and AI, with the 3D BIM model to develop a DT instance (DTI). It provided them with real-time data acquisition, an ability to handle current and historical data and modelling and decision-making capabilities in the virtual environment. It also implemented incremental learning methods that significantly enhanced the efficiency of carbon emissions predictability. Unfortunately, this model could not conduct real-time bidirectional control of the physical systems based on the analysis performed in the virtual environment. However, it updated the model fortnightly based on the received data, which helped strengthen the capability of delivering better asset management insights to operate the physical system.

In engineering education, capstone project work can make teams of different expertise develop their knowledge in multidisciplinary applications. The team can collaborate to include step-by-step digital transformation activities to develop a reliable DT project. Prospective activities are given (Figure 8) for using I4.0 and beyond technology enablers to build a sustainable DT controlling model for the HVAC system that delivers efficient energy use and asset management experience to engineering students.

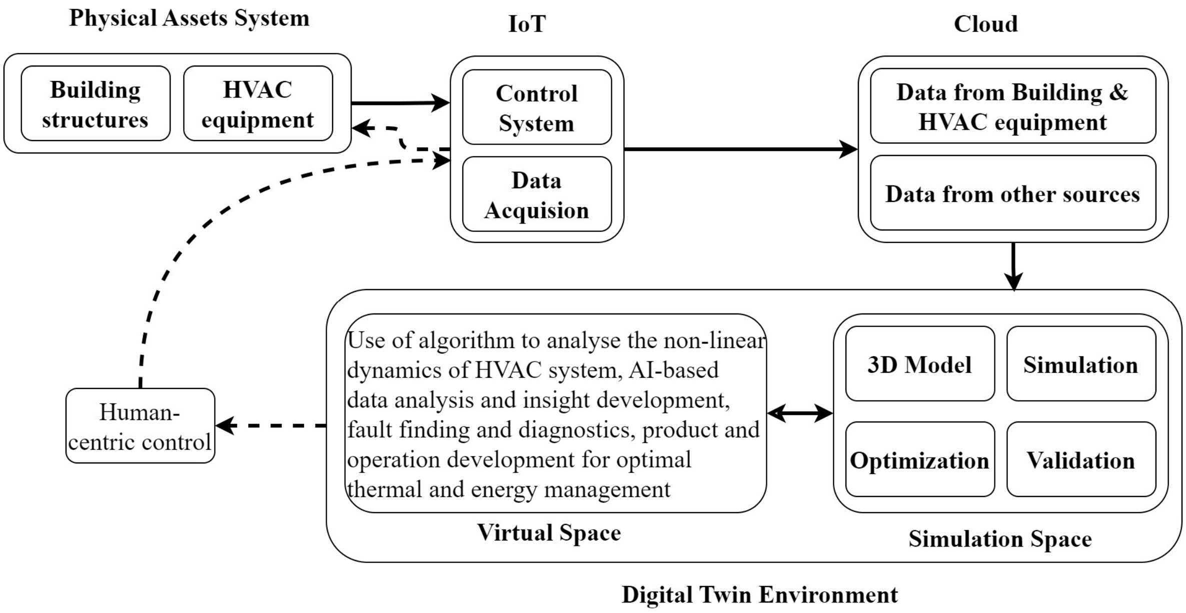

Figure 8. The potential transition of existing HVAC systems into DT models.

6.5. Student Assessment Experiences of DT-Based Learning Activities

A study conducted by Awdziej et al. [114] on digital maturity for the digital transformation of learning and teaching systems indicates that students can accept and adapt to the transformation when they earn the required competencies. Motivational support and the accessibility to resources like skilled teaching staff and innovative digital projects may influence the students to explore interdisciplinary knowledge. Liljaniemi and Paavilainen [60] have observed that the DT technology-based engineering education curriculum can effectively motivate students to study and improve their learning capabilities. The authors [60] designed a course concept by adapting DT technology as a part of a machine automation course for mechanical engineering students at the university, and the research was conducted from 2016 to 2018. They observed that the IT infrastructure, resource limitations, and expertise of the teachers to accommodate the effective learning experience for the students were the key barriers. However, there was increased motivation for study from the students as it was a pathway to develop expertise in a future-ready industry program. One of the effective observations on motivation development for students in the early stage of digital technologies like DT was observed by Acker et al. [115]. The authors observed exposure of low-cost DT-based projects with the secondary educational institute students to motivate the students. The feedback from the learning experience of the students was very highly positive; for instance, more than 72% of the surveyed students showed their intention to study DT technology for future careers. Acker et al. [115] also mentioned that the enabling technologies of Industry 4.0 need to be more advanced and mature to support the efficient rollout of DT. Besides, Lee et al. [16] also observed the inclusion of DT technology to investigate the effectiveness of games and gamification in learning mathematics, which showed that the students were able to concentrate more on their learning activities due to the creation of interactive problem-solving opportunities through DT. The authors also stated that advanced mathematics learning could be more accessible, synergistic, and engaging for students from any background with the efficient DT technology-based learning system. Thus, the student assessment experience from the DT-based learning activities actually improves the students' motivation to study interdisciplinary applications to fulfil their educational requirements and potentially turn into a more effective workforce in future.

7. Future Directions

Indeed, the threat of reduced human workforce requirements in future industries due to technology-driven advancement by Industry 4.0-enabling technologies has been overturned by the core values (i.e., human centricity, sustainability, and resilience) of Industry 5.0 [73]. The most effective part of this digital transformation through DT technologies is the ability for adaptability and flexibility to integrate all the modern-day enabling technologies for monitoring, analysing, decision making, and operational activities of any system with human capabilities. Therefore, DT technology has great potential to be used as a learning and teaching tool to develop future skilled workforce. It is evident that future industries will require their employees to be skilled in multiple fields. The future workforce should be able to efficiently apply modern technologies for data acquisition and analysis along with subject matter specialisation for sustainable, fast, efficient, and resilient decision making in the respective business activities. Reforming the learning and teaching systems to train the students in interdisciplinary activities can be used to develop high-fidelity virtual models of the physical assets or processes and establish the DT framework for improved real-time operability of the process. That is how educational institutes can contribute to providing a skilled workforce to future industries. Such a massive change in the teaching and learning system will need (i) efficient policies and strategic action plans from the governments to develop a future-ready workforce through DT technologies, (ii) accelerated maturity of the technologies that are required to establish efficient learning and teaching, and (iii) development of globally recognised DT-based learning and teaching evaluation activities to identify further action plans to improve the perception and acceptance of a DT-based competency development framework. When the policies and government support are in action, the respective departments of the government can work on developing supporting frameworks to make the students understand the importance of interdisciplinary skill development to face future challenges in their careers. Learning organisations should have the ability to "self-evolve" [116] using the support of the policies and strategic action plans, which will then develop the confidence of the industries to link with the organisations to share their future requirements [117]. Technical maturity can be accelerated for DT technologies in various applications [118]. In such cases, the universities may influence the rapid improvement of DT technologies while motivating the students to utilise their competencies to help solve the bottleneck challenges facing this revolution [114]. While developing a new technological revolution in learning and teaching systems that can potentially contribute to the expected industrial progress, it is essential to establish a continuous evaluation [60,119] to improve the quality of the technology as well as teaching and learning activities. Helbig et al. [120] stated that at least four distinct dimensions are required to ensure efficient digital transformation (i.e., technical changes in organisations, changes in routines and practices, technologies as a learning medium, and technologies as consulting and decision-making tools). Good leadership is also essential to ensure the efficient transformation of these challenging learning activities. Therefore, a future educational program based on DT technology can be expected to evolve globally, not only in engineering education but also in other specialised educational programs like health and business.

8. Concluding Discussions

DT technology offers many benefits to engineering education, including an improved understanding of complex systems, more realistic and interactive scenarios, and immersive learning experiences. The technology also provides a platform for educators to assess student performance and provide feedback. The greater flexibility offered by the DT development framework allows the user to build the model for a particular operation or the whole system based on the capabilities of the enabling technologies. The user needs to identify the tools to engage as fit-for-purpose. Engineering graduates must be trained with multidisciplinary skills to find themselves suitable for modern industries. While providing realistic and interactive learning skills to the students, DT can be daunting to the education providers due to implementation costs and issues developing operators' skills. Besides industrial collaboration regarding data supply from real plants or operations, software supports are essential to convert the learning into an authentic experience. Apart from collaboration and investment issues, the implementation of DT systems also creates challenges with technical capabilities, user adoption, and security and trust related to data management. The identified capabilities of the education providers by the Australian Council of Engineering Deans (ACED) can help build students' trust in learning and training as the future necessitates. Implementing DT systems in the teaching and learning practice can help meet most of the categories identified by ACED. Thus, the students may also possess hard skills in soft contexts through exposure to engineering knowledge and professional skills.

In summary, DT technology has the potential to revolutionize engineering education, making it more engaging and efficient. Also, DT demonstrates how combining this technology with high levels of human participation can significantly aid decision-making situations requiring great technical insights. DT has the potential to advance relationships between industry and academic institutions, resulting in sustainable employment for the professional workforce. However, it is essential to note that the technology is still in its early stages, and there is much room for improvement [97]. More data and use cases are needed to measure the effectiveness of DTs as a teaching tool. In order to maximize the potential of DT technology in engineering education [121], it is necessary to establish clear guidelines and standards for the use of DT technology. The framework from Education 4.0 can work as a good guideline while using the enabling technologies in DT frameworks to design learning content for engineering students.

Collaboration of the engineering higher education institutes with the leading DT technology provider industries [117] like Siemens, PTC, Ansys, Cisco Systems, General Electric, Microsoft Azure, IBM, Oracle, QiO Technologies, PETRA, Dassault Systems, and Bosch (Robert Bosch GmbH) [122,123] can help to advance the transformation of engineering teaching and learning globally. With proper planning, engineering students can learn to securely manage confidential data through professional-level collaboration rather than defining these as challenges [117]. These activities have prospects to instil professional skill sets essential in the workplace. Besides, academic research can help develop standardised design frameworks for consistently developing DT systems with zero-defect manufacturing to meet future industry requirements [124].

The case studies indicated that laboratory transformation into DT systems is still very early, and engineering laboratories are undertaking many initiatives worldwide. Industrial project-based collaboration and DT solutions can significantly advance multidisciplinary skill development. Several universities are conducting postgraduate courses to employ their academic knowledge in project-based research. Introducing a remote digital studio also greatly facilitated engineering laboratory training for students studying by distance or online. However, due to the requirement for skilled engineers, undergraduate students may not be able to engage in the DT transformation projects as much as postgraduate students may contribute. In such cases, only a developed system can be offered to undergraduate students so that they can experience the teaching and learning plans through small-scale activities. There will be a shortage of skilled workforce to develop and operate the DT systems if all the engineering higher education applied laboratory and project courses are transformed into DT models. Postgraduate research students can be a great source of the future workforce to meet the collaboration investment by all parties and to achieve their respective project milestones for professional growth. Different universities have progressed so far as per their own established resources. However, a sustainable approach is needed to encourage the universities with a realistic approach towards improving their learning and teaching goals through digital transformation.

While proposing transforming a project-based learning program into a DT system, a mix of different skills to meet the project execution goals must be considered in the teams formed. There is a rich mix of different engineering knowledge in this project. Hence, team development guidelines, technical resource support from the universities, and DT technology providers for the respective applications can strengthen the learning motivation of undergraduate students. A similar learning-by-doing approach was planned for the graduate students in the laboratory experiment course in the University of California's Systems Architecting and Engineering graduate program [125]. The prospective transformation of the project-based learning program from Central Queensland University has the potential to progress further with a collaborative approach from the industries as the problem practised by the students is realistic and creates transferable skill sets for the graduating students. Hence, the digital transformation of the engineering higher education system with the DT system begins in such a way.

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