Digital Twins and Engineering Education: Current Status

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This paper presents a comprehensive review of the use of Digital twins in engineering education among various disciplines. A total of 83 research papers were analyzed, spanning the last decade from 2012 to 2022. Almost all publications were reported after the year 2018, indicating a recent surge in interest and development in this area. The review reveals that digital twin technology offers students an interactive experience with virtual models of real-world products and systems, significantly enhancing the effectiveness of engineering education. It also improves industrial competitiveness through predictive maintenance and fault diagnosis. Digital twins can be used in various engineering disciplines and for personalized learning. However, challenges such as model accuracy and data transfer must be considered when implementing them. Overall, this technology can improve student learning outcomes, increase education accessibility and cost-effectiveness, and improve production systems' safety, visibility, and accessibility. Future requirements of the field are also discussed in this paper.

Keywords: Digital twin, Engineering education, Literature review, Digitalization, Digital transformation

Introduction:

In recent years, the adoption of digital technologies has become increasingly prevalent in society, marking the start of the industry 4.0 (I4.0) era. This includes the development of the IoT, artificial intelligence, Cyber-Physical Systems (CPS), and analysis of big data. These advancements have underscored the necessity of interaction of humans and critical thinking, paving the way for what is envisioned as Industry 5.0. This emerging phase of industry is characterized by sustainability, human-centricity, and resilience. Among the technologies poised to facilitate this transition to Industry 5.0 is the utilization of Digital Twins (DTs), digital replicas of physical systems employing sensors and 3D modeling to create virtual representations. DT technology has found application in education, particularly in fields such as engineering and technical subjects that require hands-on training on various systems, tools, and instruments.

DTs prove to be effective tools for communication in education due to their applicability and representation in multiple domains, allowing for the enhanced visualization of the functioning of systems for a deeper understanding. Moreover, DTs facilitate individualized student work on systems, a feat often constrained with physical twins due to resource limitations. This approach also fosters reliable learning experiences and effective knowledge construction, enabling students to grasp the behaviors of their physical counterparts under diverse operational conditions. DTs are particularly useful in problem- and inquiry-oriented learning during system development and testing. Additionally, DTs allow each student to work individually on a system, which is not possible with a physical twin due to limited resources. They also serve as invaluable assets for distance learning students who lack easy access to their physical counterparts. However, developing effective digital twin models in any field can be challenging due to various obstacles such as incomplete understanding of the system being modeled, sensor or component malfunctions, errors in data transfer or coding, and concerns with data collection, validation, and accurate data fusion, the computer processing, and the time required for data analysis and response to the physical twin. These challenges extend to the educational realm, where virtual labs employing real equipment are increasingly utilized for educational purposes [1].

Traditionally, engineering courses have provided students with specialized knowledge specific to a particular industry, with laboratory work playing a key role in this education [1]. However, as industries embrace digital transformations, there arises a demand for cross-disciplinary expertise, challenging traditional educational paradigms. Leveraging DTs as a virtual tool in engineering education and research can provide a possible solution to this challenge. By creating DTs of laboratory equipment, researchers and students can implement trials virtually, even if access to physical laboratories is limited due to aspects such as the COVID-19 virus or the increasing prevalence of online distance education. DTs provide a platform to simulate, access, experiment with, and study various scenarios of a system remotely, enhancing effectiveness and efficiency of engineering education in the digital era. This review paper aims to identify the use of DTs in engineering education in academia over the past decade and provide guidance for researchers who have not utilized DT technology for engineering education [2].

Objectives:

This review paper aims to systematically analyze and synthesize the application of Digital Twins (DTs) in engineering education within academic settings over the past decade. The objective is to map trends, identify common practices, and highlight innovative uses of DT technology in this context. By providing a comprehensive overview, the study seeks to offer practical guidance and insights for researchers and educators who are interested in incorporating DT technology into engineering education. The findings of this study will serve as a foundational resource for future research and instructional design, promoting the effective integration of DTs into engineering education curricula. No such review paper exists in the literature as of now.

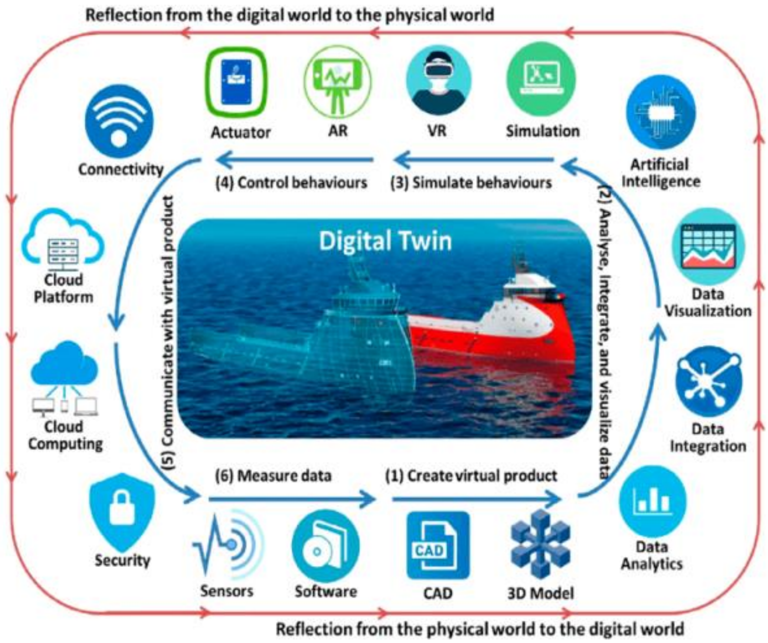

Figure 1: A depiction of Digital Twin and its Enablers [3][4]

Digital Twin:

The origins of the term "Digital Twin" (DT) and the initial research on DT models can be traced back to Dr. Michael Grieves and his lecture on Product Lifecycle Management [5]. DT is a simulation model that aims to "replicate the real/physical environment through a computational/digital model. It is composed of three components: the physical/real environment, the digital medium, and the link connecting them through data. These characteristics allow the models to be used as a prototype, testing tool, and performance monitoring and data extraction tool. DT models are also a key component of Industry 4.0, which aims to develop smart factories" [6]. See figure 1 for a pictorial representation of the concept of digital twins. According to Tao, Zhang, and Nee [4], digital twins are virtual counterparts that interact with physical objects throughout their lifecycle and provide intelligence for optimization, evaluation, and prediction. Digital twins are characterized by the bidirectional and seamless integration of data between the digital and physical spaces of a system, enabling automatic exchange of data, control, and modification by the physical twin. They are designed to accurately mimic the physical entity and have the ability to adapt as well.

Digital twins come in various models, including three and five-dimensional systems. The three-dimensional model encompasses three core components: virtual space, physical space, and connection [4]. The five-dimensional model includes these fundamental components, as well as two additional components: data and service. Enabling technologies for digital twins can be classified into five categories based on the core components of the five-dimensional model: physical entity, service, virtual model, data management, and connection. Additionally, literature also provides insight into a four-dimensional architecture [7]. The choice of architecture depends on the constructive objectives of the model. While there are various ways to design and construct a DT model, there is currently no consensus on the best method for capturing and transmitting data between the real environment and its corresponding model [6]. According to Kritzinger et al [8], "there are three types of digital replications, distinguished by their methods of communication between the real and digital environments.

Real-time communication of data is a complex process; however, it is crucial for fulfilling the assumptions and objectives of the models. One solution that literature proposes for this problem is to use certain software and means of communication to ensure low latency between the generation of the data and it's feeding into the model" [9]. DT models can prove useful as prototypes, testing tools, and performance monitoring tools, aligning them closely with the principles of Industry 4.0 and the development of smart factories. The architecture of a DT model can vary, ranging from 3-dimensional to 5-dimensional systems. The enabling technologies for digital twins can be classified into five categories based on the core components of the five-dimensional model. However, there remains a lack of consensus on the optimal approach to capture and communicate data between real and digital environments. Real-time data communication, while complex, is indispensable for meeting various assumptions and objectives of the models [6].

According to Erikstad [10], digital twins possess five key characteristics: representation, identity, state, behavior, and context. These characteristics allow digital twins to represent a unique physical asset and capture its physical manifestation in a digital format with metadata. The digital twin also allows the real-time rendering of its quantifiable measures, reflecting its basic responses to stimuli, and describing its operating context. This information is captured in real-time, which allows for the digital twin to be updated and adapted as the physical asset changes. Additionally, Cabos and Rostock [11] proposed that digital twins have three essential elements: asset representation, behavioral model, and condition and configuration data. These elements work together to enable decisions and predictions on the physical form of the twin through simulation and data reflecting the status and changes to the physical object throughout its lifecycle. This allows for the digital twin to not just reflect the current state of the physical asset but also predict future states and behaviors based on collected data from the physical asset. This can be used for monitoring and optimization of the physical asset. Digital twins incorporate encoded logic, enabling predictions and decisions regarding the physical twin through simulations and data that reflect the status and changes of the physical object throughout its lifecycle [12].

Digital twins use cutting-edge technologies such as virtual reality, machine learning, mixed reality, and augmented reality to replicate and monitor real-world processes and objects in order to assess system performance. They provide real-time data and insights by creating a digital replica of the physical asset [12]. By using the virtual model of a digital twin, simulations can be run to gather data, test the performance of actual physical equipment, identify issues, and propose potential improvements. The ability to simulate and test in a virtual environment can save time and resources compared to physical testing. Digital twins are used in a wide range of industries including manufacturing, healthcare, construction, meteorology, transportation, agriculture, education, aerospace, and energy. They can be applied in various situations such as predictive maintenance, performance optimization, and design validation. The architecture of a digital twin consists of three key components: a physical entity, a virtual model, and the relationship between them [12]. Digital models are representations of existing or future real items without automatic data exchange, while digital shadows are one-way automated data flows connecting physical and digital objects that already exist. In contrast, digital twins involve seamless data exchange between fully integrated physical and digital items, with data flowing freely in both directions between a system's physical and digital representations and the ability for a digital twin to automatically share data with its physical twin or be modified by it. While digital twins are often compared to simulation, there are important differences between the two. Simulation is a process of creating a model of a system in order to predict the behavior of the system, while digital twins are a real-time representation of a physical system, providing the ability to monitor, analyze, and control the physical system. Digital twins can adapt and learn from the physical system, unlike simulations, which are typically static [12]. Table 1 provides a comparison of simulation and digital twins.

Table 1: Simulation vs. Digital Twin

Simulation	Digital Twin
Digital model	Digital model

Single scenario Simulations	Many scenario Simulations
Single process analysis	Multiple process analysis
Real-time data is not too helpful	Relies on two-way information flow
Single perspective	Various perspectives
Static data will work	Real-time data required
Sensors and devices for data collection not involved	Sensors and devices for data collection involved
May not lead to problem identification	This leads to problem identification and potential solutions for various scenarios
Does not use algorithms for problem and solution identification	Uses various algorithms for problem and solution identification
Can run on roughly made depictions of the physical entities	Need precise depiction of the physical entity in terms of geometry, properties, behaviors, and rules on a variety of scales or levels, and should alter at the same rate as the physical entity

There are several types of digital twins [6], including Digital Twin Instance (DTI), which represents a physical counterpart throughout its entire lifecycle, continuously monitoring its state and any changes or evolution it undergoes. DTIs are useful for validating the expected behavior and performance of a product or object. The second type is a Digital Twin Prototype (DTP), which gathers and stores information and characteristics about a physical twin in the manufacturing and production process, such as CADs, BOMs, and drawings. Digital Twin models, such as Design Digital Twins (DDT), Manufacturing Digital Twins (MDT), and Performance Digital Twins (PDT), can simulate and test various aspects of a physical product or process, such as design, manufacturing, and performance, in order to identify and address potential issues before they occur in the real world, ultimately reducing costs and operational time. Performance Digital Twins (PDTs), equipped with smart capabilities, analyze monitored information from their physical counterparts to generate actionable data for tasks like design optimization, maintenance strategy development, and performance analysis [6].

The growing interest in DT models is undeniable, yet their widespread adoption faces significant hurdles, notably the limited access to tools for model construction and the absence of freely available software for knowledge dissemination in academic and small organizational settings. There is a need to explore alternatives for the construction of a DT model using free or open-source software, such as game engines, which can provide good visualizations, physical simulations, and artificial intelligence integration. Researchers suggest that Unity3D, Blender3D, and Visual Studio programming can be the optimal choice for building the model due to their user-friendly interface, large user base, and availability of online courses [12].

DT and Engineering Education: Importance, Benefits, and Challenges:

Maksimović et al [13] highlighted in recent years, the integration of digital technologies, also known as digital transformation, into the education system has changed the way engineering education is conducted at universities worldwide. Digital transformation in education refers to how teachers think, behave, and interact with each other and with students. This transformation is impacting the management, engagement, education, and research operations of Higher Education Institutions (HEIs). There is a notable drive to revolutionize the entire educational system to adapt to and take advantage of new technologies and tools in order to accelerate the digital transformation process. Anticipations regarding the reform of higher education, driven by digital learning technologies, have been prevalent. Efforts have been directed towards making changes or reforms possible by enhancing the personalized, adaptable, and student-centric nature of digital education, (as outlined in the European Commission's Digital Education Action Plan for 2021-2027). One key aspect of digital transformation in academia is the use of DT technology in laboratories and classrooms. DTs have become feasible due to advancements in sensor technology, enhanced product connectivity, cost-effective processing capabilities, and accessible data storage solutions.

The availability of DTs has opened up numerous possibilities for analysis and applications, leading to enhanced learning outcomes and the ability to take corrective actions promptly. One of the key advantages of DTs is their cost-effectivity, allowing students to study a digital version of an instrument or process rather than the actual object, thereby improving accessibility and reducing expenses. In the context of engineering education, DTs contribute in improving the learning experience and increasing student motivation [7]. The field of engineering is evolving rapidly, facing challenges related to sustainability, industry demands, and digitalization. As automation and digitalization become more prevalent, the skills and competencies required of engineers are also changing. Successful engineering education involves not only imparting knowledge but also developing practical problem-solving abilities and fostering adaptability. Employability skills, technical competence, and the ability to quickly learn are highly valued in the engineering industry. Designing engineering courses is crucial to incorporate advanced technologies and innovative methods of teaching in order to prepare students for the evolving engineering field as well as the updating of course materials in light of digital transformation [13]. Engineering education needs to be more digital in order to effectively teach and support the development of students' academic abilities. This can be achieved through the use of digital twins, which are virtual representations of systems, products, or processes that can be used in the classroom and laboratory to explore and understand their structures, functions, and behaviors. By using DT technology, students can learn and understand complex systems more quickly and safely in a controlled, simulation-driven environment, while also developing valuable systems-thinking skills.

The literature presents several advantages of implementing DTs in the engineering field, one of them is the ability to cut costs and avoid resource waste. It is observed that by utilizing DTs, a virtual model of the equipment can be created and made available to a larger number of students, saving the university money and resources instead of investing in expensive equipment. DTs can also enhance the speed and effectiveness of prototyping and product redesign. Moreover, they can identify problems and failures in complex or multi-material products, enabling predictive maintenance planning and continuous validation and enhancement of system processes. They can be used to quickly develop specialized products and enable students to enroll in online programs, access resources, work on various scenarios using real devices, and perform simulations to accomplish predetermined laboratory tasks. Furthermore, they provide safe virtual programs and reduce the risk of failing equipment by allowing remote access to virtual models and being predictive in nature. DTs enable teamwork, facilitating collaboration among all stakeholders, even if they are not physically connected to each other or the system [7].

Implementing DT technology in Higher Education Institutions (HEIs) indeed poses several challenges, with Information Technology (IT) infrastructure being a significant concern. DT requires complex tools and software, necessitating a robust and scalable IT infrastructure to support the development and use of this technology. In order to have an accurate virtual representation of the physical object, the availability of extensive data is required. This heterogeneous data should be collected and managed (system, product, network, environmental, hardware-, and software-related data, etc.) in a seamless manner. This data is used for finding the patterns and extracting useful information for the sale of assessment of system planning, system process enhancement, solution optimization, correcting faults, etc. Systems, assets, and data must be secured adequately to ensure privacy in order to adapt technology in education. Trainers and teachers often hesitate to fully adopt DT technology due to a lack of trust in its accuracy. When educators are unsure about the reliability of DTs, they may not incorporate digital twins effectively into student learning experiences. HEIs can harness the full potential of

DTs only when they are confident in their precise performance as anticipated. Although the usage of DT in education is expanding, more understanding of the concept and judiciousness on the prospects related to DT implementation are required. There is a huge gap in the literature on standardization and regulations of DT design and modeling. Designing and modeling DTs form the foundation of their application. It's crucial to adhere to a standardized process throughout all stages of DT development, from initial design to implementation and simulation. Standardization of interfacing, modeling, protocols, and data is required for the implementation of DTs, yet it often lacks uniformity. Insufficient teaching skills are also a major obstacle in adopting the DT technology into engineering education. Given the rapid pace of technological advancements, regular updates to course curricula are essential to keep pace with evolving technologies. [7].

Effectiveness, Student Engagement and Learning Outcome:

Digital twins, while relatively new in educational contexts, provide several distinct advantages over traditional teaching methods, particularly regarding effectiveness, student engagement, and learning outcomes. Unlike traditional approaches, digital twins offer realism and context by allowing students to interact with virtual representations of real-world systems, facilitating a deeper understanding of complex concepts. They enable students to experiment and simulate within a virtual environment, fostering problem-solving skills and active learning through risk-free exploration. Digital twins can generate real-time feedback, helping students immediately see the impact of their actions and giving instructors a detailed view of student progress, thus enhancing learning effectiveness. In terms of student engagement, digital twins often use interactive and immersive elements, like Augmented Reality (AR) and Virtual Reality (VR), which can make learning more engaging compared to standard lectures and textbooks. Gamification elements further boost motivation, encouraging active participation and fostering persistence. These environments promote collaboration and teamwork, supporting a more participatory learning experience where students communicate and work together.

Digital twins also lead to improved learning outcomes by providing hands-on learning opportunities not typically found in traditional settings, enhancing retention and practical skill development. They help bridge the gap between theoretical knowledge and practical application, allowing students to prepare better for real-world engineering challenges. Their adaptability and personalization features enable individualized learning paths, catering to various learning styles. However, digital twins come with challenges. They require significant technical resources, including software, hardware, and expertise, which can be a barrier for some institutions. There is a learning curve for both instructors and students, which can affect the initial implementation's effectiveness. Additionally, integrating digital twins with traditional teaching methods requires careful planning to maintain a cohesive learning experience. Despite these challenges, digital twins offer a more interactive, engaging, and effective learning experience compared to traditional methods, with a strong potential to enhance student engagement and learning outcomes. Yet, their success depends on addressing resource requirements, learning curves, and proper integration into educational frameworks.

Methodology:

Due to its recent adoption in engineering education and the associated challenges stemming from limited awareness and understanding of its development tools, the literature review focuses exclusively on the past decade (2012-2022) to capture the evolution and current state of Digital Twin utilization in this field. This paper determines the adoption of digital twin technology in engineering education as a comprehensive overview, encompassing all engineering disciplines.

Data Collection:

A thorough search of the literature was conducted using the following keywords: “digital twin engineering education”, “digital twin university education”, and “digital twin academia”.

Search engines such as ScienceDirect, SCOPUS, EBSCO, Google Scholar, and Web of Science were utilized to search the keywords mentioned previously. The research papers purely applied in the engineering education discipline, were selected for inclusion in the literature review on Digital Twin adoption from 2012 to 2022. A variety of papers were selected for this review because of the possibility of students learning from this experience. Research encompasses a range of publication types, including work-in-progress, conference papers, and research journal articles.

Data Screening:

Each paper underwent a meticulous screening process based on its abstract to ensure relevance to the review's scope, with particular attention given to excluding non-engineering education articles. Table 2 presents selected articles, along with their respective publication sources, sorted in descending order based on publication year. A total of 127 research papers were identified, however, after a thorough review, 83 articles were finally selected for this study.

Table 2: Review of Research Papers on Digital Twins in Engineering Education

Year	Discipline	Paper type	Research Methodology	Topic of Research
2020	Control System Design	Journal	KJ Technique	"What are the benefits and limitations of DT and confirming earlier findings that DT technology can improve student engagement and motivation when implemented correctly." [14]
2018	Product Development	Conference	PBL	"The research aims to educate MSc students in simulation-driven product development methodology using a case-study and advanced tools and techniques, with the goal of developing specialists capable of innovative product design." [15]
2021	Electrical engineering	Conference	Case study	"The research aims to introduce advanced simulation techniques, such as Digital twin technologies, Cloud services, and Big data processing, into the educational process of electrical engineers to prepare them for Industry 4.0 and keep up with the demand of industry digitalization." [16]
2018	Mechanical Engineering	Journal	Teaching Factory	Application in mechanical engineering [17]
2020	Construction Engineering	Journal	Case study, PBL Scientific semi-structured interviews	"The research aims to evaluate the effectiveness of advanced digital technologies, such as virtual and augmented reality and digital twin, in teaching architecture, engineering, and construction courses remotely, by implementing novel construction modules, and providing educators with useful tools to teach students in a virtual environment." [18]
2021	Construction Engineering	Journal	Case study, Interviews	"The research aims to propose a framework that utilizes digital twin and IoT technology to measure and improve sustainability in buildings in real time, by testing it on a pilot building and using it to support decision-making related to sustainability throughout the building's life cycle, aligning with the EU Green Deal's goal of a sustainable economy." [19]
2021	General Engineering Education	Conference	Theoretical	"The research aims to propose a new, personalized, and agile educational system that takes into account the body of knowledge, experience, and humanity to adapt to the fast-paced knowledge doubling and diversity of individual abilities and styles of learning by involving digital twin technology in the symbiotic relationship between the educational system and humans." [20]
2018	Cyber-Physical Systems, Mechatronics Engineering, Mechanical Engineering	Conference	Use case scenarios	"The research presents the use and observations of an overhead crane platform for university education, research, and innovation purposes, specifically focusing on the Digital Twin concept and discussing the technical properties, opportunities, and challenges of the platform as well as how the university should manage it while collaborating with industry partners." [21]

2018	Production engineering	Conference	Didactic methodology	"The research proposes using a digital twin of manufacturing processes as an effective tool for training and education in Industry 4.0 by creating a digital twin with pedagogical extensions, providing design considerations, and use-case scenarios to foster concrete learning experiences and address limitations of traditional learning factories." [22]
2019	Systems Architecting and Engineering	Conference	Experiential Learning, Instructional approach	"The research presents an innovative approach using digital twin technology to enhance student learning in a laboratory setting by providing authentic experiences and immediate feedback. This approach aims to equip students with relevant knowledge and skills in a cost-effective and safe way before they enter the workforce." [23]
2022	Industrial Engineering System	Journal	Design and development	"The research aims to develop a standardized framework for implementation of digital twin in industrial energy systems by identifying the most important requirements for digital twin of IES and proposing a platform with a low level of abstraction that addresses current technical implementation barriers and ultimately bridge the gap between the latest research on digital twin and its implementation in the traditional energy sector." [24]
2022	Construction Engineering	Journal	Theoretical, Virtual, and Static Model	"The research aims to develop a standardized framework for implementation of digital twin in industrial energy systems by identifying the most important requirements for digital twin of IES and proposing a platform with a low level of abstraction that addresses current technical implementation barriers and ultimately bridge the gap between the latest research on digital twin and its implementation in the traditional energy sector." [25]
2019	Manufacturing System Engineering	Journal	Learning Factories	"The research is to describe the process of designing digital twins for educational institutions, explaining how and why they are used, and discussing the advantages and disadvantages and economic considerations." [26]
2020	Mechatronics Engineering	Journal	Hardware and Software Models	"The research shows the steps of designing digital twins, explains how and why they can be used in educational institutions and the process of creating software models of industrial plants, and discusses the advantages, disadvantages, and economic considerations of using digital twins for engineering study." [27]
2018	Civil and Environmental Engineering. Geotechnical, & Coastal Engineering	Conference	Exploratory Tasks	"The research aims to develop simple yet meaningful digital twins for civil engineering classrooms using simple graphical user interfaces and focuses on providing students with a key understanding of IoT mechanics and its potential applications in the construction industry." [28]
2022	Systems Engineering	Journal	Simulation, Product Lifecycle	"The research aims to investigate the possibilities and challenges of applying Digital Twin technology in education to conduct industrial-like labs virtually, focusing on a case study of an automation line with full-scale industrial equipment and emphasizing the

			Management, Modeling	need for educational curricula that include laboratory applications and theoretical understanding of DT technologies, and the human-centric aspects of Industry 4.0 and Industry 5.0." [9]
2022	Engineering education	Journal	Methodology	Application in engineering education [29]
	Marine Engineering, Mechanical and Industrial Engineering	Report	Product Model	"This research documents the development of a digital twin of a research vessel, R/V Gunnerus, and its potential use in marine technology education to strengthen discipline insight and understanding of digitization in products and engineering processes." [30]
2021	Mechatronics Engineering	Conference	5-step development framework based on the work of: [31]	"The research aims to use digital twin technology in remote laboratory assignments for a Mechatronics course at the University of California, Merced to enhance students' simulation skills and culminate in a group project." [32]
2022	Mechatronics, Mechanical Engineering	Journal	Modeling	"The research aims to create a digital laboratory for training and programming industrial robots with customizable and cost-effective features that improve teaching and machine operation." [33]
2018	Manufacturing Engineering	Conference	Kolb's experiential learning	"The research aims to investigate the use of Digital Twins in the education sector, specifically in fostering the education process of flexible manufacturing systems based on Kolb's Experiential Learning Theory, and presents a use case of the proposed framework." [34]
2019	Manufacturing Engineering	Journal	Exploratory Tasks, Interviews	"The research aims to use a modern industrial robot and its digital twin in a virtual environment to train first-year engineering students in spatial skills, and evaluate the effectiveness of the training through a post-workshop questionnaire." [35]
2022	Industrial Engineering	Journal	Modeling & Simulation	"The research introduces a novel teleoperation platform that utilizes Industry 5.0 and digital twin technology to reduce educational and resource inequality by providing remote access and learning opportunities for robotics, allowing for remote programming, monitoring, scheduling, and social interaction between users, and presenting experimental results." [36]
2020	Control System Engineering	Conference	Hardware-in-the-loop, Extended Reality	"This research explores how digital twin technology can be applied to control systems in extended reality, with the goal of facilitating industrial use through training and supervision, it uses a multi-tank system laboratory model and presents the theoretical and technical development with experimental results." [37]
2019	Cyber manufacturing	Conference	Education Model	"This research aims to create a cyberlearning environment for cyber manufacturing education at a specific university, to address the lack of cyber manufacturing education

	Engineering, Digital Manufacturing, Manufacturing Engineering			in current manufacturing education knowledge model and to adapt to Industry 4.0 technology." [38]
2021	General Engineering	Journal	Education model	"The research examines the design and use of digital twins in engineering education, as software-models of industrial plants in universities and training centers, and discusses the advantages and challenges of using this technology in engineering studies and its economic considerations." [39]
2020	Mechanical and electrical engineering	Conference	Education model	"This research aims to analyze the potential application of digital twin technology in education, specifically in the form of holographic classrooms, and its potential benefits such as improving learning space, distance learning, maker education, vocational education, management and control of teaching facilities and dynamic evaluation of teaching in the context of the emergence of intelligent economy and the integration of virtual and real worlds." [40]
2021	Electrical engineering	Online Repository	Virtual reality modeling	"This research aims to create a simple method for lecturers to create their own virtual laboratory tutorials using generic models and presents a case study to demonstrate the feasibility of this approach in light of the need for remote learning during the COVID-19 pandemic." [41]
2021	Electrical engineering	Conference	PBL, Didactic Optimization Using Design-Based Research	"This research aims to improve the use of digital technology for laboratory practicals by promoting learner-centered teaching methods and reducing reliance on costly equipment to increase student motivation and engagement." [1]
2020	Process engineering, Mechanical engineering	Thesis	Education model	"This research examines the potential uses of digital twins in a process-related practical learning environment, specifically in the context of remote working practices due to the COVID-19 pandemic, by conducting user research with teaching staff and students to identify the needs for development and presenting possible applications and their applicability." [42]
2021	Cybersecurity, Smart grid, Electrical engineering	Online Repository	Modeling	"The purpose of this research is to build a digital power twin for a physical test-bed for cyber security studies on smart grids, to overcome limitations of the physical test-bed, such as modifying physical configurations and difficulty to scale, and to illustrate its typical use with a case study of a cyber-attack." [43]
2022	Computer Engineering,	Journal	Smart campus, Extreme Learning	"The purpose of this research is to present the design and implementation of a digital twin for a university data center to ensure the safety and protection of critical and costly

	Computer Science		Machine, Modeling, Implementation	mission infrastructure and guarantee business continuity, enhance efficiency, and sustain development." [44]
2021	General Engineering, Systems analyst	Journal	Compare the competencies of engineering specialists with enterprise processes	"The research aims to assess the competencies of an engineering specialist by using the digital twin of an enterprise, which includes all major pre-production, production, and production support processes, and a method of comparing the normal mode of execution of the enterprise processes to the new competencies of the specialist." [45]
2018	Mechanical and Industrial Systems engineering	Thesis	Envision-Process Identification-Learning Objectives Identification-Pilot Twin-Deploy Twin-Monitor	"The purpose of this research is to propose the use of digital twins as an alternative learning platform for production engineering courses, and to develop a pedagogical digital twin that facilitates automated assessment of the learner's competency level and fosters concrete learning experiences through reflective observation of manufacturing processes." [46]
2022	Control System engineering	Journal	Simulation	"The goal of this research is to investigate the implementation of cost-efficient tools for digital twin and X-in-the-Loop (XIL) simulations in control education, specifically for load swinging attenuation using a simple gantry crane model. This aims to bridge the gap between industrial requirements and educational practices, and enhance control education in standard undergraduate and graduate courses." [47]
2018	Manufacturing engineering	Journal	Modeling and Simulation	Application in manufacturing engineering education [48]
2022	Design and Manufacturing engineering	Journal	Education model, Teaching unit Future: geometrical variations management	Application in design and manufacturing engineering education [49]
2022	Manufacturing engineering	Conference	Machine Learning Technique	"The purpose of this research is to create a digital twin application for fault detection and classification using machine learning techniques demonstrated in a compact educational turbocharger prototype, that aims to be an affordable alternative for

				teaching and education on the digital twin and Industrial Internet of Things concepts." [50]
2022	Electromechanical engineering	Conference	Teaching model	"The article discusses the challenges faced by engineering education during the post-epidemic era, where emphasis on practical teaching via experimentation is hindered by the pandemic, and suggests the use of digital twin technology to reduce design schemes, optimize prototype production costs, improve the quality of engineering students, and eliminate the risks associated with experimental teaching operations as a solution to this issue." [51]
2022	Construction engineering	Journal	Object-oriented learned from Information Engineering	"The article discusses the use of a digital twin framework powered by the Unreal Engine and MQTT, an IoT communication protocol, to improve the quality of education in construction at the Reference Construction Site Aachen West in Germany, by creating a virtual representation of the site for students to explore and providing real-time interaction and data from on-site machinery and processes, which was validated by a group of students and planned to be transferred to research and construction projects. " [52]
2021	Industrial engineering	Conference	Design and modeling	"A current challenge for engineering education is keeping up with emerging technologies such as the Digital Twin (DT), which is a virtual representation of a physical system used in Industry 4.0 manufacturing processes, and providing access to practical problems close to the real world in safe virtual environments, as face-to-face access to laboratories was compromised during the COVID-19 pandemic." [53]
2020	Computer engineering	Journal	Modeling and Training Manual	"This paper presents a maintenance training manual for EV vehicles utilizing digital twin technology, various sensors, and VR to provide high immersive Ness to users, allowing for the creation of detailed scenarios for maintenance and inspection and the display of 3D parts by procedure, animation, and effects for maintenance situations, which can improve the quality of education, safety, and correct maintenance process, and help users to learn how to use equipment naturally and maintain EV vehicles." [54]
2021	Civil engineering	Journal	Graphical and numerical modeling, PBL	"In this paper, the authors present an e-learning effort to establish a series of digital twins of experimental setups for teaching building physics, energy in buildings, and indoor environment, as a way to provide an attractive teaching alternative for remote e-learning which is complementary to physical experiments, and also allows for larger and more complex study cases, these digital twins are designed for teaching operation and balancing hydronic heating systems, their numerical models and graphical user interfaces are created with the LabVIEW programming environment. " [55]
2022	General engineering	Journal	Artificial Intelligence based	"The proposed English classroom situational teaching mode uses digital twin technology, virtual reality, and computer image technology to provide a new set of methods for students' language learning, it analyses the system implementation

			situational model for teaching English in any scenario including engineering	methods, expresses the system core algorithm flow in the form of diagrams and tables, and obtains the overall system framework and finally, it is evaluated the effect of the English classroom situational teaching model proposed in this paper through experimental research, which showed that the teaching model proposed in this paper is very effective. " [56]
2018	Civil and construction engineering, Environmental engineering	Journal	Cyber-physical system, longitudinal analysis of data	"The paper discusses the use of digital twin technology to create a comprehensive digital representation of the new UCL Campus at Here East on the Queen Elizabeth Olympic Park, using real-time data from IoT technologies and advanced 3D visualization to improve the process of visualizing, modeling, and working with the complex urban systems." [57]
2020	Manufacturing engineering	Journal	Learning factory, Finite element analysis, simulation	"This paper presents an approach for the planning and implementation of an academic learning factory tailored to the requirements of the metal forming industry, which will be operated at the Chair of Metal forming at the Monta Universität Leoben, with the objective of monitoring and controlling forming units of different technological maturity in a common system, by using industrial software such as ibaPDA for data logging and ibaAnalyzer for automated further processing, and implementing Analog to Digital (A/D) converters and machine hour counters to illustrate the retrofitting approach in practice, in addition to planning and implementing Digital Shadows and Digital Twins through the use of common Finite Element (FE) simulation programs, in order to demonstrate the possibilities of connectivity between machines, simulation programs, and automation software." [58]
2021	General engineering	Journal	Learning objects	"This article establishes a methodology for educational institutions to design and implement predictive machine learning models based on Artificial Intelligence (AI) to improve students' learning experience and their relationship with the institution by automating the construction of analytical models using a taxonomy based on learning objects while addressing challenges such as data fusion and ethics of data use." [59]
2022	Mechanical engineering and robotics	Journal	Experimental exploration, Web application environment	"The article discusses the concept of Industry 4.0 and the use of digital twin technology, which allows for the simulation and elimination of design flaws in physical prototypes by creating mathematical models of objects, processes, or services that reflect their dynamic behavior and can be integrated with control systems for testing in a virtual environment; the paper presents the idea of building simplified digital twins in a web application environment for educational and small production line design purposes." [60]

2022	Control System engineering	Journal	Proposal and a prototype	"The study proposed Reimagine Lab as a framework for leveraging digital twins and extended reality technologies to streamline the development and operation of hands-on, virtual, and remote laboratories in control engineering, increasing student engagement and interaction, immersion, and collaboration while addressing concerns with traditional hands-on labs." [61]
2022	Electrical engineering	Journal	Action (Design) Research	"This article presents a model for improving the cyber-resilience of Critical Cyber Infrastructures (CCIs) by utilizing a digital twin to address the integration of computational, communication, and physical aspects of CCIs, focusing specifically on cybersecurity in the electric power sector, to increase cyber situational awareness, and enhance response capacity in order to minimize response time and reduce the impact of cyber-attacks on organizations and society." [62]
2020	General engineering	Journal	Data mining	"This research presents a framework that uses process mining and digital twin concept to analyze event log data from Learning Management Systems (LMS) to better understand and improve online student learning patterns, with the use of inductive and fuzzy miner algorithms found to produce better results in understanding student behavior than previous methods." [63]
2021	Architecture, Built Environment, and Construction engineering	Conference	Modeling, Case study	"This research work proposes a soft Digital Twin (DT) based on a Building Information Model (BIM) with a low level of Geometry (LOG) coupled with an IoT network to monitor and correct the indoor conditions of educational buildings on a real-time basis, in order to protect occupants and preserve educational spaces where learning activities can take place during the COVID-19 pandemic." [64]
2022	Sports engineering	Journal	Simulation, Quantitative experimental analysis, Hidden Markov models	"The paper proposes a method to improve the efficiency and intelligence of somatosensory recognition technology in physical education teaching practice by using a combination of induction recognition technology, the Internet, the Kinect sensor, and the hidden Markov model (HMM) to simulate experimental data and create a gait recognition algorithm that can identify motion behavior and display results on a cloud-based web platform, and also addresses issues in physical education practice by using a digital twin system for monitoring and identification, real-time data analysis, and personalized training plans based on Body Mass Index (BMI)." [65]
2020	Informatics and Telecom engineering	Journal	Simulation	"The article proposes a solution for creating a high-precision model of a system of high-level indicators of an educational organization using a dynamic model within the digital twin concept, utilizing BPMS ELMA as a technological platform, and incorporating a recommendation module using optimal control methods and recursive filters, which will increase in accuracy as more digital shadow data is collected." [66]

2022	General engineering, Computational intelligence	Journal	Experimental teaching and analysis	"The article describes an approach in which digital twin technology is used to connect the real teaching space with the virtual teaching space in order to become the mainstream of online teaching, and how this has a strong impact on traditional bilingual teaching mode and concepts. It suggests that digital twin technology experimental teaching in bilingual teaching can produce certain results, with the results being higher than the control class." [67]
2020	Construction and civil engineering	Journal	Functional design and simulation	"This article explores the use of digital twin technology to improve information management and provide better services for stadiums in colleges and universities, specifically in the context of the 14th National Games of China in Shaanxi Province, by creating virtual copies of real stadiums for smart planning, construction, and operation management, including comprehensive data simulation and operation management, with the goal of designing intelligent stadiums with various functions such as information, social, game-watching, and data analysis. " [68]
2018	Automobile Production engineering	Journal	Modeling the cyber-physical system	Application in automobile production engineering education [69]
2022	Design and production engineering	Journal	Modeling	"This research discusses the use of digital twin technology and data mining to improve teaching methods by developing a student evaluation tool module and data analysis tool module for digital twin education, analyzing student performance, personal information, and evaluation data to support decision-making, and testing the system in an experimental environment with positive results in terms of improved innovation and self-evaluation abilities for students." [70]
2022	Computer science and engineering	Journal	Developmenta l framework	"This paper addresses the challenges of achieving the highest possible student engagement and adoption of new technologies in an educational context by proposing a framework based on Unity3D for integrating innovative technologies such as Digital Twin, Virtual/Augmented Reality, and Gamification into Learning Management Systems (LMS) to facilitate the teaching of Programmable Logic Controller (PLC) and Virtual Commissioning." [71]
2022	Architectural, Civil, Environmental and Energy Engineering	Journal	Evaluation and assessment framework	"This paper proposes a digital twin-based assessment framework to determine the best energy-saving technologies and strategies for existing buildings using a digital twin that integrates the building's hardware system, operational schedule database, and a probabilistic model of occupant behavior, resulting in a reduction in power consumption by more than 60% by implementing an off-strategy involving a passive infrared sensor or manager and adjusting the luminance level to an appropriate range in most classrooms." [72]

2022	Electrical engineering	Journal	Physical modeling, Virtual modeling	"This paper presents the use of digital twin technology in the education sector, specifically in the field of automatic control, through the development of virtual replicas of real systems, such as rotary motion equipment and a cart-pendulum platform, built in the MATLAB/Simulink environment and used to propose control exercises for students of automatic control courses." [73]
2021	Civil and construction engineering	Thesis	Survey research	"This study proposes a seven-year roadmap strategy framework to adopt Building Information Modelling and Digital twin technology in Nigerian Tertiary Institutions to bridge the knowledge gap and increase awareness among upcoming construction professionals in Nigeria, and align the Nigerian construction industry with other developed nations where these technologies have been adopted." [74]
2020	Civil and construction engineering, Environmental engineering	Journal	Complex Adaptive Systems framework, Modeling	"This paper proposes the concept of using smart campuses as a smaller-scale testbed for experimenting with novel information and communication technologies in the field of smart cities, by integrating building information modeling tools with IoT-based wireless sensor networks for environmental monitoring and emotion detection to provide insights into the level of comfort, and explores the ability of universities to contribute to local sustainability projects by sharing knowledge and experience across multi-disciplinary teams." [75]
2022	Automotive Mechatronics, Electrical engineering	Journal	Educational modeling	"The article discusses the advancements in Digital Twin technology in recent years, specifically the combination of virtualization through Digital Twins and interoperability based on the OPC UA standard, and presents an experimental workplace and educational-development environment for designing Digital Twins using Unity and interoperability, which was practically verified on available digital technologies." [76]
2022	Robotics engineering	Conference	Mixed reality modeling	"The use of robotics in industry is increasing and requires tailored education and training programs, and the combination of immersive technologies like mixed reality with robotics education can provide more intuitive and easy access to fundamental knowledge of industrial robotics, this work aims to facilitate the use of mixed reality based digital twin platform for robotics education by expanding and investigating a combined system of desktop robotics and mixed reality for entry into robotics courses. " [77]
2020	General engineering	Thesis	Design and Construction (incremental)	"Virtual Commissioning, a technology that uses digital twin models of automated systems to test, debug, and validate them, is becoming increasingly popular in Industry 4.0, and companies like HIFA AB are using it to create virtual models of their educational labs for validation and supplementing real systems." [78]
2019	General engineering	Conference	Modeling	"The use of digital twin technology, which allows for the creation of virtual models of processes, products, or services for simulation and early detection of problems, is being

				researched as a way to enhance educational purposes in remote and virtual laboratories." [79]
2020	Automation engineering	Conference	System architecture designing in 3D modeling tools	"This paper describes a cost-effective solution for training automation students by using a WBT server and OPC server architecture to create a remote laboratory, where students can access digital 3D twin models of machines through internet services and practice programming tasks of a PLC on virtual CAD models without having to be present at the real machine." [80]
2022	Mechanical engineering	Journal	Simulation and modeling, Machine Learning	"This project aims to study the performance of reinforcement machine learning algorithms Proximal Policy Optimization and Soft Actor-Critic in simulating autonomous sailboats and their responses to different wind directions while avoiding obstacles, and the effect of imitation learning algorithms Behavioral Cloning and Generative Adversarial Imitation Learning on them." [81]
2022	Software and System engineering	conference	Cyber-physical systems development, Pilot testing	"The paper reports on the development of a capacity-building system in Cyber-Physical System (CPS) development, designed to educate engineering-interested students and workforce with multidisciplinary skills to meet the increasing demand for skilled developers and informed users, using a mixed-mode structure of tangibles and digital twins as a central to the program which provides an effective way of learning about the foundations of CPS engineering from software and systems engineering. The program has already been successfully introduced and the paper discusses the approach used to design a cross-disciplinary engineering program, lessons learned from several development iterations of the program, and the synergies and commonalities between CPS development and development education." [82]
2022	Civil and Construction engineering	Conference	Teaching methodology, PBL	"The paper examines the value of including digital twin technology as a hands-on learning activity in a graduate-level building construction course, presenting the methodology of teaching digital twins, evaluating the benefits of introducing this topic within the framework of several learning objectives using real-life cases of the campus football stadium and collecting feedback from the students, finding it to be highly valuable in providing a framework for students to understand the potential offered by various technologies in visualizing a facility throughout its lifecycle, and helping students to understand how each technology best fits and how several technologies could be used in concert with one another." [83]
2018	General engineering, Computer engineering	Journal	Teaching methodology	"The paper proposes a novel virtual reality-based cyber-physical education system (VR-CPES) for efficient education on a mobile platform which utilizes cyber-physical systems technology and digital twin to integrate the real world into virtual reality, and designs real-time network technology interworking software and a path selection

				algorithm to ensure functionalities and performance in terms of packet loss and delay." [84]
2018	Materials and Manufacturing engineering	Conference	Modeling, Product Lifecycle Management	"The University of Cincinnati is partnering with Siemens PLM software to create a curriculum that teaches the fundamentals of Additive Manufacturing using a cradle-to-cradle approach, with the goal of preparing students for the digital workforce of the future and Industry 4.0." [85]
	Electronics and Communication engineering, Electro magnetic engineering	Journal	Survey	"This article reviews the basic concepts of modeling and simulation in computational sciences, including the use of virtual labs in engineering education, and introduces virtual tools that can be used in electromagnetic engineering." [86]
2022	Civil and Construction engineering	Journal	PBL	"This article reviews the use of problem-based learning (PBL) in architectural education, focusing on the inclusion of not only design but also estimation and construction based on real-world cases, and reports on the results of PBL implementation in interior renovation and outdoor furniture installation projects at a college campus, finding improvements in architectural space expression, construction safety, and estimation accuracy, but also highlights issues such as students not getting a realistic understanding of the construction process." [87]
2022	Industrial and Manufacturing engineering	Journal	Learning Factory	Application in industrial manufacturing engineering education [88]
2020	Manufacturing engineering	Journal	Learning Factory	"A method of building a simulated changeable learning factory and linking it to the physical system to create a digital twin using open-source low-cost changeable automated system, Robo DK simulation and programming environment, and industrial communication protocols is presented in this paper." [89]
2019	Manufacturing engineering	Journal	Teaching Model	"The study proposes the use of digital twins as an alternative to current solutions, presents an approach towards modeling a digital twin using ontologies to develop a formal representation of the domain, and discusses a use-case for a pedagogic digital twin before proposing future directions for work." [90]
2020	Manufacturing engineering	Journal	Learning Factory	"The paper provides an approach for the planning and implementation of a learning factory specifically tailored to the metal forming industry and to be operated at the Monta Universität Leoben, with the goal of monitoring and controlling forming units of different technological maturity using industrial software and retrofitting techniques, and by using common Finite Element simulation programs to demonstrate the

				possibilities of connectivity between machines, simulation programs and automation software, making an important contribution to the training of future specialists with special consideration of the increasing interdisciplinarity in manufacturing technology." [58]
2022	General engineering	Journal	Learning Factory, Prototyping	"The D3 concept, consisting of physical, cyber, and intelligent activity worlds, is proposed to support engineers in cyber-physical production systems, and a prototype system is presented to embody and verify the concept, with an experiment showing performance improvement by engineers." [91]
2022	Robotics engineering	Journal	Teaching model, Survey	"The COVID-19 pandemic has greatly impacted Higher Education institutions and in response, many are considering blended or hybrid models to facilitate the transition back to normality, and this study specifically proposes a blended learning model for Robotics courses using Virtual Reality technology and the Digital Twin model to perform laboratory activities without physical presence of students." [92]
2019	Computer Science and engineering	Journal	Teaching curriculum	"The paper provides a framework for education in Industry 4.0 using a case study of Wageningen University, which is aligning with IT and Artificial Intelligence developments to shift content and address skills such as critical thinking, creativity, and problem-solving through project-based learning." [93]
2020	Systems and control engineering	Journal	Simulation and modeling	"Model-based and knowledge-based system engineering brings new demands to master degree teaching process and programs, requiring the establishment of gluing technologies between individual courses while covering full STEM education scope and this paper suggests using simple hardware-in-the-loop (HIL) simulators to help during the whole training period while respecting the needs of already established courses such as modeling and simulation, control design, industrial IT and communication, control HW and electronics, sensors and actuators, the concept is demonstrated with examples from primary and secondary control courses." [94]

Results:

Among 83 publications included in this research, 26 were published in conferences of national and international repute, 53 were published in peer-reviewed journals, 4 were published as thesis, 1 was published as work-in-progress, and 2 were published in archives. Figure 3 shows the frequency of publications with respect to the years. The research encompassed contributions from various countries, Australia, Austria, Bosnia, Herzegovina, Brazil, Canada, China, Czech Republic, Denmark, Egypt, Estonia, Finland, France, Germany, Hong Kong, Hungary, Ireland, Israel, Italy, Japan, Korea, Malaysia, Mexico, Netherland, Nigeria, Norway, Pakistan, Poland, Russia, Singapore, Slovakia, Spain, Sweden, Thailand, UK, and US. Figure 4 represents a geographical breakdown of these research sources.

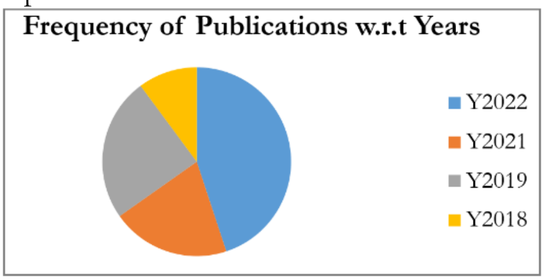

Figure 2: Frequency of Publications w.r.t Years

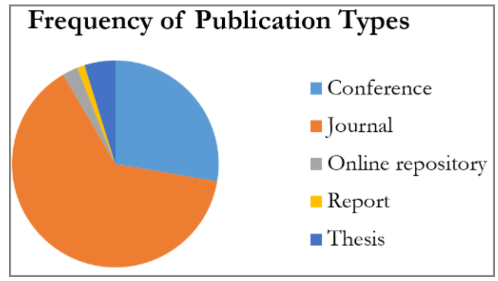

Figure 3: Frequency of Publications types

Most of the publications included in this research were reported from 2022. Specifically, thirty-one publications were reported in 2022, 14 were reported in 2021, 17 were reported in 2019 and 7 were reported in 2018. Figure 2 represents a visual representation of these publication years. The disciplines identified in this research, where engineering education benefits from the digital twin technology are: electrical, cyber-physical systems, mechatronics engineering, construction engineering, control systems, smart campuses, marine sciences and engineering, civil engineering, structural engineering, soil mechanics, hydraulics, environmental engineering, coastal engineering or structural dynamics, education monitoring, teleoperations, robotics, robotic arms, virtual reality, holographs, process engineering, and cyber security etc.

This research aims to explore the applications of digital twin technology in engineering education. This study analyzed the use of digital twins in simulating product development for MSc students, creating a virtual learning environment of a flexible manufacturing system, incorporating digital twins into construction education, to teach about the operation of overhead cranes, remotely controlling a physical campus, conducting virtual industrial labs, controlling physical systems with web-based, and to teach marine technology. Digital twin technology was also used in virtual reality-based education systems, holographic classrooms, remote laboratories, process engineering education, and the advanced training of engineering specialists. In addition, digital twins were employed to create a flexible manufacturing system for assisted learning and to develop a digital twin of a data center at an educational institution. The majority of these publications emerged in 2022, marking a notable trend in digital twin adoption in engineering education, with no recorded publications on this topic before 2018.

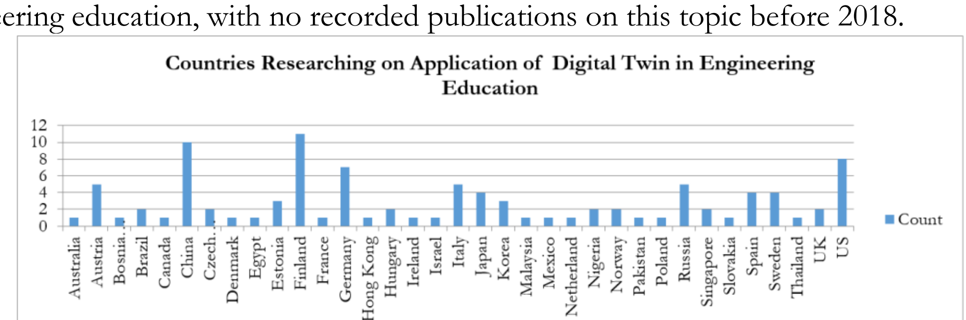

Figure 4: Countries researching on Digital Twins in Engineering Education

Discussion:

Industry 4.0 encompasses the trend in the manufacturing industry towards automation and the exchange of data through the use of technology, such as the Internet of Things (IoT). A central component of Industry 4.0 is the utilization of digital twins, which are virtual representations of physical objects or processes that can be used for simulation and testing. These digital twins function as digital copies of physical models, allowing them to be observed in both the real and virtual worlds simultaneously. They are becoming more common in advanced industries for a variety of purposes, such as representing the elements and dynamics of IoT devices. They can also be used in education to improve the effectiveness and efficiency of labs, classroom environments, and learning experiences. Digital twins can also be used in resource-poor situations to provide access to necessary equipment remotely. Moreover, it can be used for various purposes, including simulation, forecasting, fault detection, and fault recognition. Creating a digital twin can be a complex process that involves collecting operational data from a physical system and using machine learning techniques to create a digital model that accurately represents the system.

These digital twins can be used in a variety of ways, including in the design of small production lines and in the training and education of individuals. Additionally, digital twins can be used to increase cyber-resilience in Critical Cyber Infrastructures (CCI), specifically in the electric power sector, by providing actors with increased situational awareness and enhanced response capacity in the event of a cyber-attack. Digital twins can also be applied to the field of public transportation, allowing for the simulation and optimization of transportation systems. In the area of healthcare, digital twins can be used to create virtual patient models that can be used for training and simulation purposes. A digital twin-based assessment framework can also be used to determine the most effective energy-saving technologies and strategies for existing buildings.

The DT technology is being used to create a more comprehensive and efficient educational process by allowing students to engage with a virtual model of a real product, enabling a thorough investigation of a problem and quantitative analysis of the system's efficiency. The technology is also being used to improve the competitiveness of industrial enterprises by enabling predictive maintenance and fault diagnosis, increasing the reliability of equipment, and reducing downtime. Digital twin technology is being implemented in various engineering disciplines, including control systems design, electrical engineering, and construction management and engineering. It is also being used to create a personalized learning system that can match the diversity of individual abilities and learning styles. The technology is being implemented through a variety of methods, including action research, the KJ technique, and teaching factory methodology. Overall, the use of digital twin technology in engineering education is improving the educational process and helping students to develop real-world skills.

In the educational setting, digital twins can be used as software models of industrial plants that are simulated and visualized similarly to their real-world counterparts and are synchronized with them. They can be used to demonstrate key concepts with a high degree of interactivity and provide a better understanding of the mechanics of the Internet of Things (IoT) for students. Digital twin technology, initially an industrial engineering concept, has become an influential tool in education, fostering a range of notable trends. Integration with STEM education is a key trend, with digital twins providing hands-on learning in fields like engineering and physics, offering interactive simulations of real-world systems. This approach promotes experiential learning, allowing students to experiment without the risks associated with physical prototypes. Virtual laboratories and industry collaborations further expand the scope of digital twin education, with partnerships bridging the gap between theory and real-world applications. Digital twins also enable customization and personalization, letting students tailor their learning paths, which enhances engagement and retention. Cross-disciplinary learning is another advantage, encouraging connections between fields like engineering, data science, AI, and the arts. The technology is instrumental in remote and distance learning, facilitating interactive education from any location, while gamification elements make learning more engaging and enjoyable. Additionally, the integration of augmented reality (AR) and virtual reality (VR) creates immersive experiences, enriching the educational context. Beyond traditional education, digital twins are increasingly used in workforce training, offering a safe environment for skill development. These trends underscore the growing importance of digital twins in education, pointing to a future where this technology plays a central role in transforming learning and skill acquisition.

Digital twins can also be used in production systems to increase visibility, safety, and accessibility, as well as to reduce time and cost through digital experimentation. Implementing digital twins comes with challenges, including ensuring the accuracy of the model, and properly transferring data and codes between the digital and physical versions. Digital twins can also be used in higher education settings, particularly as distance learning becomes more prevalent and access to physical laboratories is limited. The use of digital twins in education can provide benefits such as increased flexibility, accessibility, and cost-effectiveness, as well as improved student engagement and learning outcomes. Digital twins can be used to reduce educational inequality by providing remote access to facilities and enabling learning and training from any location. They can also be used to improve the efficiency and effectiveness of education in a variety of settings, including robotics, virtual reality, and higher education. Digital twins can be integrated into cyber-physical systems and the Internet of Things to provide immersive and interactive educational experiences, which can be used to improve the safety, visibility, and accessibility of production systems.

However, there are challenges to implementing digital twins in education, including ensuring model accuracy and properly transferring data and codes between the digital and physical versions. Digital twins can also be used to conduct industrial-like labs virtually, but this requires multi-domain expertise and careful consideration of the consequences of design decisions on the accuracy of the model. Overall, the use of digital twins in education has the potential to improve student learning outcomes and increase the flexibility, accessibility, and cost-effectiveness of education. The current educational system is not adequately equipped to keep pace with the rapid doubling of knowledge and the need for professionals to have multiple jobs over their lifetime. A new personalized system is needed that is based on both the body of knowledge and the body of experience, and that is sufficiently agile and interactive to evolve in symbiosis with humans. Digital twins can be used to improve education by fostering the development of production-related competencies, enhancing the efficiency of faculty based on learning outcomes and interests, and monitoring and analyzing student outcomes, teacher performance, attendance records, and content delivery. Digital twins also encompasses training in spatial skills and improve the efficiency of laboratory work. However, there are challenges to implementing digital twins in education, including ensuring model accuracy and properly transferring data and codes between the digital and physical versions.

Digital twins can also be employed in the analysis of log data from Learning Management Systems (LMS) to improve online learning patterns for students. In this way, digital twins can be used to represent and analyze the behavior of students and identify any discrepancies between those who pass and those who fail a course. In the context of education, digital twins can create a high-precision model of an educational organization's system of high-level indicators. This model can be refined and made more accurate over time through the collection of digital shadow data. Digital twins connects real and virtual teaching spaces, leading to the transformation of traditional bilingual education into digital bilingual education. In the management of university stadiums, digital twins can provide support for smart stadium planning, construction, and operation management through comprehensive data simulation and operation management. In data mining, digital twins can be used to visualize and analyze data in order to make informed decisions and improve efficiency.

Digital twins facilitate the integration of digital technologies, such as virtual and augmented reality and gamification, into LMS to improve the online learning experience. These technologies can be used to create virtual laboratories that allow students to access practical tasks remotely and safely, reducing costs and increasing efficiency. In the field of education, digital twins can be used to create virtual models of educational systems to better understand, simulate, predict, and optimize real systems. This approach can be further utilized for a variety of purposes, including analyzing student behavior and improving the learning experience, optimizing energy consumption in educational buildings, and enhancing the training of vocational and engineering students in practical tasks. Digital twins can also be used to improve the design and operation of transportation systems and to create virtual patient models for healthcare training and simulation.

The adoption of digital twins in engineering education varies significantly across regions due to differences in technology infrastructure, investment in education, industrial presence, government policies, and academic focus. North America, with the United States and Canada as early adopters, has strong industry collaboration and advanced infrastructure. Europe, particularly Germany, the UK, and the Netherlands enjoys a robust industrial base and government support, fostering high adoption rates. In the Asia-Pacific region, rapid growth and innovation drive the widespread use of digital twins, with substantial government backing and industry partnerships. The Middle East shows emerging adoption, driven by high-tech investments and global partnerships, while Latin America sees a slower uptake due to infrastructure and investment challenges, with some localized efforts. Africa, in the early stages of adoption, faces barriers from limited resources but exhibits growing interest through international partnerships. Overall, while North America and Europe lead in digital twin adoption, the Asia-Pacific region is catching up quickly, and other regions are gradually integrating digital twins into their engineering education frameworks.

Future Improvements Required and Identified from the Literature:

In order to successfully create and implement Digital Twins (DTs) that meet the demands of the future, there are several key areas that require attention. One of the most important considerations is the use of modular approaches, which allow the creation of DTs that are flexible and can adapt to a wide range of evaluation criteria in a time-efficient manner. Additionally, ensuring modeling consistency is crucial, as it enables the reuse of knowledge and improves the interoperability of production systems, leading to enhanced DT functionality and more coherent decision-making outcomes. Improving DT simulation is also vital, and this can be achieved by utilizing real-time simulation techniques to enable operators to identify and resolve issues in shop-floor systems. Another cost-effective solution to improve visualization and strategy development in collaborative systems is by incorporating virtual reality integration. Furthermore, efficient mapping between physical and virtual data can be achieved by updating traditional data acquisition and processing approaches, which enables the implementation of communication interfaces, leading to increased user confidence and system reliability. Seamless integration with manufacturing systems and the incorporation of cloud/edge computing and big data analytics can further optimize DT functionality and forecast effectiveness [95].

Limitations:

The paper is specifically written for digital twins that were used in the context of engineering education. Therefore, the literature review was conducted with a strict criterion that selected papers must specifically mention digital twins. Furthermore, the review excludes papers related to simulation and modeling, as there are distinct differences between these areas and digital twin technology.

Conclusion:

Digital twin technology is being used to improve engineering education by allowing students to interact with virtual models of real-world systems. This enables a more comprehensive and efficient educational process, as well as improving the competitiveness of industrial enterprises through predictive maintenance and fault diagnosis. Digital twins can be used in a variety of engineering disciplines, including control systems design, electrical engineering, and construction management, and can be implemented through action research, the KJ technique, and teaching factory methodology. Digital twins can also be used to create a personalized learning system that is tailored to individual abilities and learning styles. Digital twins can be used in higher education settings to provide remote access and facilities to improve student engagement and learning outcomes. However, there are challenges to implementing digital twins, including ensuring model accuracy and properly transferring data and codes between the digital and physical versions. Digital twins can be used in industrial-like labs virtually, but this requires multi-domain expertise and careful consideration of the consequences of design decisions on the accuracy of the model. Overall, the use of digital twins in education has the potential to improve student learning outcomes, increase the flexibility, accessibility, and cost-effectiveness of education, and improve the safety, visibility, and accessibility of production systems.

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