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The role of Digital Twin technology in transforming engineering education

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Abstract: *Higher education institutions (HEIs) have acknowledged the significance of digital transformation in the educational environment, especially during the COVID-19 pandemic. The adoption of new technologies has enabled HEIs to change their education, research, and business models. The goal of digital transformation in HEIs is to create new, advanced, and efficient techniques and practices to further the mission of higher education. Digital Twin (DT), one of the most promising new technologies at the moment, has the ability to give engineering students learning opportunities that go beyond the confines of the classroom. This paper, with a focus on engineering education, aims to understand the underlying concept of DT technology and to emphasize the benefits that may be gained through its use in engineering education as well as the challenges associated with its adoption in HEIs.*

Keywords: *Digital Twin; engineering; education; benefits; challenges*

1. INTRODUCTION

The COVID-19 pandemic has brought attention to the importance of integrating digital technologies into education and speeding up the adoption of digital transformation in education. The process of digital transformation ultimately involves a change in the paradigm of education, altering how people think, behave, and interact with one another and the outside world [1]. In other words, significant elements of Higher education institutions (HEIs) management, engagement, education, and research operations are transforming as a result of the digital transformation. The entire educational system must adapt and change in order to benefit from new technologies and tools, as well as to create plans of action and play a proactive part in the digital transformation process [2]. Higher education is predicted to undergo reforms thanks to digital learning technologies. According to the European Commission's (EC) most recent Digital Education Action Plan (2021–2027) [3], digital education should enable more individualized, adaptable, and student-centered teaching.

Educational institutions worldwide are increasingly implementing digital transformation to make sure that the student's learning is supported by digital tools. Students, teachers, and companies can all obtain new knowledge thanks to the use of new digital technologies. One of the fundamental pillars of the digital transformation process is the Digital Twin (DT) technology. It enables the creation of a digital counterpart of a physical entity, whose behavior can be observed in real-time, resulting in enhanced productivity and efficiency [4]. Increased sensor ubiquity, product connectivity, processing power, and data storage all contribute to the viability of this idea. As a result, numerous analyses on the DT are possible, which can shed light on the real one and prompt corrective action. In this way, DT is a brand-new educational tool since it allows students to study a digital version of something rather than the actual object.

Every academic discipline, including engineering, has the ability to use DT to vastly improve the learning experience. When used properly, DT technology can improve learning and boost students' motivation to study and take responsibility for their education. This may have a significant effect on students' career opportunities [5].

This paper presents an attempt to summarize the role of DT technology in engineering education and to highlight all the advancements and challenges related to its implementation in HEIs. Therefore, the rest of this paper is organized as follows. After the introduction, the second section gives a summary of the current state of engineering education and predictions for the future. The third section presents the concept of DT technology. The use of DT technology in engineering education and related benefits and challenges are presented in the fourth section. The last section concludes the paper.

2. ENGINEERING EDUCATION FOR TODAY AND TOMORROW

The exponential growth of knowledge and innovation in science, engineering, and technology during the Fourth Industrial Revolution (Industry 4.0) era highlights the necessity of revolutionizing the educational system. The needs of today's digital, varied, global, constantly changing, and quickly evolving society must be addressed in engineering education. Engineering as a discipline will be significantly impacted by the numerous issues that the digital era will present. According to [6], most of the engineering education challenges are related to sustainability (a crucial topic in engineering education), industry demands, and digitalization. Engineering profiles will change as a result of the environment in which engineering tasks are carried out and the equipment and tools employed to do these tasks. In other words, the expected role of engineers will change as automation and digitalization spread, and the engineering profile will transform to meet the demands of the skills and competencies needed for new-generation engineering positions [7]. In addition to applying science to solve problems, engineering involves improving knowledge through study and experimentation. Along with learning how to acquire and apply their theoretical knowledge to real-world issues, engineering students must also learn to be independent, autonomous, and critical thinkers. Systems thinking, interdisciplinary thinking, creative thinking, cross-cultural communication and collaboration, and a global mindset are skills that engineers of the 21st Century must possess [8]. The success of engineering students depends not just on what they know but also on how they use advanced engineering technologies. Demonstrating technical competence is a requirement and possibly the most crucial component for all engineering students. Engineers with employability skills and quick learning and adapting abilities are needed by the industry [6]. All of these urges for the modernization of educational systems through the use of advanced technologies, the adoption of innovative teaching and learning methods in engineering education, as well as the updating of course materials in light of the digital transformation [7].

There is no doubt that engineering education will be rethought and redesigned as a result of the digital transformation trends (Fig 1.). The learning and teaching processes need to be designed and delivered in a more digitized manner. Understanding the three components of engineering learning will make it easier to decide how to support and assess a student's academic development (Fig. 2) [9]. To improve education, it is necessary to constantly revise and update course curricula, and create sophisticated, adaptive learning systems that connect students' evolving learning demands with cutting-edge practices, tools, and technologies [1, 7].

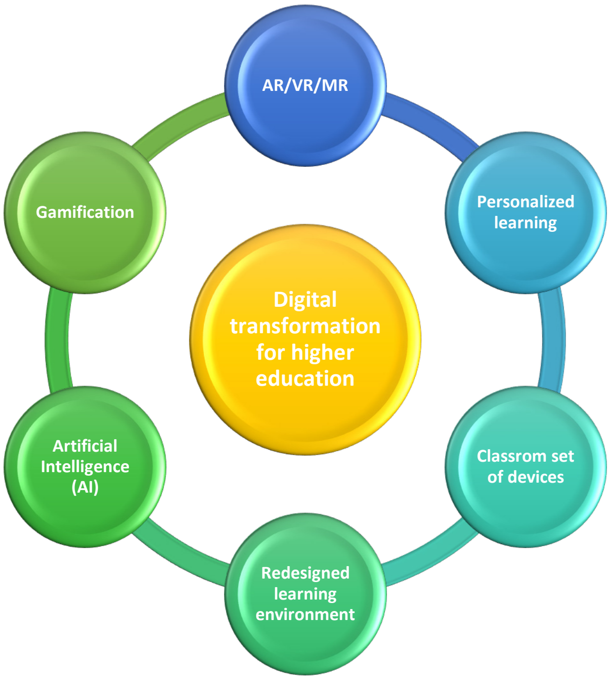
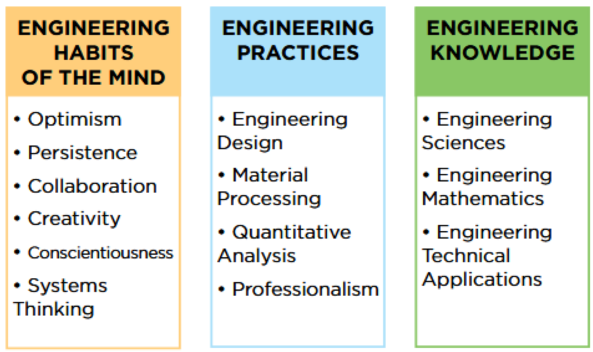


Figure 1. *Top six digital transformation trends in higher education*



In order to address the numerous issues related to engineering education, student-centered learning, contextual and practice experiences, and digital tools must be implemented [6]. This will result in increased efficiency and efficacy of engineering education, hence bridging the gap between academic engineering skills and the digital competencies needed in the industry [7].

Future engineers must be well-prepared with a wide variety of skills and competencies to be able to deal with the myriad problems that the digital era will bring. They should be self-motivated, responsible, and capable of contributing to the development of innovative approaches to the engineering and societal problems of the 21st Century [8]. The current engineering education system must be improved, and this is feasible only through the creation of new teaching and learning strategies.

3. DIGITAL TWIN (DT) TECHNOLOGY

A virtual, real-time depiction of a physical product or process is essentially what the term "digital twin" refers to. With advancements in machine learning, virtual reality (VR), augmented reality (AR), mixed reality (MR), Geographic Information System (GIS), and other technologies, DT technology is now able to duplicate and monitor real-world processes and objects, as well as more precisely forecast the results of certain scenarios [10-12]. DT incorporates both the physical structure and the dynamics of the system and is used by engineers to evaluate the behavior of already-built devices or complex systems under particular circumstances. In order to gain helpful data that can be applied to the actual physical equipment, the virtual model can be used to perform simulations, look into performance issues, and come up with potential improvements. DT is already in use across a range of application domains (i.e., manufacturing, construction, healthcare, meteorology, agriculture, education, transportation, aerospace, energy sector, etc.) [13], where it is becoming an increasingly important and informative tool.

The physical entity, virtual model, and their relationship are the three essential parts of the DT architecture [11]. DT is divided into three subcategories [14, 15]:

- Digital Model - digital representations of already-existing or future real items, without automatic exchange of data.
- Digital Shadow - one-way automated data flow that connects physical and digital objects that already exist is presented.
- Digital Twin - data is exchanged between completely integrated physical and digital items.

Data need to flow seamlessly and in both directions between a system's physical and digital realms, and a DT can automatically share data with its physical twin or can be modified by it. As a result, the DT can be thought of as the real system's controller. The physical entity must be mimicked by a DT, which must also be flexible and parameterizable [16]. DT and simulations are similar, although they differ greatly. Both use digital models to simulate a system's multiple operations, but DT is essentially a virtual world that can run as many practical simulations as necessary to analyze different processes, whereas a simulation frequently only focuses on one particular activity. Another distinction is that real-time data is frequently not helpful for simulations, while DT relies on a two-way information flow [17]. Compared to traditional simulations, DT enables the study of more topics from a greater variety of perspectives.

Fig. 3 demonstrates how to create a DT utilizing a number of supporting technologies. In other words, DT enables visualization of the situation based on data collected from a variety of sensors and devices, evaluation of the collected data using intelligent software, and, if a problem exists, searching for multiple potential solutions as well as choosing smart algorithms and implementing the most appropriate solution.

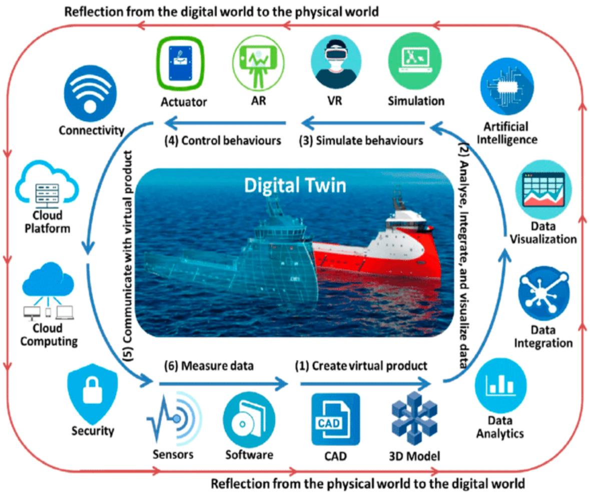


Figure 3. *The DT's enabling technologies [18]*

Implementing a DT is a labor-intensive process that requires a variety of tools and technology to function together. The following categories can be used to group the technologies that enable the creation of DT: [11, 12]:

- Technologies for physical objects,
- Technologies for data construction and management,
- Technologies for virtual modeling,
- Services technologies,
- Connection and data transmission technologies, and
- Environment coupling technologies.

DT should precisely mirror 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 [19].

4. DT TECHNOLOGY IN ENGINEERING EDUCATION

Nowadays, the usage of DT technology in education is starting. The goal of DT adoption in engineering education is to advance engineering knowledge. Currently, there are a lot of ongoing projects that are intended to provide engineering learning platforms based on the DT of any system, product, or process of interest for a particular course. DT technology can be applied in the classroom to present, explore, and explain a system's structure and intended function. In the laboratory, a DT can be utilized to investigate the system's behavior and constraints under various simulated what-if scenarios, comprehend failure mechanisms, and grasp how sensitive a system is to changes in various system parameters and outside disruptions. Because system behavior may be changed more easily in a virtual representation than in its real counterpart, students learn and understand it more quickly in a controlled, safer, and simulation-driven environment. Since they must imagine a significant portion of the envisioned system when creating simulations, students acquire valuable systems thinking skills and a learning experience [20].

Some of the examples of DT technology's inclusion in engineering education are present in [5, 16, 20-25]. In [5], the authors have chosen a Simulation in a control system design course for utilizing and studying DT technology, while [21] presents the Electric Power Drive System Diagnostics as an example of DT technology's implementation in the electrical engineers' educational process. Authors of [22] have studied the potential for DT adoption in marine technology study where they presented DT adoption within courses in mechanical engineering, hydrodynamics, and other relevant fields. Building useful DT civil engineering courses was the goal of research performed in [24]. In [25] it is stated that it is possible to generate a digital copy of a student (Fig. 4) utilizing information about their behavior, academic background, habits, and used digital learning resources. A student's DT includes this kind of information, which can be automatically gathered by a variety of technologies or manually added by the student.

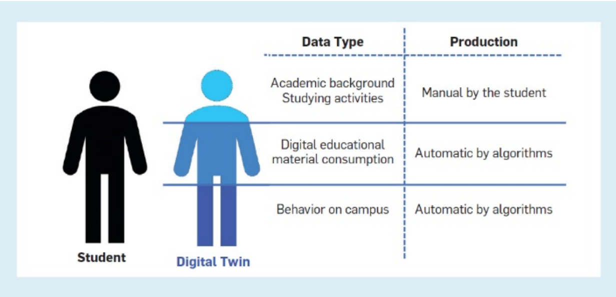


Figure 4. *The student's DT [25]*

4.1. Benefits of DT implementation in engineering education

By making it easier for engineering students to access current research topics, the main goal of DT technology adoption in education is to improve their learning results. The gap between theory and practice will thus be smaller.

The main benefits of DT technology, which can be also related to DT implementation in engineering education, can be summarized in [13, 19]:

- Reducing costs and waste: The physical equipment is costly, and many HEIs lack the resources to purchase it. DT technology enables the creation of virtual laboratories that can be used within different engineering courses. Because DTs are mostly developed using virtual resources, the prototyping is cheaper, material waste is reduced, the variety and quantity of devices can be easily changed, and testing in a variety of test settings, including destructive ones can be easily performed and without any additional costs. All of these help to create a future that is more sustainable.
- Shorter production times and more efficient product re-designing: DT can be used at various points throughout the product design process, shortening design and analysis cycles and enhancing the speed and effectiveness of prototyping and product re-design. Students benefit from this in terms of gaining learning experience and developing important systems thinking skills.
- System planning and problem prediction: DT can be used to identify problems and failures at different stages of a product's lifecycle, especially of a product that has a complex structure or is made of various materials. It is far simpler, less expensive, and faster for the students to diagnose potential equipment problems or misbehavior, as well as to fix the faults.
- Optimizing solutions and better maintenance: DT can enable the prediction of damage and defects at various stages of the product's lifecycle, which enables considerably earlier detection of system faults. This contributes to more precise predictive maintenance planning and continuous validation and enhancement of the system's process.
- More specialized products and services: To quickly respond to market trends and stakeholder preferences, more individualized products, and services can be quickly developed with the use of DT.
- Accessibility: It's often difficult, if not impossible, to get a detailed, real-time perspective of a large physical system. Making virtual copies improves system accessibility, allows for remote performance monitoring and modification, and allows for the quick detection and resolution of any problems. DT technology makes it possible for students to enroll in online courses and training programs, access learning resources, design different scenarios for the usage of real devices, perform simulations for accomplishing pre-determined laboratory tasks and study from any location. In situations like the COVID 19 pandemic, this is of immense importance.
- Safer than physical counterpart: DT can be used to create more effective, illustrative, and safe courses than traditional ones. Because DT can access its physical counterpart remotely and is predictive in nature, it can help to reduce the risk of

failures. Also, DT enables the introduction of the failures and dangerous malfunctions that can be found in real life, making it safe for students that work with the virtual replicas of systems. Students can practice how to schedule necessary maintenance in advance based on identified or projected failures. Hence, one of the major benefits of DT is that there is no risk of real device destruction as a result of improper or careless handling, which is a very real possibility during laboratory exercises.

- Personalized learning, increased motivation, and better learning experience: The main advantages of DT technology are the growth of expertise, interactive, customized, and easier learning, as well as increased interest in studying. The growth of DT technology-related skills is the obvious advantage. Both professors and students learn new things, and the enhanced enthusiasm for learning and DT technology-related abilities that students acquire have the potential to assist students to find work and succeed in their potential vocations [5].
- Teamwork: Teamwork is an important source of creativity, innovation, and change. DT ensures that all parties involved in the learning process are included and working together even if they are not physically present in the physical system. Hence, DT has the potential to support students' learning, interaction, and collaboration with others. Joint decisions foster greater commitment and a shared understanding of what must be accomplished [4, 26].

4.2. Challenges related to DT adoption in engineering education

In addition to the many advantages DT brings to engineering education, there are many challenges related to DT adoption in the educational sector [19, 27, 28]:

- Information technology (IT) infrastructure: Potential IT issues could be a barrier to DT technology adoption in education. Due to the complexity of DT tools and software, it is crucial to have resources and a well-designed and scalable IT infrastructure. It is important to have fast, reliable, and available connectivity, maintain software updated and be ready for any problems that might arise [5].
- Useful data: The accuracy of the virtual representation of the physical object increases with the amount of data available. Hence, the adoption of DT requires the collection and management of a large amount of heterogeneous data (i.e., product data, system data, environmental data, network-, hardware-, and software-related data, historical data, real-world data, virtual-world data, etc.). Finding the patterns and extracting useful information from these data is crucial for performing the tasks of interest (i.e., system planning, solution optimization, system process enhancement, correcting faults, etc.).
- Privacy and security: Any HEIs can gain a lot from DT technology, but only if privacy and security are adequately addressed. In other words, systems, assets, and data must be effectively protected for DT technology adoption in education to be beneficial.
- Trust: The adoption of DT in education will depend on building trust. The main concern is whether the data from a DT can be relied upon. HEIs can only use a DT to its full potential if they are confident that it will perform as expected.
- Expectations: Despite the fact that the usage of DT in education is expanding, more understanding of the concept and prudence on the expectations related to DT implementation are still needed. If an HEI has a well-designed and scalable IT infrastructure and a better understanding of the data necessary to execute analytics, it is expected that it will adopt DT technology. Today's higher education students are accustomed to using digital technology in their daily lives and will increasingly demand educational approaches that make the most of the opportunities provided by digital learning tools [29].
- Standardization and regulations: Since modeling is essential for the practical application of DT, it is necessary to follow a consistent process from the initial design stage to the simulation of the DT. Standardization of modeling, interfaces, protocols, and data is essential.
- Teaching skills and teaching content: Teachers may not always have fast answers to all of the issues as a result of working with new technology and using it in this manner [5]. Therefore, insufficient teacher skills are one of the main obstacles to incorporating DT technology into engineering education. As technology is advancing quickly, continuing education and course curriculum updates are required.

5. CONCLUSION

We have witnessed significant technical advancements during the past 20 years, including new and disruptive developments in hardware and software. These modifications are resulting in the phenomenon known as digital transformation. HEIs all around the world have recently gone through rapid, significant changes that are a result of digital transformation. New educational strategies and tools must be introduced and put into practice in order to adequately educate students for today and the future. Therefore, HEIs have led various programs to investigate novel digital technologies to improve students' learning experiences. The digitalization of education is just one of the many factors that have an impact on education globally. During the COVID-19 pandemic, the pace of reform in the educational system has had to accelerate.

In this new digital era, engineering graduates must be able to move from technology to solutions and from those solutions to operations. Future electrical engineers will have to deal with a rise in IT-related issues that involve fault diagnostics and predictive maintenance. Wide-ranging skills are needed for this.

Knowing that learning is a laborious process, and that physical equipment is expensive, DT adoption in education gives a lot of flexibility and opportunities to improve field competencies. The aim of this paper is to highlight all the benefits and challenges associated with DT technology's implementation in HEIs. As has already been mentioned, DT has numerous advantages such as simple experiment or training preparation (hardware installation or testing is not necessary), real-time monitoring, control, and data collection support for informed decision-making, predictive maintenance and efficient scheduling, enhanced efficiency, improved risk analysis, safer work, contribution to the fulfillment of sustainability goals, increased accessibility, personalized learning and the ability to adapt and extend based on the course objective, etc. On the other hand, implementing a DT takes time, necessitates a certain level of expertise, and requires a variety of tools and technologies that must work together. Another drawback is the high price of software licenses but in general, the overall costs are reduced. DT should be created with some caution, but due to its many benefits, it becomes an essential tool in today's technological and academic environment.

The development of DT technology is anticipated to have a significant impact on engineering education. This is the reason why engineering education has embraced DT technology. With the use of DT technology, engineering classrooms will enable students "learn by doing" approaches. The students will be able to resolve the complex diagnostics problems thanks to these and play a crucial role in converting academic knowledge into real-world applications, keeping up with the rapidly and continually changing environment.

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