Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #46946

Using digital twin to introduce sustainable manufacturing in engineering education

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Abstract

Sustainability is a concept that denotes the ability to be maintained or endured over a long period. In general, this word has been broadly used in reference to practices that are reputed to be environmentally friendly. However, it's a holistic approach that balances environment, social and economic factors. Nonetheless, Industry 4.0 is advancing exponentially and restructuring the ways of individualistic life and work and optimistically it offers opportunities for sustainability. One of the Industry 4.0 technologies is the digital twin, which is a virtual representation of physical system or process, that uses real time data to enable understanding of monitoring and optimization.

This study aims to show how state of art digital twin technology can be used to introduce sustainable manufacturing in an advanced manufacturing curriculum. For this, a digitalized physical manufacturing system connected by cyber-physical interface (CAD/CAM) is utilized. Integrating these technologies, a manufacturing system is developed that will be a combination of human and machine-controlled decisions in making a sustainable product. The system will predict energy consumption and the wastages in manufacturing of the product. Thus, this characterization will also render an optimal solution for sustainable manufacturing.

The outcome of this study is a teaching module that uses a digital twin model, which optimizes the process parameters for sustainable manufacturing. Also, a case study based on feminist pedagogy uses hands-on activities to offer inclusive and equitable learning of the digital twin system for resource efficient manufacturing, digitally and in the real-world. The module will be implemented during instruction in smart manufacturing and on internet of things courses. This module will be assessed using a pre-and-post survey of students understanding sustainable production processes, and their perceptions of how a digital twin can be used to optimize a production operation for sustainability. Moreover, the end term course evaluation also shows improvements in course ranking.

Introduction

After years of devastating wars, environmental degradation, and pollution, member states of the United Nations (UN) reached a historic agreement in 2015 to create a safe and sustainable environment for humanity and other life forms. This agreement resulted in the introduction of seventeen Sustainable Development Goals (SDGs), with targets set to be achieved by 2030 [1]. Among these, sustainable manufacturing stands as one of the key objectives aimed at fostering a cleaner and more suitable environment. According to the United States Environmental Protection Agency (EPA), sustainable manufacturing is defined as "the creation of manufactured products through economically sound processes that minimize negative environmental impacts while conserving energy and natural resources" [2]. This concept is crucial not only for industry transformation but also for engineering education, making it imperative to integrate the knowledge and skills of sustainable manufacturing into academic curricula in alignment with industry needs.

The advent of Industry 4.0 and Education 4.0 has significantly reshaped engineering education by integrating advanced technologies and modern pedagogical methods [3]. These technological revolutions have broadened the scope for revamping engineering curricula, tools, techniques, and teaching aids, offering opportunities for more effective and interactive learning environments. While high-tech tools have empowered educators to teach sophisticated systems, there remains a pressing need to simplify the teaching methods to ensure sustainable manufacturing principles are effectively and affordably communicated to students.

One of the transformative technologies within Industry 4.0 is the digital twin. A digital twin is an innovative approach wherein a physical system is replicated in a virtual environment to simulate, analyze, and optimize its behavior based on real-time data and various parameters [4]. This technology holds considerable potential for enhancing the teaching of sustainable manufacturing concepts in engineering education. In this context, the literature on digital twin technology in engineering education can be categorized into three distinct areas: (1) the role of Industry 4.0 in engineering education, (2) the use of digital twin technology as a pedagogical tool in engineering education, and (3) the application of digital twins for teaching sustainable manufacturing concepts in engineering.

The role of Industry 4.0 in engineering education

The digital transformation in advanced manufacturing is represented in the revised SME Four Pillars of Manufacturing Knowledge with the Industry 4.0 and Automated Systems and Control knowledge block as explained by Irwin et al. [5]. This area included the most revised topics along with the Process Design area that experienced major revisions with topics such as Digital Twin and Computer Aided Process Planning. Coskun et al. [6] proposed a comprehensive three-pillar roadmap for integrating Industry 4.0 technologies into engineering university curricula. This roadmap focuses on curriculum development, laboratory support, and the establishment of student clubs to foster hands-on experience with cutting-edge technologies. Similarly, Onar et al. [7] conducted an evaluation of 124 engineering programs across various institutions and found that these programs are increasingly offering interdisciplinary courses that combine production technologies with ICT (Information and Communication Technologies) in their curricula. However, both studies highlight the ongoing need to benchmark existing courses and programs against the evolving demands of Industry 4.0 to ensure they remain relevant and comprehensive. Bordel et al. [8] presented a comparative analysis of the adoption of Industry 4.0 tools and methods in teaching microcontroller-based courses for telecommunication and biomedical engineering programs. Their study demonstrated that incorporating Industry 4.0 technologies into these subjects not only enhanced student motivation but also led to improved academic outcomes. Kumar and Ekren [9] emphasized the importance of skills development for the effective implementation of Industry 4.0 technologies in engineering education. Their research identified key attributes that need to be integrated into engineering curricula, such as critical thinking, problem-solving, and holistic thinking, to better equip students for the challenges of the modern industrial landscape. Bautista et al. [10] reviewed the importance of implementing a Virtual Learning Environment (VLE) to facilitate the teaching and learning of Industry 4.0 technologies, underscoring its potential for enhancing the effectiveness of engineering education. They also demonstrated how VLEs can be embedded into engineering curricula to promote engagement and interactivity. In a similar vein, Lin et al. [11] proposed an integrated engineering education framework designed to foster the acquisition of Industry 4.0 knowledge and skills, aiming to better prepare students for the demands of the evolving technological landscape. Additionally, Elizondo and Reyes[12] introduced a five-pillar framework for the development of human resources in industrial and systems engineering, emphasizing the need to equip students with the knowledge and skills essential for thriving in an Industry 4.0-driven environment.

Use of digital twin technology as a pedagogical tool in engineering education

Liljaniemi and Paavilainen [4] developed a digital twin (DT)-based system designed to teach the operation of Programmable Logic Controllers (PLCs). This research highlighted both the effectiveness and the challenges of incorporating digital twin technology into engineering education. A key concern raised in the study was the cost of CAD/CAM software, which posed a significant barrier to broader implementation of digital twins in educational settings. Maksimović and Nikola Davidović [13] explored the benefits and challenges associated with using DT technology for teaching engineering courses. They emphasized that digital twins facilitate both individual and group learning, but noted the significant challenge of developing high-tech teaching tools and successfully implementing them within academic environments. Furthermore, several researchers have proposed DT-based solutions to enhance the teaching of industrial plants, high-tech equipment, and laboratory environments to engineering students. Zacher[14], Arras[15] and Guc [16] all presented methodologies for employing digital twins to simulate complex industrial systems, thereby improving student understanding of these advanced technologies in a practical, hands-on manner. These proposals suggest that digital twin technology can play a pivotal role in bridging the gap between theoretical knowledge and real-world application in engineering education. In the context of sustainable supply chains, Kamble et al. [17] provided a comprehensive review of current trends in the use of digital twins. The research primarily outlined methodologies for implementing digital twins in sustainable supply chain management but lacked detailed specifications regarding the parameters and systems required for effective implementation. Similarly, David et al. [18] and Eriksson et al. [9] proposed methodologies for developing digital twins for flexible manufacturing systems (FMS), which are designed to adapt dynamically based on changing needs and variables. While their work provided a framework for FMS adjustment, it was noted that the systems presented were largely commercialized, limiting the scope for customization in educational contexts.

Application of digital twins for teaching sustainable manufacturing concepts in engineering

Ball and Badakhshan [19] conducted a systematic review on the application of digital twin technology in the context of sustainable manufacturing. Their review, based on 55 research projects, explored the utilization of digital models and digital shadows for sustainable manufacturing. However, it is evident from the findings that most studies on DT and sustainability focus on proof-of-concept applications within industrial settings, with limited implementation in academic environments. To address this gap, the current research proposes a digital twin model for sustainable manufacturing within an academic laboratory setting. This model connects the input process parameters and variables involved in sustainable manufacturing via a graphical user interface (GUI), providing an interactive tool for learning and decision-making. The proposed digital twin system is designed to enable learners to engage with real-time data, helping them make informed decisions regarding machining parameters to optimize tool life and minimize power consumption. The research also establishes a correlation between tool wear, chatter, and vibration during machining processes, demonstrating that increased power consumption is linked to accelerated tool wear, which in turn is exacerbated by higher levels of chatter and vibration.

This paper is structured into five sections. The first section introduces the fundamentals of the research, provides a literature review, and outlines the problem statement. The second section delves into the development of the digital twin for the CNC milling machine. The third section details the arrangements for measuring variables using sensors and equipment. The fourth section discusses the design of the graphical user interface (GUI), illustrating the relationship between the process parameters and the corresponding variables. The fifth section outlines the teaching pedagogy employed in this study, followed by a discussion and concluding section that presents the implication barriers, digital twin learning versus traditional learning and conclusions of the research.

Digital Twin

A digital twin is a representation of twin components—physical and digital systems—interconnected through cyber-physical integration. Any change in parameters within the digital system is mirrored in the physical system, and vice versa. Figure 1 illustrates the digital twin utilized in this study. A conventional CNC milling machine (Denford TRIAC PC) has been replicated as a 3D model through CAD software. This model is then integrated with a graphical user interface (GUI) to visualize the impact of process parameters on real-time machining variables.

Figure 1: Digital Twin of CNC Milling Machine (Denford TRIAC PC)

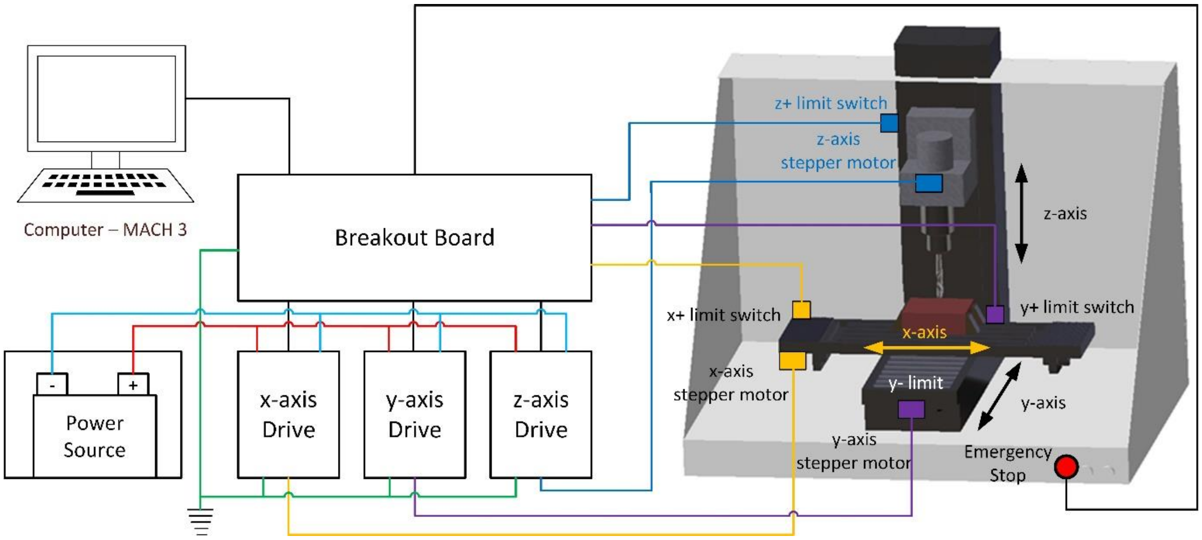

Figure 2: Retrofitting of CNC milling machine

The Denford TRIAC PC CNC milling machine has been retrofitted with open-source stepper motor drives, which regulate the movement of the stepper motors along the machine's three axes. These drives are controlled through a breakout board, which acts as an intermediary between user inputs via a PC and the execution of commands through open-source software, MACH3. Additionally, the breakout board receives signals from the limit switches of the three axes, thereby managing the operation of the stepper motors by determining when to initiate or halt their movement. Figure 2 presents the schematic diagram of the retrofitted milling machine. MACH3 is an open-source software that collects data related to the positioning of the axes, speed, feed rate, and spindle speed by utilizing position encoders, sensors, and MOSFETs (signal amplifiers). Communication between the machine's hardware and the software is facilitated by the Modbus protocol, which supports data transmission via serial ports, Ethernet, or Wi-Fi. In this project, both Ethernet and Wi-Fi communication protocols have been implemented to enable integration with the digital twin system. A Visual Basic (VB) script was developed to establish a communication link between the CAD model in CATIA and MACH3 software, enabling seamless data exchange from MACH3 to CATIA within the 3D Experience Workbench environment. The digital model of the CNC milling machine functions as the digital twin, and the data is continually updated on a graphical user interface (GUI) for the visualization of the machining process. Key parameters, including axis positions, speed, feed rate, and spindle speed, are controlled through the digital twin interface.

In practice, suboptimal selection of these parameters can lead to inefficient power consumption (measured in amperes) and increased machine vibrations, which ultimately result in higher energy usage and frequent tool failures. The subsequent section discusses how these variables are measured and controlled through the adjustment of process parameters, with a focus on optimizing machine performance and energy efficiency.

Energy and Vibration Measurement

The primary objective of this research is to demonstrate the control of machining parameters to reduce power consumption and minimize chatter during machining, thereby enhancing the sustainability of the process in terms of resource efficiency and tool wear costs. Reducing power consumption contributes to lowering carbon footprints, while minimizing chatter extends tool life, both of which improve the overall efficiency and sustainability of the manufacturing process.

To measure the energy consumed, the AMEC Power and Energy Logger (Model PEL 103, Cat. 2137.52) was employed. This device features three clamps that are attached to the machine's main power supply to measure power consumption in watts. The PEL 103 provides real-time data, which is accessed through its plugin in the DataView™ software. Vibration and chatter during machining were monitored using the enDAQ vibration recorder (Model S4-D40), a durable sensor connected to the computer via Wi-Fi and Ethernet. The enDAQ recorder provides the vibration profile in hertz (Hz), with a sampling rate of 40,000 Hz and a bandwidth range of 0 to 300 Hz.

The output data from both the PEL 103 and S4-D40 sensors is collected and integrated into a graphical user interface (GUI) developed in Python, utilizing the enDAQ library for Python. This GUI presents real-time values of power consumption (in watts) and vibrations (in hertz), providing users with immediate feedback on the machining process. This integrated approach enables the continuous monitoring and optimization of machining parameters, contributing to improved process sustainability.

User Interface of Digital Twin

The same interface also receives input from CATIA and displays the values of axis positions, speed, feed rate, and spindle speed. The interface is designed to present both parameters and variables, with fluctuating variables displayed alongside their allowable thresholds. This enables users to monitor energy consumption and vibration levels effectively. The schematic of the interface is shown in Figure 3.

The charts displayed in the GUI allow the user to monitor axis acceleration and motor current consumption, clearly illustrating chatter and excess energy usage by the CNC milling machine. Spindle speed and feed rate can be adjusted using the "Controls" section of the GUI, located alongside the machining parameters. Increasing or decreasing the spindle speed and feed rate may help reduce chatter and motor current (amperage). The "Optimize" button adjusts the spindle speed and feed rate to their optimal values, determined through an offline design of experiments. Optimizing these parameters enhances the sustainability of the machining process by reducing energy consumption and extending tool life through minimized chatter and vibration during the milling process.

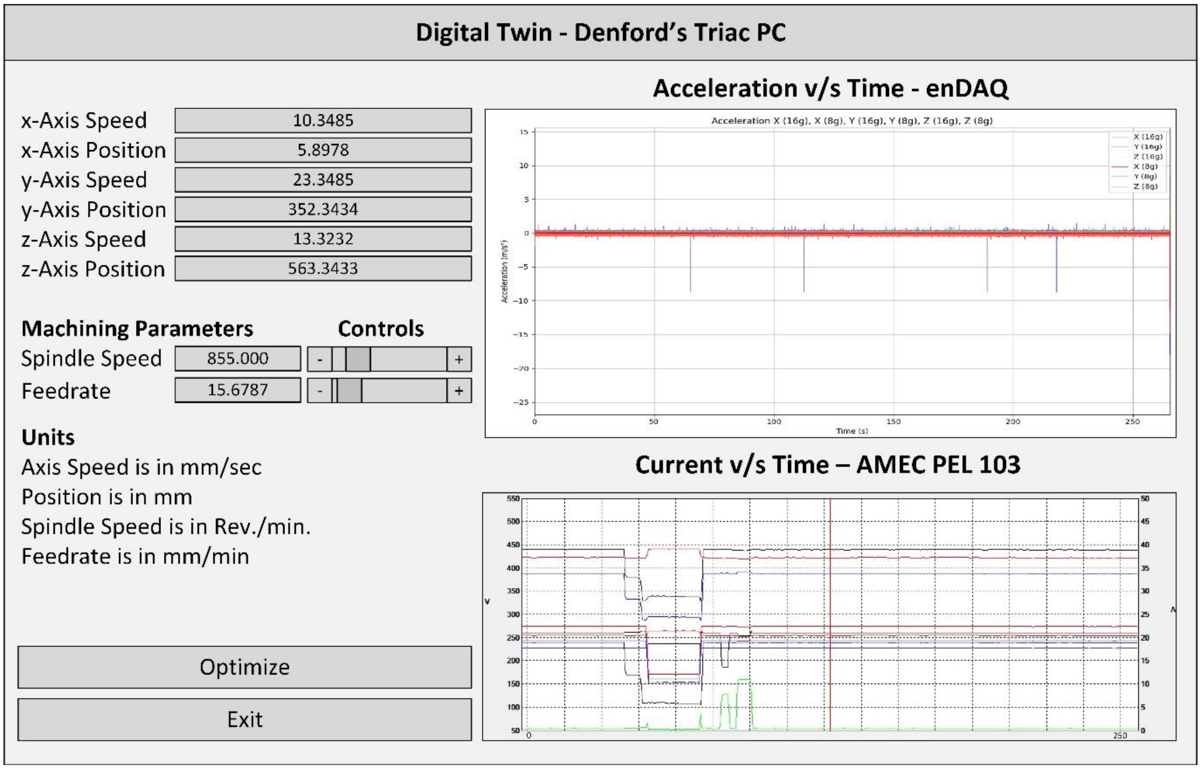

Figure 3: Graphic-user-interface (GUI) for the Digital Twin

Case Study: Teaching Pedagogy in Digital Twin System Application

In this case study, a module was developed to illustrate the functioning of a digital twin system and was applied to two key courses: Smart Manufacturing and the Internet of Things (IoT). Both courses are offered to students in their senior years. To assess the impact of this teaching module and the effectiveness of the pedagogy applied, a questionnaire-based survey (Appendix A) was conducted, focusing on the implementation of feminist pedagogy principles in the classroom. Feminist pedagogy, as discussed by various scholars, promotes values such as knowledge co-creation, empowerment, and reflection, which were identified as the primary tenets guiding of this study [20] . Feminist pedagogy has significant implications for engineering education, as it challenges the traditional, hierarchical methods of teaching and promotes a more inclusive, participatory, and student-centered approach. Feminist pedagogy, advocates for a learning environment where knowledge is co-constructed through interaction among all participants—students and instructors alike. This shift toward co-creation of knowledge is particularly valuable in engineering fields, where innovation thrives in environments that foster creativity, critical reflection, and collaboration.

Figure 4 presents survey results. For each question, the responses are broken down into three options (Option a, Option b, and Option c) with corresponding to how many participants selected each option.

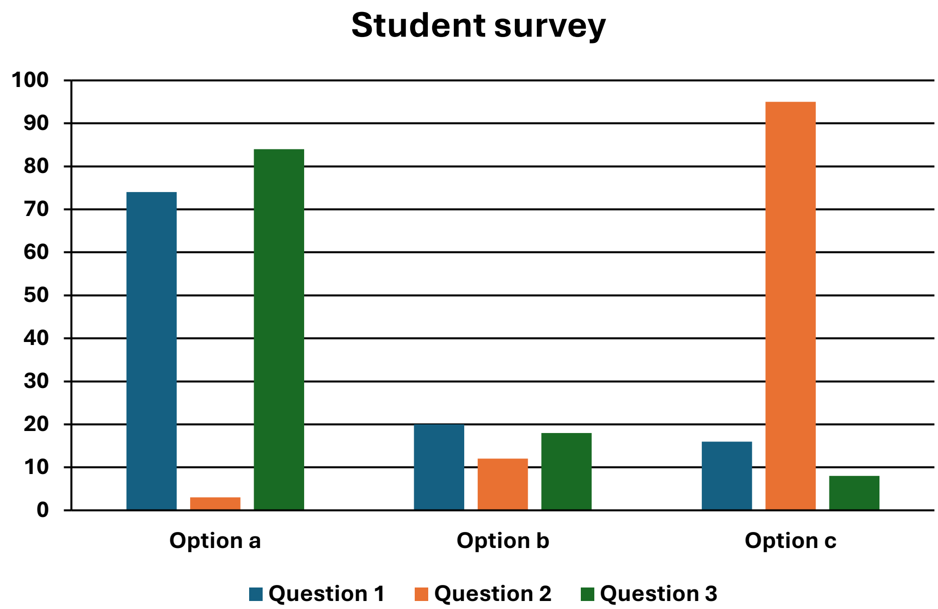

Figure 4: Post survey result

For Question 1 (To what extent do you understand the concept of sustainable manufacturing and digital twin?), the majority of respondents, 67%, selected Option a, indicating a high level of familiarity with the concepts of sustainable manufacturing and digital twins among the participants. This suggests that a significant proportion of students have acquired substantial knowledge in these areas. In contrast, Option b (neutral) received 18%, and Option c (not familiar) garnered 15%, suggesting a smaller subset of respondents were either uncertain or lacked familiarity with these concepts, though the majority demonstrated a clear understanding.

In Question 2 (To what extent do you feel the current engineering courses integrated sustainability and digital twin principles?), the results diverged significantly. Dominant 86% of respondents chose Option c (not at all), reflecting a lack of integration of sustainability and digital twin principles in the current engineering curriculum. This stark contrast with the other options highlights a gap in the inclusion of these critical concepts within academic courses. The substantial difference between Option c and the other choices indicates that sustainability and digital twin technologies are not being sufficiently addressed within the curriculum, which may point to an area for curriculum development.

For Question 3 (Which teaching method is most effective in learning sustainability in engineering?), the trend shifted back toward Option a, with 76% of participants indicating a preference for experiential learning activities—such as simulations, field trips, and problem-based learning—as the most effective approach to learning about sustainability. This preference underscores the value students have for hands-on, practical learning experiences in understanding complex concepts like sustainability. In comparison, Option b (student autonomy, including projects, self-study, and group study) was selected by 16%, while Option c (traditional methods, such as lectures, classroom discussions, and guest lectures) was chosen by only 7%. These results suggest that students favor more interactive and dynamic learning environments, with traditional lecture-based formats being the least preferred.

In summary, the survey reveals clear trends in student preferences across the three questions. While students exhibit a solid understanding of sustainability and digital twin concepts, there is a notable deficiency in their integration into engineering courses. Additionally, students express a strong preference for experiential learning over traditional teaching methods, highlighting the importance of practical, hands-on learning experiences in effectively conveying the principles of sustainability. These findings suggest potential areas for curriculum improvement and pedagogical shifts to better align with student learning preferences, highlighting the traits of the feminist pedagogy.

Demonstration:

A sample part of a given material (Aluminum 1100) has been designed with a pocket milling tool path and cutting parameters. Figure 5 shows a sample part to be machined with the CNC milling machine.

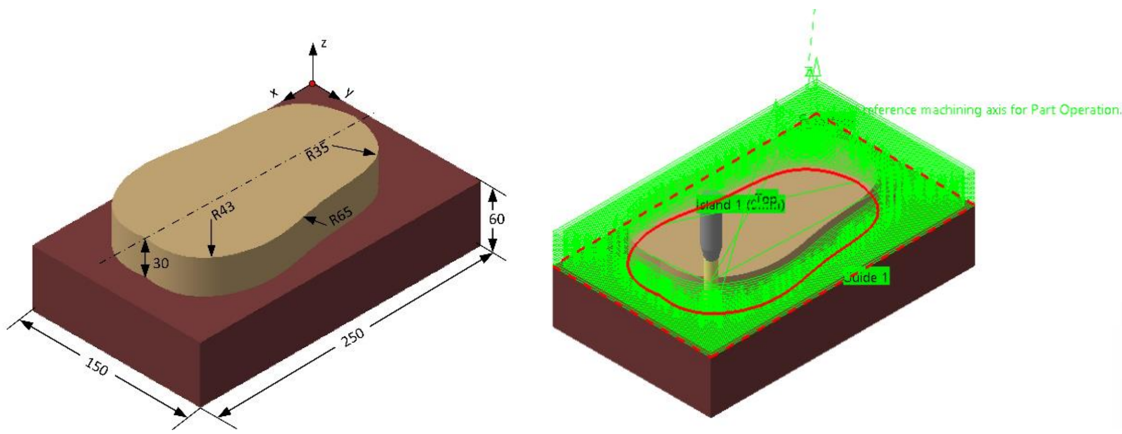

Figure5: Sample part for the case study

Table 1: Tool and Machining Parameter

Tool Parameter	Value	Machining Parameter	Value
End-mill Cutter Diameter	10 mm	Feedrate	20 mm/min
End-mill Cutter flute length	50 mm	Spindle speed	1200 rpm
Overall length	100 mm	Depth of cut	1mm top and 1.5 mm
Cutter Material	HSS	Cutting Condition	Dry

Table 1 identifies the cutting tools and machining parameters selected for the machining process. The G&M codes were generated using CAM software by selecting the appropriate postprocessor for the Denford TRIAC PC. The machine setup was configured by defining the reference system on the sample part, as illustrated in Figure 6. The AMEC PEL 103 energy data logger was mounted on the machine, while enDAQ S4 sensors were affixed to the machine’s vice to monitor the aluminum blank. The total machining time was estimated to be approximately 20 minutes.

Vibration data recorded by the sensor (as shown in Figure 6) revealed a peak vibration of 0.85 during the initial phase of machining. Following user optimization, the vibration level decreased to 0.7, with further reductions observed as machining progressed towards completion. The optimal machining parameters, which minimized vibration, were determined to be a spindle speed of 1550 rpm and a feed rate of 16.5 mm/min. In a similar manner, Figure 7 presents the current consumption data, demonstrating a notable reduction in power consumption when the optimized machining parameters were applied. This indicates that the adjustments not only reduced vibration but also contributed to more energy-efficient machining.

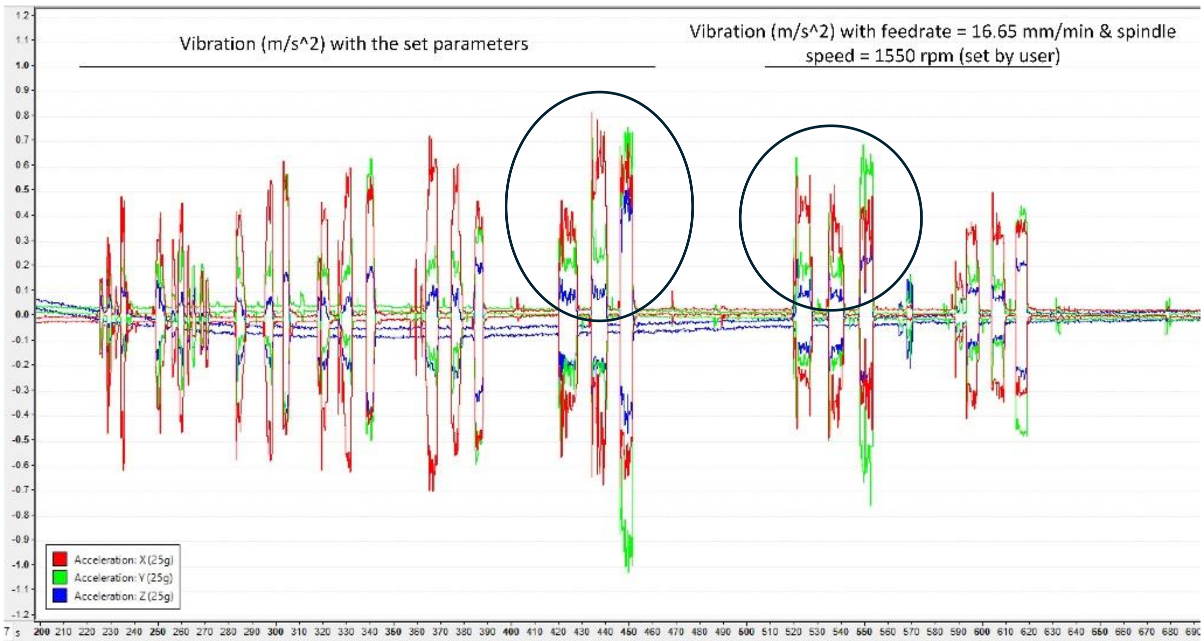

Figure 6: Vibration during the machining of sample part

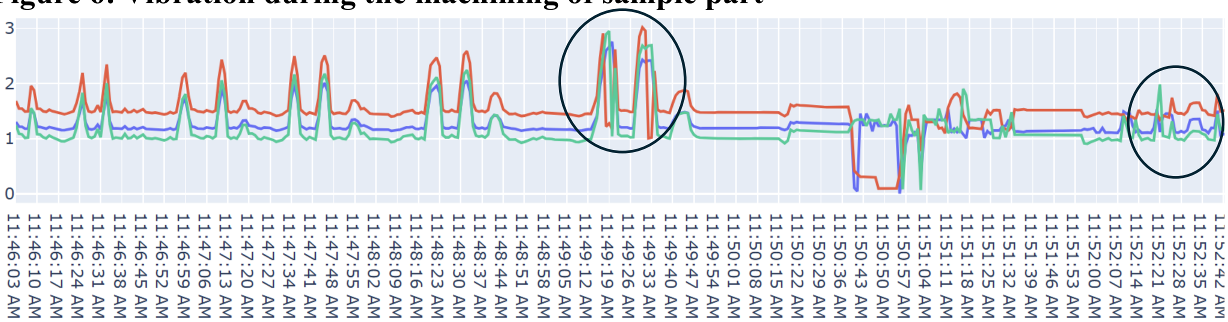

Figure 7: Current (in ampere) during the machining of sample part

Assigned study

Students were assigned different materials and were asked to work in groups to identify the optimal machining parameters for the given material with energy consumption and tool vibrations as the focus. Once identified they were asked to compare the results with the manufacturers' recommendations and produce a commentary report.

Introducing this module has provided students with an opportunity to learn through hands-on experiences. This practical approach encourages active engagement, allowing them to directly apply theoretical concepts and gain valuable skills. By interacting with the material or tasks in real-time, students can better understand complex topics, develop problem-solving abilities, and build confidence in their knowledge. Hands-on learning fosters a deeper connection to the subject matter and enhances retention, preparing students for real-world applications of their learning. Moreover, the course evaluation for Smart Manufacturing and Internet of Things (IoT) over two semesters, reflecting both the pre (semester 1)- and post (semester 2) implementation phases of this study, is presented in Table 2. The table reflects student feedback across four key areas: interest stimulation, content relevance, support from course materials, and overall satisfaction (Appendix B). For the Smart Manufacturing course, student engagement and satisfaction saw significant improvements between Semester 1 and Semester 2. In Semester 1, the course received relatively low ratings in all categories, with a particularly low score for interest stimulation (6.021). However, by Semester 2, ratings rose substantially across the board, with the interest stimulation score increasing to 8.612. This suggests that adjustments were made to enhance student engagement and course content. Similarly, the relevance of the course content, which was rated at 6.995 in Semester 1, improved to 8.347 in Semester 2, indicating that the material became more aligned with students' expectations. The support provided by course materials also improved significantly, rising from 6.031 in Semester 1 to 8.612 in Semester 2, highlighting the effectiveness of the materials in aiding student understanding. Overall satisfaction with the course, in terms of its coverage, increased from 6.004 in Semester 1 to 8.469 in Semester 2, suggesting a more comprehensive and well-received course in the second semester.

In contrast, the Internet of Things (IoT) course consistently received high ratings across both semesters, with only modest improvements. In Semester 1, interest stimulation was rated at 8.182, and it increased slightly to 9.159 in Semester 2, showing that the course effectively engaged students throughout. Content relevance also remained strong, with ratings of 8.139 in Semester 1 and 9.102 in Semester 2. Course materials for IoT were rated at 8.12 in Semester 1, rising to 9.167 in Semester 2, indicating that students found the materials helpful in supporting their understanding of the subject matter. Overall satisfaction with the course coverage was similarly high, increasing from 8.088 in Semester 1 to 9.166 in Semester 2, suggesting that the course consistently met or exceeded students’ expectations in both semesters.

Overall, the feedback shows that while the Smart Manufacturing course underwent significant improvements in the second semester, the IoT course maintained a high level of student satisfaction throughout. These findings underscore the importance of responsive course adjustments and the continued relevance of course content and materials in enhancing student learning experiences (See Figure 8).

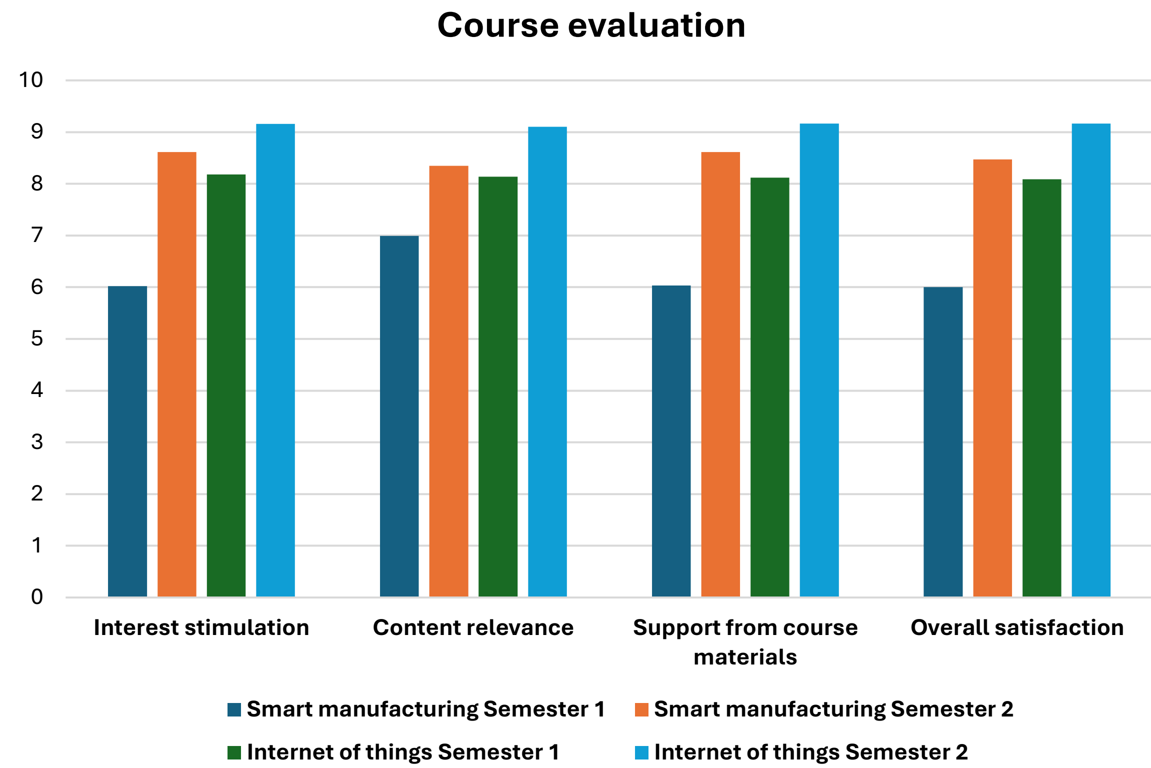

Figure 8: Course Evaluation Results

Furthermore, the responses to Question 4 of the survey (Appendix A), as illustrated in Table2, offer valuable insights into the various dimensions of influence derived from student feedback, reinforcing the relevance and practical applicability of this study in understanding the impact of digital twin technology on sustainability initiatives. This list has been recreated to highlight five key dimensions of influence based on the student responses. The survey results demonstrate a strong comprehension of the benefits derived from integrating digital twin technology with sustainability objectives, emphasizing its potential to optimize operational efficiency, reduce environmental impact, and foster business growth. This learning activity, which integrates digital twin technology and sustainability, reflects a forward-thinking approach by students towards achieving sustainability objectives. Ultimately, the findings emphasize the critical role that digital twins can play in empowering engineering education to excel in a market that places increasing value on both operational efficiency and environmental sustainability.

Table 2: Student response to question 4 in different dimensions.

1	Help me understand the connection between sustainability and digital twin.
2	Grasp understanding how technology plays an important role in achieving sustainability goals.
3	Business growth by optimizing operation due to reduced energy and waste.
4	This exercise reflects a clear understanding of the topic and integration of both concepts.
5	Digital twin can be applied to other sustainability indicators too.

Discussion

This study explores the implementation of digital twin technology for sustainable manufacturing and its impact on student learning. The research examines how integrating this technology into educational settings can enhance both the practical understanding of sustainable manufacturing processes and the development of critical skills among students. By focusing on the use of digital twins, the study aims to assess the potential benefits and challenges associated with using advanced technologies in engineering education, particularly in fostering hands-on learning experiences that align with Industry 4.0 advancements [21]. All required equipment was available within the household, and the software utilized was either accessible on-site or open source. However, several challenges impede the effective and comprehensive deployment of these technologies. These challenges include a shortage of skilled personnel, the complexity of the technology and its compatibility with existing equipment, funding by no means, the absence of a formal plan or strategy, and insufficient training and essential skills. Overcoming these barriers is essential to ensuring the thorough integration of digital twin technology within the context of sustainable manufacturing.

Digital twin-based learning offers a dynamic, interactive platform where students can engage with real-time simulations of complex systems, providing an immersive experience that bridges theoretical knowledge and practical application. It allows for data-driven learning [22], where students can analyze vast amounts of data generated by the system, enhancing analytical skills [23]. However, the technical complexity and cost of implementing digital twin technology can limit its accessibility, and it may not provide the same tactile, hands-on experience as physical labs, which are essential for developing manual skills. On the other hand, traditional lectures remain valuable for delivering structured theoretical knowledge efficiently to large groups of students, but they often lack interactivity and practical application, potentially limiting student engagement [24]. Simulations, while providing a safe environment for testing theories and modeling various scenarios, often involve simplified models that may not capture the full complexity of real-world systems, potentially affecting the depth of learning [25]. Lastly, hands-on labs provide crucial practical experience, allowing students to develop manual skills and engage directly with equipment, but they are often resource-intensive and may not be feasible for modeling larger, more complex systems. Each approach has its merits and limitations, and the effectiveness of each method depends on the learning objectives and the resources available. While digital twin technology provides immersive, data-driven learning experiences, traditional methods like lectures and hands-on labs continue to play an important role in engineering education. Ultimately, a balanced combination of these approaches may offer the most comprehensive educational experience for students, preparing them for the challenges and opportunities of Industry 4.0.

Conclusion

This work is aimed at addressing the implementation of a digital twin technology for sustainable manufacturing in higher education curriculum, focusing engineering faculties. The content is provided for integrating the physical machine with a CAD model and a GUI interface to demonstrate real time control in machining parameters to reduce current consumption and vibration. A case study is presented to showcase the application of feminist pedagogy to incorporate the proposed methodology to the courses of smart manufacturing and internet of things. The survey results show that the technological trends embedded in education have stimulated critical thinking, entrepreneurial and digital skills among students and have successfully enriched curricula adjustments.

References

[1] "United Nations: Department of Economic and Social Affairs." https://sdgs.un.org/goals (accessed.

[2] "Enviromental Topics." https://www.epa.gov/sustainability/sustainable-manufacturing#:~:text=Sustainable%20manufacturing%20is%20the%20creation,employee%2C%20community%20and%20product%20safety. (accessed.

[3] M. Hazrat, N. Hassan, A. A. Chowdhury, M. Rasul, and B. A. Taylor, "Developing a skilled workforce for future industry demand: The potential of digital twin-based teaching and learning practices in engineering education," *Sustainability,* vol. 15, no. 23, p. 16433, 2023.

[4] A. Liljaniemi and H. Paavilainen, "Using digital twin technology in engineering education–course concept to explore benefits and barriers," *Open Engineering,* vol. 10, no. 1, pp. 377-385, 2020.

[5] John L. Irwin, Suzy Gorospes Marzano, Ismail Fidan, and N. Littell, "Advanced Four Pillars of Manufacturing Knowledge," presented at the 2024 ASEE Annual Conference & Exposition, Portland, Oregon, June,23,2024, 2024, 18. [Online]. Available: https://peer.asee.org/46523.

[6] S. Coşkun, Y. Kayıkcı, and E. Gençay, "Adapting engineering education to industry 4.0 vision," *Technologies,* vol. 7, no. 1, p. 10, 2019.

[7] A. Ustundag, E. Cevikcan, S. Cevik Onar, A. Ustundag, Ç. Kadaifci, and B. Oztaysi, "The changing role of engineering education in industry 4.0 era," *Industry 4.0: managing the digital transformation,* pp. 137-151, 2018.

[8] B. Bordel Sánchez, R. P. Alcarria Garrido, and T. E. Robles Valladares, "Industry 4.0 paradigm on teaching and learning engineering," *International Journal of Engineering Education,* vol. 35, no. 4, pp. 1018-1036, 2019.

[9] B. Y. Ekren and V. Kumar, "Engineering education towards industry 4.0," in *Proceedings of the International Conference on Industrial Engineering and Operations Management*, 2020, pp. 10-12.

[10] C. B. Moncada, J. F. Buhangin, and N. Q. Angalan, "Review of industry 4.0 competencies and virtual learning environment in engineering education," *The International journal of engineering education,* vol. 36, no. 1, pp. 40-47, 2020.

[11] W. Lin and M. Low, "An integrated engineering education alignment model towards Industry 4.0," in *Proceedings of the international conference on industrial engineering and operations management*, 2021, pp. 1204-1213.

[12] B. L. Treviño-Elizondo and H. García-Reyes, "What does Industry 4.0 mean to industrial engineering education?," *Procedia computer science,* vol. 217, pp. 876-885, 2023.

[13] M. Maksimović and N. Davidović, "The role of Digital Twin technology in transforming engineering education," in *9th International scientific conference Technics and Informatics in Education*, 2022, pp. 264-270.

[14] S. Zacher, "Digital twins for education and study of engineering sciences," *International Journal on Engineering, Science and Technology,* vol. 2, no. 2, pp. 61-69, 2020.

[15] P. Arras and G. Tabunshchyk, "Implementation of digital twins for industry 4.0 in the engineering study program," in *Grabchenko's International Conference on Advanced Manufacturing Processes*, 2021: Springer, pp. 677-686.
[16] F. Guc, J. Viola, and Y. Chen, "Digital twins enabled remote laboratory learning experience for mechatronics education," in *2021 IEEE 1st international conference on digital twins and parallel intelligence (DTPI)*, 2021: IEEE, pp. 242-245.
[17] S. S. Kamble, A. Gunasekaran, H. Parekh, V. Mani, A. Belhadi, and R. Sharma, "Digital twin for sustainable manufacturing supply chains: Current trends, future perspectives, and an implementation framework," *Technological Forecasting and Social Change,* vol. 176, p. 121448, 2022.
[18] J. David, A. Lobov, and M. Lanz, "Learning experiences involving digital twins," in *IECON 2018-44th annual conference of the IEEE industrial electronics Society*, 2018: IEEE, pp. 3681-3686.
[19] P. Ball and E. Badakhshan, "Sustainable Manufacturing Digital Twins: A Review of Development and Application," in *Sustainable Design and Manufacturing: Proceedings of the 8th International Conference on Sustainable Design and Manufacturing (KES-SDM 2021)*, 2022: Springer, pp. 159-168.
[20] "University of Pittsburg." https://teaching.pitt.edu/ (accessed.
[21] J. S. Brennen and D. Kreiss, "Digitalization," *The international encyclopedia of communication theory and philosophy,* pp. 1-11, 2016.
[22] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital Twin in Industry: State-of-the-Art," *IEEE Transactions on Industrial Informatics,* vol. 15, no. 4, pp. 2405-2415, 2019, doi: 10.1109/TII.2018.2873186.
[23] E. Negri, L. Fumagalli, and M. Macchi, "A Review of the Roles of Digital Twin in CPS-based Production Systems," *Procedia Manufacturing,* vol. 11, pp. 939-948, 2017/01/01/ 2017, doi: https://doi.org/10.1016/j.promfg.2017.07.198.
[24] D. Laurillard, *Teaching as a Design Science: Building Pedagogical Patterns for Learning and Technology*, 1st ed. New York: Routledge, 2012, p. 272. [Online]. Available: https://doi.org/10.4324/9780203125083. Accessed on: 18 June 2013.
[25] A. D. Costa Marion, L. C. Pereira, and D. Lucia Moura Pinho, "The effect of interprofessional simulation practice on collaborative learning: A randomized controlled trial," *Journal of Interprofessional Care,* vol. 39, no. 1, pp. 14-21, 2025/01/02 2025, doi: 10.1080/13561820.2022.2147153.

Appendix A

Student survey questionnaire
Date:
Institution:

1. To what extent do you understand the concept of sustainable manufacturing and digital twin? **(co- knowledge)**
    a. Very familiar
    b. Neutral
    c. Not familiar

2. To what extent do you feel the current engineering courses integrated sustainability and digital twin principles? **(co-knowledge)**
    a. Many
    b. Few
    c. Not at all

3. Which teaching method is most effective in learning sustainability in engineering? **(empowerment)**
    a. Experiential learning (simulation, field trips and problem base learning)
    b. Student autonomy (projects, self-study, group study)
    c. Traditional (lectures, classroom discussions, guest lectures)

4. How do you think this exercise influences your understanding of the concept of sustainability and digital twin? **(reflection)**
    ____
    ____
    ____

Note: Question 4 was a post-teaching session question.

Appendix B

Course evaluation questions:
B1. Did the Course stimulate your interest and thoughts on the subject area?
B2. Was the course content relevant and up to date?
B3. Was Course materials support your understanding?
B4. How satisfied are you with the course overall in terms of its coverage?