

In Teaching Lean Manufacturing with Digital Twin: A Modern Approach to Engineering Education

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Abstract

Engineering education must evolve beyond conventional classroom techniques as technology advances rapidly and Industry 4.0 practices become increasingly prevalent. This study explores integrating digital twin technology into engineering education as an innovative and effective approach to teaching lean manufacturing principles. The central research question guiding this work is: Can digital twin-based learning improve students' understanding and application of lean manufacturing concepts compared to traditional teaching methods? A total of 40 senior-year students were surveyed, revealing an overall 63% improvement in course evaluation following the adoption of digital twin-based learning. Focusing on sensor stamping in renewable energy applications, the digital twin was developed using CAD tools such as Fusion 360 and NVIDIA Omniverse to create interactive virtual manufacturing systems. Students conducted time-motion studies, defect analyses, and production cycle optimizations through iterative simulations involving three manufacturing methods: traditional hammering, manual pressing, and automated stamping. Results demonstrated the value of design optimization and force-controlled stamping, validating the digital twin's effectiveness in enhancing process understanding and decision-making. Overall, this study highlights the transformative potential of digital twin technology to foster experiential, data-driven learning and align engineering education with Industry 4.0 competencies.

1. Introduction

The manufacturing sector is undergoing a significant transformation, driven by the convergence of automation, data-driven systems, and lean philosophies—collectively encapsulated within the paradigm of Industry 4.0. As a result, engineering education must also evolve to prepare future professionals for this dynamic landscape (Irwin et al. 2024). While theoretical instruction remains a cornerstone of engineering curricula, a considerable gap persists between

classroom learning and practical industrial application. Bridging this gap is essential for developing engineers who are not only technically proficient but also capable of fostering continuous improvement in complex manufacturing environments (Adrian et al. 2020).

A Digital Twin (DT) is a virtual replica of a physical asset, process, or system that is continuously updated with real-time data to mirror current operational conditions. Initially adopted for predictive maintenance and performance monitoring in advanced manufacturing, DTs have matured into powerful tools for simulation (Phanden, Sharma, and Dubey 2021), optimization (Anis Fatima, Muhammad Wasif, and Irwin 2025), and decision support (Grieves and Vickers 2016). In manufacturing contexts, DTs facilitate experimentation without disrupting actual operations, allowing engineers to explore "what-if" scenarios, test process improvements, and visualize system-wide impacts.

Lean manufacturing—originating from the Toyota Production System—emphasizes maximizing value while minimizing waste (Womack and Jones 1996). Traditionally, lean principles are taught through lectures, case studies, and physical simulations such as the "LEGO factory" model. These methods introduce foundational concepts like muda (waste), kaizen (continuous improvement), and takt time, but often fall short in capturing dynamic process interactions, real-time data usage, and system-level thinking (Dombrowski and Mielke 2013). A major limitation in conventional lean education is the inability to simulate the cascading effects of localized inefficiencies across the broader production system. This restricts students' understanding of lean manufacturing as a cohesive, integrated methodology rather than a set of isolated tools.

The literature suggests that digital twin technology can offer students an interactive, immersive experience with virtual models of real-world systems, thereby enhancing the effectiveness of engineering education. However, most of the research around digital twins (DTs) continues to centre on factory-level or

industrial implementations, such as process optimization (Roquini et al. 2026), value-stream mapping (Nwamekwe et al. 2025; Reslan et al. 2025), and predictive maintenance (van Dinter, Tekinerdogan, and Catal 2022). Meanwhile, a parallel body of literature on computer simulation - typically static or fixed-scenario models rather than dynamic twin-based systems- has been used in lean manufacturing education, offering a useful but less immersive alternative. Also, to maintain relevance, this review focuses exclusively on simulation studies published within recent years, highlighting the latest advancements in virtual/computer simulations. Cudney et al (Cudney, Corns, and Gadre 2014) developed a virtual simulation platform using the VE-Suite virtual engineering framework, which allows students to experience multiple applications of lean in a real-world setting. Talbi et al (Talbi et al. 2025) propose a framework for a virtual laboratory in mechanical and industrial engineering that leverages virtual reality (VR) to simulate laboratory environments while integrating lean manufacturing principles to optimize flow shop processes. Similarly, Salleh et al (Salleh et al. 2024) employ FlexSim software to visualize a production line system and develop a virtual game platform, enabling students to apply basic assessments of lean principles and identify challenges within lean manufacturing systems. Terkaj et al (Terkaj et al. 2024) present a framework for developing virtual learning applications that address multidisciplinary requirements through an open-source solution, utilizing VR to support innovative higher-education learning activities in industrial engineering.

Recent developments in the digital twin (DT) field further highlight the potential of new frameworks to support real-time monitoring and dynamic reconfiguration of production lines in response to disturbances. However, studies examining the use of DTs specifically to bridge the gap between theory and practice in lean manufacturing education remain limited. Barbieri et al (Barbieri et al. 2023) highlight how visualization technology enhances student comprehension beyond theoretical or numerical representation. In their work, a digital twin of a factory layout was developed, enabling control and optimization through the interaction of various DT components. Similarly, Hazrat et al (Hazrat et al. 2023) demonstrate the advantages of DTs in teaching lifecycle management, including predictive maintenance, remote diagnostics, and remote operations. Nwamekwe et al (Nwamekwe et al. 2025) integrate digital twins (DTs) with a lean manufacturing framework to optimize value stream flow, minimize waste, and enhance real-time decision-making capabilities. The study examines layered DT architecture encompass-

ing physical, virtual, and communication interfaces, while incorporating Lean tools such as Kaizen, Kanban, and Just-in-Time (JIT) to facilitate continuous process improvement. Ortiz et al (Ortiz et al. 2025) demonstrates that integrating Digital Twin technology into engineering education can enhance active learning by linking physical teaching modules with a virtualized industrial process. Using an S7-1200 PLC and WinCC HMI interface, students could monitor and control the cocoa production process in real time, resulting in a 38% reduction in task execution time compared to conventional methods. The findings suggest that Digital Twins improve student performance through immersive, interactive simulations and also offer practical benefits for optimizing industrial processes in line with Industry 4.0. Guo and Mantravadi (Guo and Mantravadi 2024), in a systematic literature review of 33 studies on supply chains and digital twins using the SCOR framework, found that digital twins primarily support planning, production, and delivery processes, enhancing information flow, logistics optimization, and just-in-time practices. The study also highlights their contributions to supply chain coordination and resilience, proposes a framework for smart lean supply chain management, and emphasizes the need for further research on digital twin mapping, interaction, cognition, services, and education.

These advances suggest untapped opportunities for DTs to more effectively support lean manufacturing education by providing richer immersive experiences, live data feedback, and scenario-based learning that go beyond static simulations. Despite the growing emphasis on Industry 4.0 and lean manufacturing, traditional engineering education remains largely theoretical, relying on static classroom simulation exercises that limit students' exposure to real-world manufacturing challenges. For example, in sensor production for the energy sector, customized stickers are applied to clean and tested sensors before final packaging, a process critical for both quality and efficiency. Conventional training typically emphasizes manual hammering techniques or press stamping, offering little opportunity for students to analyze process efficiency, identify sources of waste, or evaluate quality outcomes. To address this gap, this study develops a digital twin of the stamping die and the entire sensor manufacturing line using Fusion 360 and Siemens Tecnomatix software. The digital twin enables students to simulate and optimize the stamping process, providing hands-on experience with lean manufacturing principles, system-level interactions, and data-driven decision-making, practical skills that remain underrepresented in traditional engineering curricula.

2. Methodology

This study employed an experimental mixed-methods approach to evaluate the effectiveness of digital twin–based learning in teaching lean manufacturing principles to engineering students. The methodology consisted of three main phases: module design, development of the digital twin model, and performance evaluation and analysis of the course.

3. Module Design and Participants:

The study was conducted within a senior-level undergraduate course on Lean Manufacturing and Quality Techniques, involving 40 senior engineering students. A dedicated laboratory module was developed to facilitate hands-on learning. The learning objectives for students included:

1. Identifying sources of muda (waste) within the system.
2. Calculating cycle time and balancing workloads across the production line.
3. Perform DPMO (Defects Per Million Opportunities) analysis and identify root causes.
4. Performing a comparative analysis of stamping methods.

The study executed as follows:

Phase I (Traditional Learning): Evaluation data were collected from student surveys after they were introduced to lean manufacturing principles through conventional lectures and manual lab exercises. Students were provided with two scenarios:

1. **Hammering** – Stickers were stamped using a wooden die and a manual hammering technique. This method relied heavily on human operation, resulting in variable stroke force and inconsistent motion.
2. **Manual Press** – A steel die was mounted on a mechanical press and operated manually. This setup reduced unnecessary operator movement and improved control over the stamping action.

These activities provided a baseline for comparison with the digital twin–based learning approach implemented in Phase II.

Phase II (Digital Twin–Based Learning): The same lean manufacturing concepts were reinforced using a digital twin model used in laboratory sessions. By building a full-featured digital twin within NVIDIA Omniverse, students moved beyond static diagrams and theoretical concepts. Near real-time data visualizations demonstrated how process variations directly impacted key performance indicators (KPIs), such as cycle time, production velocity, yield,

and product quality. In addition to the previous two scenarios (Hammering and Manual Press), a third scenario was introduced:

- **Automated Stamping Process** – Using the digital twin platform, students analyzed the effects of different loads and punch speeds. This setup eliminated manual delays, resulting in a high-throughput, standardized system with predictable and stable performance.

To ensure high-fidelity simulations and practical relevance, the materials selected closely replicated industrial stamping operations:

- **Servo Stamping Press:** A servo-driven stamping press was employed to conduct stamping of stickers. The servo press allows precise control of ram position, speed, and force. Its programmable motion characteristics were particularly advantageous for analyzing cutting forces and material deformation behavior.
- **Die Material:** The die was made of mild steel due to its cost, machinability, and because it resists deformation under repetitive loading.
- **Sticker Material:** The sticker was a composite structure with three layers: a 1 mm sticker label (paper), a 1.5 mm acrylic adhesive core, and a 0.5 mm bottom release layer. This was critical in measuring the cutting force required.
- **Base Surface:** A nylon board served as the pressing surface during manual testing, offering stability, shock absorption, and die protection.

4. Development of digital twin model

The design and analysis of the stamping die were performed entirely within Fusion 360, a widely adopted CAD/CAM platform used in both industrial and academic settings. The process began with reverse engineering the original die, followed by the redesign and optimization of a mild steel die to enhance performance (Figure 1).

The redesign focused on improving structural integrity, ensuring consistent stamping performance, and enabling seamless integration with subsequent simulation and testing stages. The stamping setup was implemented using Fusion 360's CAM-integrated force control, with a force application range of 10–250 N and a punch speed (stamping velocity) adjustable across 25 incremental steps. Precise part positioning was also defined within the simulation to enhance accuracy and repeatability. Outputs from the automated stamping method included time-

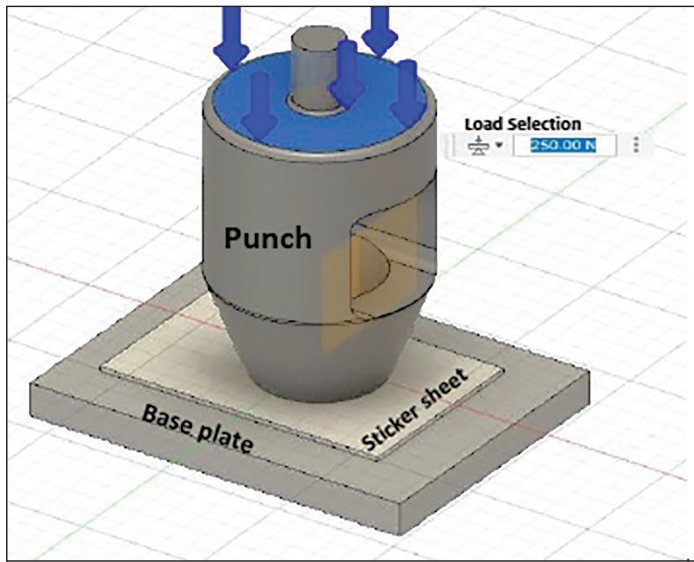


Figure 1. CAD model for the stamping process.

based deformation data and visualizations of stress distribution, providing insight into material behavior under varying process conditions.

Fusion 360 supports Universal Scene Description (USD) files, a universal format for 3D data that facilitates the integration of CAD models, simula-

tion results, and real-time information within a single environment (Tran et al. 2023). In this workflow, CAD models designed in Fusion 360 were exported as USD files and imported into the NVIDIA Omniverse platform, which uses USD as its core format to enable real-time collaboration and photorealistic visualization. Simulation data was also integrated into Omniverse via the Omniverse ParaView Connector, bridging simulation outputs with the USD ecosystem and merging CAD models and simulation data into a cohesive digital representation. Real-time press data, including force, incremental velocity, and position, was streamed into Omniverse using the Omniverse Kit and connectors. The result is a fully integrated digital twin environment that combines engineering accuracy with real-time visualization, allowing interactive analysis, validation, and optimization of designs.

A virtual model of the sensor production line was developed using Siemens Tecnomatix software and subsequently linked into the NVIDIA Omniverse platform (Figure 2). Key performance indicators (KPIs) were tracked, which included cycle time, yield, defects per million opportunities (DPMO), and overall system efficiency. These metrics enabled a comprehensive evaluation of how

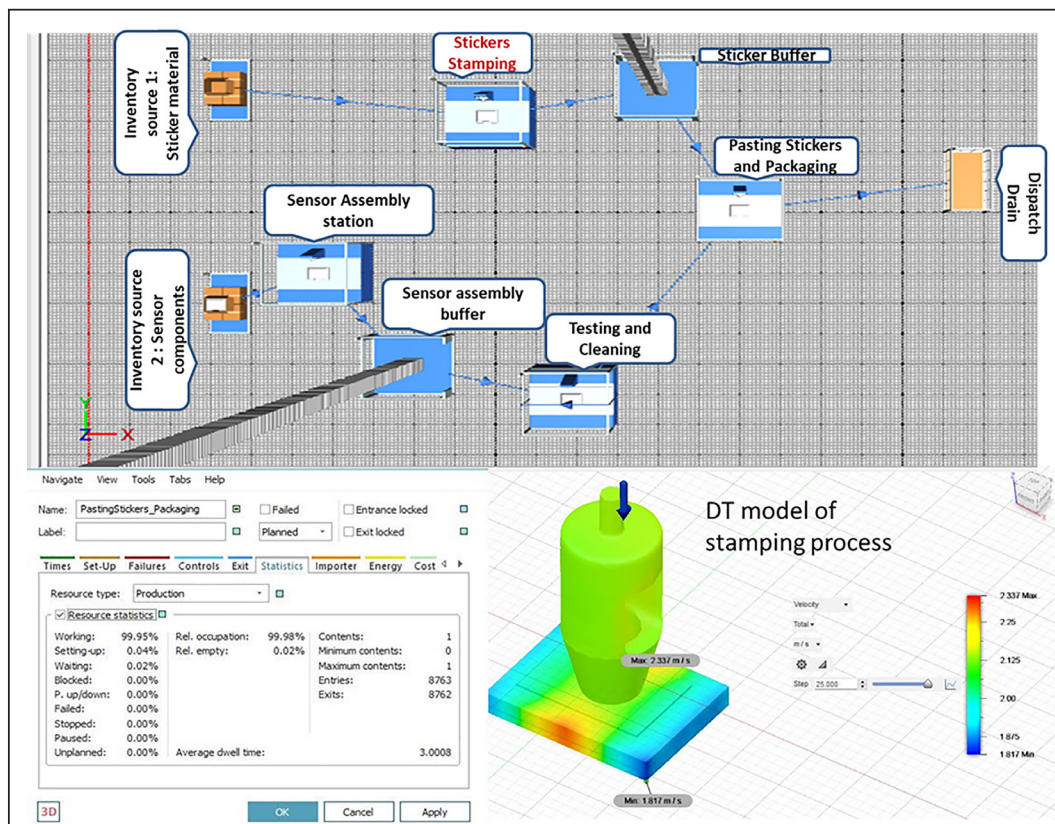


Figure 2. Digital twin for sensor manufacturing.

changes at the stamping station affected overall system output, highlighting the cumulative impact of localized process improvements on total manufacturing performance. This Production line model incorporates the following stations:

1. Inventory Source 1 & 2: Feeding raw material to the line
2. Assembly station: sensors are assembled
3. Buffer Zone: Temporarily held semi-finished items for synchronization
4. Testing and Cleaning Station: Ensured quality control before sticker application
5. **Stamping Station: The optimized stamping method was deployed here**
6. Sticker application and packaging Station: Applied stamped stickers to tested products and is identified as the pacemaker controlling takt time
7. Dispatch Drain: Completed products exited the system

4.2. Results and Discussion: Insights from the Digital Twin–Based Learning Activities

4.2.1 Reduction in Cycle Time

One of the primary goals of this study was to reduce the cycle time associated with the stamping operation. Figure 3 shows that the manual press decreased cycle time by nearly 18%, while the automated method provided an additional improvement, reducing total stamping time by 22% compared to hammering. This reduction in cycle time is brought by optimized stamping velocity and load selection.

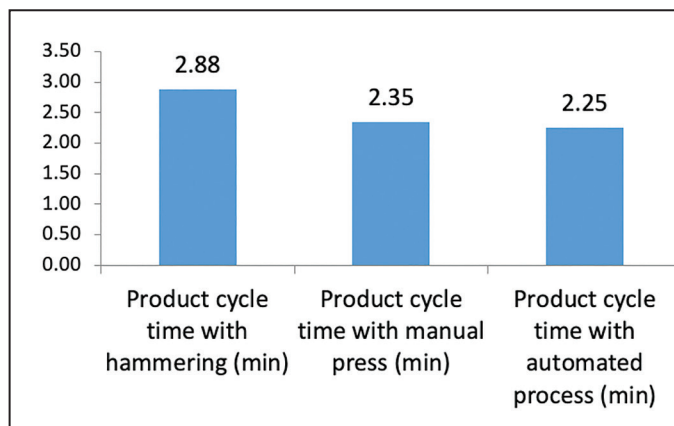


Figure 3. Decrease in cycle time of stamping process.

4.2.2 Quality Improvement Through DPMO Reduction

The transition from a traditional hammering process to a digitally optimized stamping approach

resulted in a substantial improvement in quality, as measured by defects per million opportunities (DPMO). Manual operation generally produces fewer defects compared to hammering, primarily due to improved control over loading during the stamping process. While automated stamping methods achieved a DPMO of zero, demonstrating that the controlled force and part positioning application effectively eliminated inconsistencies in the stamping process (Figure 4). In contrast, the hammering method consistently produced defects due to its variability and lack of precision, further reinforcing the necessity for process redesign and controlled operational parameters.

4.2.3 Yield Increase at Six Sigma Levels

Yield is a fundamental performance metric in both Lean Production and Six Sigma methodologies. In this study, a significant increase in yield was observed—from 81% in the conventional hammering process to 100% under Six Sigma-compliant methods (Figure 5). This improvement is both statistically meaningful and economically impactful. Achieving a perfect yield not only enhances customer satisfaction but also leads to substantial reductions in material waste, rework, and labor costs—all of which are critical to driving a successful lean transformation.

While individual improvements in stamping processes are valuable, the true impact of lean manufacturing emerges when these localized enhancements lead to system-wide benefits (Garcia, Bregon, and Martínez-Prieto 2022). To evaluate this, a discrete digital twin model of the entire production line for a sensor product was developed. This model was used to analyze how optimization of the stamping process influenced overall production efficiency. Within the simulation, the packaging station was identified as the pacemaker, setting the system's takt time and governing the flow rate. As a result, improvements at upstream stations—particularly at stamping—needed to be carefully aligned to prevent issues such as underutilization or overproduction.

When the hammering method was used for stamping, its inconsistent output and frequent delays led to severe downstream bottlenecks. This was reflected in the system's total efficiency, which was limited to just 10%, accompanied by buffer over-accumulation, as well as idle time at packaging stations. Following the implementation of the manual press method, improvements in cycle time and yield significantly reduced idle times and rework in subsequent stages. The system-wide efficiency improved to 75%, with significant reductions in work-in-progress (WIP) inventory and pro-

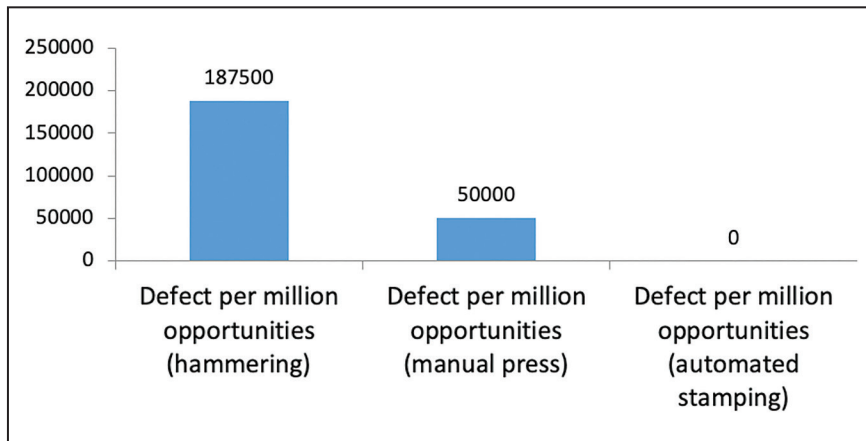


Figure 4. Decrease in DPMO.

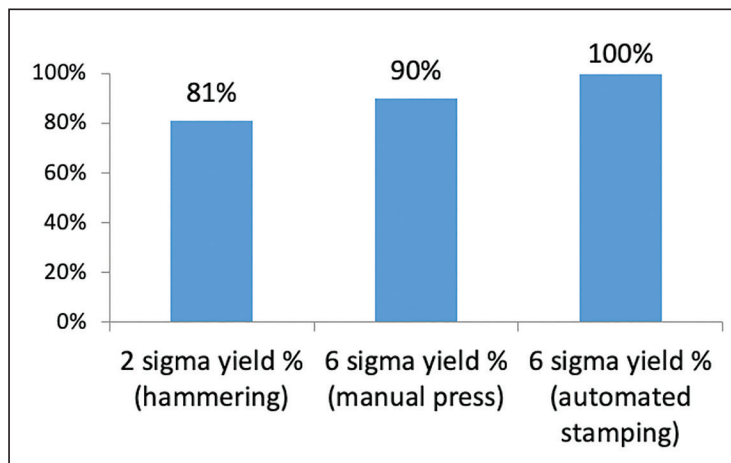


Figure 5. Increase in yield after achieving Six Sigma.

duction stoppages. Importantly, the buffer zone was better synchronized, maintaining a smooth material flow and reducing over-processing. The final transformation came with the adoption of the automated stamping process through digital twin. The speed, loading and positioning of the punch over base surface was controlled through DT model of stamping process. With the highest stamping velocity and a DPMO of zero, the system efficiency reached a staggering 99%. It was noted that the stamping station becomes capable of copying the rhythm of the pace-maker station and has developed the capabilities to abolish both upstream accumulations and downstream shortages. Through this study it was shown that even small and limited technical developments could trigger holistic excellence in operations.

5. Evaluation Metrics of the course

The results, based on a survey (Appendix A) of 40 senior-year engineering students and analyzed at a confidence level of 95% ($\alpha = 0.05$), indicate a

substantial improvement in students' perceptions of the lean manufacturing course following the integration of digital twin-based learning (Table 1). Interest stimulation showed the highest increase, with the overall criterion improving by 93%, and individual items such as "The course content captured my interest and kept me engaged" and "The use of technology made the course more interactive and exciting" showing 100% improvement, reflecting the strong engagement and motivation generated by the interactive simulations. Content relevance increased by 34%, suggesting that students found the topics and exercises more closely aligned with real-world applications after using the digital twin, with consistent improvements across all items in this category. Support from course materials improved by 69%, highlighting that resources, independent usability, and instructor guidance were perceived as significantly more effective in aiding learning. Finally, overall satisfaction increased by 63%, with students reporting greater confidence in applying course concepts and acknowledging the positive contribution of the course to their learning. Collectively, these results demonstrate that the digital twin-based approach significantly enhanced student engagement, understanding, and perceived learning outcomes, with the improvements being statistically significant at the 5% level, validating its effectiveness as a teaching tool in lean manufacturing education.

Open-ended feedback emphasized that the digital twin approach was highly effective in making complex manufacturing concepts more tangible, interactive, and easier to understand. Learners particularly valued the hands-on experience and real-time visualization, which helped bridge the gap between theoretical knowledge and practical application. However, several participants suggested providing more in-depth tutorials and structured guidance on using software tools such as Fusion 360 and NVIDIA Omniverse to strengthen technical proficiency and confidence in applying digital twin concepts. Additionally, the module's pace was considered somewhat fast, with extensive coverage of traditional lean tools but limited time dedicated to exploring and learning from the digital platform.

Table 1. Lean Manufacturing course evaluation (average).

Evaluation Criteria	Lean manufacturing		Improvement
	Semester 1: Before	Semester 2: After	
Interest stimulation	5.00	9.67	93%
The course content captured my interest and kept me engaged	5.00	10.00	100%
The activities and exercises encouraged me to explore concepts further	5.00	9.00	80%
The use of technology made the course more interactive and exciting	5.00	10.00	100%
Content relevance	6.00	8.03	34%
The topics covered were relevant to current industry practices	6.00	8.00	33%
The course helped me understand practical applications of the course	6.00	8.00	33%
The exercises enhanced my understanding of real-world processes	6.00	8.10	35%
Support from course materials	5.10	8.60	69%
Resources (slides, readings, and tutorials) were helpful for learning	5.00	8.50	70%
I was able to use the course materials independently to complete tasks	5.00	8.70	74%
The instructor provided adequate support and clarification during the exercise	5.30	8.60	62%
Overall satisfaction	5.39	8.76	63%
The course met my expectations regarding learning outcomes	5.40	8.80	63%
I feel more confident applying course concepts after this course	5.30	8.70	64%
This course contributed positively to my learning	5.46	8.77	61%

The box plot analysis of the 40-student course evaluation data clearly illustrates the substantial impact of integrating digital twin-based learning into the lean manufacturing course (Figure 6). For all four evaluation criteria - Interest Stimulation, Content Relevance, Support from Course Materials, and Overall Satisfaction - the “After” box plots are positioned significantly higher than the “Before” plots, showing a strong upward shift in student responses. The median scores increased from approximately 5–6 in Semester 1 (before implementation) to around 8.5–9.5 in Semester 2 (after implementation), indicating a marked improvement in perceived engagement, relevance, and learning effectiveness. Moreover, the boxes in the “After” plots are narrower, suggesting reduced variability and more consistent positive feedback across the class. The whiskers for

the after scores extend toward the upper end of the scale (8–10), with few or no low outliers, emphasizing that nearly all students benefited from the new teaching approach. This visual distribution supports the statistical findings of a 63% overall improvement, confirming that digital twin-based instruction significantly enhanced students’ learning experience.

6. Discussion

This study explores the implementation of digital twin technology for lean manufacturing and its impact on student learning. It investigates how integrating digital twins into educational settings can enhance students’ practical understanding of industrial processes, develop critical problem-solving and decision-making skills, and provide hands-on learning experiences aligned with Industry 4.0 advancements.

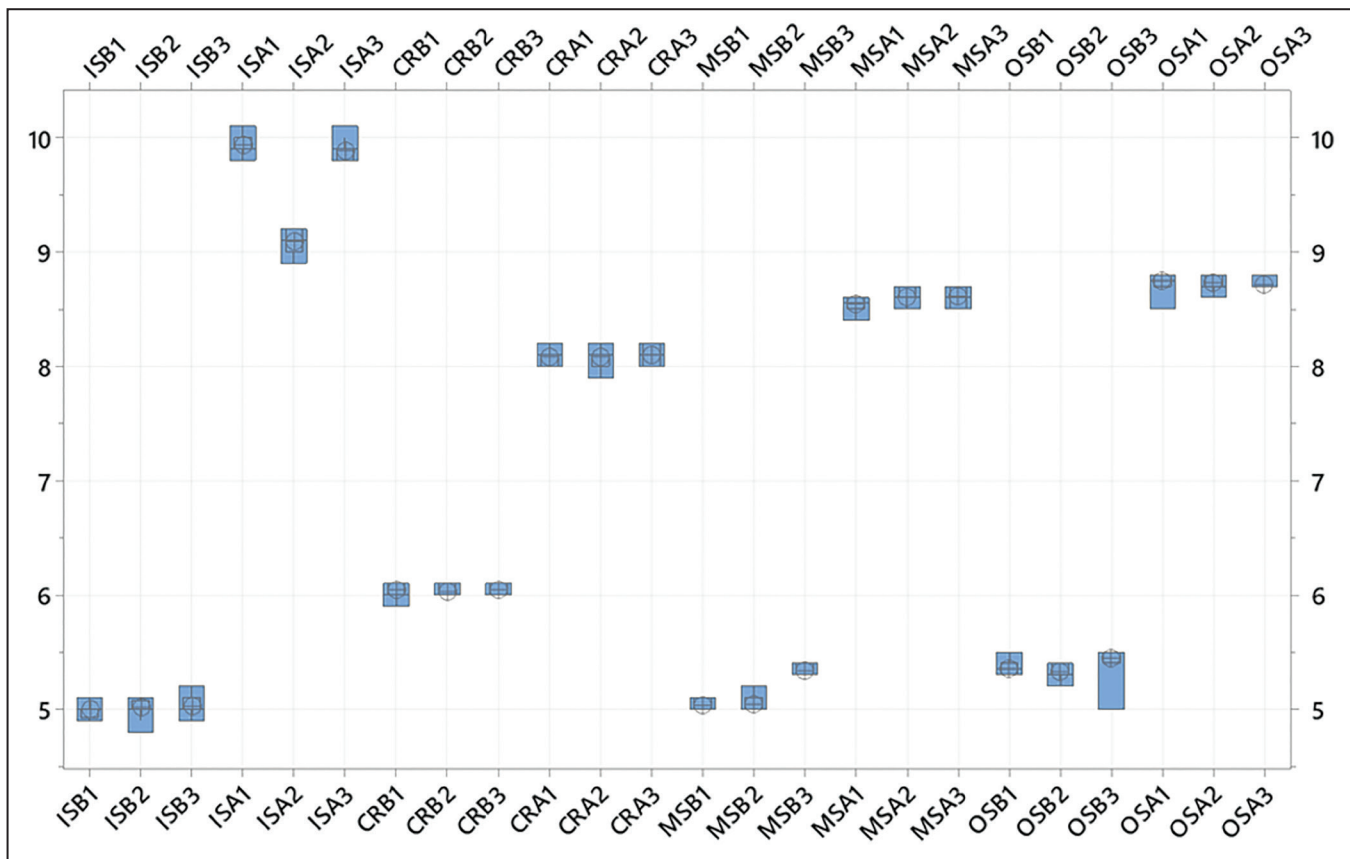


Figure 6. Box plot illustrating student evaluation scores before (B) and after (A) the implementation of digital twin-based learning across four criteria: IS1–IS3 (Interest Stimulation), CR1–CR3 (Content Relevance), SM1–SM3 (Support from Course Materials), and OS1–OS3 (Overall Satisfaction).

Within the digital twin environment, students engaged with real-time simulations of a manufacturing system, making decisions such as selecting stamping force levels or stamping velocity, and observing the downstream effects on system performance. This interactive, data-driven approach enabled students to witness the immediate consequences of their decisions, bridging the gap between theoretical knowledge and practical application. A key advantage of digital twin-based learning lies in its ability to make traditionally “invisible” forms of waste—such as waiting time, excess inventory, over-processing, and unnecessary motion—tangible. Through DT, students could observe how inefficiencies manifest dynamically within a production system. This visualization allowed learners to better diagnose problems, discuss solutions, and propose targeted improvements, which are often difficult in conventional textbook-based curricula that rely on theoretical instruction, Gemba walks, or visual boards for tracking metrics.

From a pedagogical perspective, the module aligns with several established learning theories. According to Kolb’s experiential learning theory (Kolb 2014), learning is most effective when learners engage in

concrete experiences, reflect on their observations, conceptualize insights, and actively experiment. The digital twin environment supports this cycle by enabling iterative experimentation and immediate feedback. The module also fosters situated learning (Lave and Wenger 1991), as students engage in tasks closely resembling authentic industrial scenarios, thereby promoting the transfer of knowledge to real-world applications. Furthermore, it supports cognitive apprenticeship (Collins, Brown, and Newman 2018), allowing learners to acquire expertise through guided interaction with complex systems. This experiential, data-driven approach enhances analytical and critical thinking skills, as students interpret simulation outputs, identify inefficiencies, and propose process optimizations. By integrating digital twins, students interact with complex, data-rich environments, strengthening computational thinking, digital literacy, and systems thinking, key competencies for Industry 4.0, thereby fostering technology-enhanced learning (Redecker and Punie 2017). Moreover, the module incorporates gamification and motivational learning (Deterding et al. 2011), as simulation-based tasks with real-time feedback and observable out-

comes increase engagement, motivation, and intrinsic learning drive. Together, these pedagogical foundations create a highly immersive, interactive, and reflective learning experience that bridges theory and practice, equipping students with both the technical skills and cognitive abilities required for modern engineering and manufacturing environments.

This study has several limitations. First, the digital twin was implemented in a controlled setting, which may not fully capture the complexities and variability of real-world manufacturing environments. Broader adoption of digital twin technology is further challenged by factors such as a shortage of skilled personnel, limited funding, a lack of a formal implementation strategy, and insufficient training to develop and operate digital twins effectively. Second, the sample size for feedback and evaluation was relatively small, limiting the generalizability of the findings. Third, the study primarily focused on integrating digital twins with lean manufacturing concepts and relied on specific software platforms, so the results may not be directly applicable to other tools or ecosystems. Future work can address these limitations by implementing digital twins in diverse industrial settings, including quality control, supply chains and/or predictive analytics, providing a more comprehensive understanding of DT benefits in engineering education. Exploring alternative software platforms and interoperability standards would enhance the scalability and adaptability of the approach. Additionally, ensuring that adequate funding is available and providing targeted training for personnel would facilitate broader adoption and effective utilization of Industry 4.0/5.0 technologies. Finally, longitudinal studies tracking skill development and process improvements over time would offer deeper insights into the long-term educational value of digital twin integration.

7. Conclusion

This paper presents a novel educational framework that integrates digital twin technology with lean manufacturing principles to enhance engineering education. Focusing on the stamping process of sensor manufacturing, the study demonstrates how digital modeling and real-time simulations can enhance student engagement and learning outcomes. Beyond these quantitative results, the work emphasizes the pedagogical value of teaching lean manufacturing through interactive, real-time simulation environments. Rather than being passive recipients of lean concepts, students actively identified inefficiencies, implemented corrective actions, simulated outcomes, and validated improvements using digital twin models. This approach effectively bridges the

gap between classroom theory and real-world application, transforming lean manufacturing from an abstract concept into a practical capability.

As engineering education evolves to meet the demands of Industry 4.0, integrating digital twins and data-driven simulations into the curriculum becomes increasingly essential. This study presents a replicable model where process optimization, lean manufacturing education, and smart manufacturing technologies converge, equipping students to become future-ready engineers. The key contributions of this study to engineering education are:

1. This study demonstrates how digital twin technology can be effectively combined with lean manufacturing principles to create immersive, interactive learning experiences that bridge the gap between theory and practical application.
2. The approach fosters critical problem-solving, decision-making, and analytical thinking by allowing students to experiment with real-time simulations, observe immediate consequences, and identify inefficiencies in a manufacturing process.
3. By making traditionally intangible forms of waste, such as waiting time, over-processing, and unnecessary motion, visible within a simulated environment, students can better diagnose problems and propose targeted improvements.
4. The framework supports experiential, situated, and cognitive apprenticeship learning, promoting iterative experimentation, reflection, and knowledge transfer, and provides a foundation for broader implementation of digital twins in educational settings, including scalability, interoperability, and longitudinal skill assessment.

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Appendix

Course Evaluation Survey

Course Title:

Semester/Term:

Instructor Name:

Please rate the following statements about the course on a scale of 1 to 10, where 1 = Strongly Disagree and 10 = Strongly Agree.

Interest stimulation	
The course content captured my interest and kept me engaged.	
The activities and exercises encouraged me to explore concepts further.	
The use of technology made the course more interactive and exciting.	
Content Relevance	
The topics covered were relevant to current industry practices.	
The course helped me understand practical applications.	
The exercises enhanced my understanding of real-world processes.	
Support from Course Materials	
Resources (slides, readings, and tutorials) were helpful for learning.	
I was able to use the course materials independently to complete tasks.	
The instructor provided adequate support and clarification during exercises.	
Overall Satisfaction	
The course met my expectations regarding learning outcomes	
I feel more confident applying course concepts after this course.	
This course contributed positively to my learning.	

Open-ended feedback:

What did you like most about this course?

What improvements would you suggest?

Muhammad Shamikh Khan

Muhammad Shamikh Khan is affiliated with Soluzione Solare S.r.l., Vicenza (VI), Italy. His professional interests include renewable energy systems and sustainable engineering solutions. He is actively involved in industry-focused projects related to solar energy and sustainable technologies.

Anis Fatima

Dr. Fatima is an accomplished academic in Manufacturing and Mechanical Engineering Technology at Michigan Tech. She has developed and delivered graduate and postgraduate courses, supervised numerous PhD

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John Irwin

Dr. Irwin is a Professor of Mechanical Engineering Technology at Michigan Technological University. He teaches Product Design and Development, Parametric Modeling, and Senior Design. With five years in engineering design, industry consulting experience, and over 30 years of teaching, his research focuses on teaching and learning in CAD, analysis, and manufacturing.