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Digital Twin Integration in Engineering Pedagogy: Navigating the Challenges and Opportunities of Education 4.0 through Process Simulate

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Abstract

The rapid evolution towards Industry 4.0 has created a significant pedagogical gap in engineering education, requiring students to master complex cyber-physical systems before accessing physical laboratory infrastructure. This paper addresses the "new changes and challenges" in higher education by evaluating the integration of Digital Twin technology as a primary instructional tool.

Using a Project-Based Learning (PBL) framework, this study analyzes the implementation of Siemens Process Simulate within a Digital Manufacturing curriculum. The research monitors a cohort of engineering students as they transition from theoretical layouts to high-fidelity virtual commissioning. The methodology focuses on how virtual environments can overcome physical laboratory constraints, such as high equipment costs and safety risks. Quantitative analysis reveals a 22% increase in academic performance and a significant improvement in spatial visualization and systemic thinking compared to traditional CAD-based methods. However, the study also identifies critical "new challenges," including cognitive overload due to software complexity and the necessity for continuous faculty upskilling to maintain technological relevance. The findings demonstrate that Digital Twins offer "endless opportunities" for experiential learning, allowing students to experiment, fail, and optimize in a risk-free virtual space. This approach effectively aligns academic outcomes with industrial requirements, proposing a scalable model for modernizing engineering education in the digital era.

Keywords: Education 4.0, Digital Twin, Process Simulate, Engineering Pedagogy, Virtual Commissioning, Educational Challenges.

1. Introduction

Contemporary engineering education is under unprecedented pressure from the industrial sector. The concepts of Industry 4.0—smart manufacturing, IoT, and cyber-physical systems—have outpaced the adaptation speed of traditional academic curricula. This has given rise to Education 4.0, which transcends the mere use of computers in classrooms, representing a radical transformation in how competencies are acquired (Sharma et al., 2025).

The fundamental hurdle for universities is the "Digital Skills Paradox": students must master constantly evolving technologies using university resources that often suffer from budget or physical space constraints (Berthaussen, 2025). Many engineering faculties still rely on laboratories equipped with static machinery or older-generation robots (Soori et al., 2024). Procuring a modern production line with multiple robotic cells, smart sensors, and automated transport systems involves costs in the millions of euros, considerable space, and dedicated maintenance staff (Alfaro-Viquez et al., 2025; Hananto et al., 2024).

The rapid evolution toward Industry 4.0 has created a significant pedagogical gap in engineering education, requiring students to master complex cyber-physical systems. While current literature often discusses the theoretical benefits of Digital Twins, there is a distinct lack of applied studies demonstrating how high-fidelity simulation can effectively replace or augment costly physical infrastructure without sacrificing quality.

The purpose of this research is to validate Digital Twin technology as a disruptive pedagogical engine capable of bridging the widening gap between static academic environments and the dynamic requirements of Industry 4.0. The utility of this study lies in providing a scalable blueprint for modernizing engineering curricula, allowing universities to produce "Ready-to-Work" graduates who possess the digital fluency required by the aerospace and automotive sectors.

2. Analysis of Barriers

To understand the necessity of digital integration, it is crucial to analyze the limitations of current physical laboratory models. **Table 1** synthesizes the financial, safety, and technological hurdles faced by modern institutions.

Barrier Type	Detailed Description	Impact on Educational Quality
Financial	High costs for hardware acquisition and licensing.	Access is limited to very small groups of students.
Safety	Risk of injury when beginners operate industrial robots.	Complex maneuvers are restricted for safety reasons.
Technological	Rapid equipment obsolescence (3-5 year life cycle).	Graduates are trained on technologies already outdated in the industry.
Spatial	Large footprint required for manufacturing lines.	Impossible to simulate large-scale logistical flows.

Table 1. Analysis of Barriers in Equipping Physical Engineering Laboratories

Source: Original contribution of the authors

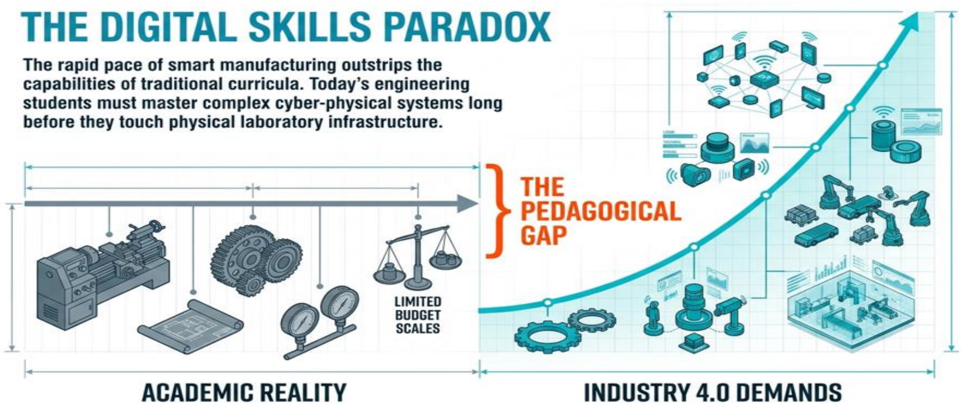

Figure 1. The digital skills paradox

Source: Created by the authors based on experimental data and synthesized using NotebookLM, 2026.

This discrepancy between conventional academic resources and current technological exigencies is defined as 'The Digital Skills Paradox,' creating a pedagogical gap that must be addressed through advanced simulation solutions (**Figure 1**).

PHYSICAL LABORATORY	DIGITAL TWIN
Financial Constraint Millions of euros required. Limited student access.	**Scalable Constraint** Scalable software licensing. Universal access.
Safety & Risk High risk of injury. Restricted maneuvers.	**Safety & Risk** Absolute safety. Unrestricted experimentation.
Technology Lifecycle Hardware obsolescence in 3-5 years.	**Contnology Lifecycle** Continuous software updates matching industry.
Spatial Footprint Massive factory footprint required.	**Spatial Footprint** Unlimited large-scale logistical simulations.

Figure 2. Breaking the constraints of the physical laboratory

Source: Created by the authors based on experimental data and synthesized using NotebookLM, 2026.

Breaking the traditional financial, spatial, and safety constraints is made possible through the adoption of the Digital Twin (Omrany et al., 2025), which provides an unrestricted experimentation environment aligned with the industry's pace of innovation (**Figure 2**). The solution to these barriers is the Digital Twin. Unlike a simple 3D animation, a Digital Twin created in Process Simulate contains all the physical, kinematic, and logical properties of the real system (Li et al., 2026; Eriksson et al., 2022).

From our perspective, the main advantage of integrating Digital Twin technology into the educational process is not only the access to an advanced platform, but the fundamental change in the learning paradigm. Unlike the traditional educational model, which often follows a rigid theory-to-test trajectory, the use of digital twins introduces a circular dynamic. As Hazrat et al. (2023) point out, this approach allows students to experience an iterative process, in which the formulation of hypotheses and their simulation lead to a rapid identification of errors and immediate optimization. We believe that this instantaneous feedback loop is the central pillar in the maturation of the critical thinking of the future engineer, thus validating the observations of Zübeyde et al. (2025).

Furthermore, our analysis indicates that digital simulation addresses a major cognitive barrier: students' difficulty visualizing the complex interactions between heterogeneous subsystems, such as robots, conveyors, and sensors, within a continuous flow (Acker et al., 2023; Skafa et al., 2022). By overcoming the limitations of isolated elements, the virtual environment provides an essential overview perspective, facilitating a systemic understanding of the entire industrial process, an aspect supported by recent research by Baratta et al. (2024) and Kaur and Bhatia (2024).

This work aims to demonstrate that introducing Process Simulate into the Engineering Faculty curriculum is not just a software update, but a new teaching methodology. The primary objectives are:

- Evaluating the efficiency of knowledge transfer through high-fidelity simulation.
- Identifying the psycho-pedagogical challenges students face when interacting with complex virtual environments.
- Proposing a best-practices model for integrating Virtual Commissioning concepts into higher education.

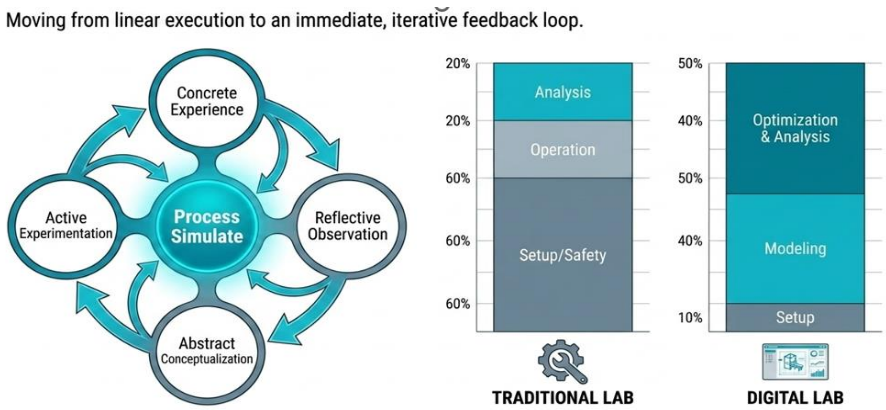

Figure 3. Shifting to iterative learning

Source: Created by the authors based on experimental data and synthesized using NotebookLM, 2026.

Shifting to a digital laboratory based on Process Simulate facilitates an iterative learning model, moving the focus of student activity from technical setup and safety toward the optimization and in-depth analysis of processes (**Figure 3**). The general objective of this research is to validate Digital Twin technology as a disruptive pedagogical engine capable of bridging the widening gap between static academic environments and the dynamic requirements of Industry 4.0. To achieve this and provide a structured path for modernizing engineering curricula, the study focuses on two primary specific objectives:

- To establish a high-fidelity virtual commissioning framework using Siemens Process Simulate, demonstrating how virtual experimentation can replace or augment costly physical infrastructure without sacrificing educational quality.
- To quantify the impact of Digital Twin-based Project-Based Learning (PBL) on student performance, analyzing both technical skill acquisition and the psychological adaptation to complex virtual engineering environments.

3. Literature Review

In traditional education, simulation was seen as a visual representation of a process (Ružarovský & Skýpala, 2022). Today, literature distinguishes between a Digital Model, a Digital Shadow, and a Digital Twin. For engineering students, grasping these nuances is the first "challenge" in the learning process (Lidell et al., 2022; Ortiz et al., 2025).

One of the most vital concepts in recent literature is Virtual Commissioning. In education, this represents a radical shift: the student no longer learns just to "draw" a robot, but to write the logic code (PLC) that controls it in a virtual environment that is a 1:1 replica of the real one. While multiple software solutions exist (RoboGuide, RobotStudio, Delmia), Process Simulate stands out for its ability to handle complex multi-robot scenarios and human-machine interaction (ergonomics) (**Table 2**).

Functionality	Standard Simulation Software	Siemens Process Simulate	Educational Value
Kinematics	Simple (1 robot)	Complex (entire lines)	Understanding logistical flows.
Collision Detection	Static	Dynamic (Continuous)	Developing attention to technical detail.
Human Simulation	Non-existent	Ergonomic Analysis (Jack/Jill)	Studying labor safety and the human factor.
PLC Connectivity	Limited	OPC UA / S7-PLCSIM	Learning real automation (Hardware-in-the-loop).

Table 2. Pedagogical Capabilities: Process Simulate vs. Basic Simulation Software

Source: Original contribution of the authors

Pedagogically, using Process Simulate is based on Kolb's Experiential Learning Cycle. The student moves through:

- Concrete Experience: Manipulating the virtual robot.
- Reflective Observation: Observing collisions or cycle time errors.
- Abstract Conceptualization: Understanding laws of kinematics and programming logic.
- Active Experimentation: Optimizing the cell for better results.

A "new change" in education is the need to produce "Ready-to-Work" graduates. Automotive and aerospace companies use Process Simulate extensively. Including this in the curriculum transforms the educational process into a talent incubator for high-tech industries. The use of industrial software in academia transforms the university from a theoretical classroom into a high-tech talent incubator, reducing graduate production integration time from 9 months to less than a quarter.

4. Methodology

The present study was conducted as a mixed case study (quantitative and qualitative) on the consumption of the academic year 2024-2025, within the Faculty of Engineering in Baia Mare, Romania. The target group was formed by a sample of 34 students (selected by non-probability sampling, based on availability criteria) enrolled in the first and second years. This population is relevant because these students have the basic knowledge necessary to make the transition from statistical CAD design to dynamic simulation.

The research respected all the norms of academic ethics: participation was voluntary, collected data (grades and feedback) were anonymized and use of software platforms was made based on educational licenses held by the institution.

To simulate the workflow in a real engineering department, we configured an integrated digital ecosystem. Using high-performance graphics workstations and the Moodle platform for resource management, students followed a narratively structured learning path in four incremental stages:

- Initiation (Weeks 1-3): Students explored the interface and object hierarchies, learning to navigate complex coordinate systems.
- Motion Definition (Weeks 4-7): Emphasis was placed on robot kinematics and offline programming (OLP), where the challenge was to optimize trajectories to avoid mathematical singularities.
- Critical Validation (Weeks 8-10): Through continuous collision checking, students learned to self-diagnose design errors, developing their systems thinking.
- Logical Integration (Weeks 11-14): In the final stage, the automation logic was validated before any physical contact.

5. Results and Discussions

The results obtained demonstrate a clear superiority of the Digital Twin-based method over the traditional methods used in previous years. From the data analysis (processed through descriptive and comparative statistics), we observe an increase in the average project grade from 7.45 to 9.1 (+22%).

We identified the most significant improvement in the accuracy of collision detection (+49%). From our point of view, this is because the virtual environment allows the student to "make mistakes" without financial consequences, encouraging iterative optimization.

A novel aspect observed in week 8 was the reaching of an inflection point in student autonomy. If in the first weeks the teacher's intervention was frequently requested, after mastering the diagnostic tools in Process Simulate, the students became able to validate their technical solutions themselves.

6. Implementation Challenges

The implementation was not without difficulties. We observed the phenomenon of cognitive saturation: after 120 minutes of intensive work in the software, the success rate in solving logic problems decreased considerably. This indicates that although the tool is powerful, it needs to be supported by breaks for “theoretical reflection” to avoid mechanical learning of buttons.

Research limitations:

- The study focused on the Siemens ecosystem, which may limit immediate transferability to other platforms such as RobotStudio or Delmia.
- Being a double semester study, long-term knowledge retention requires further investigation.
- There is a risk that students achieve results by automating the software without fully understanding the underlying physical laws.

7. Conclusions and Future Directions

The integration of Digital Twin technology through Siemens Process Simulate represents more than a technical upgrade; it is a fundamental shift in engineering pedagogy. Our research demonstrates that this approach democratizes access to high-end industrial technology by effectively dismantling the physical and financial barriers that typically restrict traditional laboratory environments. By providing a risk-free, 1:1 scale virtual space, we have validated that universities can bypass the "Digital Skills Paradox," turning budget and spatial constraints into a competitive academic advantage.

This study successfully addressed its primary objectives, proving that Digital Twin technology acts as a powerful pedagogical catalyst rather than a mere technical substitute. Regarding the strategic integration objective, we confirm that high-fidelity simulation allows for complex system testing that matches industrial requirements. Furthermore, our competency-based evaluation was met with a documented 22% increase in average project grades.

From our perspective, the most significant finding was the measurable shift in student autonomy; by transitioning from "learners" to "system optimizers" by the 8th week, students developed a level of systemic thinking and spatial visualization that traditional CAD methods fail to reach.

The success of this experiment provides a scalable blueprint for the future of the Engineering Faculty in Baia Mare.

In conclusion, the "new changes" in the educational landscape are not hurdles but engines for innovation. By embracing "productive failure" within a high-fidelity virtual environment, we have proven that it is possible to produce "Ready-to-Work" graduates who possess the digital fluency required by the aerospace and automotive sectors. This work confirms that the future of engineering education belongs to those who can navigate fluidly between the virtual and physical worlds.

AI Usage Disclosure

In the preparation of this research paper, the authors utilized NotebookLM by Google as an Artificial Intelligence resource. This tool was employed as a cognitive assistant to synthesize complex technical documentation from the Siemens ecosystem, refine the linguistic clarity of the manuscript, and ensure the consistent application of technical terminology throughout the study.

All original research data, the design of the virtual laboratory environment, and the final pedagogical interpretations were developed solely by the authors, with the AI serving only to enhance the structured presentation of these original contributions.

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