Enhancing the Teaching of Industrial Plants Dynamics through 3D Simulation and Virtual Reality

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Abstract: With the introduction of new technological innovations, there are great opportunities to enhance traditional teaching methods in engineering education. The integration of 3D simulation and virtual reality emerges as a promising approach, offering a fully immersive and interactive learning environment for students. This paper delves into the integration of Siemens Tecnomatix Plant Simulation with VR technologies, presenting a novel approach to teaching key dynamics of industrial plants. Through this methodology, students gain an intuitive and comprehensive understanding of the principles governing industrial plant operations. This approach not only enriches the learning process but also equips students with the skills and knowledge essential for navigating the complexities of modern industrial environments. The paper describes the methodology used to design an effective simulation to convey the understanding of key principles of industrial plants operations to engineering students. The specific simulation is then implemented to not only allow real-time observation of an industrial plant's processes but also offer a virtual immersion within the plant. This setup enables students to modify key parameters and directly observe the impacts of various design and management decisions to gain greater understanding of the subject. The paper reports also the results of the preliminary testing of the simulation in virtual reality. Finally, insights from the practical experiences are described, highlighting advantages and limitations to evaluate the effectiveness of this innovative approach.

Keywords: Simulation, Virtual Reality, Engineering Education

1.Introduction

Educational institutions are continually seeking innovative teaching methods that can bridge the gap between theory and practice. Enhanced teaching methods are needed to not only improve the engagement and retention of knowledge but also to prepare students for the dynamic and technologically advanced work environment they will face after graduation.

Advancements in digital technologies such as 3D simulation and virtual reality (VR) offer promising solutions. Virtual reality is a cutting-edge technology that creates a simulated environment, distinct from the real world. Using computer technology, VR places the user inside a three-dimensional experience, where they can manipulate objects or perform a series of actions. This is typically achieved through VR headsets equipped with special screens and sound systems that help simulate a user's physical presence in this virtual world (Alcácer & Cruz-Machado, 2019; Pirker et al., 2022).

These technologies have the potential to transform traditional classrooms by providing students with immersive and interactive learning experiences. 3D simulations allow students to visualize and manipulate engineering concepts in a virtual space, thereby enhancing understanding and retention. VR takes this a step further by placing students inside a fully immersive environment, where they can interact with virtual representations of industrial plants as if they were physically present.

Moreover, traditional teaching methods in industrial plant dynamics often struggle to convey the complex, real-time interactions between various components of a manufacturing plant. For instance, students learning about process optimization and losses propagation might find it difficult to visualize how changes in one part of the plant affect operations elsewhere.

The aim of this paper is to explore the integration of a 3D simulation of industrial plants with virtual reality technologies to teach dynamics of industrial plants more effectively. This study builds on existing research (Alcácer & Cruz-Machado, 2019; Trebuna et al., 2023) to provide a comprehensive understanding of these technologies' educational benefits. By adopting this innovative approach, we seek to provide students with a more intuitive and comprehensive comprehension of industrial plant operations, fostering a better understanding of the governing principles of operations management. Through this work, the paper aims to contribute valuable insights into the potentials and limitations of these technologies in modern educational settings, offering guidance for integration in operations management courses.

This paper is structured as follows: Section 2 describes the background on VR technology used for simulation visualization and training, Section 3 describes the methodological approach used to design and implement this educational content, Section 4 describes the implementation process for the 3D simulations and the integration with VR, Section 5 presents a discussion about ongoing results and future development while Section 6 relates the concluding remarks of the work.

2.Background

The use of Virtual Reality (VR) in the simulation of industrial plant operations has become a crucial technology for enhancing training, safety, and operational efficiency. VR provides a realistic, interactive environment where complex industrial processes can be simulated, allowing for better understanding and optimization of operations. Indeed, integrating VR with discrete event simulation has shown significant potential in visualizing and optimizing production and assembly processes, which is critical for implementing Industry 4.0 strategies (Trebuna et al., 2023). VR technologies also facilitate safe and comprehensive training environments for industrial experiments, overcoming the limitations of real-life setups that can be hazardous or logistically challenging (Kang, 2022; Liagkou & Stylios, 2019). Furthermore, virtual assistant systems are being developed to bridge the gap from initial project requirements to the virtual commissioning of modular plants, enhancing both customer interaction and project execution.

On the other hand, virtual reality and simulation are useful tools to improve the engagement and understanding of university engineering students. Through simulations, students can conduct experiments, test theories, and see the results in a safe setting. This hands-on approach helps in understanding complex systems and enhances critical thinking, problem-solving, and decision-making abilities, which are essential for succeeding in Industry 4.0 (Eriksson et al., 2021; Tseng et al., 2020).

By using VR, students can engage in detailed simulations like operating machines, managing an industrial facility, or working in a virtual laboratory, all while avoiding real-world risks. This technology supports the development of practical skills and provides valuable experience in a simulated setting (Hernandez-de-Menendez & Morales-Menendez, 2019; Trebuna et al., 2023; Tvenge et al., 2020).

Indeed, the introduction of virtual technologies is aimed also to spark curiosity in young students, exposing them to important topics with an innovative approach and bridging the existing gap between education and future work experiences, providing them with relevant practical experiences with innovative technologies (De Giorgio et al., 2023). Existing research highlights the critical role of VR in fostering comprehensive student engagement across cognitive, behavioral, and emotional aspects. It points out that the use of VR in educational settings is becoming increasingly popular, growing within higher education, with notable adoption rates of 46% in U.S. universities and as high as 96% in some cases (Jindal et al., 2023; Lin et al., 2024).

3.Methodology

The methodological approach proposed is depicted in Figure 1.

The first step regards the selection of a simulation software suitable to implement relevant simulation scenarios in virtual reality (Kovbasiuk et al., 2021). After this choice, the educational simulation is designed. This includes identifying the key principles of industrial plants operations to convey to engineering students, design the simulation scenarios and the interactive elements of the simulation (Radianti et al., 2020).

Thus, the actual implementation of the different simulation scenario is to be carried out in the selected simulation software. Before full deployment, the simulation undergoes pilot testing where it is run on a smaller scale to identify any issues or areas for improvement. Feedback is gathered from the pilot test participants and used to refine and update the simulation. This may involve adjusting scenarios, interface improvements, or fixing bugs.

Once the simulation is finalized and updated, it is deployed in the classroom setting. Here, students engage with the simulation as part of their coursework.

The final step involves the evaluation of the effectiveness of the simulation in meeting learning outcomes. This can include both qualitative and quantitative assessments to measure knowledge gains, engagement, and skill development (De Giorgio et al., 2023).

Each step builds on the previous one, ensuring that the simulation is effectively integrated into the learning process and enhances educational outcomes.

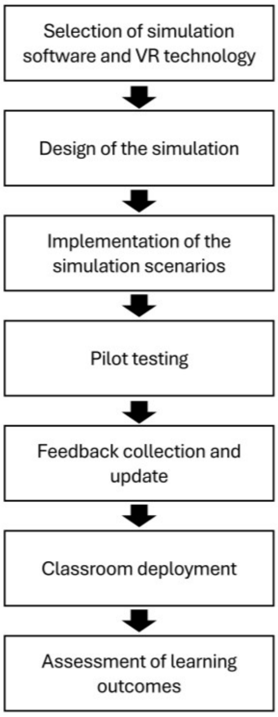


Figure 1: Methodological approach.

4. Implementation

4.1. Selection of simulation software

Siemens Tecnomatix Plant Simulation, a widespread commercial simulation software, has been identified as the ideal platform for developing educational materials, ensuring the presence of specific functional requirements. The software’s extensive object libraries and support for 3D modeling and VR-based visualization, were critical characteristics in order to allow the development of immersive learning experiences that engage students actively. This choice is supported by studies highlighting the software's effectiveness in educational contexts (Trebuna et al., 2023; Tvenge et al., 2020)

4.2. Design of the simulation

The design of the simulation comprises two steps: first, the identification of relevant key principles to convey, then the identification of associated simulation scenarios.

Overall Equipment Effectiveness (O.E.E.) is a universal performance metric commonly used in the manufacturing sector to assess the effectiveness of a piece of equipment or operations. The simulation scenarios involving varying conditions and the integration of theoretical cycle times (Tc), macro stops (failed time and setup time), efficiency performance, and quality rate (waste or rework), directly tie into teaching the components of O.E.E.:

- Availability: highlighted by incorporating failed times and setup times that change with the transition between different productions.
- Performance: demonstrated through the manipulation of processing times and variable generation times for raw materials.
- Quality: addressed by scenarios that involve scrap or rework, affecting the overall quality rate of the production process.

Another important topic to include is bottleneck management: simulations involving multiple machines in a line with different theoretical cycle times and the effects of macro stops help students understand how bottlenecks can form and affect the flow of production. By adjusting buffer sizes, students can see directly how constraints can be managed or shifted within a production line. In scenarios where students manipulate buffer sizes, they learn how buffers serve as a method for balancing the flow between processes and preventing bottlenecks. This principle is crucial for understanding how to maintain operational efficiency and minimize downtime in a production line.

Moreover, through simulations that allow students to adjust the position of quality control within the production line, students can explore how the positioning of quality checks affects the overall quality output and efficiency of the line. This teaches principles related to process design and quality assurance, also highlighting the difference implication on raw materials costs.

Setting up simulations that compare different layouts—like production lines versus department-based setups—students can analyze how different operational setups affect the saturation levels of machines and overall production efficiency.

Finally, when students can adjust the production volume by varying the generation speed, they learn about the effects of production volume on machine saturation. This scenario leads students to evaluate how changes in production volume impact the utilization and efficiency of machines.

These principles are fundamental to industrial engineering and management, and using simulation and virtual reality to illustrate these concepts allows students to engage in active learning through direct experimentation and observation. Table 1 reports the different scenario defined.

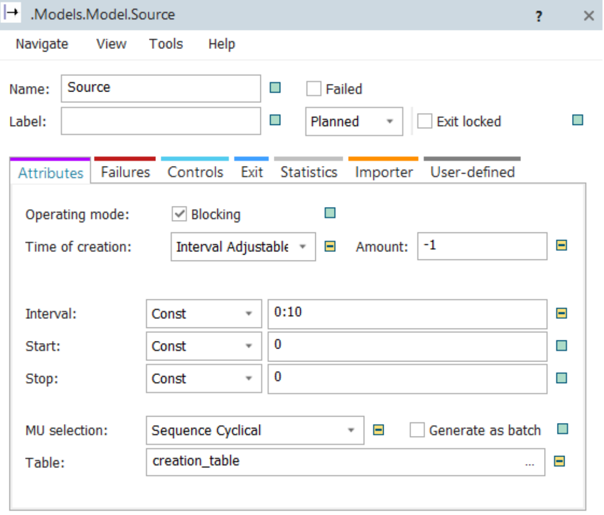
Table 1: your table’s caption

Scenario	Variant
Availability	Setup for different products
	Failures
Quality rate	Position of quality control
	Scrap/rework
Efficiency performance	Blockages, starving and buffer dimension
Layout	Line vs. Department

4.3. Implementation of the simulation scenarios

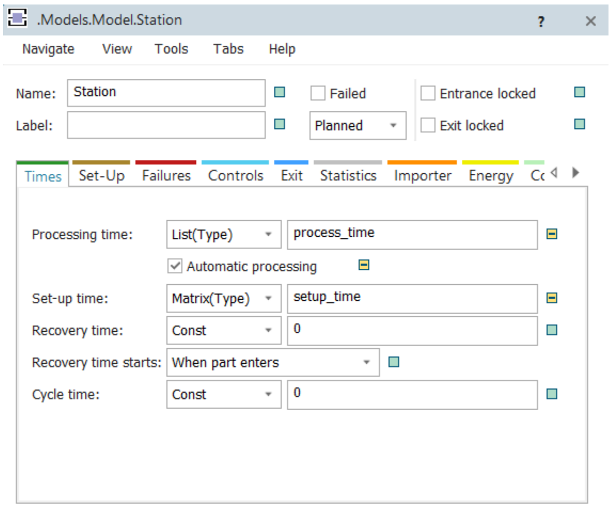
Siemens Tecnomatix Plant Simulation, a widespread commercial simulation software, has been identified as the ideal platform for developing educational materials, ensuring the presence of specific functional requirements. The software’s extensive object libraries and support for 3D modeling and VR-based visualization, were critical characteristics in order to allow the development of immersive learning experiences that engage students actively. The version of the software used was Plant Simulation version 2302.

To implement setup operations inside the simulation, a matrix has been defined to collect setup times necessary to switch from one product to another, for each possible pair of products (Figure 2, Figure 3, Figure 4). In particular, three different products have been implemented in order to allow this phenomenon to be observed adequately.



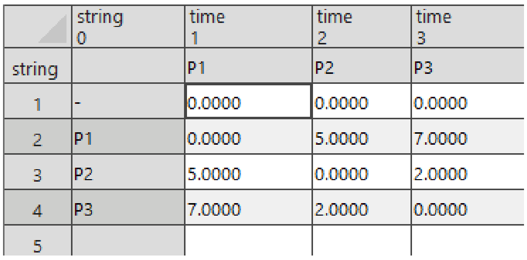
Name: Source ☐ Failed
Label: Planned ☐ Exit locked
Operating mode: ☑ Blocking
Time of creation: Interval Adjustable Amount: -1
Interval: Const 0:10
Start: Const 0
Stop: Const 0
MU selection: Sequence Cyclical ☐ Generate as batch
Table: creation_table

Figure 2. Definition of different types of products though the use of source settings.



Name: Station ☐ Failed ☐ Entrance locked
Label: Planned ☐ Exit locked
Processing time: List(Type) process_time
☑ Automatic processing
Set-up time: Matrix(Type) setup_time
Recovery time: Const 0
Recovery time starts: When part enters
Cycle time: Const 0

Figure 3. Implementation of setup procedures for the station.



	string 0	time 1	time 2	time 3
string		P1	P2	P3
1	-	0.0000	0.0000	0.0000
2	P1	0.0000	5.0000	7.0000
3	P2	5.0000	0.0000	2.0000
4	P3	7.0000	2.0000	0.0000
5				

Figure 4. Definition of setup times for different product type

As far as the definition of defect rates is concerned, these were created using the creation of new attributes for each specific station which, linked to an appropriate method, would allow the products themselves to be characterized as defective at the time they were processed by the station (Figure 5). In the same way, quality control was treated using an ad hoc method for the detection and treatment of defective products (Figure 6). In each simulation, two buttons have been set to allow you to start, lock and reset the simulation directly within the virtual environment.

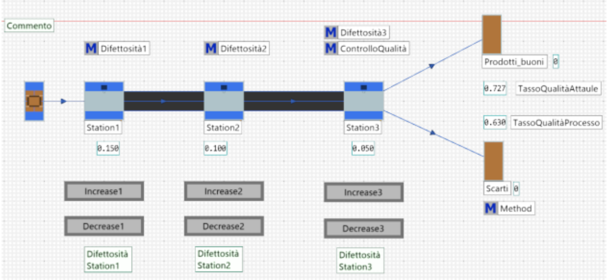


Figure 5. Planning view of the simulation scenario variant with 3 stations with quality control only at the end.

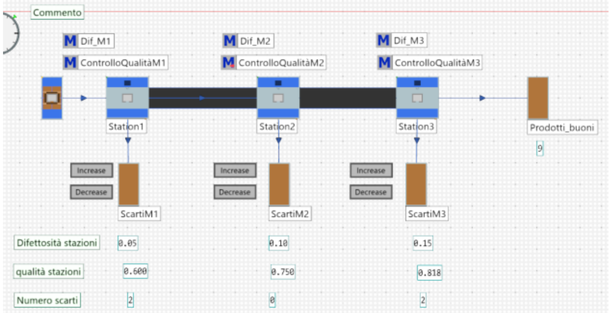


Figure 6. Planning view of the simulation scenario variant with 3 stations each with quality control.

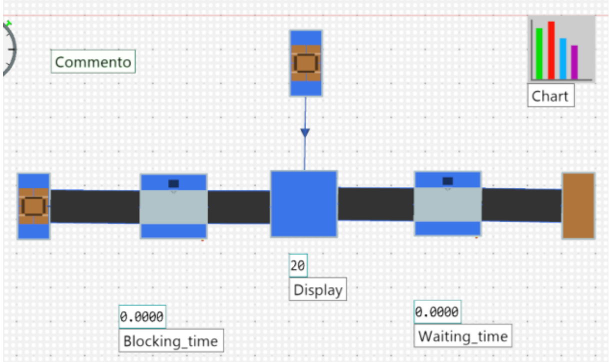


Figure 7. Planning view of the simulation scenario variant with failures and buffer size to affect waiting and blocking time.

To promote interactivity, the parameters to be modified have been defined and buttons have been created directly to make the change within the simulation itself during the simulation run. Indeed, “basic interaction” is seen as a key design requirement for educational VR applications (Radianti et al., 2020).

In this way, students will be able to directly observe how varying certain quantities such as the availability to failure or the defect rate of the products also impacts the rest of the performance of the other stations.

4.4. Pilot testing

Siemens Tecnomatix Plant Simulation has a specific “go VR” function that allows to execute the run of the simulation on a VR headset. However, it is important to note that only recent versions of the software, such as 2201 and 2302, have this additional function, whereas version 16 does not allow for VR interactions (Figure 8).

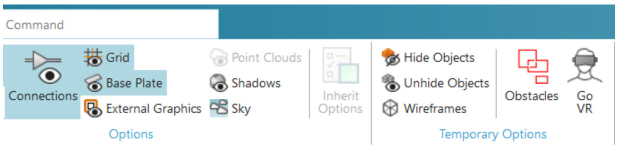


Figure 8. Detail of the Go VR function in Siemens Tecnomatix Plant Simulation 2302.

Since the software uses the SteamVR platform to enable connection to a VR headset it is necessary to install SteamVR on the computer beforehand. Starting Plant Simulation and opening the 3D simulation model is possible to start the run of the simulation on the VR headset pressing the "Go VR" button in the View tab.

HTC VIVE headsets are recommended for this implementation, thus pilot testing was conducted primarily using a VIVE Pro 2 Headset. However, additional tests confirmed the possibility to use Meta Quest 3 too.

Figure 9 presents a screenshot of the 3D view of one simulation scenario while Figure 10, Figure 11 and Figure 12 depict the pilot testing of VR functionalities.

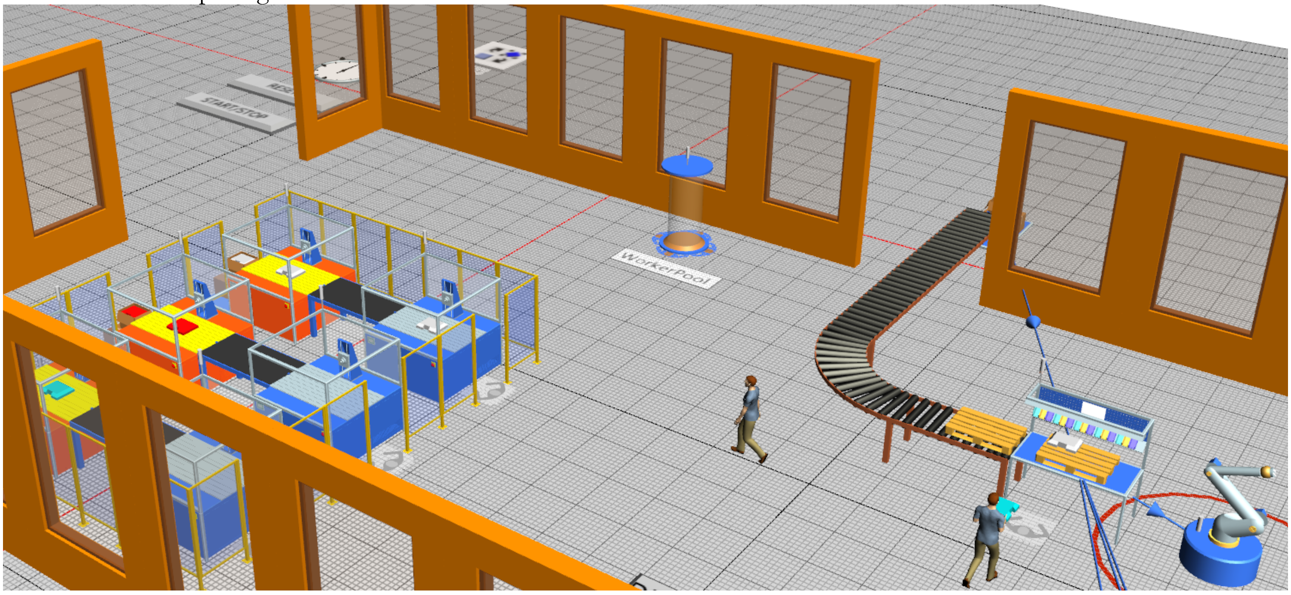


Figure 9. Screenshot of 3D view.

Figure 10. VR Pilot testing.

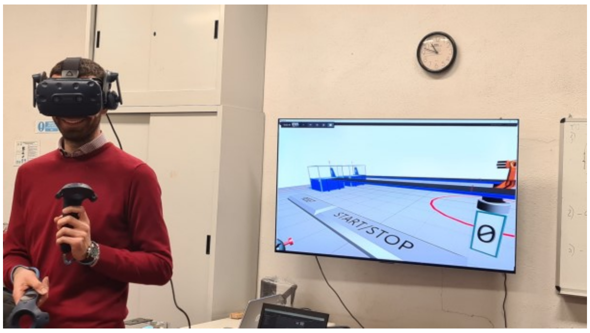


Figure 11. Photo from pilot testing: details of interactive buttons implemented to enable start and stop of the simulation inside the VR environment.

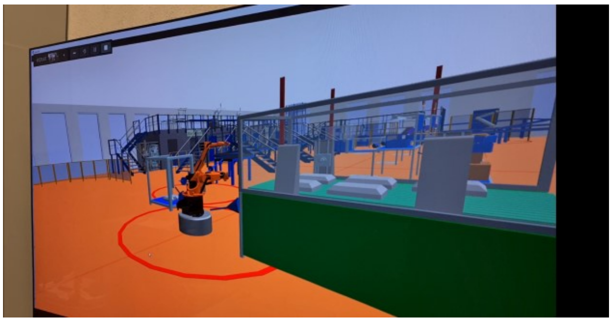


Figure 12. Photo from pilot testing: details of 3D view as seen by the person with the VR headset.

4.5. Feedback collection and update

During pilot testing feedback have been collected to identify deployment issues and possibility of improvement. In particular, feedback suggested the implementation of changes in the graphical aspects, such as buttons positioning to improve interactivity, display presence and the setting of a lower running speed when in the presence of assembly and disassembly operations. To prevent the simulation run from lagging it has also been noted that it is preferable to use the HTC VIVE Pro 2 headset or a Meta Quest 3 one, but only if the headset in question remains connected to the computer through USB instead of streaming the contents through Wi-Fi, especially for complex simulation scenarios. The identified improvements have been implemented in preparation for the classroom deployment.

4.6. Classroom deployment

This step has not yet been implemented since the selected course is scheduled for the next semester. However, some preliminary preparations have already been carried out. Necessary infrastructural modifications were made to accommodate the VR hardware and the simulation software. This included setting up VR stations with sufficient space for movement, installing high-performance computers capable of running the simulations, acquiring the necessary software licenses, and installing them, and ensuring robust network connectivity to handle VR data throughput.

4.7. Assessment of learning outcomes

To evaluate the theoretical and practical knowledge acquisition of students, structured quizzes or tests will be administered both before (pre-test) and after (post-test) the simulation sessions (De Giorgio et al., 2023; Radianti et al., 2020). These tests are designed with specific questions aimed at measuring students' understanding of key concepts such as OEE, availability, quality rate, effectiveness, material flow dynamics and storage policies:

- Pre-test: assesses prior knowledge of students to establish a baseline and identify any knowledge gaps.
- Post-test: measures what students have learned during the simulation, directly assessing the educational impact of the VR technology and the simulation.

Additionally to quantitative tests, qualitative feedback is crucial for understanding students' experiences with the simulation and VR. This feedback will be gathered through:

- Interviews: conducted at the end of sessions, these interviews will allow students to freely discuss their impressions, challenges faced, and key learning moments.
- Satisfaction surveys: completed by students, these surveys will evaluate various aspects of the learning experience, including the ease of use of the VR interface, engagement, and perceptions of the utility of the simulation in applying theoretical concepts practically.

After collection, the data will be analyzed to evaluate various aspects of the educational intervention. The analysis will include a comparative evaluation of pre-test and post-test results to assess improvements in understanding key concepts, an assessment of how virtual reality has influenced engagement and interactivity based on qualitative feedback and analysis of interactions during simulation sessions, and an identification of improvement areas through the analysis of technical difficulties encountered, survey responses, and interview feedback to identify strengths and areas for improvement in both technology and pedagogical approach.

Based on the results of the assessment, modifications will be implemented in subsequent cycles of the course, continually enhancing the learning experience and effectiveness of educational tools. The simulation scenarios and interfaces will undergo iterative refinements, including technical adjustments (graphics, user interfaces, or optimizing VR performance to reduce lag and improve the realism of simulations), content updates (complexity of scenarios) and pedagogical enhancements (modifying educational strategies).

5.Discussion

The integration of VR into engineering education is expected to enhance students' understanding of complex concepts through immersive experiences. This expectation is supported by existing research indicating that VR can significantly improve student engagement and understanding (Eriksson et al., 2021; Tseng et al., 2020). However, challenges such as technological adaptation, cost implications, and varying student receptivity to new learning tools could affect the deployment.

5.1 Expected benefits

By immersing students in a virtual environment where they can interact with complex industrial systems, VR is expected to significantly enhance engagement and understanding. VR simulations can serve as a bridge between theoretical knowledge and practical application, providing a practical understanding of industrial dynamics. The flexibility of 3D simulations allows for educational experiences that can be tailored to show specific aspects of plant dynamics or to challenge students based on their competency levels. Moreover, since virtual reality is one of the enabling technologies driving Industry 4.0 and the digital transformation, it is also useful to provide engineering students with first-hand experiences on its use.

5.2 Criticalities and barriers

Some criticalities and implementation barriers should be highlighted. Some criticalities (specific challenges related to the use of VR technology) and implementation barriers (broader issues such as cost and logistics) should be highlighted. The implementation of VR in education is technologically demanding, requiring robust hardware, specialized software, and some technical support. Ensuring an integration of these technologies into existing educational frameworks can be complex and resource intensive. The initial setup cost for VR equipment and software can be significant, since it should be considered not only the purchase price, but also ongoing costs related to maintenance, updates, and training of faculty and staff. Moreover, deploying VR on a large scale involves logistical challenges, including sufficient physical space for VR setups and managing increased bandwidth demands. To acquire a clear understanding of the weaknesses and strengths of the implementation it will be also critical to conduct the assessment phase with a significant number of participants and following the systematic approach defined in the methodology.

6.Conclusion

This paper presents an approach to integrate 3D simulation and virtual reality into the teaching of industrial plant dynamics. Using Siemens Tecnomatix Plant Simulation combined with VR, we have introduced a novel educational approach that enhances the learning experience of engineering students by providing a more intuitive and interactive understanding of complex industrial processes. This integration aims to bridge the gap between theoretical knowledge and practical application, preparing engineering students more effectively for the work environment. The methodology used in this project serves as a guideline for educators looking to implement advanced simulation technologies in their curriculum. The detailed steps—from software selection and scenario design to pilot testing and feedback integration—provide a replicable framework. Moreover, the approach presented highlights critical implementation steps and gives suggestions about practical aspects of the deployment. Allowing students to manipulate key parameters and directly observe the outcomes of their decisions has been deemed effective in enhancing their understanding of operational dynamics. However, at the moment this study has several limitations, notably the absence of real classroom applications and the subsequent lack of evaluation based on student feedback. Future research will aim to address these limitations. Indeed, the next step of the research will be the integration of this technology into selected courses, which will allow us to gather data on its impact on student learning outcomes, completing this investigation. As we continue to deploy and refine these technologies, we anticipate they will become an integral part of educational practices.

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