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Research Article

From visualization to discovery, a transdisciplinary framework to re-engineer engineering practices

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Abstract

One way business students apply theoretical knowledge and enhance their decision-making skills is by using digital simulators and seldomly in real life due to the strategic and economic nature of the consequences involved. Besides, engineering students practice their knowledge and skills in laboratories and or actual companies, in many cases, due to the economic and tactical nature of the decisions involved. Due to the COVID pandemic starting in 2020, many engineering schools closed their laboratory access while companies also paused their students' involvement. Hence, many engineering faculties searched for new ways to keep educational schedules and standards. The contribution of this work supplies a transdisciplinary framework (involving faculty, students, and practitioners) to redesign engineering practices to achieve and improve pre-pandemic learning levels. A Six Sigma experience using a web-based Virtual Reality production facility illustrates the framework through three iterations: one-way information flow, two-way interaction with limited capabilities, and complex systems simulations to explore sophisticated challenges. Results show that students experience a more substantial engagement in these novel practices where they expose themselves to challenges that, in many cases, could not be possible in a real-life experience due to safety and economic consequences.

Keywords: digital and open learning for engineering, engineering education, experimental design, interactive simulation for engineering, transdisciplinary design.

1. Introduction

In engineering courses related to Lean Manufacturing, Six Sigma, and Operations Management, among others, the importance of "learning by doing" and putting knowledge into practice is generally emphasized. Real hands-on projects conducted in local industries are often required from professors to be carried out by students. These projects commonly represent a significant percentage of the course evaluation.

Engineering faculty teaches the importance of going to the shop floor (Genba in Japanese) to be present in the place where transformation processes occur (Imai, 2012). However, coordinating visits to industrial processes is not always feasible for logistics, safety, and product integrity reasons. It is also difficult for companies to allow students to walk among industrial equipment, observe, and carefully interact with the processes. Also, it is generally not feasible for students to conduct experiments, change variables and see the consequences of their decisions in actual processes due to the potential costs involved.

The COVID-19 pandemic represented an additional challenge since students (in our experience) were not allowed at all to do on-site visits to companies. Therefore, an academic team (AT) at Tec de Monterrey, Mexico, decided to develop a small virtual reality manufacturing plant where groups of students interact remotely using their laptop computers. They had the opportunity to work in a simulated Genba environment, interact among them inside the plant, safely observe and discuss the processes, sample the non-conforming levels, and make recommendations for improvement actions as a team (Figure 1).

Tec de Monterrey is a Mexican institute of technology that includes 26 campuses in Mexico, with over 94,000 students and over 21,000 professors and collaborators, offering several multi-campus face-to-face/online domestic/international programs (Tecnologico de Monterrey, 2022). One of these programs hosted the implementation presented in this article.

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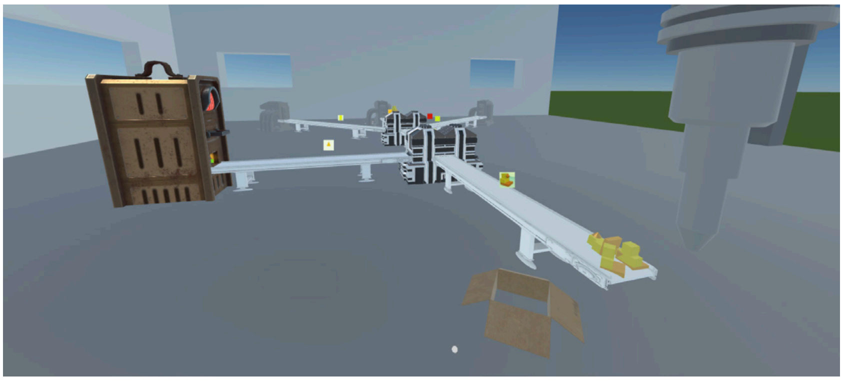


Figure 1. Initial virtual reality manufacturing plant.

The initial version had limited visualization of the process, and very restricted interaction with the process's elements was available. However, according to students and professors (through a feedback instrument) who used this original virtual plant, it was a successful educational experience since it allowed students to learn and practice their decision-making skills in an environment closer to reality than structured textbook problems. However, users found areas of opportunity.

Engineering education faces the challenge of transferring theoretical knowledge to practical work, providing students with a smooth transition from university to professional practice (Tamayo-Enriquez, 2019), and preparing them for real-world challenges. Universities need to associate with companies to give students a more solid formation. Since it is not always feasible to provide full access to students to these proposed associate companies, the joint development and validation of these simulators could give a more effective way to train students before they start their professional work. Simulators of this kind are a special kind of gaming with an educational purpose. From Trepte et al. (2012, p. 832), "[...] online gaming may produce strong social ties [...]."

TE (2020) state that transdisciplinary engineering "[...] is a methodological approach, explicitly incorporating social sciences to gather information and to guide implementation of engineering solutions in practice." The AT at Tec de Monterrey considered this a critical approach to incorporate for further improvement of the first engineering practice educational experience.

A second design, supported by the experience and resources of a technical team, solved several of the problems identified in the original design, allowing direct interaction, the possibility of validating causal relationships, and the use of the transdisciplinary engineering methodology to solve several different engineering practices. Overall, students and professors again evaluated this upgraded plant as a successful experience.

The process continued in the second upgraded educational experience attempt. The obtained results, and the possibility of using this free learning experience for the further development of more case studies, resulted in developing a transdisciplinary framework for engineering education to contribute to the enrichment of tactical engineering decision-making skills required by students.

In the second upgrade, limited interaction and experimentation were feasible. With the possibility of walking inside the plant using VR, this feature was engaging and exciting for our students. However, they still wanted to explore more options. A third upgrade included more sophisticated experiences and new scenarios. This upgrade use simulation software (FlexSim, 2022). This simulation software allows the use of VR for the visualization of simulations. Therefore, the complete cycle from visualization to limited interaction to complete interaction and redesign (under specific rules) was closed.

The contribution of this work relates to the future of engineering education (digital and open learning) by developing a transdisciplinary framework for Digital Simulation Engineering Practice Development, Evaluation, and Improvement. This paper is a revised and extended version of Trigos & Tamayo (2022).

The rest of the paper includes: Section 2 shows the initial challenge and the development of the original educational experience, Section 3 states the transdisciplinary framework developed, Section 4 illustrates the potential of virtual reality implementation, Section 5 works an example showing how the framework guides the development of upgraded versions of the original educational experience, results achieved, and finally Section 6 includes conclusions and ideas for further research.

2. The need and development of the original educational experience

The COVID-19 pandemic generated a challenge that required an immediate solution for the AT that developed the original virtual plant: The goal at that point was to generate an educational experience that allowed students to have a challenge similar to what they will face in a genuine factory with equal or better academic learnings.

Therefore, the first task was the development of a shortlist of the characteristics that a genuine factory presents to engineering students at engineering practices. This list included unstructured problems, complex causal chains, lack mathematical causal models, unique work culture, and restrictions due to safety and productivity loss risks. The AT decided that some of these elements would not be easy or feasible to include in a fast and low-budget virtual plant design. Therefore, the AT chose to focus on those elements within reach: Unstructured problems, complex causal chains, and the lack of mathematical causal models; on the other hand. The AT decided not to provide factors such as production and non-conforming data. So, students needed to determine the related sample size and where to sample. The AT developed several study cases to provide different challenges to students according to the curriculum of the first pilot class.

The AT also realized that some restrictions in real factories were nonexistent in the virtual factory: safety and productivity risks, communication barriers, and access restrictions, among others. The absence of these restrictions allowed students to effectively use their time to solve the challenges of the study cases. Figure 1 shows a screen of the initial virtual model.

According to students' evaluations, this first plant was a success. Students appreciated the effort of quickly developing an alternative to industrial visits. Some of the characteristics of shop floors were available: complexity, non-structured data, decision-making of what to sample, how large the sample size should be, unclear definition of the problem, and the steps required. They also liked that they could visit and move around at their own pace. In general, students reported that they enjoyed solving the challenges.

It was unexpected that students did not complain about the plant's modest resolution and design resources; The AT considered that they focused more on solving the challenges of their task than on the quality of the graphics. Their main improvement recommendation was to increase the interaction possibilities. Students wanted to change process parameters and see in real-time the effects of their decisions on the processes' outputs.

Motivated by this initial success and because COVID-19 did not end in one academic semester, the AT decided to use the lessons learned from the first plant to develop an upgraded virtual plant.

3. Transdisciplinary framework for digital simulation engineering practice development and valuation

The upgraded framework (Figure 2) profits from the experience shown in the previous section and further improvement stages of this academic experience.

The AT considered that sharing this framework and experiences with different engineering majors will only result in many improvement ideas. The team has started an open repository of study cases at Tec de Monterrey. Until now, this effort has been a Tec de Monterrey project, but now Tec authorities have granted to share this experience globally. La Planta Virtual de Patos (2022) [Spanish for Duck Toys Virtual Plant] shows this virtual reality initiative link.

Using these kinds of virtual engineering cases makes it possible to make engineering practice and experience available to more students in a less costly fashion. In addition, universities could share virtual engineering practices among campuses, schools, and fellow universities, creating more shared value. The interaction between academia and industry is essential to increase the complexity of the models and the comprehensiveness of the experiences and lessons learned without endangering the personal safety of the stakeholders involved cost-efficiently.

4. The framework in practice

Now let us illustrate the framework described in the previous section throughout a pilot study to teach quality control concepts to undergraduate students.

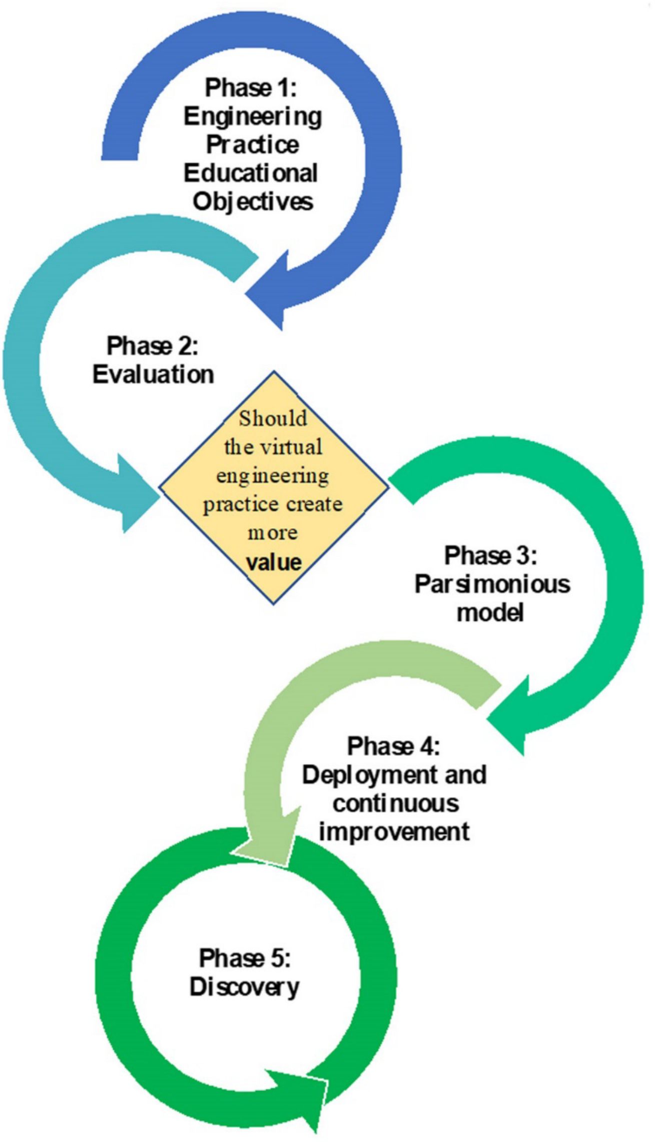
4.1. Phase 1: Engineering practice educational objectives

Step 1. Select an engineering practice to analyze: Students work in teams to calculate the baseline capability of a process and improve it using Statistical Process Control (SPC), Design of Experiments (DOE), and Value Stream Maps (VSMs).

Step 2. Identify the academic objectives of the engineering practice: Students work in teams to practice their knowledge of SPC, DOE, and VSM.

Step 3. Identify and prioritize the key elements and resources of the practice: Students make decisions and change process parameters to see if their choices lead to an improved process.

Step 4. Identify the practice's Assessment of Learning (AOL): Students report baseline and improved processes, including the tools used and the assumptions considered. Friendly competition is done among teams to recognize those teams that achieved the best results.



Phase 1:

1. Select an engineering practice to analyze.
2. Identify the educational objectives of the engineering practice.
3. Identify and prioritize the key elements and resources of the engineering practice.
4. Identify the Assessment of Learning (AOL) involved.

Phase 2:

5. Evaluate the feasibility of the virtual engineering practice.
6. Develop an evaluation frame to compare in-site versus virtual engineering practice.

VALUE ASSESSMENT

Phase 3:

7. Draft a virtual engineering practice involving a transdisciplinary team (professors, students, practitioners, etc.). Design a parsimonious* VR model.

Phase 4

8. Run a field version of the virtual engineering practice.
9. Run the AOL activities and feedback from stakeholders.
10. Identify areas of opportunity and feasibility to achieve the objectives of the engineering practice (Step 1)
11. If the areas in Step 10 be feasible to implement, implement them in the virtual engineering practice; if not, terminate.
12. Select the number of sections, campuses, and students to run the current version appropriately.
13. Improve the field version of the virtual engineering practice:
    a) Stakeholders' usability feedback
    b) Challenge the educational objectives

Phase 5

14. Challenge the scope and depth of the VR model
    a) Challenge Functionality (interactivity, mobility, growth, elasticity, etc.)
    b) Challenge the feasibility of accommodating new educational objectives
15. VR remodeling

Go to step 3

*Recommendations: Start with a visual model on the first iteration, a limited-interactive model on the second iteration, and from the third iteration, explore enhancing the model scope.

Figure 2. Transdisciplinary framework.

4.2. Phase 2: Evaluation

Step 5. Evaluate the feasibility of the virtual engineering practice: The possibility to add more interaction was beyond the initial AT expertise and tools. In addition, more ideas for improvement and user experience solutions were in order. An extended team was formed, including more professors, VR-experiences designers, and instructional designers. An upgraded, functional, virtual plant needed to be developed within two months to be ready for the start of the academic period. The usual development time for equivalent virtual experiences was of 6 months. Nevertheless, considering that a working prototype was available as a reference, the extended team determined that it was possible to finish the upgraded engineering practice on time for the next academic period.

Step 6. Develop an evaluation frame to compare site versus virtual engineering practice: The extended team developed a matrix to evaluate the advantages of the virtual experience versus textbook cases versus going to industrial facilities. Although solving real problems is critical for learning and the professional development of engineers, the extended team decided that this virtual plant provided the possibility of a lot of experimentation, in a safe environment, with an engaging, unstructured, and complex challenge that will prepare students for industrial challenges. The extended team also knew from the original plant that students liked to work in a virtual plant more than with textbook problems.

Value Assessment: Given the previous advantages, the extended team concluded that the upgraded engineering practice was feasible and of added value.

4.3. Phase 3: Parsimonious Model

Step 7. A transdisciplinary team (professors, students, practitioners, etc.) drafted and tested the virtual engineering practice using a low-cost prototype. The engineering practice is now ready to be tested before a pilot student section: Given this challenge of agile development, the extended team met weekly. This team included professors with long industrial and practical experience. They were responsible for assuring that the practice was similar to industrial cases and that the virtual plant looked and sounded like an actual plant. The team coded a low-cost initial prototype within two weeks. This prototype obtained additional feedback from students and industry practitioners.

4.4. Phase 4: Deployment and continuous improvement

Step 8. Run a field version of the virtual engineering practice: The extended team was able to finish and test the upgraded virtual prototype in less than eight weeks. The VR experts and instructional designers reported that the development process was speedy compared to other educational projects because of the experience (what are the priorities, what ideas worked, and what updates are required) obtained by the AT and the availability of the original working prototype. Figure 3 shows a screenshot of this upgraded virtual plant.

Figure 3. Upgraded virtual reality manufacturing plant.

This version's virtual plant aesthetics are superior, but the main upgrade focused on interaction feasibility. In the original plant, students were observers and were now allowed to observe the process and run data sampling, and they were required to generate improvement plans now. In this version, students could modify the production parameters in each of the four production machines. Changes in these parameters affect the final product's overall height (since it is an assembly operation). Students can make these changes in the Control Panel of each of the four machines. Figure 4 shows a screenshot of the Control Panel of Machine four.

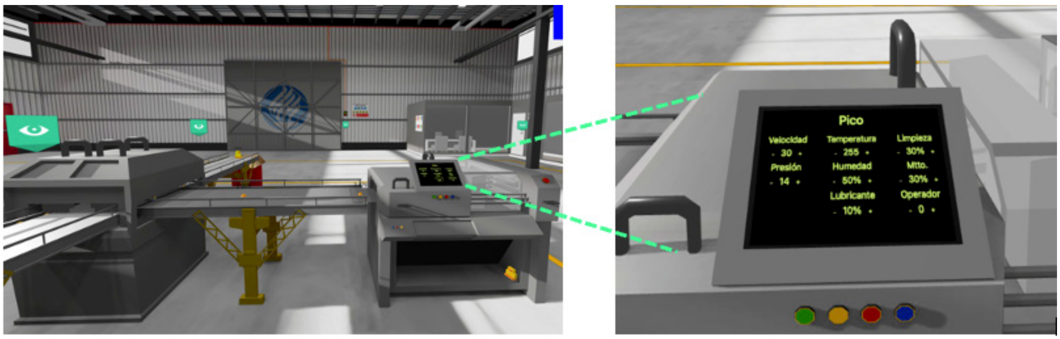


Figure 4. Zoom of a control panel in the upgraded virtual reality manufacturing plant.

The average height of the last 20 final products (rubber ducks) is always available on screen for the benefit of the students.

Step 9. Run the AOL activities and feedback from stakeholders. The AT runs AOL, and students provide feedback. The information obtained from student interviews and anonymous surveys is precious. The AT received responses from 69 students (8 sections from 8 campuses) since this course is part of an online Lean Six Sigma Certification. Overall, the results were positive, and in general, most students liked and would recommend this or similar educational experiences. The AT selected three key metrics to guide future improvement: engagement, effectiveness, and immersiveness (see Figure 5, Figure 6, and Figure 7). Results are similar in these three metrics, with most of the students in agreement, but a group of around 30% of students did not like this virtual experience. Students with industrial experience also reported that in the virtual plant, they could establish hypotheses, modify parameters and see the results quickly. The latter is seldomly viable in real organizations, where the cost of a mistake or experiment with actual production could be high.

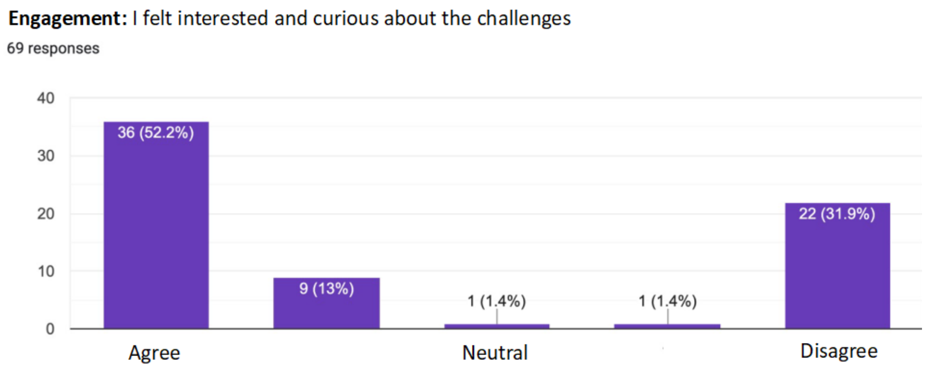


Figure 5. Engagement question and achieved results.

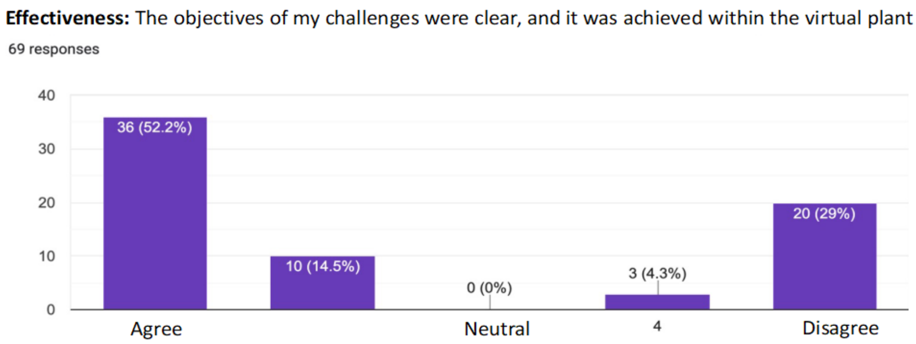


Figure 6. Effectiveness question and achieved results.

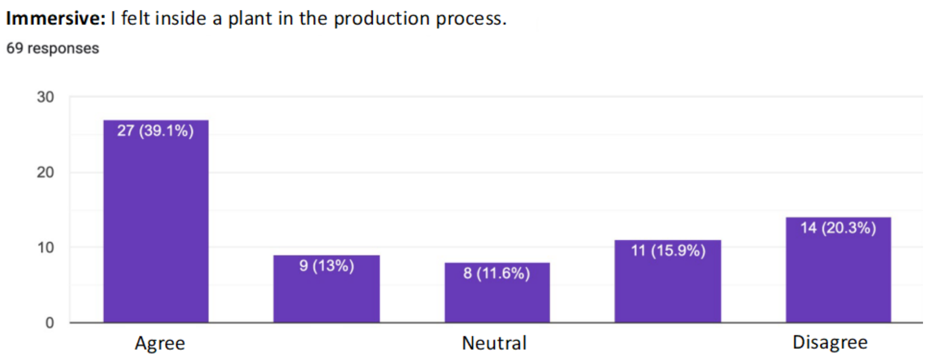


Figure 7. Immersive experience question responds.

Step 10. Identify areas of opportunity and feasibility to achieve the engineering practice's objectives (Step 1): The extended team revised the work evaluated the goals, and determined them as met. Feedback from students was positive, and they requested more interaction possibilities. They also expressed some frustration because data was unavailable as an Excel file, but sometimes this is what happens in the industry. Therefore, the AT determined to leave it unchanged. Users detected some minor issues (some of them related to Internet bandwidth capacity).

Step 11. If the areas in Step 10 are feasible to implement, implement them in the virtual engineering practice; if not, terminate. Even though the AT could add more interaction to the plant, they decided to request permission (first) to open this academic experience, as a free resource, to all interested stakeholders worldwide. The purpose is to obtain better ideas and possibilities by sharing this resource with the world. A webpage (Planta Virtual, 2022) with over 15 case studies is now available for professors, students, and practitioners. This way, users can contribute with cases, ideas for improvement, and issue reports.

Step 12. Select the number of sections, campuses, and students to run the current version appropriately: The extended team decided that the virtual plant was ready to be shared with the world. Different campuses at Tec de Monterrey have requested more information and case studies. Two prominent local universities at Monterrey have already used the plant and reported successful results.

Step 13: Improve the field version of the virtual engineering practice: Something interesting to evaluate in further iterations of the proposed framework is using VR headsets. These virtual plants were ready for VR headset usage since the first iteration. However, the lack of VR headsets in most students' homes did not allow the use of this kind of hardware at first. As the COVID pandemic approached its end and students started to return to universities, we have been able to use the VR laboratories available at several university campuses to confirm the status of this educational experience and additional opportunities. Students have reported very positive experiences using VR simulations.

Bowman (2014) considers that VR experience limitations differ from the real world. Thus, interactions that allow users to go beyond the limits of perception or human action, reducing the need for physical effort and allowing tasks that are impossible, risky, or expensive in the real world, are feasible with VR. While implementing the proposed transdisciplinary framework, it was possible to validate some of these possibilities using computer screens. Still, the use of VR headsets confirmed that we were able to provide more value to the virtual experience.

VR is becoming more popular as a medium to provide knowledge (Bis, 2018). As cited in Tamayo-Enriquez (2019), Steuer states that VR could change how knowledge is shared because VR allows the incorporation of different senses, generating new experiences. During the implementation of the proposed transdisciplinary framework, it was possible to witness how this tool changes the role of the professor from instructor to coach since students can move around, practice and experience by themselves.

Step 13a: Stakeholders' usability feedback: The AT discussed with practitioners, professors, and students the usability of the plant. In these discussions, they reported some minor issues. Some of them become part of the experience since they occur in existing plants (processes will not stop; too many data points; fast-moving processes; data is not easy to obtain). Other issues were solved using the information in the stakeholder's feedback.

Step 13b: Challenge the educational objectives: Students wanted to be able to do more things inside the plant. Some of them detected, for example, that conveyors were too long and generated a less productive operation. The AT wanted to allow more interaction possibilities without making significant changes and adding complexity levels to the existing plant.

4.5. Phase 5: Discovery

14. Challenge the scope and depth of the VR model. After trying the second iteration model with several practitioners, professors, and students from different universities and organizations, the AT initially selected the following functionality change to include.

14a. Challenge functionality (interactivity, mobility, growth, elasticity, etc.). The AT decided that allowing students to change the length of the conveyors would allow them to witness the consequences (both positive and negative) of this decision. However, this was a significant change since additional features are now in order from the virtual plant, like the track of time, number of entities, and distances.

14b. Challenge the feasibility of accommodating new educational objectives. The AT liked the possibility of combining statistical-based decision-making with lean manufacturing principles. Using SPC and DOE to tackle the statistical issues is compelling, but using lean principles and VSM to redesign the layout and validate productivity improvement would be a significant addition to engineering courses. The AT discussed these items with the technical team and understood that this was not a minor change while feasible.

15. VR remodeling: Students wanted "more control" of the VR Plant. They had ideas of how to improve the layout. Students also had questions regarding the precision required for the subassemblies and final assemblies. They also wanted to know more about productivity and potential inventories. None of these elements was feasible in our second iteration, developed specifically to assess non-linear causal relationships between input and output variables, required to understand and practice with industrial statistics and Six Sigma quality problems.

Our AT looked for a solution to this problem. It was essential to allow participants to have more interactions and to enable instructors to have the possibility of developing more adapted challenges to their academic requirements.

The AT identified a 3D Simulation Modeling and Analysis Software called FlexSim (2022). This software could provide a solution: It has a VR option that is limited but free for everybody through FlexSim Free (2022), and it allows working on laptop computers; therefore, this solution is open to all interested parties. It also allows 2D visualization but offers the possibility to connect VR headsets for a more immersive experience.

Finally, this software allowed a different experience since now the results obtained depended on the changes proposed by practitioners, so they could discover their consequences that were not limited by the designed algorithm but by the conditions of the complex system.

FlexSim Free is the base for a pilot plant similar to the second web-based VR plant. Emphasis was not on the product's dimensions (as in the second web-based VR plan) but on the layout, distances, and conveyor speed (see Figure 8).

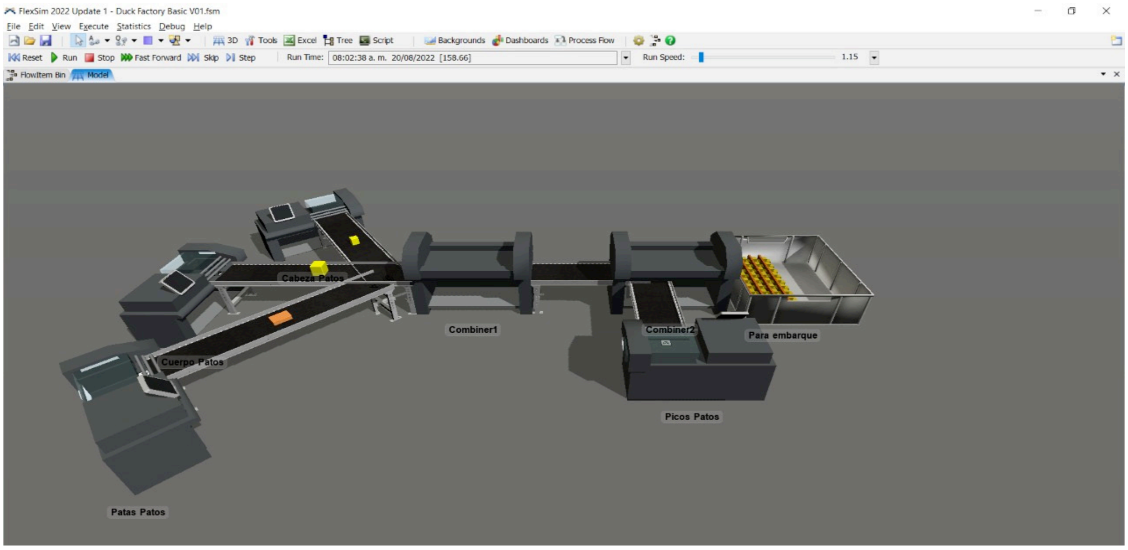


Figure 8. Virtual Plant in Simulation Software.

A pilot group of engineering students was appointed to confirm the results of this new experience. Students used the second web-based VR plant to solve some challenges. Then, they work to improve other elements, like changing the conveyors' distances and speeds. They tried different configurations, discovering that there were bottle-necks that restricted the system. Students must plan carefully to increase throughput without generating a lot of inventories or collapsing the capacity of conveyors and stopping the production line.

Students reported that they enjoyed the possibility of having different tools to solve other issues of this same line. They also said they liked the option of gradual immersion (from PC to VR) in both platforms (web-based and FlexSim®).

5. Conclusions and further research

On-site (at companies' facilities) engineering practices are designed for students to obtain hands-on experience on different topics in their bachelor's or graduate programs. The contribution of this work relates to the future of engineering education (digital and open learning) by developing a transdisciplinary framework for Digital Simulation Engineering Practice Development and Evaluation. The idea is to evaluate if some digital well-designed experiences could provide equal or more valuable experience to students than actual hands-on practices. Some of these cases could be oriented to tactical engineering decision-making learning experiences but are not limited to Quality Control, Six Sigma, Lean Manufacturing, etc. The idea has its origins in the use of case studies in management for strategic decision-making.

The results obtained in the engineering practice described in Section 3 show that the hands-on experience related to some engineering topics could be achieved and improved throughout a virtual case and not only through actual industrial hands-on practice.

The partnership and contribution of all stakeholders (professors, students, practitioners, and employers) are paramount to developing successful virtual experiences and increasing the topics a virtual case could cover. This way, co-designing educational experiences that include engineering and non-engineering disciplines considering all stakeholders is an example of Transdisciplinarity.

Further work pends ahead: Finding the general characteristics and limits of these experiences is yet to be explored. The optimal level of complexity of the virtual model and the abilities assimilated by students are yet not determined. The ad-hoc design of efficient assessment of learning tools is also a line to be explored. Exporting this framework to other non-engineering-related disciplines is also yet to be carried out. Finally, finding the balance between entertainment, gamification, and learning seems essential for current students' needs and learning styles.

6. Acknowledgements

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