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A Transdisciplinary Framework for Engineering Education, Developing Tactical Engineering Decision Making Skills

Federico TRIGOS[a,1] and Francisco TAMAYO-ENRIQUEZ[b]
[a] *Tecnologico de Monterrey, EGADE Business School, Monterrey, Mexico*
[b] *Tecnologico de Monterrey, Monterrey, Mexico*

Abstract. The use of digital simulators is a well-known practice in managerial courses as tools for strategic decision-making. On the other side, engineering students are used to practicing theoretical knowledge in laboratories or real factories due to the tactical nature of the decisions involved. During the COVID pandemic, universities were forced to limit or cancel access to physical facilities. Engineering professors were challenged to keep educational schedules using digital tools. The contribution of this work is a transdisciplinary framework on how to design engineering practices through digital simulation models to keep or improve pre-pandemic learning levels. The societal challenge involves a change in paradigm for professors, students, and practitioners. The proposed framework was used to design, implement, and feedback a senior student Six Sigma project course, using a tailormade web-based simulator. Two iterations of the framework are currently deployed: one-way information flow, and two-way interaction. The information obtained so far was the base for the third iteration of the framework which involves three-dimensional virtual reality interaction. Case-based learning and management simulators have been successful at bridging theory and practice for management students. The work in this paper builds on these management practices to achieve equivalent learning levels for engineering students.

Keywords. Digital and open learning for engineering, engineering education, experimental design, interactive simulation for engineering, six-sigma practice, transdisciplinary design

Introduction

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

Students are taught the importance of going to the shop floor (genba in Japanese) to be present in the place where transformation processes occur [1]. However, it is not always feasible to coordinate visits to industrial processes and due to logistics, safety,

[1] Corresponding Author, Mail: ftrigos@tec.mx.

and product integrity reasons, it is also difficult for companies to allow students to "walk between industrial equipment", and to carefully observe and interact with the processes.

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 Tec de Monterrey, Mexico, decided to develop a small "virtual reality manufacturing plant", where teams of students remotely using their laptop computers, had the opportunity to work in a simulated genba environment, interact among them "inside" the plant, safely observe and discuss the processes, sampling the defective levels and making recommendations of improvement actions as a team (see Figure 1).

Tec de Monterrey [2] is a Mexican institute of technology that includes 26 campi 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. The virtual experience presented in this work was implemented in one of these programs.

According to students and professors (through a feedback instrument) of the courses that 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, several opportunities for improvement were highlighted.

Engineering education faces the challenge of transferring theoretical knowledge to practical work, to provide students a smooth transition from university to professional practice [3]. Universities need to associate with companies to provide students with 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 provide a more effective way to train students before they start their professional work. Simulators could be regarded as a special kind of gaming with an educational purpose. From [4] "online gaming may produce strong social ties".

The International Society of Transdisciplinary Engineering (ISTE) [5] states that transdisciplinary engineering "is a methodological approach, explicitly incorporating social sciences to gather information and to guide implementation of engineering solutions in practice". The academic team at Tec de Monterrey considered that this was an important approach to be incorporated for further improvement of the original engineering practice educational experience.

A second design, supported with 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 a number of engineering practices. Overall, students and professors once 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 multiple case studies, resulted in the development of a transdisciplinary framework for engineering education, to contribute to the enrichment of tactical engineering decision-making skills required by students.

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 rest of the paper is described as follows: Section 1 shows the initial challenge and the development of the original educational experience, Section 2 states the transdisciplinary framework developed, Section 3 illustrates the potential of virtual reality implementation, Section 4 include an example of how this framework was used to develop the upgraded versions of the original educational experience, results achieved, and finally Section 5 includes conclusions and ideas for further research.

1. The need and development of the original educational experience

The COVID-19 pandemic generated a challenge that required an immediate solution for the academic team 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 real factory with equal or better educational learnings.

Therefore, the first task was the development of a shortlist of the characteristics that a real factory presents to engineering students at engineering practices. This list included elements such as unstructured problems, complex causal chains, lack of mathematical causal models, unique work culture, and restrictions due to safety and productivity loss risks. The academic team decided that some of these elements would not be easy or even feasible to include in a fast and low-budget virtual plant design. Therefore, the academic team decided to focus on those elements within reach: Unstructured problems, complex causal chains, and the lack of mathematical causal models; production and defective data were not provided, so students needed to decide where to sample and the sample size. Several study cases were developed to provide different challenges to students, according to the curriculum of the class.

The academic team also realized that some restrictions that exist 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 more effective use of their time for solving 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, where some of the characteristics of real shop floors were available: Complexity, non-structured data, decision-making of what and how much to sample, unclear definition of the problem, and the steps required. In general, students reported that they enjoyed solving the challenges.

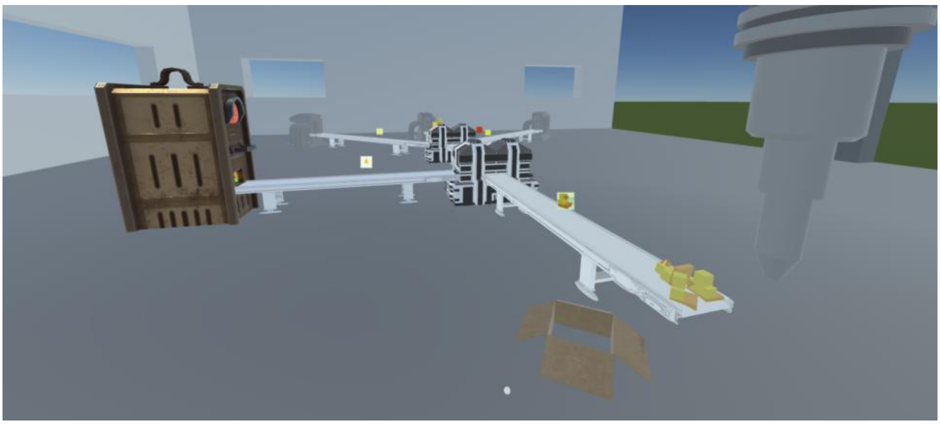


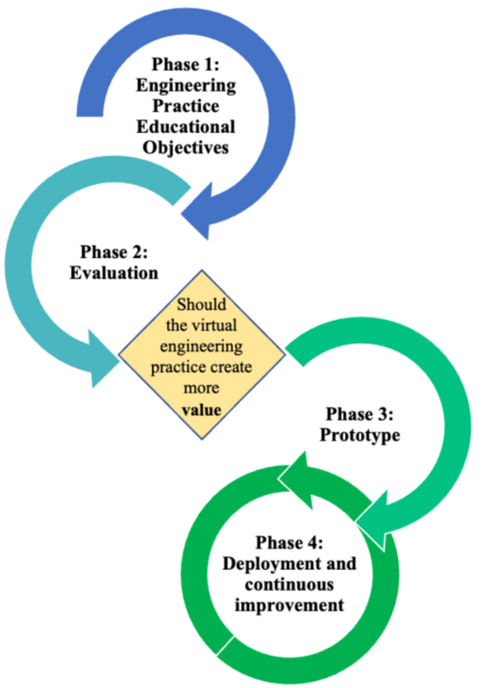
Figure 1. Initial virtual reality manufacturing plant

On one hand, it was unexpected that students did not complain about the modest resolution and design resources of the plant; we considered that they focused more on solving the challenges of their task than on the “quality of the graphics”. On the other hand, their main improvement recommendation was to increase the interaction possibilities. Students wanted to be able to change process parameters and to see in real-time the effects of their decisions in the processes' outputs.

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

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

Based on the experience shown in the previous section, the following framework (Figure 2) is proposed.



Phase 1:

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

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. Through a transdisciplinary team (professors, students, practitioners, etc.) develop a draft of the virtual engineering practice throughout a low-cost prototype to be tested before a pilot student section.

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. Should 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, campi, and students to appropriately run the current version

*** Go to step 8

Figure 2. Transdisciplinary framework

This framework was used as a reference for the development of the second and third iterations of the simulator.

The academic team also considered that sharing this framework and experiences with different engineering majors will only result in many improvement ideas. At Tec de Monterrey, the team has started an open repository of study cases. Until now this effort has been a Tec de Monterrey project, but permission has already been granted to globally share this experience. The link to access this virtual reality initiative could be found at [6]. By using this kind of virtual engineering cases, it is possible to make available engineering practice and experience to more students in a less costly fashion. In addition, universities could share their virtual engineering practices among campi, 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 in a very cost-efficient fashion.

3. The framework in practice

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

3.1. 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 control charts and design of experiments (DOE).

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

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 Assessment of Learning (AOL) of the practice: Students report their 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.

3.2. Phase 2: Evaluation

Step 5. Evaluate the feasibility of the virtual engineering practice: The possibility to add more interaction was beyond the initial academic team expertise and tools. Also, more improvement ideas and user experience solutions were required. An extended team was formed, including more professors, VR-experiences designers, and instructional designers. An upgraded, functional, virtual plant needed to be developed within 2 months, to be ready for the start of the academic period. The usual development time for equivalent virtual experiences was of 6 months. Nevertheless, and 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.

Step 6. Develop an evaluation frame to compare in site versus virtual engineering practice: The extended team developed a matrix to evaluate the advantages of the virtual experience versus textbook cases and versus going to industrial facilities. Although solving real problems is key for learning and for 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 more to work in a virtual plant 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.

3.3. Prototypes

Step 7. Through a transdisciplinary team (professors, students, practitioners, etc.) develop a draft of the virtual engineering practice throughout a low-cost prototype to be tested before a pilot student section: Given this challenge of agile development, a weekly meeting was established with an extended team. In this team, professors with a lot of experience working in industry were invited, with the responsibility of assuring that the practice was similar to industrial cases and that the virtual plant "looked and sounded" like a "real plant". A low-cost initial prototype was developed within 2 weeks. This prototype was shared with students and industry practitioners, for additional feedback.

3.4. 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 time in less than 8 weeks. Both the VR experts and instructional designers reported that the development process was very fast when compared to other projects since an original working prototype was available and because the original academic team had learned from the previous virtual experience and had a very clear idea of what worked, what upgrades were required, and what were the priorities. A screenshot of this upgraded virtual plant is presented in **Figure 3**.

Figure 3. Upgraded virtual reality manufacturing plant

The aesthetics of the virtual plant was significantly upgraded, but the main upgrade was regarding the interaction feasibility. In the original plant, students were basically observers, allowed to observe the process, take data, and generate improvement plants. In this version, students can modify the production parameters in each of the 4 production machines. Changes in these parameters have effects on the overall height of the final product since it is an assembly. These changes are done in the Control Panel of each one of the 4 machines. A screenshot of the Control Panel of Machine 4 is presented in **Figure 4**. The average height of the last 20 final products (rubber ducks) is always available on a screen provided for the students.

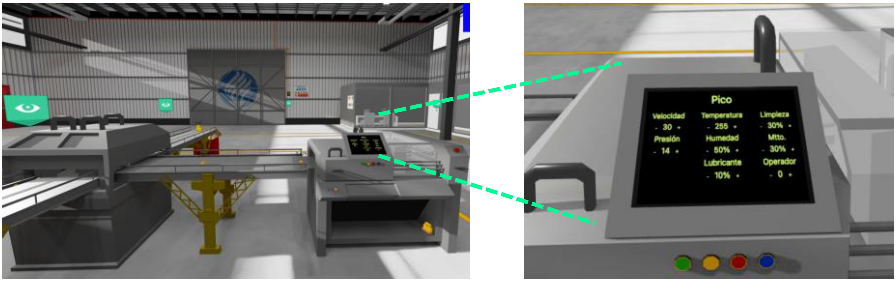


Figure 4. Zoom of a control panel in the upgraded virtual reality manufacturing plant

Step 9. Run the AOL activities and feedback from stakeholders. AOL was run and feedback was requested from students. Interviews and anonymous surveys were conducted with students at the end of the semester. We obtained responses from 69 students (8 sections from 8 campi) since this course is part of an online Lean Six Sigma Certification. Overall, results were positive, and in general, most students liked and would recommend this or similar experiences. We selected 3 key metrics to guide future improvement: engagement, effectiveness, and immersiveness (see **Figure 5**, **Figure 6**, and **Figure 7**). Results are similar in these 3 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 were able to establish hypotheses, modify parameters and see the results. This is seldomly viable in real organizations, where the cost of a mistake or experiment with real production could be catastrophic.

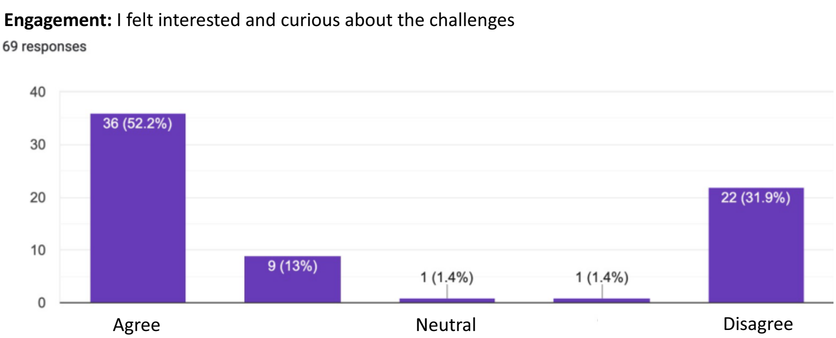


Figure 5. Engagement question and achieved results

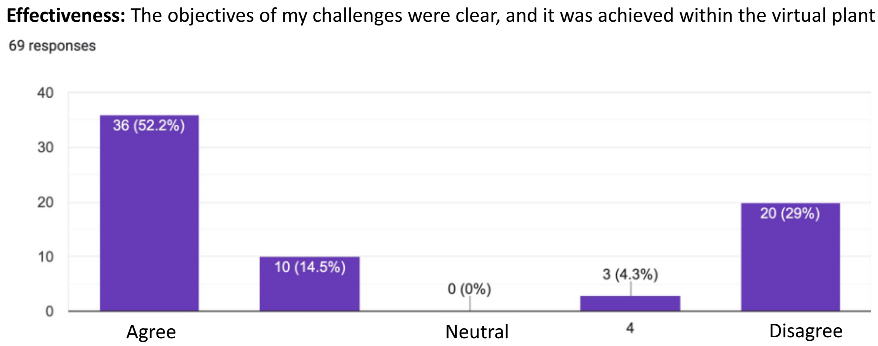


Figure 6. Effectiveness question and achieved results

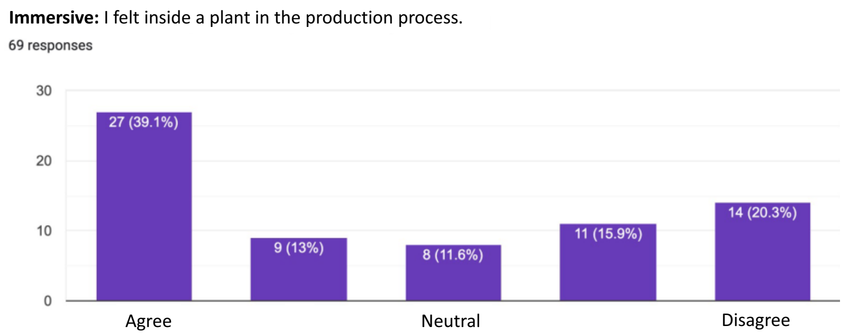


Figure 7. Immersive experience question and achieved results

Step 10. Identify areas of opportunity and feasibility to achieve the objectives of the engineering practice (Step 1): Based on the results achieved, the extended team considered that the objectives were achieved. Feedback from students was positive and basically, they requested more interaction possibilities. They also expressed some frustration because "data was not available in Excel", but sometimes this is exactly what happens in industry. Some minor usability issues (some related to Internet bandwidth capacity) were also detected.

Step 11. Should the areas in Step 10 be feasible to implement, implement them in the virtual engineering practice, if not, terminate: The extended team considered that more interaction could be added to the plant, but rather decided to first request permission to open this academic experience, as a free resource, to all interested stakeholders. The extended team considered that better ideas and possibilities could be obtained by sharing this resource with the world. A webpage that currently has over 15 different case studies is available for professors, students, and practitioners. All users are invited to contribute with more cases, ideas for improvement, and to report usability issues.

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

4. Virtual reality potential to be assessed

Something interesting to evaluate in further iterations of the proposed framework is the use of VR headsets. These virtual plants have always been ready for VR headset usage. The lack of VR headsets at most students' homes did not allow the use of this kind of hardware at this time. As the COVID pandemic seems to be approaching its end, and students start to return to universities, we will be able to use the VR laboratories available at several university campi, in order to confirm the status of this educational experience and additional opportunities.

Bowman [7], considers that VR experiences limitations are different from those of the real world. Thus, interactions that allow users to go beyond the limitations 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. During the implementation of the proposed transdisciplinary framework it was possible to validate some of these possibilities using computers screens, but the use of VR headsets might provide more value to the virtual experience.

VR is becoming more popular as a medium to provide knowledge [8]. Steuer, as cited in [3] states that VR could change the way in which knowledge is shared, because VR allows the incorporation of different senses, generating whole 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 a coach, since students are able to move around, practice and experience by themselves.

5. Conclusions and further research

On-site (at companies' facilities) engineering practices are designed for students to obtain hands-on experience on different topics of their bachelor's and graduate programs at universities. 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 real hands-on practices. Some of these cases could be oriented to tactical engineering decision-making learning experiences like but 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 than from only using a real 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. In this way the co-design of educational experiences that include engineering and non-engineering disciplines considering all stakeholders are a sound example of transdisciplinarity.

Further work pends ahead: Finding the general characteristics and limits of these experiences is yet to be explored. The relation between the complexity of the virtual model versus the abilities assimilated by students is also to be found. The ad-hoc design of efficient assessment of learning tools is also a line to be explored. Exporting this frame to other non-engineering-related disciplines is also yet to be carried out. Finally, finding the balance between entertainment, gamification, and learning, seems to be key for the needs and learning style of current students.

Acknowledgment

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