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A Transdisciplinary Framework to Design Immersive Progressive Complexity Learning Experiences

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Abstract. The incorporation of immersive technologies in education is rising as they help students visualise abstract concepts and engage them with realistic or semi-realistic experiences. Learning experiences should be considered the backbone of an educational program, so they must be designed effectively. To prevent cognitive overload, students typically begin to work on complex problems starting with relatively simple-structured learning tasks, and, as their expertise, skill, and knowledge increase, they work on more complex endeavours to get the job done. Students in the early stages receive initial information, deep support, and guidance from the educator, and this assistance should gradually be reduced as students enhance their skills and knowledge. This work proposes that to accelerate the benefit of immersive technologies in education, instructors should use a transdisciplinary approach (considering all stakeholders, such as students, instructors, faculty, and industrial practitioners) to design immersive progressive complexity learning experiences along with dynamic guidance, appropriate support information, assessment, and feedback. The contribution of this work is twofold 1) a framework for the transdisciplinary design of immersive progressive complexity learning experiences, and 2) an illustrative instance of how to go from a simple learning task to a final complex-immersive challenge with limited additional support will be presented.

Keywords. Augmented reality, complex problems, education, gamification, immersive technologies, the case method, storytelling, transdisciplinary design, virtual reality

Introduction

Traditional engineering education usually provides students with concepts, tools, and exercises. Professors in some engineering courses state the importance of learning by doing (knowledge into practice). Therefore, some professors require students to conduct hands-on projects in local industries. Professors usually put a significant percentage of the course evaluation [1] upon these projects. "Engineering education often faces the challenge of transferring theoretical knowledge into practical work to students, thus offering a smooth transition from studies to professional life" [2, p. 1].

Although the previous approach has some logistics and practical difficulties, using real hands-on projects has successfully provided a bridge between university and

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professional practice. It has offered the students practical experience using their acquired knowledge and some soft skills required to deal with real-life situations [1].

It is proposed in this work that a new approach is required to face current and future educational challenges, considering two recently increasingly relevant factors for engineering education, immersive technologies and transdisciplinary engineering. Both elements can significantly enhance the current models of engineering education [3,4,5,6]. However, there is a need to carefully devise and implement strategies to simultaneously provide students with increasing levels of complexity, immersion, and transdisciplinarity to allow them to assimilate the previous levels and move confidently to the next ones.

1. Progressive increase in knowledge complexity and students' autonomy

According to van Merriënboer [7], effective learning tasks require variability, different levels of complexity, and decreasing levels of support and guidance.

Regarding variability, van Merriënboer [7, p.4] considers that "effective inductive learning will only be possible when there is variability over learning tasks. That is, learning tasks must be different from each other on all dimensions on which tasks in the later profession, or in daily life, are also different from each other. Only then, it will be possible for students to construct cognitive schemas that generalise or abstract away from the concrete experiences; such schemas are critical for reaching transfer of learning". "To prevent cognitive overload, students will typically begin to work on relatively simple learning tasks and, as their expertise increases, work on more and more complex tasks" [7]. "At the first level of complexity, students will be confronted with learning tasks that are based on the easiest tasks a professional might encounter; at the highest level of complexity, students will be confronted with the most difficult tasks a beginning professional must be able to handle, and additional levels of complexity may be added in between to guarantee a gradual increase of complexity over levels" [7]. van Merriënboer [7] states that students often receive support and guidance when working on learning tasks. When students start to work on more complex tasks, thus, progress to a higher level of complexity, they will initially receive a lot of support and guidance. Then, support and guidance will gradually decrease [7].

This article proposes to design a scheduling matrix to achieve this progressive increase in knowledge complexity. In this matrix, students work in different but related challenges (variability), using tools of progressive complexity (levels of complexity) with decreasing support for their instructor (levels of support and guidance).

2. Immersive technologies in education

"Immersive technologies create distinct artificial experiences by blurring the line between the real and virtual worlds" [3, p.1]. "The incorporation of immersive technologies in education is on the rise as they help students visualise abstract concepts and engage them with a realistic experience" [3]. "Further, immersive technologies help students to develop special skills that are much harder to attain with traditional pedagogical resources. Immersive technologies have been shown to improve participation and amplify engagement" [3]. "Immersive learning facilitates learning using technological affordances, inducing a sense of presence (the feeling of being there), co-presence (the feeling of being there together), and the building of identity (connecting the visual representation to the self)" [3].

Immersive technologies allow safe practice (safety for students and security of processes in which they are involved) while providing students with close-to-reality challenges and scenarios [1,3]. As more instructors include these technologies in educational practices, they will discover more immersive technologies' capabilities for enhancing education.

However, not all students are familiar with current and ever-changing immersive technologies and their specific use for enhancing learning experiences. Therefore, it is critical to design a schedule to allow students to gradually familiarise themselves with these immersive technologies to avoid having them deal simultaneously with new knowledge, less support, and new, unfamiliar technology used in a new context.

3. The transdisciplinary approach to education

Moser [4] states that "successful engineers are not only conversant in their own field, but also prepared and proactive to engage with a range of disciplines, technical and social, especially user and practitioner communities ... Engineering for complex sociotechnical system challenges stretches one beyond the assembly of the work of specialists". Moreover, according to Lavi & Bagiati [5], engineers are currently called upon to solve complex global challenges such as climate change, water and food scarcity, and pandemics, among others. "Within this context, tackling such complex global challenges requires holistic educational approaches that combine multidisciplinary knowledge and updated multidisciplinary teaching and research methodologies. This demand for more holistic approaches should be reflected in present-day engineering curricula and in the instructional way engineers of the future are formally trained" [5].

4. The need for a transdisciplinary framework

Education of the future, and the present, requires a transdisciplinary approach to allow future professionals to work towards solutions to complex challenges [4, 5]. This statement applies not only to engineering education but to education in general. However, students need to gradually learn to work with a transdisciplinary approach, starting with comfortable interactions and moving towards relevant negotiations with other teams where real gains and losses happen. They must also work in different challenges, with increasing knowledge complexity and autonomy, while using more realistic immersive technologies.

There is relevant work related to educational programs with a gradual increase in complexity and decrease of required support [7], frameworks for designing immersive engineering education practices with a transdisciplinary approach [1], and frameworks for gradually increasing the interaction capabilities of immersive technologies [8]. Still, academic literature is scantly related to a framework that combines progressively increasing the complexity of the tasks and simultaneously increasing the transdisciplinary interaction capabilities with these immersive technologies. Hence, the need for a transdisciplinary approach to solving complex learning experiences while still maintaining the interest of the students and the focus on approaching real-life engineering decision-making and problem-solving situations. The contribution of this work is twofold it proposes a transdisciplinarity framework to increase complexity simultaneously with the inclusion of immersive technologies, and it provides an actual implementation of the framework for illustrative purposes.

5. Transdisciplinary framework to design immersive progressive complexity learning experiences

According to Brown [9, p.33], to operate within an interdisciplinary environment, "an individual needs to have strengths in two dimensions—the 'T-shape' person ... On the vertical axis, every member of the team needs to possess a depth of skill that allows him or her to make tangible contributions to the outcome"; but that is not enough. On the horizontal axis, an individual needs to have "the capacity and—just as important—the disposition for collaboration across disciplines" [9] and both dimensions are required to have a genuinely transdisciplinary approach. Therefore, students need to practice with skills in these two dimensions.

Based on Trigos and Tamayo [1,8] and considering [10], this work proposes an upgraded model to allow the progressive use of the variety, increasing complexity, and decreasing guidance [7], while requiring the gradual use of immersive technologies and a transdisciplinary approach using skills of the two T-dimensions described previously [9]. Table 1 shows the proposed framework. The framework integrates careful planning of objectives, learning practices, immersive experiences, and transdisciplinary interactions.

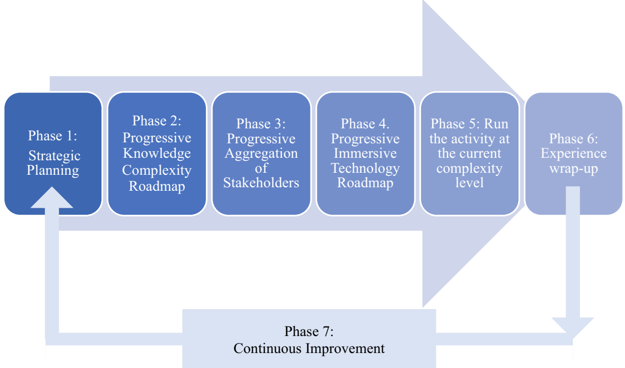
A more straightforward approach could have been to gradually increase the complexity of these elements separately (first, increase complexity, then increase immersive technologies). The authors consider the latter would not be efficient (due to the time required) or real. Additionally, they also believe that the proposed framework is in line with the core principles of the NEET Program [5] developed by MIT for what students' education should do: Focus on preparation for developing new technologies; prepare them to become makers and discoverers, with engineering fundamentals applicable to both research and in practical careers; constructed around the way students learn best and must be both effective and engaging for the current era; and empower them to think more effectively and learn more effectively by themselves.

6. The framework in practice

This section illustrates the framework described in Table 1 throughout a pilot study to teach undergraduate engineering students the topic of statistical quality control (within an engineering course).

The framework in Table 1 is initially inspired by sources [1] and [8]. The main contribution of this work is the increase in the levels of task complexity, immersion and depth of the transdisciplinary interaction. Thus, the explanation will start at step 7.

Table 1. Transdisciplinary Framework to Design Immersive Progressive Complexity Learning Experiences



Phase 1: Strategic Planning

1. Select the engineering topic to analyse.
2. Define the transdisciplinary team: Faculty, practitioners, and other stakeholders.
3. Identify the final academic objectives of the engineering topic.
4. Identify the immersive technologies to use.
5. Develop or find an existing virtual model.
6. Identify the Assessment of Learning (AOL) of the topic.
7. Identify the self-contained academic complexity steps:
   - 7.1 Theory.
   - 7.2 Information about the exercise.
   - 7.3 Goals.
   - 7.4 Steps of complexity for knowledge/support, stakeholders' aggregation, and technology.
8. Define the scheduling matrix for Step 7.4.
9. Faculty-student gradual interaction rules.
10. Students' interaction rules.
11. Assessment of learning (AOL).

Phase 2: Progressive knowledge complexity roadmap

12. Develop an initial assessment of the current state of course theory
13. Provide the theory related to the scheduling matrix's complexity step (classroom).
14. Provide the information related to this complexity step.

Phase 3: Progressive aggregation of stakeholders

15. Set up the stakeholders' involvement aligned with the scheduling matrix.

Phase 4: Progressive immersive technology roadmap

16. Familiarise students with virtual models of progressive complexity (aligned by scheduling matrix).
17. Confirm comfortable familiarity with the immersive technology used.

Phase 5: Run the activity at the current complexity level

18. Inform the students of the goals and rules of engagement among students and faculty.
19. Run the practice related to this step of complexity and technology according to the scheduling matrix. Continuous professor monitoring is required.
20. Evaluate phase goals accomplishment in knowledge/support, stakeholders' aggregation and immersive technology.
21. Obtain students' feedback on this practice.
22. Activity wrap-up.
23. Go to the next level of the scheduling matrix.
24. Go to Step 8 until finishing the scheduling matrix.

Phase 6: Experience wrap up

25. Wrap up the whole practice regarding knowledge/support, stakeholders' aggregation and media/immersive technology.
26. Prepare students for the following course (that builds on this one) to be taken in their program.
27. Student feedback.

Phase 7 Continuous improvement

28. Faculty gather with stakeholders to discuss the experience and return to step 1.

The transdisciplinarity team designed the activities in steps 7 through 9 of Phase 1 to become a self-contained learning experience. Faculty will implement these activities within 80 minutes course sessions.

Framework Phases 2 through 5 are explained in sections 6.1 through 6.4. Classroom activities contain some storytelling, rules and challenges, a closing of the experience, and a reward (extra points, where the amount granted was proportional to the challenge difficulty).

Table 2 shows the scheduling matrix to guide overall efforts.

Table 2. Scheduling matrix for a course in Statistical Quality Control

Activity	Knowledge complexity	Support and guidance provided	Immersive technology	Transdisciplinary approach
Stage 1	Basic statistics and the review of their applications	Complete support during the exercises. Teacher interacts team-by-team	Basic AR and web-based experiences: Visualisation/interaction (change parameters and confirm results)	Only interactions within their team. Award to teamwork (easy to achieve award)
Stage 2	Basic statistics comparisons using boxplots	Decreasing support, more focalised on interpretation	Web-based experiences: Visualisation/interaction (change parameters and confirm results). Only one machine is used.	Interactions within their team, but each student has relevant individual goals to meet. Team and individual awards
Stage 3	Use of correlations and linear models	Decreasing support, more focalised in interpretation and only when requested by teams/students.	Web-based experiences: Visualisation/interaction (change parameters and confirm results). Two data sources are used.	Interactions among teams, with collaboration required to meet goals (competition and teams awards)
Stage 4	Optimisation of a complex system using models with multiple variables and costs	Limited support is provided since it is a class challenge.	VR experiences for visualisation, interaction, and optimisation. Students show their solutions in VR.	Full cooperation is required among teams to find an optimal solution (all teams or no team gets an award)

6.1. Scheduling Matrix Stage 1: Low complexity: Basic statistics and the review of their applications

1. A virtual plant visualised as web-based, Virtual Reality (VR), or Augmented Reality (AR) was set up for students [11]. This plant builds a final product (toy duck) which is an assembly of 4 components (beaks, body, head, and feet). Each component is manufactured on a machine with eight tun-up parameters. These parameters may (or

may not) have linear or non-linear effects in the measurements of each piece and, therefore, in the final measure of the finished product. The professor briefly reviews the class with basic statistics and examples.

2. Each team of students was assigned as responsible for a virtual process within the virtual plant. Figure 1a shows process 4: beak-manufacturing machine. A simple AR visualisation provided target value and specification limits, as shown in Figure 1b.
3. Each student was randomly assigned as the technician that could modify one of the parameters of the machine. These parameters would be their "vertical skill".
4. Teams of students were asked to calculate the mean and standard deviation of the beaks with the original parameters (baseline) and to draw a histogram.
5. Students were requested to test one different parameter level and to visually compare and decide if these new levels represented an improvement towards the target values.
6. Finally, students were requested to review their results as a team and, with the available information, select a process set up to improve the baseline.
7. Interaction and teamwork were required, but only within teams of students. A few extra points were granted to teams that evidenced improvement (almost every team achieved this, as designed).

Figure 1a. Beak-building machine inside the plant, with eight parameters and one result (2.420cm beak dimension).

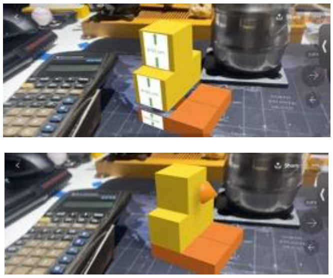


Figure 1b. Target values, tolerances, and assembly sequence are provided with AR.

6.2. Scheduling Matrix Stage 2: Medium-low complexity: Basic statistics comparisons using boxplots

For this Phase, the same virtual plant [11] that students already know was used. After theory and some examples were provided to students, they worked in teams.

1. To strengthen their "vertical skills", students left their original teams and shared information with students from other teams that worked with the same manufacturing parameter (*temperature experts*, for instance). They were requested to do boxplots to compare their solutions toward the goal.
2. Students returned to their original teams with stronger "vertical skills". The practice included two elements of gamification: five extra points to the team that achieved the *best solution* using a combination of parameters and one additional point to all students of the vertical parameters chosen by each team. The purpose was to force them to negotiate and develop *horizontal skills*. Students experienced a need for cooperation (to achieve the best solution as a team) and an interest in having their vertical parameter chosen (to earn one point for all their *vertical skill* colleagues).

3. Students used boxplots to compare their team results from the baseline and with a product specification and tolerance (2.0mm $\pm$0.1mm). Each team selected its best combination of parameters.

6.3. Scheduling Matrix Stage 3: Use of correlations and linear models

The same virtual plant [11] that students already know is used for this stage. Still, students were allowed to take turns to view and walk around the virtual plant using VR headsets in the classroom to introduce them to VR visualisation of industrial facilities. After theory and some examples were provided to students, they worked in teams.

1. Students were requested to obtain paired data individually and to draw correlation lines between the levels of their "vertical" parameters and the beak values obtained. Students were asked to individually confirm their correlation coefficients and p-values between their assigned parameters and the result.
2. Teams were requested to obtain paired data and to draw a correlation line between the beak values obtained (in process 4) and the final product values (at the end of the line). Students now need to move around the plant and use different data sources, and teams must confirm their correlation coefficients and p-values between beaks and final product values.
3. Teams are requested to use linear models, considering p-values, residuals, and r^2-adjusted to obtain the best possible set of their beak parameters (in Process 4) to meet final product tolerances. They compare their results using boxplots.
4. Teams competed against each other. The team with the best Cp_k value (calculated by the instructor) won the award.

6.4. Scheduling Matrix Stage 4: High complexity: Optimisation of a complex system using models with multiple variables and costs

For this stage, the students worked on the virtual plant [11], but now they were trained in the appropriate use of VR headsets by a VR-experts, and each one was provided with a VR headset at a VR Lab. Now familiar with using their controls, the process, and the plant, students can operate the virtual plant using multiple VR headsets for a more immersive experience. Students' teams were now split into new ones to carry out the following activities:

1. Each team of students was assigned a manufacturing process in the plant, different from the beak-manufacturing machine (heads, bodies, feet). AR (Figure 1b) provided each piece's target values, tolerances, and overall assembly.
2. Teams were requested to model their machines and validate the effect of different values on the overall dimensions of the assembled duck.
3. The professor included a cost for moving parameters at different machines; this allowed students to compare solutions.
4. Teams were requested to share information, work together as a plant, and improve the capability of their final process versus the baseline's capability.
5. The award was given to the group of teams (Group A vs Group B) with the best result, considering the value of the real process capability Cp_k and the cost of the proposed solution.
6. The design of statistical experiments is not within the scope of this specific course. Still, the concept was presented to students so that they could understand the

advantage of this powerful tool for process optimisation and prepare them for this course, which they would need to take after the end of this class.

7. Students were requested to evaluate the results of this whole activity, divided into four stages. Some of the results are presented in Figure 2. The professor also asked for comments and quantitative feedback.

6.5. Phase 6. Experience wrap up

At the end of the course, the class (of 35 students) was asked to voluntarily respond to an anonymous survey of questions on a 1-5 Likert scale, where five was *Strongly Agree*, and one was *Strongly Disagree* using www.mentimeter.com (32 of them responded). The results are included in Figure 2. The questions were designed to test the perception of the students on the use of a progressive approach from basic teamwork to inter-team work (1), the preference of this type of immersive experiences versus theory and class exercises (2), the immersion achieved with the presented experiences (3), their perception of better learning using this approach (4) and their engagement and interest of trying new versions and immersive plants (5). All averages were above 4. As shown in Figure 2, the results are encouraging.

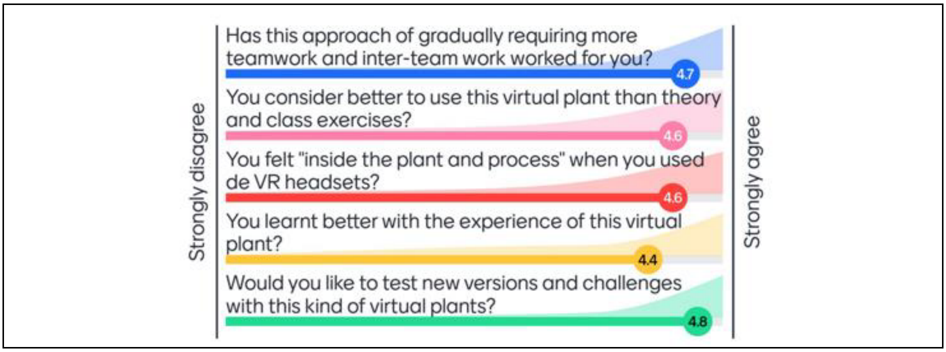


Figure 2. Results of evaluation by students of elements of this framework (n=32, average in circles).

It is worth mentioning at this time that even though the syllabus of this course ends with quality control charts and process capability calculations, this was the first time in the teaching of this course that students were able to advance all the way to process optimisation. The latter validates the effectiveness of the framework.

7. Conclusions and further research

According to van Merriënboer [7], an integrated curriculum is a prerequisite for reaching transfer of learning, that is, to ensure that learners can apply what they have learned to new situations inside and outside the educational program.

The transdisciplinary framework proposed in this work focuses on the design of immersive progressive complexity learning experiences. Its objective is to enhance this transfer of learning by combining the van Merriënboer model [7] simultaneously with the power of immersive technologies within a transdisciplinary approach. The framework proposed includes a gradual increase in a) the complexity of the learning tasks, b) the technical skills required to use different immersive technologies, and c) the requirements to work with a transdisciplinary approach to negotiate, interchange information and collectively achieve the best possible solutions to the challenges provided.

The framework was tested in a pilot study in an undergraduate engineering course, and its results were encouraging (see Figure 2). Most students considered this integrated-progressive approach better than traditional models and appreciated the gradual increase in transdisciplinary interactions.

According to the pilot implementation, the framework is on the right track. Students commented encouragingly about this approach, such as, "This has been the best class in my entire undergraduate program".

Further research pends ahead regarding the comparative evaluation of transferable knowledge acquired by students with this progressive approach versus what could be achieved with classic teaching techniques.

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