# JUST-IN-TIME LEARNING PRODUCT DESIGN AND DEVELOPMENT THROUGH GAMIFICATION

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## ABSTRACT

Solving design problems is a core activity in the engineering field. Design teaching is often project based and follows a cycle from idea to implementation, which perfectly fits the Conceive Design Implement Operate (CDIO) approach. However, it is challenging to design teaching using problems that resemble those found in real engineering practice in a single course. Real problems are typically complex and multidisciplinary, requiring the course to cover both the general design content and the content from each specific discipline. Indeed, to support their work during the design process, the diverse engineering disciplines use different tools and techniques, which must be effectively combined. This multidisciplinary content must also be meaningfully linked and delivered in a way that prevents students from losing their interest when dealing with content from a different discipline. This paper proposes an approach to solve this challenge, which combines gamification and just-in-time learning in a flipped-classroom and project-based learning setting. The gamified project creates a scenario (set of specific tasks/problems) for the just-in-time pulling of learning content, which is made available online. The students learn as needed to play the game in class and are assessed according to their reflections on their game choices and results, rather than whether they win or lose the game. This paper explains the proposed approach's background, describes its gamification elements and dynamics, shows its use in a mechanical engineering master's course intervention, and reflects on the results from the intervention implementation. The students' feedback shows that the approach was able to bring awareness on how the different engineering disciplines contribute to the design problem solution while keeping the students motivated and engaged in the course's activities.

## KEYWORDS

Design Teaching, Active learning, Blended Learning, Gamification, CDIO_Standard 4, CDIO Standard 8

## INTRODUCTION

Engineering education must help learners develop analytical, communication and teamwork skills, alongside independent learning, while meeting ever-increasing content demands for solving engineering practice problems (Jonassen, 2015; Johri et al., 2011). In this context, design is widely considered to be a core and distinguishing activity of engineering and is probably the most common kind of problem in engineering practice (Simon, 1996; Mills &

Treagust, 2003). Design problems are typically complex and require an interdisciplinary approach, thus integrating multiple content domains.

Due to the amount of content involved, teaching product design and development (PDD) in a setting that resembles reality is a challenge (Dym et al., 2005). It requires covering the general design and development process theory and the content from each involved discipline (i.e. design tools and techniques typically used by the discipline). It also must provide a meaningful relationship between these areas while making sure that students do not lose interest when dealing with the content from disciplines that are not their own. In addition, not only do the diverse engineering disciplines use different tools and techniques (T&T) that can be combined in different ways, but new T&T also become available every day. Therefore, learning how to choose and combine promising T&T during each PDD phase and defining an appropriate PDD processes to specific PDD scenarios is an important learning goal.

The underlying research question behind this work is, 'How can design T&T choosing be taught so that an adequate development process is defined according to a realistically complex and multidisciplinary PDD scenario?' To contribute to answering this question, this paper aims to propose, explain and discuss the results from the implementation of an intervention in a mechanical engineering master's course, which served as a preliminary validation of an approach that uses gamification to pull just-in-time learning in a flipped-classroom and project-based learning setting. The choice of a gamified scenario instead of a real development is motivated by the complexity of including an actual multidisciplinary product development and its common possible issues (what-if analysis) in the context of a single course. The proposed approach embeds the Conceive-Design-Implement-Operate (CDIO) framework in a game in which the 'product' is the PDD process that each team has to define, serving as a competition for how to best solve the proposed challenge.

This paper is a follow-up from Pereira Pessoa, Oude Alink, et al. (2021) and Pereira Pessoa, Wachter, et al. (2021), which proposed but did not implement need-based learning (NBL) and gamification in the Ingenious game. The following sections present the background behind the gamified approach development, detail the developed game and gamification approach elements and mechanics, describe a design course intervention by using the approach, discuss the intervention implementation and the achieved results and reflect on the achieved results and on the students' feedback.

## BACKGROUND

The developed gamified approach relied mainly on the NBL pedagogical model (Pereira Pessoa, Oude Alink, et al., 2021) and gamification theory, particularly through the Octalysis Framework (Chou, 2016) and the Ingenious game (Pereira Pessoa, Wachter, et al., 2021). Note that 'need' in the context of NBL is about the students' need of knowledge to perform a task or to overcome a challenge and not about identifying the users' needs during a design process. Therefore, in NBL, the students learn when and what is needed.

### *Need-Based Learning*

The NBL model is composed of six activities (Pereira Pessoa, Oude Alink, et al., 2021) that require combining different pedagogical approaches: project-based learning (PBL), just-in-time learning (JIT learning), the flipped classroom and gamification. JIT learning is an individual or organisational learning approach that promotes need-related training be readily available exactly when and how it is needed by the learner (Riel, 2000), thus avoiding pre-scheduled education sessions that occur regardless of the immediacy or scope of need (Brandenburg & Ellinger, 2003). Although blended learning approaches, such as flipped classrooms, have been used to change the classroom focus to a more practical approach and let students reach the theoretical content online (Bergmann & Sams, 2014), they are limited in terms of adaptiveness and just-in-time content delivery. The challenge in using JIT learning is anticipating the various learners' needs and creating focused and accessible content (Govindasamy, 2001), which is why it is normally used in more predictable contexts like job trainings. In NBL, the game creates such a context by scoping the learning content to be pulled.

In Figure 1, the activities with grey backgrounds are led by the lecturer, while the activities with white backgrounds are mainly student driven. The NBL's student-driven activities embed the CDIO approach, which is in line with Crawley et al. (2014), who stated the capacity for PBL to incorporate CDIO. The activities 'select', 'create' and 'reflect' relate to CDIO's 'conceive and design', 'design and implement' and 'implement and operate', respectively.

Course design under NBL requires first setting the project challenge characteristics and creating a game that represents the project execution. The supporting theory is made available online using methods such as videos, articles and wiki pages. This theory is necessary for playing the game (executing the project) and can be accessed as needed. Before coming to class, the students use the theory to define their gameplay strategy (flipped classroom). The gameplay and the playing reflection take place during class time. The lecturer gives feedback, further explains the theory and ends the cycle by performing a summative evaluation of the students' performance. Technology support is only necessary for hosting the theoretical material, and the game does not need to be based on software.

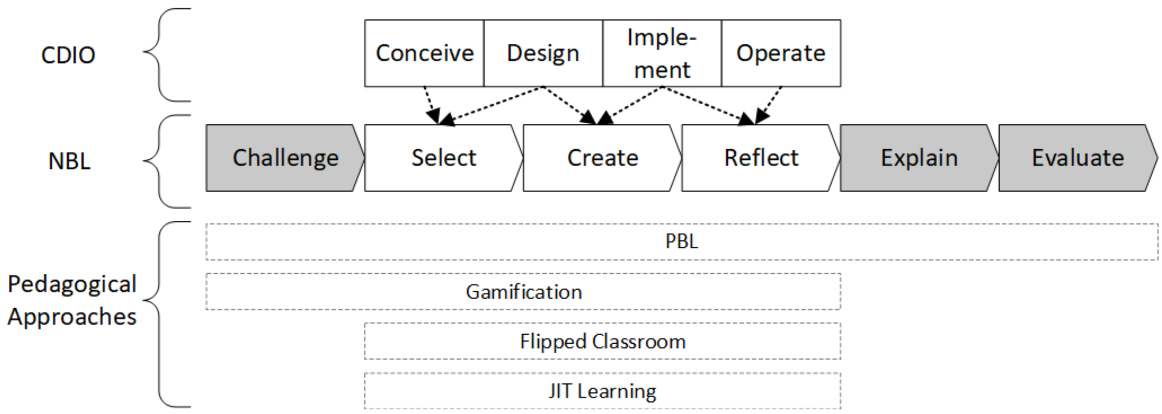


Figure 1. NBL-specific elements.

***Games & Gamification***

While games are normally self-contained, played individually or in groups, and can include collaborative and/or competitive elements, gamification is the use of game elements and game-design techniques in non-game contexts, thoughtfully applying typical game-like elements to real-world or productive activities (Chou, 2016; Deterding et al., 2011; Werbach & Hunter, 2012). Gamification can be integrated with other class activities, potentially as a part of individual or group activities (Díaz-Ramírez, 2020). Gamification, therefore, does not require a self-contained 'game' (but it can use one), and its success relies on creating the motivation necessary to induce desired actions.

Chou (2016) proposed a practical gamification design framework called Octalysis, which includes eight core drives that function as prerequisites for fostering motivation and triggering the planned behaviour: (1) **Epic Meaning and Calling** refers to when people believe they are doing something greater than themselves; (2) **Development and Accomplishment** drives one to perform better, develop skills and achieve mastery; (3) **Empowerment of Creativity and Feedback** engages players in a creative process; (4) **Ownership and Possession** motivates players through the feeling that they own or control something; (5) **Social Influence and Relatedness** incorporates the social elements that motivate people; (6) **Scarcity and Impatience** drives wanting something simply because it is difficult to reach; (7) **Unpredictability and Curiosity** creates engagement because of the uncertainty of what comes next; and (8) **Loss and Avoidance** is the motivation to avoid negative consequences.

The potential pedagogical importance of active learning games was already highlighted by Weck et al. (2005) in the 1st CDIO International Conference. They argued that playing carefully planned and executed active learning games allows students to reinforce their understanding of key concepts while representing a welcome break from the passive learning mode and helps to lengthen attention span and engagement. In addition to this early CDIO paper, 23 more papers were identified in the proceedings from the 1st to the 17th CDIO Conferences (years 2005 to 2021) that had the keywords ‘game’ or ‘gamification’. And out of those, only three discussed to some extent the use of games to support product design and/or development teaching. McManus et al. (2007) taught lean design principles through a hands-on gamified simulation where groups of students competed while using building blocks to model a product; Appleton & Short (2008) used a standard deck of playing cards to create metaphors of PDD that could be played by the students; Ha et al. (2019) used gamification in which soft skills and creative design were used to solve specific ‘game problems’. None of this work, though, dealt with the challenge of choosing and integrating design T&T.

## THE INGENIOUS GAME AND THE PROPOSED GAMIFICATION APPROACH

In this implementation, the learning game, which is the core learning method of NBL, has the objective of teaching the students to select the adequate design T&T in a multidisciplinary PDD scenario. The students conceive, design, implement and operate a PDD process in a fictitious yet realistic game scenario. The learning game used in this implementation is an adaptation of the Ingenious game initially proposed by Pereira Pessoa, Wachter, et al. (2021)

The Ingenious game is a collaborative and competitive card game in which groups of students compete against each other to develop a PDD process that effectively solves the issues that arise during gameplay. The game elements were specifically designed to fulfil the implementation’s purpose and to bring modularity and flexibility features. Therefore, the game can be played standalone or as a part of a course gamification. The game is also expandable, thus allowing the inclusion of new engineering disciplines, techniques and background scenarios. The game elements (in bold) and their link to the Octalysis drivers (underlined) are presented in sequence. In this version of the game, the <u>empowerment</u> driver was not included since the game was envisioned to be played only once during a course, and it was not possible to represent the teams gaining experience.

- The **game scenario** describes the development challenge and gives <u>meaning</u> to the game.
- The **risk level** contributes to the sense of loss during the game, so <u>loss avoidance</u> is about keeping the risk level low. Succeeding in solving all the issues reduces the risk level, while carrying unsolved issues to the next rounds increases it.

- The **risk dice** adds an element of unpredictability. They are rolled for each issue card to check if its related risk is triggered.
- The **budget** is the amount of money available for the team to acquire and play the techniques. The budget adds elements of loss avoidance, scarcity and accomplishment to the game.
- The **engineer cards** represent the engineering disciplines playing the game (e.g. mechanical, electrical, software) and needed to solve the game scenario. These cards provide meaning and a sense of ownership. Each player in the team has a card, and some techniques are more effective if acquired and played by specific engineers.
- The **tool and technique cards** represent 63 design and development T&T and show their capability for solving development issues according to their traits. The T&T contribute to the sense of ownership, as they are not the team's property but the property of each engineer that acquired (learned) them.
- The **issue cards** represent typical issues from each design and development phase. A certain number of cards is randomly drawn in each round, which contributes to the game's unpredictability. To solve an issue card, the players need to play a set of techniques in which the traits' values are equal or higher than the ones required by the issue. Each issue card also includes a risk, which may be triggered depending on the risk dice results.

Besides the game itself, the gamification setting includes online material, online quizzes and a results board (Figure 2). The online material and quizzes cover the general design process theory and information about the design T&T included in the game. The results board displays the teams' results (actual budget, risk level and number of performed iterations), thereby increasing the social pressure and sense of accomplishment.

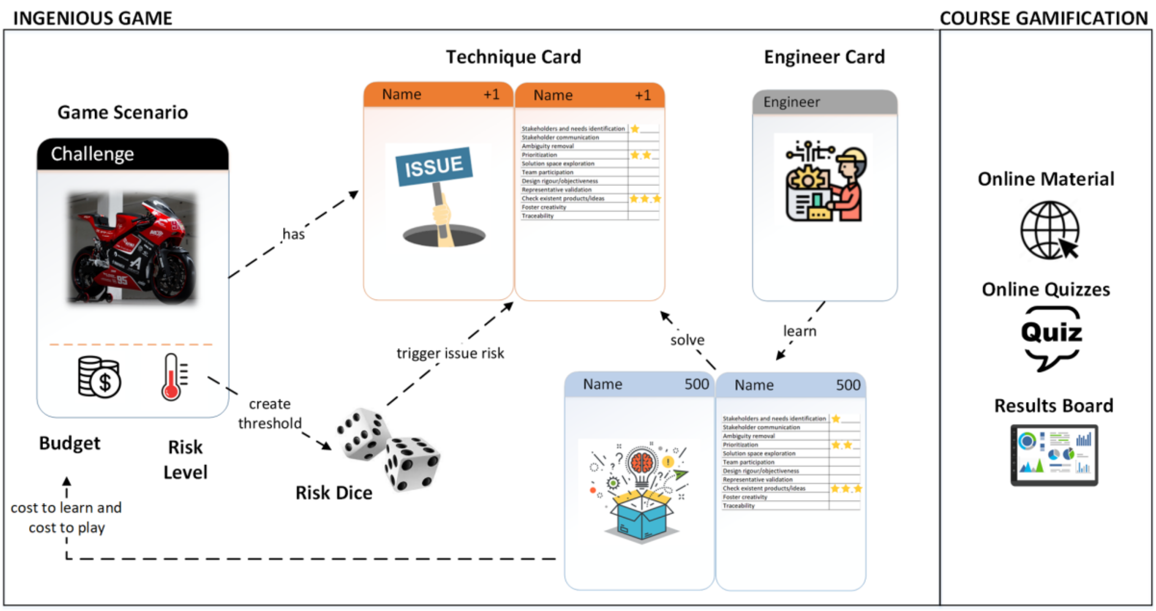


Figure 2. Ingenious game and gamification elements.

The game is played in four rounds based on a typical design and development process (Ulrich & Eppinger, 2012). The rounds represent the conceptual design, system design, detail design, and integration and validation phases. Each member from a group of six players impersonates an engineer from a different discipline (mechanical, electrical, software, system, production and industrial design engineering). While going through the gamified project's phases, the students must select the knowledge to learn ‘just in time’ by making use of online material. This knowledge supports the teams strategy in selecting the T&T, which will compose the PDD process they will play in the phase. Issues cards are drawn and risks are triggered, which represent typical phase issues that could have been prevented by having selected the right design techniques. By successfully solving the issues, the team of players can go to the next round; if the result is negative, they rework until they get acceptable results.

At the end of each phase, the students reflect on the rationale behind the strategy they chose, the effectiveness of their choices, what they could have done differently and why. The lecturer then gives feedback (explain) based on the reflection. The final activity is to evaluate the students’ work; summative assessment is based on the quality of the reflections and not on the game results. Figure 3 shows the game and the gamification mechanics using a simplified sequence diagram (Omg & Object Management Group, 2019), which includes the gamified course activities sequence and the game activities sequence.

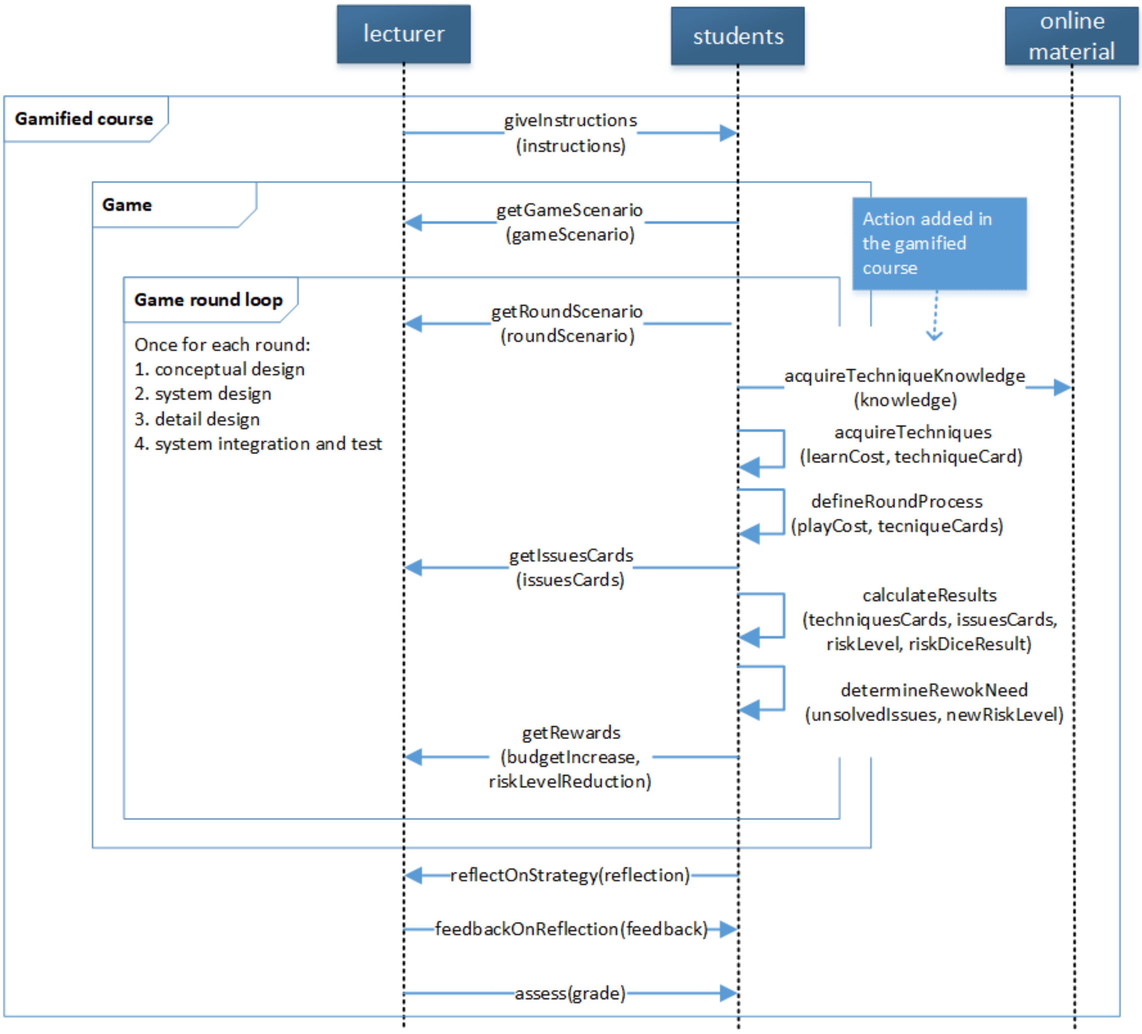


Figure 3. Ingenious game and gamification mechanics.

## USING THE APPROACH IN A COURSE INTERVENTION

The Ingenious game and the gamification approach were used to intervene in the Modelling of Technical Design Processes (MTDP) course from the University of Twente's mechanical engineering master's program. The course's six learning objectives (LO) were not changed from the previous year. The intervention aimed to increase the number of covered T&T from 21 to 63 and to use the game to both motivate and create a more dynamic discussion on how to and when (which development phase) to integrate the T&T (LO3, 4, and 5). It also strived to foster more in-depth reflections on the impact of the T&T integration decisions and the likelihood of PDD success (LO1 and 6). The MTDP course relates to CDIO Standards 4 and 8, as it provides the framework for engineering practice in process building and implements active learning. In sequence, I list the LO and describe what took place during each course week.

LO1. Summarise the main challenges for a successful PDD.
LO2. Determine the appropriate PDD model (waterfall, iterative, spiral or agile[1]), considering the product's technical and requirement uncertainty.
LO3. Determine the appropriate design and development T&T for each PDD phase, considering the disciplines needed during the process (i.e. mechanical, electronic, software).
LO4. Integrate into the PDD the best practices for organisational process definition, engineering, and engineering support according to the CMMI-Dev 1.3.
LO5. Integrate creative design techniques into the PDD.
LO6. Reflect on how to use the learnings from LO1 to 5 in a tailored PDD definition.

The MTDP is a nine-week, 5EC (European Credits) course, with two 2-hour classes per week:

- Week 1 – Introduction to the course and the gamified activities.
- Weeks 2 to 5 – In each week, a phase of the game is played by competing groups of six students. The game implementation followed the method presented in the previous section. The students define the T&T to play before coming to the week's first class and playing a game phase. After the first class, they reflect on the results, and the conclusions from their reflection are presented and discussed in the week's second class.
- Week 6 – The student groups reflect on the impact of their game choices in the whole product lifecycle, particularly when the product is used, serviced and decommissioned.
- Week 7 and 8 – Guest lectures with industry practitioners.
- Week 9 – Exam.

During weeks 2 to 6, no content is to be given beforehand, and the game's challenge requires the JIT learning of the content necessary to play each of its rounds. The necessary knowledge is available online, and the students can access it at their own discretion. The gameplay, the teams' results reflection and the lecturer's feedback took place face to face.

## THE INTERVENTION IMPLEMENTATION AND RESULTS

The intervention was implemented in the period from September to November 2021. Twenty-nine (29) students took part of this pilot, and there were no restrictions to face-to-face meetings. Quantitative and qualitative feedback was gathered from all attendees. Quantitative feedback

[1] This is not a complete list of possible PDD models, but those that are tough during the MTDP course.

(Table 1) focused on understanding to which extent the intervention kept the course at a master's level, demanded the expected effort from a 5EC course, the students' perception that the LO were achieved and to which extent they considered the gamified approach capable of motivating and keeping them engaged during the course. From the results, while the students recognised the motivation benefits (Questions 4 to 7), the approach fell short on the achievement of the LO, particularly the number of hours spent in the assignments and their difficulty.

Table 1. Quantitative feedback results.

| Question | Mean | Std. Dev. | Rating explanation |
|---|---|---|---|
| 1. Hours spent working on the assignments | 1.76 | 0.77 | mean < 2: less than 5EC<br>2 < mean < 3: around 5EC<br>mean > 3: more than 5 EC |
| 2. Assignments' degree of difficulty | 2.55 | 0.5 | mean <2.5: below master level<br>mean >2.5: above master level |
| 3. The course learning objectives were achieved | 3.97 | 0.56 | 1: completely disagree<br>2: disagree<br>3: neither agree nor disagree<br>4: agree<br>5: completely agree |
| 4. The approach turned the lectures more interesting | 4.17 | 0.70 | |
| 5. The approach made students more motivated and active through all the course | 3.93 | 1.05 | |
| 6. The approach gave more motivation to attend the lectures | 4.07 | 1.01 | |
| 7. When choosing a future course, I will consider it a positive if this course also uses a similar approach | 3.90 | 0.55 | |

Further qualitative feedback was gathered to understand the intervention implementation's strong and weak points. In summary, the students positively highlighted that the intervention was successful in motivating them to come to class ('more fun') and to keep up with their studies. It was also helpful in keeping them engaged in group discussions (particularly the more competitive students) in a way they considered 'closer to real life'. They mentioned that the gamified course made the student groups more interested and interactive, thus encouraging critical thinking about the design steps and about different approaches towards the design process. They considered that it made it easier to learn several new T&T in a short period of time, particularly due to each round's select->create->reflect cycle, which led to more in-depth analysis and understanding. Finally, they pointed out that the gamification facilitated their recollection of the theory due to it being contextualised in the game.

In terms of weak aspects, the students pointed to the need to both improve the game scenario and to revise the traits in the technique cards. Some techniques have acquiring and playing costs that are not realistic compared to those of the other techniques in the game. The values from the technique cards' traits do not always fit the round or the issues they are capable of solving. Finally, the game scenario and the issues are not 100% related, which made the scenarios less realistic. The students also made further suggestions for improvement:

- A test round would facilitate the understanding of the game rules.
- Having all the groups present their reflection every week became repetitive once the played techniques and explanations from the different groups became very similar. The suggestion was to add more in-depth and specific assignments directed to the reflections.
- Having a set of technique cards per phase, thus avoiding checking techniques that do not apply to the phase.

- One of the significant downsides of the game is that one can play it without paying much attention to what the techniques do and how they can be applied in a realistic scenario. A description of the issues could be found beforehand, and the team would then decide which techniques to play. Only after the techniques were chosen would the teams allot the technical traits required for solving the issues; so, the selections were not solely based on numbers.

## REFLECTION ON THE RESULTS FROM THE INTERVENTION IMPLEMENTATION

Four intervention implementation success factors (SF) were identified to fulfil the stated objective and support answering the research question. They relate to the students recognising that the approach is capable of:

SF1. Having a game scenario that is realistic and requires multiple engineering disciplines to solving.
SF2. Representing the challenge of choosing and integrating design T&T during PDD.
SF3. Keeping the motivation and engagement during the course activities, which includes preparation before coming to class and the execution of the class activities.
SF4. Delivering the MTDP course learning objectives while keeping the course at the master's level and the course attending effort compatible to 5EC.

The feedback gathered during the intervention implementation stated that all key success factors, although satisfactorily achieved, have further opportunities for improvement.

- Although helping to keep the students motivated, both the game scenario and the techniques cards would benefit from further improvements to make the game more immersive and realistic (SF1).
- The Ingenious game mechanics helped the student groups to learn about new design techniques (in total 63) and how to integrate them to solve typical PDD problems. A suggestion was to make visible which T&T are applicable to each phase and thus saving time spent on going through them (SF2).
- The flipped-classroom format, the online material and the gamified approach were highly appreciated and considered to be important factors for keeping the students motivated and engaged (SF3). More in-depth techniques descriptions and practical use examples could be added to the online material and/or presented during the class discussions.
- Although the learning objectives were mostly delivered, the assignments difficulty and the required hours for elaborating the assignments were below expected for a 5EC master course. As suggested by the students, specific and more in-depth questions could be included as part of the game rounds' reflections (SF4).

Finally, the NBL cycle that included select->create->reflect during each round was appreciated by the students and was an important mechanism for learning. When selecting the techniques, the student groups conceived their strategy and started the design of their PDD, During the create stage, they finished their design and implemented it into the game play. They then reflected on their operationalisation. Therefore, the intervention implementation embedded a complete CDIO where the 'product' was the PDD process the student groups created for playing each game round.

## FINAL REMARKS

After reflecting on the results from the intervention implementation, it can be said that this paper's objective was achieved. The proposed gamified approach, which integrates gamification and just-in-time learning in a flipped-classroom and project-based learning setting, contributed to answering the question, 'How to teach design T&T choosing so that an adequate development process is defined according to a realistically complex and multidisciplinary PDD scenario?'

The results show that the students considered the gamified approach motivating, both in executing their activities and in coming to class. Other positive aspects were fostering critical thinking and showing the connection among topics and techniques, which are often presented as standalone topics. Valuable feedback was also given in how to improve the Ingenious game and the gamification setting to increase the learning outcome.

The MTDP intervention implementation results give preliminary evidence that the proposed approach can support CDIO, particularly in the context of CDIO standards 4 and 8 and is a good practice for exploring design problem scenarios where the students reflect on their strategies and their decision-making process rather than on the details of the engineering issues.

The main limitation of this work is that the intervention was implemented in just one course, and all 29 students were from the mechanical engineering master's programme. Further research is needed, particularly in a multidisciplinary setting in a class that includes students from different engineering disciplines so that the feedback capture their different PDD perspectives.

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