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GAME-BASED LEARNING IN ENGINEERING EDUCATION: USING THE GOLDRATT SIMULATOR TO LEARN ABOUT THE THEORY OF CONSTRAINTS

APRENDIZAGEM BASEADA EM JOGOS NO ENSINO DE ENGENHARIA: USANDO O SIMULADOR GOLDRATT PARA APRENDER SOBRE A TEORIA DAS RESTRIÇÕES

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ABSTRACT

Purpose: The present study evaluated an application of the Goldratt Simulator as a supporting tool used during a Theory of Constraints (TOC) course. To this end, an evaluation instrument was developed to analyze the learning outcomes of game-based learning.
Methodology/Approach: Action research consisting of planning, action and evaluation phases was employed in the Research. The study was conducted as part of a Production Engineering undergraduate program in Brazil.
Findings: Students who used the game reported that classes were more interesting. The combination of the game with the evaluation instrument highlighted doubts that students had regarding concepts previously taught by the professor.
Research, practical & social implications: Game-based learning is a promising approach in higher education; yet, some students declined to participate in the activities. Students who participated, however, declared the activity to be enjoyable and The Goldratt Simulator a suitable tool for learning about TOC. The results highlight the importance of striking a balance between traditional and new educational approaches.
Originality/ Value: The game-based learning literature lacks analysis of approaches to teach topics related to the TOC.
Keywords: Game-based learning; Production engineering; Theory of constraints; Action research.

RESUMO

Objetivo: Este estudo avaliou a aplicação do Goldratt Simulator como uma ferramenta de apoio em uma disciplina de Teoria das Restrições (TOC). Além disso, esta pesquisa desenvolveu um instrumento de avaliação para analisar os resultados educacionais da aprendizagem baseada em jogos.
Metodologia/Abordagem: Esta pesquisa utilizou um método de pesquisa-ação composto pelas fases de planejamento, ação e avaliação. O estudo foi realizado em um curso de graduação em Engenharia de Produção no Brasil.
Resultados: Os alunos que participaram do jogo relataram que as aulas ficaram mais interessantes. A combinação do jogo com o instrumento de avaliação evidenciou dúvidas que os alunos apresentavam em relação a conceitos previamente ensinados pelo professor.
Contribuições, implicações práticas e sociais: A aprendizagem baseada em jogos é uma abordagem promissora no ensino superior; ainda assim, alguns alunos se recusaram a participar das atividades. Os alunos que participaram, no entanto, declararam prazer na atividade e adequação do Goldratt Simulator para aprender sobre a TOC. Estes resultados destacam a necessidade de encontrar um equilíbrio entre as abordagens educacionais tradicionais e as novas.
Originalidade/Valor: A literatura sobre aprendizagem baseada em jogos carece de análise de abordagens para ensinar tópicos relacionados à TOC.
Palavras-chave: Aprendizagem baseada em jogos; Engenharia de Produção; Teoria das Restrições; Pesquisa-ação.

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1. INTRODUCTION

Higher education needs to prepare new generations with the competences required by society (World Economic Forum, 2013), something which evolves over time in accord with the latest challenges faced by the world (Jääskä & Aaltonen, 2022; Janssenset al., 2021). The recent curricular directive for engineering education implemented in Brazil (Brasil, 2021) has set goals aimed at reducing the gap between the competences achieved by graduated engineers and society's demands: increasing educational quality, reducing absenteeism rates, allowing higher flexibility in course structures, and offering activities aligned with future demands. One of the ways the country hopes to achieve these goals is by instigating the use of different educational approaches, such as active methodologies (Brasil, 2021).

Active methodologies “engage students in the process of learning through activities and/or discussions in class, as opposed to passively listening to an expert” (Freeman et al., 2014, p.8413); that is, students have an active role in the learning process (Kober, 2015). Active methodologies have been widely employed in higher education due to their prominent support of student learning (Alves et al., 2017; Braghirolli et al., 2016 Whalen et al., 2018). Among the different approaches within the active methodologies field (e.g., problem-based learning, peer learning, and flipped classroom), is the game-based learning approach.

“Game-based learning” is an expression which refers to the use of educational games as learning activities (Crocco et al., 2016). There is no precise definition of what an educational game is. It can be understood as a game that - with its features of game mechanics, visual aesthetics, narrative, incentives, and musical score - requires and develops skills related to given learning objectives (Plass et al., 2015). Game-based learning has been regarded as having the potential to improve cognitive abilities and domain-specific competences (Platz, 2022). Students can remember a learning topic and its context because of the repetition, emotion, and immersion provided by a game (Jääskä et al., 2021). It can support students in improving competences such as decision-making, critical thinking, problem-solving, collaboration, and communication (Jääskä, & Aaltonen, 2022). Educational games involve engagement on cognitive, affective, behavioral, and sociocultural levels, emphasizing user experience (Plass et al., 2015). Moreover, in subjects such as science and engineering that often generate anxiety and low confidence in students, a game-based learning approach can reduce such negative feelings, creating a more enjoyable environment (Crocco et al., 2016).

Different subjects in higher education have already employed the game-based learning approach (Jääskä & Aaltonen, 2022), such as economics (Platz, 2022), science (Crocco et al., 2016), and engineering (Ebner & Holzinger, 2017; Ross et al., 2014). Within the field of production engineering (including the terms industrial or manufacturing engineering), different topics have been taught with games, such as the circular economy (Whalen et al., 2018), project management (Jääskä & Aaltonen, 2022) and operation management (Alves, 2018; Johnson & Drougas, 2002). However, some fields of engineering knowledge, such as the theory of constraints (TOC), are underrepresented in the literature (e.g., Zheng et al., 2009). Thus, this study aims to fill these gaps by presenting an evaluation tool to be applied to game-based learning approaches during TOC courses. Practical ways of learning can be especially important for topics related to operations management (Johnson & Drougas, 2002; Zheng et al., 2009) due to their capacity to encourage experimentation without the consequences of real world involvement (Jääskä & Aaltonen, 2022). Moreover, testing new approaches is a valuable way of seeking more engagement and interest from students (Braghirolli et al., 2016). This research focused on action research conducted in a Production Engineering undergraduate program at a Brazilian university.

After this introduction, the next section briefly describes the TOC. Next, the method section presents the steps employed in the action research, followed by a section with the results, discussions, and limitations of the research.

2. LITERATURE REVIEW

2.1 Theory of constraints (TOC)

The TOC was developed by Eliyahu Goldratt and was made famous through his best-selling book: The Goal (Goldratt & Cox, 2016). In essence, according to the TOC, every production system presents at least one constraint that prevents it from achieving its fundamental goal. TOC relies on five guiding principles to achieve this outcome: 1) Identify the constraint; 2) Exploit the constraint; 3) Subordinate and synchronize to the constraints; 4) Elevate performance of the constraint; and 5) Repeat the process.

Some aspects reinforce the scientific predicate of TOC (Naor, Bernardes, & Coman, 2013). Firstly, due to its clear definition, well-defined domains, capacity for relationship building, predictive capabilities, and empirical support, it can be considered a valid scientific theory. Additionally, it has the required virtues of uniqueness (elements that are different from other theories), conservatism (elements that replace the inferior elements of other theories), generalizability (it can be applied in different areas), fecundity (it can generate new models), parsimony and simplicity (it has simple representations), internal consistency (its variables have established relationships), empirical riskiness (it can be refuted), and abstraction (it does not depend on time and space).

The TOC was developed in the manufacturing environment. However, its practices can be applied in different organizational contexts to support problem-solving (Taylor III, & Thomas, 2008). The TOC has developed specific approaches to application in different organizational areas, such as: 1) Accounting, with the Throughput Accounting (Throughput, Inventory, and Operating Expense); 2) Production Planning and Control, with both Drum-Buffer-Rope (DBR, also with its simplified version S-DBR) and Buffer Management; 3) Project Management, with the Critical Chain Project Management approach; and 4) Thinking Process, employing logical tools to support the achievement of solutions for any kind of problem (Ikeziri et al., 2019).

TOC approaches have also been adapted and employed in different areas, such as logistics (Souza & Pires, 2010) and supply chains (Ikeziri et al., 2023), sales and operation planning (S&OP) (Rota & Souza, 2021), and stock level management (Narita et al., 2021). A branch of TOC has also been applying its theory concepts in educational environments (Suerken, 2020), such as an educational methodology to develop problem-solving skills among undergraduate students (Cooper & Loe, 2000). However, with few exceptions (Johnson & Drougas, 2002; Luo & Munson, 2022), the literature lacks analysis of teaching approaches for TOC concepts. To contribute to this topic, the present work presents an action research study of a game-based learning approach applied within a TOC course.

3. METHODOLOGY

To accomplish the goal of evaluating learning outcomes through the game-based learning approach for the study of TOC , the authors adopted the action research method. Action research is a scientific, participative, and collaborative method in which knowledge is created and applied (Eden & Huxham, 1996, Susman & Evered, 1978). It is commonly used in educational research (Eden & Huxham, 1996; Jääskä et al., 2021; Schratz, 1992). Action research usually embraces the general planning, action and evaluation phases through a cyclical approach (Susman & Evered, 1978). These three phases are described next.

3.1 Planning phase

In the planning phase for the present research, the authors deemed it important to map the literature on the theme to support the development of an evaluation instrument to be applied to the proposed game during the action research phase. Thus, the authors performed a systematic literature review for this phase of the research. There are different strategies and reasons for carrying out a literature review (Paul & Criado, 2020), not least among them being to support the next phase of a research project (e.g., Lima et al., 2022), being the case for the present research. To perform the systematic literature review, the authors adopted, with some adaptation, on the PRISMA (Preferred Reporting Items for Systematic Reviews with And Meta Analysis) protocol (Moher, Liberati, & Tetzlaff, 2009), which is a common approach applied in literature reviews (e.g., Lima & Mariano, 2022; Lima et al., 2024).

The first step of the literature review is to select the database to identify the articles. The authors chose the Scopus database, which is one of the main databases used in literature review studies, as it embraces a higher number of high-quality papers (Paul & Criado, 2020).

The second step is to select the keywords to be used in the search. The authors selected three groups of keywords: related to the main theme (i.e., "serious game" and "educational game"), the specific theme within the general theme (i.e., evaluat*, validat*, experimental and metric), and the area of knowledge within the research scope (i.e., "production engineering", "industrial engineering", "manufacturing engineering", administration and business). The Boolean operator OR was used among keywords in each group, and the Boolean operator AND was used to link the three groups. In line with other literature reviews (e.g., Lima and Mariano (2022); Lima et al. (2023); Salibi et al., 2022)), the present search was limited to studies published in journals (to increase the quality of the articles located), and the keyword search was applied to the title, abstract, and keywords of articles. This process resulted in the following research string: (TITLE-ABS-KEY("serious game" OR "educational game")) AND ("production engineering" OR "industrial engineering" OR "manufacturing engineering" OR administration OR business) AND (evaluat* OR validat* OR experimental OR metric*) AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE,"English")) AND (LIMIT-TO (SRC-TYPE,"j")).

The third step of the literature review is the process by which the located documents are screened. The aforementioned search string located 256 papers. However, 54 of these were not available to the authors in their entirety, and thus were removed from the sample. The authors recognize that this is a significant number of papers, but as the literature review had the purpose of supporting the action and evaluation phases of the research, rather than being a main goal of the research, the authors did not consider that removing these articles would be a problem for the research goals. The abstracts of the remaining 202 papers were screened by the first and second authors in order to identify the articles aligned with our research goals. The sample was divided between the two lead authors, who then discussed any doubtful cases. Again, the authors recognize the flaws in dividing the sample, but this approach was adopted considering that the literature review was only a supporting method for the research. Based on the exclusion criteria of removing papers that were not related to application and evaluation models to be used in a game-based learning approach, 134 more were removed in the abstract screening process, resulting in a sample of 68 papers.

In the fourth step of the literature review, the 68 articles approved in the previous phase were completely read by the first and second authors to check whether they were actually in accordance with the research goals. In this way, 21 articles that met the inclusion criteria of discussing a game-based learning evaluation approach in the fields of engineering, administration, or business were considered as the final sample.

Finally, the fifth step of the literature review was the codification of the interest data of the research, that is, instruments to evaluate students learning in game-based learning approaches. The evaluation approach considered for codification in the present research was: perception, self-evaluation, and learning. The perception evaluation mainly supports the validation of the games regarding their attractiveness (usability and entertainment) and attributes (learning potential), being used to validate the immersion and engagement provided by the teaching approach employed (Khan & Pearce, 2015). Self-evaluation aims to identify alterations in the knowledge and behavior based on the perspective of the participants themselves, mainly when there is a conscientization element leading to this change (Bascoul et al., 2013). The learning evaluation analyzes the effectiveness of what was learned, learning potentially occurring at different moments before and/or after the experiment. However, the pre-evaluation is limited to indicating what would be evaluated previously in the experiment; thus, it might induce the intensification of the studies in a more focused way (All et al., 2017).

3.2 Action phase

The action-research was applied to the Production Administration IV module of the Production Engineering undergraduate program at a Brazilian university. This module has been taught by the third author of this paper since 2007. The module is divided into two parts, each covering an important topic for Production Engineering: namely, the Theory of Constraints (TOC) and Lean Manufacturing. The Goldratt Simulator was the game selected to be used during the part of the module dealing with the TOC topic. Games and simulations share similar educational concepts, including existing simulation games (Braghirolli et al., 2016; Jääskä et al., 2021). However, they also have some distinctions. The Goldratt Simulation, despite its title (Simulation), was deemed a game in this investigation; as it does not permit personalization, its configurations are predetermined, and cannot be altered. The Goldratt Simulator is a game conducted within an environment that simulates different operational production plants. Each plant has a number and variety of machines, each with a certain capacity. The aim is for the player to schedule production in order to maximize earnings and reduce costs. To achieve the objective, it is necessary to use TOC concepts relating to Drum-Buffer-Rope and resource management (TOC-Goldratt, 2023). Although it is a single-player game, students can form groups to discuss and make decisions together. It is also possible to define a target goal before playing and make comparisons between the challenge proposed and student players' achievements.

The present research was conducted in 2021, when a total of 32 students were enrolled in the module that year. During the research period, university classes were conducted online, due to the measures adopted during the Covid-19 pandemic. Universities all over the world had to adapt their educational practices because of the pandemic, online classes being a common approach implemented by them (García-Peñalvo et al., 2021). Thus, the action phase of the action research was equally developed to be conducted online.

The action phase was led by the first author, a production engineering undergraduate student enrolled in a scientific initiation project, supervised by the third author of the present research. Scientific initiation, a kind of undergraduate research in Brazil, is a common activity in Brazilian universities, in which students are advised by a professor on a project approved by a federal or regional research institution. The second author, a Ph.D. student at the same university, who is also oriented by the third author, supported the implementation of the activities. Her thesis and main focus of research is education in production engineering.

3.3 Evaluation phase

The evaluation phase of the research focused on questionnaires that the students who participated in the experiment completed. The present research adopted a pretest-posttest approach (Platz, 2022; Mayer, 2019). In the pretest, the consent form included a question about students' previous knowledge on the subject ("What is your knowledge level about the theory of constraints?": "I have never heard of it", "I do not know what it is about", "I have already heard of it, but I do not know of what it is about", "I have already heard of it and I know that it is about a management philosophy", "I have already read and / or seen lectures about it", and "I know and I can talk about the topic with authority") and five questions about their learning expectations ("I believe the subject is important for my development", "I would enroll on the module even if it were not a mandatory subject", "I believe that the assessment activities are fair", "I believe that the proposed assessments are challenging", and "I believe that the proposed methodology seems interesting"), with scales ranging from 1 (completely disagree) to 5 (completely agree). The posttest employed three questionnaires: perception evaluation, learning evaluation, and self-evaluation (Supplementary Material). The questionnaires also included optional open spaces for the students to include a comment (Ebner & Holzinger, 2007). Moreover, the observations made by the first and third authors during the action phase were also used in the analysis (Jääskä & Aaltonen, 2022). Questionnaires about the activity employed and the authors' observations (Jääskä et al., 2021; Schratz, 1992) are common approaches in action research studies. By relying on different sources and types of data (i.e., Likert scale, open questions, and observations) and having different authors analyze and collect them, potential bias can be reduced (Garcia & Yao, 2019).

4. RESULTS AND DISCUSSION

This section presents and discusses the outcomes of each of the three phases of the action research.

4.1 Planning phase

The first part of the planning phase consists of reporting information about the papers located during the literature review stage. The main information of the 21 papers is presented in the Supplementary Material (Table S1). These articles supplied information to be used in the other phases of the action research: preparation and application of the activity, including the questionnaire development.

Even though the pretest/posttest condition is regarded as important in this kind of study, due to the robustness of the analysis (Mayer, 2019), several of the studies in the reviewed literature relied only on posttest. The first codification data presented is related to the evaluation methods employed in the papers included in the literature review. Considering that more than one approach could be used at the same time, the codification was done to measure all the possible combinations of these three approaches (Table 1). The most common approach identified was perception and self-evaluation, being used together in 14 of the 21 papers of the final sample.

Table 1
Number of papers that used each combination of evaluation methods.

Evaluation method	Number of papers
Perception	0
Self-evaluation	0
Learning	2
Perception and self-evaluation	14
Perception and learning	1
Self-evaluation and learning	1
Perception, self-evaluation and learning	3
Total	21

Considering that the evaluation methods can be applied with different scales and formats, such as multiple-choice, true/false, and/or open-ended questions; the present research also codified this aspect within its sample of papers (Table 2). The style of each question is what will determine the evaluation level, which can be adjusted to the lower levels of Bloom's Taxonomy (multiple-choice questions) or transposed to higher levels. It is also possible to evaluate only the scores in the games. The Likert scale was the most common format, used by 16 of the 21 papers of the final sample. Open-ended questions and performance during the game were adopted in 8 and 6 papers, respectively.

Table 2
Number of papers that used each scale and format.

Scale and format	Number of papers
Performance during the game	6
Likert scale	16
True/False	2
Multiple-choice	1
Open-ended questions	8

Based on the aforementioned data, the authors decided to develop the present instrument adopting three evaluation methods (perception, self-evaluation, and learning) and three different scales: Likert, true/false, and open-ended questions. This approach was selected in order to have a more complete analysis across different kinds of data, thus contemplating the different approaches used and identified in the specialized literature.

4.2 Action phase

The students taking the Production Administration IV module were separated into two groups: the first was exposed to the experiment, having classes with the game-based learning approach, and the second, having traditional classes with a professor who presented the content, acted as the control group (Mayer, 2019). The game-based approach, therefore, was used only during part of the module (Tortorella & Cauchick-Miguel, 2017). Every step was previously discussed with the undergraduate students. Thus, during the first class on the module, the professor informed the students about how future classes would be developed, the module schedule and the criteria used to determine the student approval. Moreover, a consent form developed in Google Forms was handed to the students to verify whether they would agree to participate in the experimental group or not. The consent form also included a question about students' previous knowledge of the subject. Students who did not agree to participate in the experiment were included in the traditional class method but were not evaluated in the same way as those who had agreed to participate in the study. The professor emphasized that the willingness or not to participate in the study would not affect the students' grades.

The students from the Production Administration IV module who accepted to participate in the research were divided into experimental and control groups (Mayer, 2019). The separation of the groups was done in a balanced manner based on age, gender, previous knowledge, and learning expectations (Table 3). In the beginning, 15 students agreed to participate in the research. However, 5 later changed their minds and decided not to participate. 9 students had answered the consent form negatively, that is, they refused to participate in the research, and the other 8 students did not return the online form. In this way, 10 of the 32 students enrolled on the course module (31.25%) participated in the study, 6 of them in the experimental group and 4 in the control group. Although the final number of students in the research is small, it was still considered sufficient to gather insights about educational practices from (e.g., Jääskä et al., 2021; Garcia et al., 2019; Bosschaart et al., 2016; Hoffman et al., 2021; Tortorella & Cauchick-Miguel, 2017).

However, a specific comment should be made about the relatively small number of students who took part in the research, considering that less than half of those enrolled on the module were willing to participate in the research: this might represent a barrier to employing such activity. While the literature seems to agree on the benefits of using a game-learning approach (e.g., Whalen et al., 2018), students might be reluctant to engage in such activity, at least in the beginning. Recognizing this, an extra form was sent to the students who elected not to participate in the research, asking for their reasons. Of the nine students who declined participation, five (55.55%) replied to the form; two stated that they do not like games/simulations and all five said they do not have time for extra activities. The longer time for game-based learning compared to traditional classes is one of the barriers to the approach (Platz, 2022). Some students might find the approach to be time-consuming and not rewarding enough to engage in it. The learning preferences of students should also be taken into consideration, as some of them might not perceive that game-based learning is a suitable approach for them (Jääskä & Aaltonen, 2022; Plass et al., 2015). However, in the present study, it is worth mentioning that only the questionnaires for the activity evaluation and the introduction of the game were planned to be done outside the class time and students who did not participate in the game would leave the class earlier on the days on which the activity was scheduled.

Table 3

Students' profiles, considering gender and age.

Group	Student	Gender	Age
Experimental	Student 1	Male	27
	Student 2	Male	22
	Student 3	Female	21
	Student 4	Female	21
	Student 5	Female	23

	Student 6	Male	23
Control	Student 7	Female	22
	Student 8	Male	24
	Student 9	Female	23
	Student 10	Male	22

The experimental group used two games at two distinct moments during the module: the Goldratt Simulator was used to cover the TOC part of the module, while the Lean Cards was used in the Lean Manufacturing part of the module. The control group, on the other hand, were given regular classes without the use of the games. Considering that the presentation, development and application of the Lean Cards part of the module is beyond the scope of the present research, it will be presented in another paper. To properly engage in a proposed game activity, students need to understand how it works (Eden & Huxham, 1996). Thus, it is common practice to present the instructions to a game (Platz, 2022). Students in the experimental group, therefore, received an instructional manual and a tutorial video developed by the authors. Adequate instructions were necessary to enable students to understand how to play the game and also contribute to their increased motivation to participate in the activity.

On the class days when the games would be presented, the classroom was separated into groups. The experimental group had activities with the games, while the control group had activities usually applied in regular class format, i.e., lectures. These activities were carried out during the fourth and fifth classes of the course. Thus, all students had already had three traditional classes about TOC and its introductory concepts and topics before the experiment began. The activities with the control and experimental groups took place in the second half of the classes, after the initial expositive explanation by the professor. The activities with the game can be summarized as follows:

1. Installation of the software;
2. Explanation of the game rules, commands, data and plant production script;
3. Free time (10 minutes) for the students to get familiarized with the game;
4. First round of the game (30 minutes) for the students try to achieve the goal presented in the plant production script;
5. Discussion of the tasks done by the students and the results;
6. Identification of the system constraints collaboratively with the whole class;
7. Presentation of the Drum concept (resource programming with capacity constraint);
8. Students prepare the production plan and test it on the game (30 minutes);
9. Presentation of the concepts of Buffer (temporal protection provided to the restriction) and Rope (programming the release of materials to the factory);
10. Students develop a new production plan, including the Drum and Rope, and test them on the game (30 minutes);
11. Discussion of the results and practical implications.

4.3 Evaluation phase

By the end of the activities, all the students enrolled in the research (experimental and control groups), answered three questionnaires: perception evaluation, learning evaluation, and self-evaluation (Supplementary Material A, B, and C). The questionnaires also included optional open spaces for students to include a comment (Ebner & Holzinger, 2007). The 10 students who participated in the research answered the evaluation perception and learning evaluation questionnaires. However, only 9 answered the self-evaluation questionnaire

4.3.1 Perception evaluation

The evaluation perception was the first questionnaire answered by the students. There were 20 questions (e.g., “This kind of activity should happen more times”, “This activity improved my critical thinking”) on a Likert scale ranging from 1 (completely disagree) to 5 (completely agree). The average and standard deviation are represented in Table 4.

Table 4
Evaluation perception average and standard deviation for both groups.

Dimension	Question	Experimental group		Control group	
		Average	Standard Deviation	Average	Standard Deviation
Absorption Immersion	1. During the activity, I lost track of time.	4.2	0.4	1.8	0.5
	2. During the activity, I felt totally immersed.	4.5	0.5	2.8	1.5
	3. The activity made me feel self-confident.	3.7	0.8	2.8	1.5
	4. The activity made me excited.	4.5	0.5	3.3	1.5
	5. The activity stimulated my interest.	4.8	0.4	3.8	1.5
	6. The activity aroused my curiosity.	4.8	0.4	3.8	1.5
Pleasure	7. The activity gave me a good feeling.	4.5	0.8	3.8	1.5
	8. I had fun during the activity.	4.8	0.4	2.8	1.0
	9. The activity brought me joy.	4.0	1.1	2.8	1.0
	10. The activity was pleasant.	4.5	0.5	3.3	1.5
Motivation	11. This type of activity should be carried out more frequently.	4.8	0.4	3.3	1.0
	12. This is an activity that I willingly performed.	4.8	0.4	4.0	1.4
	13. This is an activity that I would participate in even if it was not linked to attendance monitoring.	4.3	0.8	3.8	1.5
	14. This is an activity that I would participate in even if it was not linked to the grade.	4.5	0.8	3.8	1.5
	15. This is an activity that I would do even though I	4.3	0.8	3.8	1.5

Dimension	Question	Experimental group		Control group	
		Average	Standard Deviation	Average	Standard Deviation
	didn't receive anything in return.				
Skills	16. This activity improved my critical thinking.	4.8	0.4	3.8	1.5
	17. This activity improved my problem-solving skills.	4.5	0.5	3.5	1.3
	18. This activity improved my analytical skills.	4.5	0.8	3.5	1.3
	19. This activity improved my time and resources management competen-cies.	4.5	0.5	3.0	1.4
	20. Some issues became clear with this activity.	4.8	0.4	2.5	1.3
	Total	4.5	0.6	3.3	1.3

The experimental group presented a higher average for the questions when compared to the control group. This might indicate that, in general, the group that used the game-based approach was more immersed, felt more pleasure during the activity, felt more motivated, and believed that their skills were improved: expected responses, according to the literature (Jääskä & Aaltonen, 2022; Crocco et al., 2016; Plass et al., 2015). Moreover, for all questions, the standard deviation in the control group was higher than in the experimental group. One highlight is that question 1, which covers the notion of "getting lost in time", presents the lower standard deviation for both groups and the biggest difference between the averages. This can be observed in an observation made by one student in the control group:

> "As a member of the control group, I believe it is important to highlight the professor's didactic capacity. In the presented content, the examples used, the speech clarity, and the attention when answering the students' questions counts a lot for a positive evaluation of the activity taught. It is worth noting that without these aforementioned points, due to the relatively long duration of each class [4 hours], I believe that I would not have felt involved and excited to make the most of the class".

As the classes are usually long, they might be tiring and, even with a sustained effort from the professor and the students, in classes which are only theoretical and expositive it might be more difficult to maintain concentration for the whole time and "get lost in time". By introducing more dynamism into a class, students can be engaged for more time, and the time "passes by faster". In addition to the aforementioned comment, a further three students gave their feedback about the activity:

> "I found the activity of using the simulator extremely helpful, it was fun and a very clear way to understand how to manage production; although there are not the same mistakes as in the real world, it is always good to have a starting point to be able to test. I still need to play the game again on my own to check if I really absorbed what was presented. However, I believe that I am already more familiar with the idea of how to make the game work out".

Educational games present information and problems that can be linked to real life, facilitating the transfer of learning (Plass et al., 2015). They provide an environment where students can make tests and mistakes without the same implications they will face in their future work, which might support their learning (Jääskä & Aaltonen, 2022). Moreover, this kind of activity might be motivational enough so that students want to play it, persist in playing and attempt to master it (Mayer, 2019). For this, the game should not be excessively easy or hard, as both extremes discourage the challenges of mastering the game (Plass et al., 2015).

> “It was much easier to understand the theoretical content by seeing the simulator working on what we have determined and to understand what should be done”

A higher interaction with the learned content provided by games has been reported as positively supporting learning outcomes (Jääskä & Aaltonen, 2022).

> “I have not thought of any means of improvement. But I would like to congratulate the idea and initiative. It was really nice!”

This last comment illustrates another potential benefit of a game-based approach: students openly stating how the proposed activity was enjoyable to participate in, added to the professor's sense of achievement at realizing that (Jääskä & Aaltonen, 2022).

4.3.2 Learning evaluation

For the second instrument, the learning evaluation, which composed of 12 True/False questions, the result was different from expected (Table 5). The control group presented a higher average (7.7) than the experimental group (6.7). One feedback received in this questionnaire might offer an explanation for this result.

> “I believe that the visualization of the game helped me a lot to understand. Having said that, I believe that 4 uninterrupted hours was a little exhaustive and could have hindered the learning outcome”.

In this way, even with a possible “lighter” class, as highlighted by the student, the duration of it is still a critical point. Just for clarification: every class had a 20-minute break between the first and second half of the 4 fours. Thus, this student’s mention of “4 uninterrupted hours” probably relates to a 4-hour credit class on the same day.

Table 5
Learning evaluation results from the true or false questions.

Question	Experimental group		Control group	
	Sum of the right answers	**Percentage**	**Sum of the right answers**	**Percentage**
1. The Theory of Constraints (TOC) argues that companies have many constraints that make it difficult to reach their goal	3	50%	1	25%
2. The Theory of Constraints (TOC) states that local optima result in global optima	4	67%	3	75%
3. Capacity-constrained resources (RRC) are resources that, if poorly managed, can become bottlenecks	5	83%	4	100%
4. Bottlenecks prevent demands from being fully met	3	50%	2	50%
5. Bottlenecks and RRCs are synonymous	5	83%	4	100%
6. The buffer is the stock of materials in process that must be present throughout the entire production line	1	17%	3	75%
7. The Rope is the sequencing of material release to the factory based on the discounted Buffer Drum	6	100%	4	100%
8. The production schedule of the Bottleneck is the Drum, and it is from there that the rest of the factory must be subordinated	6	100%	4	100%
9. An hour lost on a non-bottleneck resource is an hour lost on the entire system	5	83%	4	100%
10. An hour saved on a non-bottleneck resource is an hour gained system-wide	5	83%	3	75%
11. In the classic Drum-Buffer-Rope method, in-process buffers are dimensioned and controlled in the form of time	4	67%	4	100%
12. Non-bottleneck resources should adjust their production speeds to the Drum	1	17%	1	25%

It is worth mentioning that questions 1, 6 and 12 were those who students more often got wrong. This can be an indication to the professor that the content of these questions might be more doubtful and difficult for students to understand.

4.3.3 Self-evaluation

Next, the authors calculated the average of the values from the self-evaluation questionnaire, which ranged from 1 (I did not understand anything) to 5 (I completely understood).

In general, a high level of confidence and security in the responses of all students can be observed. Taking the most critical questions (1, 6 and 12), it can be seen that the averages, mainly for question 6, are quite high, even though the majority got these questions wrong (Table 6).

Table 6
Average of the self-evaluation questions per group.

Question	Experimental group		Control group	
	Average	**Standard Deviation**	**Average**	**Standard Deviation**
1. The Theory of Constraints (TOC) argues that companies have very FEW constraints that limit the achievement of the goal	3.6	1.3	3.8	1.5
2. The Theory of Constraints (TOC) states that local optima DO NOT result in global optima	4.8	0.4	3.5	1.9
3. Capacity-constrained resources (RRC) are resources that, if poorly managed, can become bottlenecks	4.6	0.9	4.8	0.5
4. Bottlenecks prevent demands from being fully met	4.8	0.4	4.0	2.0
5. Bottlenecks and RRCs are NOT synonymous	4.2	1.1	4.5	1.0
6. Time buffers are reflected in physical inventories located at strategic points to protect system constraints	4.0	1.4	5.0	0.0
7. The Rope is the sequencing of material release to the factory based on the Drum discounted the Buffer	4.6	0.9	4.5	1.0
8. The production schedule of the Bottleneck is the Drum and it is from there that the rest of the factory must be subordinated	4.8	0.4	3.8	1.9
9. An hour lost on a NON-bottleneck resource is NOT a system-wide lost hour, but an hour lost on the bottleneck resource is a system-wide lost hour	4.4	0.9	5.0	0.0
10. An hour saved on a NON-bottleneck resource is NOT an hour gained system-wide.	4.2	1.1	4.8	0.5
11. In the classic Drum-Buffer-Rope method, in-process buffers are dimensioned and controlled in the form of time	4.4	0.9	5.0	0.0
12. Non-bottleneck resources must NOT adjust their production speeds to the Drum. They must operate according to roadrunner logic	4.0	1.4	3.8	1.9

4.4 Limitations

Some limitations of this research should be highlighted. First it is important to mention the small sample of students that took part in the study (only 10 students agreed to participate in it). This number meant it was impossible to rely on statistical methods to analyze the data collected. Such a small number of students also made it more difficult to reduce bias during the division of groups (control and experimental), since with a higher number of individuals it is easier to mitigate the effects of "outliers". Because of this, one of the groups might have been composed of students with more facility in the subject. In spite of these limitations, it is notable that other studies in the field of education have also relied on small samples (Bosschaart et al., 2016; Hoffman et al., 2021; Jääskä et al., 2021; Mayer, 2019; Tortorella & Cauchick-Miguel, 2017). Future studies should seek to adopt bigger and more diverse samples to better understand the applicability of the Goldratt Simulator for teaching TOC content in higher education.

A second limitation is related to the voluntary nature of the activity. As a result, the students who enrolled in the activity might have a different profile than the others, which might not be the result of an obligatory activity (Hoffman et al., 2021; Strawbridge et al., 2022). Thus, future research should consider scenarios where all students participate in an activity, respecting individual preference to be part of a research project or not.

A third limitation concerns the activities being developed online, which is not usual for the university, the students or the professor, who are less used to education under this kind of format. Therefore, future research should analyze the Goldratt Simulator in a presential course and also in courses that are originally planned to be online. The questionnaires employed in the present research can be tested in these two environments. Considering that reporting teaching experiences can be useful for fostering studies in the area and sharing ideas considering teaching approaches in higher education (Virkki-Hatakka, Tuunila & Nurkka, 2013; Liu & Côté, 2021), different approaches employed can enrich the understanding of the topic.

5. CONCLUSION

Game-based learning can be a suitable approach for applying active methodologies in engineering education. One manner of employing this approach is by adopting action research, such as that presented in this article. Action research supports professors and instructors in planning, applying, and evaluating the learning activities employed. The present research sheds light on the suitability of the Goldratt Simulator for students to exercise their knowledge in TOC in an environment where errors are allowed. The evaluation instrument developed during the action research supported the implementation of the activities, as the researchers had a better view of students' motivations, expectations, and learning outcomes.

Game-based learning is a promising approach in higher education, despite the fact that some students decline to participate in this kind of activity. Students who participated, however, declared the activity enjoyable and the recognized the suitability of The Goldratt Simulator to learn about TOC. These results shed light on the necessity of striking a balance between traditional and new educational approaches, and on the necessity of developing new approaches to motivate students to try new educational methods.

Future research expects to count on the support of a teaching laboratory at a given institution, focused on the use of educational games that will allow the application of this and other activities more frequently. The authors believe that the frequent adoption of new methodologies and research of this nature will increase student adherence, as they will be more familiar with such procedures. Moreover, with the changes experienced during and after the Covid pandemic, it is expected that this kind of laboratory will meet the demands of both in-person and remote activities, allowing the development of new studies, which will be able to judiciously evaluate and compare these two different environments.

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