Engineering Design Process through Game-Based Learning for Freshmen Engineering Students

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Engineering design process through Game-based learning for Freshmen Engineering Students – A Systematic Literature Review

Abstract

The integration of engineering design process fundamentals into freshmen engineering curricula has gained considerable attention as academic institutions respond to industry demands for improved engineering education. This paper explores the potential of game-based learning as a tool to enhance the quality of teaching engineering design to first-year students. Recognizing the significance of design theory and principles in engineering professions, the research aims to address the challenges associated with teaching freshmen engineering design. This work-in-progress paper conducts a systematic literature review on the utilization of game-based learning in freshmen engineering design courses. The primary objective is to explore the existing knowledge in this domain and provide support for future scaling initiatives. The primary objective is to explore the existing knowledge in this domain and provide support for future scaling initiatives. Thus, our guiding research questions were as follows: What is the current state, trends, and future direction of teaching the engineering design process to freshmen through game-based learning? Nine publications meeting inclusion criteria from 2013 to 2023 underwent a thorough synthesis phase in our review process. These publications are categorized into four themes: student motivation and engagement, technical/soft skills, feedback, and assessment. The paper extensively discusses findings within each theme, offering insights into their implications for both research and practical applications.

Furthermore, the paper includes a descriptive analysis of current trends in game-based engineering education research. Key observations include the similarity in research questions and objectives, the applicability of game-based learning in the context of engineering design, and a significant potential for developing, testing, applying theoretical and conceptual frameworks in the realm of game-based learning in engineering education, and sample demographics.

Keywords: engineering design process; first-year engineering; game-based learning; game-based learning in engineering

Introduction

Before the introduction of computers or even early digital games seen in arcades, games were an essential part of society to evade boredom and interact with others as people whether it be physical or mental games. Games not only provide a fun and interactive way of stimulating the mind but also encourage players to make decisions and prioritize their goals to solve difficulties [1]. Players are forced to figure out solutions by using real-world knowledge applications, teamwork assistance, or even skills learned in other games. As advances are made to technology, there are new releases of varying game genres available in the community for players to choose and explore. Researchers have been investigating the application of various available games that could be incorporated to teach concepts and successfully engage learners in and outside the classroom. This has further expanded due to COVID-19 restrictions that saw a push towards more online-based learning materials for more comprehensive learning. Students in the classroom mainly struggle with staying on task due to a lack of interest and the traditional format of lecture, while

complaining that learning can be mentally exhausting, especially in a traditional lecture-based environment [2], [3].

The use of games in the classroom holds an advantage over other resources provided. Unlike documents, which lack encouragement of interaction with the material, games can provide a unique experience by replicating specific real-world situations and providing a digital first-hand experience for students [4]. Other advantages game-based learning offers is the betterment of relationships between instructors and students. Games can be used as an alternate teaching approach by the instructors to help increase students' confidence in the form of support from the instructor and class materials. Additionally, research has shown using games to teach concepts has been effective in increasing student learning outcomes [5]. Multiple types of game-based learning have seen success in the classroom including augmented reality (AR), virtual reality (VR), serious games, and stimulations with varying degrees of success which are dependent on the material type of engineering courses [6]. AR and VR are great instruments for visual based learning concepts, and they provide comprehensive learning experiences thereby helping students to relate it to their intended career path. These platforms will help students with virtual experiential learning [4], [7]. Games are helpful in socializing users with one another through "communication, cooperation, competition, and conflict" which are all important aspects covered in general freshmen and sophomore engineering courses that have a focus on teamwork [8].

Despite several advantages of game-based learning, there has not been a wide acceptance of it due to the cost and maintenance of such systems, coupled along with the complexity of developing a working system suitable for learning [9]. Other restrictions faced are the approval of replacing games as a focus in class from the professional world, but due to the recent COVID-19 pandemic, more educators have become inclined to use and explore the possibilities of this new educational tool, and recent studies have backed this as a positive approach towards education [10], [11]. Acknowledging the success and advantages of game-based learning in engineering, this proposed research study was planned. This research study aims at understanding how those advantages have been utilized to teach engineering design process. The engineering design process is being taught at different universities as a part of the curriculum. In this study, the focus is specifically on understanding the use of game-based learning as a tool to teach the engineering design process for first-year engineering students. In recent years, game-based learning has proven to be a successful educational tool, continuing to be actively employed by practitioners. This research explores the utilization of game-based learning in teaching the engineering design process, examining its advantages and disadvantages based on research that has been done on the matter.

The overarching research question guiding this study is, "What is the current state, trends, and future direction of teaching the engineering design process to freshmen through game-based learning?" To delve deeper into this inquiry, the following sub-research questions were employed for the exploration, investigation, and categorization of articles:

(1) What game genres were utilized in the sampled articles?
(2) What frameworks were applied in the sampled articles?
(3) What research designs were employed in the sampled articles?
(4) What data collection tools/formats were utilized in the sampled articles?
(5) What sampling methods and sample sizes were employed in the sampled articles?
(6) What data analysis methods were applied in the sampled articles?
(7) What game platforms were utilized in the sampled articles?

The articles we focused on in this study were those that included game-based learning utilized in engineering courses that taught engineering design or the skills that are incorporated into engineering design. The keywords employed in the search encompass various combinations of "game-based learning," "engineering design," and "freshmen" or "first-year student." The exclusion criteria, ranging from publication date and language to focus on engineering population and sample size, ensure a meticulous selection process. Preliminary findings reveal a diverse set of articles meeting the inclusion criteria, providing insights into the progress and research gaps in utilizing game-based learning for teaching engineering design. The breakdown of articles from each database, along with exclusion criteria outcomes, will be presented in the full paper. Additionally, emerging themes and synthesized information from the reviewed articles will contribute to a comprehensive understanding of the potential benefits and challenges associated with incorporating game-based learning into freshmen engineering education.

Methods

The research framework for this study is referred from several existing studies [6][12-13]. Systematic literature review first starts off by creating different search terms that pertain to the research topic and entering them into various databases. The different search terms and phrases used for this study were as follows: game-based learning, engineering design, freshmen, first-year students, undergraduate, engineering, freshman courses, systematic literature review, and introductory courses. The search terms were focused on game-based learning, not only in engineering but in introductory courses related to teaching engineering design. We wanted to centralize how effective game-based learning (GBL) would be for teaching and integrating into these introductory courses in order to hopefully create more engaging content and motivation for students. The investigation involves a thorough examination of literature related to game-based learning in engineering design. Data from reputable databases, including Scopus, Google Scholar, Web of Science, IEEE Xplore Library, Compendex, Wiley Online Library, and ERIC, is collected and independently analyzed. Inclusion and exclusion criteria are applied to screen and select the most relevant articles for further analysis.

Data Collection

The systematic literature review article selection process is displayed in **Figure 1.** Articles that satisfied any of the eleven exclusion criteria were excluded based on the study's objectives: **1)** Articles published before 2013; **2)** Articles not in English; **3)** Articles that do not use game-based learning; **4)** Articles that do not use engineering design; **5)** Articles that do not focus on engineering population; **6)** Articles that do not focus on higher education; **7)** Articles that have a small sample size (quantitative – 50+; qualitative – 5+); **8)** Articles that mention video game learning or video-based learning; **9)** Articles that mention angry birds or simple games; **10)** Articles that do not allow access; or **11)** Articles that are work-in-progress papers or workshop papers.

As presented in **Figure 1**, a total of 348 articles were obtained by inputting the eight search terms into the seven different databases. To finalize the identification phase, duplicates were eliminated from the initial set of retrieved articles, followed by the initial screening of abstracts. After, articles were fully screened in order to further identify articles to eliminate those that met one or more of the exclusion criteria. The remaining articles were further evaluated independently to identify whether or not they would pertain to the study. Ultimately, nine articles were incorporated into the conclusive synthesis phase of the review.

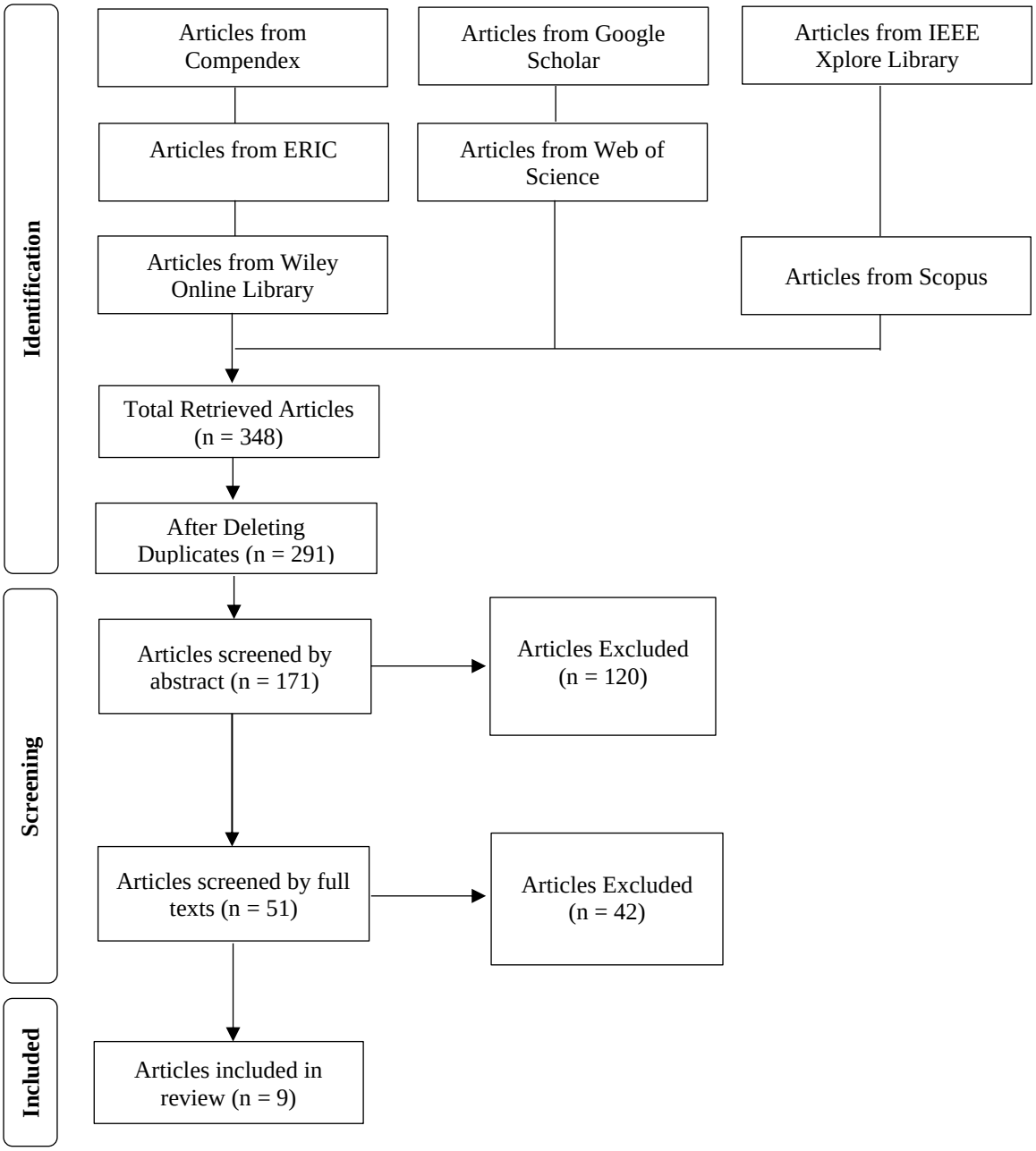

Figure 1. Systematic Review Article Selection Process

Data Analysis

Having identified the final set of nine articles, the first author engaged in a summarization process to synthesize and derive meaning from the publications. Initially, the first author independently undertook the task of reading and summarizing all the included articles. For each article, the author recorded pertinent information, including the year of publication, country affiliation of the first author, research question and/or objectives, theoretical frameworks employed, research methods applied, data recording methods, data analysis techniques, study populations, and participant demographics, sampling methods, range of sample sizes, and research findings and/or

implications. Subsequently, the generated summaries were utilized to conduct a comprehensive analysis of how each paper would contribute to the overarching objectives of the study.

Subsequently, the author devised codes to encapsulate recurrent patterns observed in all nine articles. Specific codes were formulated. Details regarding these codes, their descriptions, and corresponding exemplar articles are outlined in Appendix A. Following this, the generated codes underwent in-depth exploration and analysis, culminating in the identification of five distinct themes: student motivation and engagement, technical/soft skills, non-computer based GBL, feedback, and assessment. The author then assigned these identified themes to each of the nine articles. The data analysis in this paper is portrayed in two phases. Initially, descriptive statistics are employed to scrutinize trends within the nine articles selected for final examination. The subsequent phase entails a qualitative analysis of the nine articles within the context of the identified JUMP and CONSTRUCTIVE themes.

Strengths and Limitations

This systematic literature review offers a preliminary overview of game-based learning research, evaluating trends and the current state of knowledge in the field. The identified themes in this study come with practical and research-based implications, providing actionable guidance for instructors and researchers in the game-based learning space. The study's findings significantly contribute to expanding the understanding of research in game-based learning by categorizing existing strengths and pinpointing opportunities for future investigations. While similar systematic literature reviews on related topics exist, they often lack specificity to freshmen engineering design.

Like any research endeavor, this study has limitations. Firstly, article selection relied on exclusion criteria without incorporating a measure for the quality or distinctiveness of information. Despite using seven reputable databases in line with established system literature reviews in engineering education, the omission of a quality metric may pose limitations. Exclusion of inaccessible articles and work-in-progress papers may also have restricted the scope of information covered. Secondly, the search terms focused on the intersection of game-based learning, engineering, and specific areas of interest, potentially overlooking relevant articles or themes. Thirdly, the exclusion of articles predating 2013 and the limitation to English publications may have excluded valuable contributions and provided only a partial representation of global scholarship on game-based learning. Lastly, the review may not encompass all facets of the game-based learning landscape, leaving potential courses or programs undiscovered.

Findings

Initially, we offer a descriptive overview of trends observed in the publications throughout the decade spanning from 2013 to 2023. Subsequently, we furnish detailed descriptions, exemplary studies, and implications for research and practice associated with each of the five identified themes derived from the synthesis of the final nine articles.

Research Goals and Objectives

Table 1 provides an overview of the goals aimed at the implementation of game-based learning. Across the various articles, a commonality in goals was observed, with overlapping objectives. It's noteworthy that articles could align with one or more goal categories. The categorized goals encompassed enhancing students' motivation, improving class functionality, refining communication skills, and advancing technical skills.

Table 1. Research Goals among Sampled Articles

Goal Through PBL	Frequency	Percentage
Improving Students' Motivation	3	33
Improving Functionality of the Class	2	22
Improving Communication skills	2	22
Improving Technical Skills	2	22

Among these, the most prevalent goal shared among the sampled articles was the aspiration to enhance students' motivation (33%) in the context of teaching engineering design. The distribution of articles under the other three goal categories—improving the functionality of the class, enhancing communication skills, and advancing technical skills—remained consistent at 22%. While there wasn't a predominant goal unanimously adopted by the majority of articles, a recurrent theme emerged in the collective aim to enhance the overall motivation and retention of students within the engineering domain, specifically in engineering design, through the application of game-based learning.

Theoretical Frameworks

Among the nine articles examined, five incorporated a theoretical framework. Among the remaining four that did not utilize a theoretical framework, one adopted a conceptual framework. Notably, none of the frameworks employed were replicated across the entirety of the articles, suggesting an opportunity for further research and exploration of alternative frameworks in this context. It's worth mentioning that the use of any framework type was not explicitly specified or discussed in the remaining two articles.

Table 2. Theoretical Framework of Sample Articles

Framework	Reference Article
Activity	1
Actor Network Theory	1
Educational	1
Constructivism	1
Moral Development	1

Study Populations and Participant Demographics

In Table 3, the study populations encompassed by the nine articles in this systematic review are delineated. A significant portion, five articles (55%), concentrated solely on first-year engineering students. Two articles (22%) delved into the study of second-year engineering students and beyond, while another two articles (22%) explored engineering students without specifying their academic classifications. Despite the predominant focus on first-year students aligning with the

research goal, only five articles specifically addressed game-based learning in engineering design for first-year students. This suggests a potential avenue for further studies and research specifically dedicated to this topic.

Table 3. Study Populations within Sampled Articles

Study Population	Frequency	Percentage
First-Year Engineering Students	5	55
Second-Year Engineering Students & Up	2	22
Engineering students (not specified)	2	22

Thematic Analysis: Descriptions, Exemplars, and Implications

This section presents a snapshot of our future work as we delve into a thorough exploration of five identified themes: student motivation and engagement, technical/soft skills, non-computer-based game-based learning (GBL), feedback, and assessment. We introduce each theme, define how the articles are categorized under it, present two exemplar studies chosen for their strong connection to the theme within the group of articles, and conclude with a summary outlining the implications for future research and practice. The selection of exemplars is based on their explicit focus on the theme compared to other papers that may have only tangentially addressed the topic. Table 4 depicts each of the five themes, along with the corresponding codes mapped to each theme (refer to Appendix A for code definitions), and the number of papers categorized as related to each theme.

Table 4. Emerging Themes

Themes	Definition	N
Student Motivation and engagement	Topics that include improving motivation and engagement in GBL course assignments, projects, and exams.	3
Technical/Soft Skills	Topics that include students learning skills needed in the engineering work field. Including professionalism, communication, and time-management.	4
Feedback	Topics that include student feedback about GBL learning and coursework. Including the different opinions on formal class learning versus GBL.	8

Theme 1: Student Motivation and Engagement

Three of the nine articles focused heavily on student motivation and engagement with game-based learning. Each article under this section highlights how motivation improved after experiencing game-based learning and how it added to the course experience. Many of these articles highlighted the fact that creating different methods of learning, such as game-based learning, causes students to intrinsically feel motivated to come to class and complete class assignments. Articles describe that blending gamification in engineering allows students to mediate their time through learner-focused learning that is offered in game-based learning (Sharunova, Ead, Robson, Afaq, and Mertiny, 2019). Additionally, implementing game-based learning in engineering acknowledges the need for continuous improvement in engineering education to best suit individuals while simultaneously creating a sense of teamwork between peers. Other articles highlight the effectiveness of game-based learning on retention and engagement amongst students (Delp & Okun 2022). Pre- and post- activities surveys that result with students feeling more encouraged to do assessments and collaborative work within and outside the classroom. Significant

improvements in course work that implemented game-based learning were experienced across most articles mentioning student motivation and engagement.

***Exemplar Study*:** Exemplary study chosen for this theme was chosen to emphasize the significant impact on learning and motivation of students. Delp and Okun (2022) aimed to address the learning needs of recent generations and utilize the advancement of technology. Their approach involved integrating role-play gamification into the freshman engineering project course. In this innovative setup, students actively engaged with a diverse array of games, each featuring engineering-based scenarios intricately woven into a zombie apocalypse narrative. The goal was for students to create high quality prototypes that would help users, the students, survive the zombie apocalypse. Students would pitch their ideas during class time in order to "sell" their innovative concepts. The primary goals were to enhance students' understanding of electrical concepts, improve the quality of prototypes developed by students, and foster teamwork and coordination both within teams and across the entire class. Students demonstrated significant growth in their understanding of fundamental electrical principles. The game-based approach sparked curiosity and engagement, leading to increased interest in electrical topics. Collaborative efforts within teams and across the class were positively impacted, improving teamwork dynamics. Moreover, students reported high enjoyment levels during the project, thanks to the RPG element. Notably, the quality of prototypes showed substantial improvement compared to previous semesters.

Theme 2: Technical/Soft Skills

Four of the nice articles described the technical and soft skills relating to game-based learning. All articles under this theme addressed the technical and soft skills students are able to acquire while engaging in game-based learning and how it can boost those skills effectively. Articles suggest that game-based learning has the capability to enhance oral and written communication skills which are vital technical skills engineering students should learn before going into the work force (Cheryl A. Bodnar & Renee M. Clark, 2017). Other articles have mentioned how students have received business simulations and game-based systems to work through a project rather than a traditional group work system. Students in these studies have shown and reported that they were gaining useful skills in the class and the new gaming structure had a positive affect towards their attitude towards the engineering field, engineering design, and motivated students to affectively communicating information. Many have also mentioned the positive impact on their grades and how game-based learning has helped the understanding of engineering design.

***Exemplar Study*:** Exemplary studies in this section will be used to focus on the impact of game-based learning on students learning skills needed when going into the engineering workforce. Specifically, Nino and Evans (2015) noticed that there are similarities with video games and mastery of skills when students utilize game-based learning. Through this process, students can inherently develop important knowledge, skills, and attitudes (KSAs) useful in projects, courses, and the workforce in engineering. These games offer a unique avenue for fostering student-centered learning experiences, aligning seamlessly with the fundamental principles of constructivism. Through interactive engagement with video games, engineering students stand to cultivate a diverse array of knowledge, skills, and attitudes vital for both their academic pursuits and future professional endeavors. Among these are critical thinking, decision-making process,

perseverance, adept socialization, leadership acumen, bolstered self-assurance, and the cultivation of autonomy and self-regulation. The constructivist essence inherent in video games empowers learners to embody and refine key learning characteristics, notably self-regulation and autonomy, thereby enriching their educational journey and priming them for the seamless transfer of knowledge into practical application within their chosen careers. Moreover, the integration of video games into the pedagogical landscape fosters a distinctly student-centric approach, wherein learners are encouraged not merely to memorize information but rather to actively apply, evaluate, and make informed decisions, thereby deepening their comprehension and retention. Furthermore, the utilization of video games within the classroom environment affords students a safe and cost-effective platform to grasp and implement intricate engineering principles and methodologies, sans the associated risks or expenses often tied to real-world scenarios. Additionally, leveraging video games facilitates the implementation of innovative assessment methods, such as tasking students with crafting their own games or engaging in participatory design endeavors, thereby stimulating higher-order cognitive processes and honing problem-solving acumen. In essence, the transformative potential of video games as constructivist instructional tools in engineering classrooms lies in their capacity to nurture indispensable 21st-century competencies, engender a student-centered learning ethos, and deliver practical, immersive, and inherently meaningful learning encounters for aspiring engineering professionals.

Theme 3: Feedback

Of the nine articles, eight of them focused on student feedback of integrated game-based learning. All articles under this theme discussed the positive correlation between how students felt about game-based learning and what they have gained from the experience. Many of the articles utilized students pre and post surveys in order to track student engagement, progress, and improvement. Most of these surveys consisted of Likert scales on how to better improve game-based learning to create a more engaging and impactful experience for users (Delp & Okun, 2017; Streiner & Bodnar, 2019).

Exemplary Study: The exemplary studies chosen for this section highlight what should be focused on while creating a game based curricular based on student feedback. Ronalli & Ritzko (2013) explore the impact of integrating the commercial video game Kerbal Space Program into a first-year engineering design course as a novel student design project. This initiative aimed to engage and encourage first-year engineering students through team-based, hands-on projects, offering a reprieve from the typically heavy emphasis on mathematics and science in their curriculum. Within the framework of the larger research project funded by the National Science Foundation, which focuses on the retention and engagement of engineering students, this study sought to evaluate the efficacy of the project by comparing pre- and post-activity survey results. The project involved students designing a rocket within the game to navigate to the moon and back safely, thereby simulating real-world engineering challenges. The learning objectives centered on applying an engineering design process and fostering effective teamwork behaviors. While the study revealed gains in technology and communication self-efficacy ratings among students, there was a decline in engineering self-efficacy, highlighting the need for further guidance to bridge the gap between gameplay and academic content. Despite some challenges, the study recognized the potential of video games to enhance student engagement and understanding of engineering principles, particularly regarding rapid iteration and practical application of the design process. Additionally, qualitative feedback underscored students' enthusiasm for the game but emphasized the

importance of clear connections between gameplay and learning objectives. Overall, the study suggests that with refinement and additional support, video games like Kerbal Space Program hold promise as effective tools for teaching engineering concepts and fostering essential skills in engineering students.

Research Implications

A potential direction for further research overall in game-based learning could focus on exploring how students can regulate self-efficacy and what interventions could enhance intrinsic motivation in students to engage more deeply with game-based learning (Ranalli & Ritzko, 2013). Additionally, it is crucial for instructors to recognize the impact of their attitudes towards game-based learning, as research indicates that instructors' attitudes significantly influence students' perspectives and perceptions of educational innovations (Steiner & Bodnar, 2019). Understanding and addressing these factors can lead to more effective implementation and utilization of game-based learning strategies in engineering education, ultimately enhancing student engagement, learning outcomes, and overall educational experiences. Further research in these areas could provide valuable insights into optimizing the integration of game-based learning into engineering curricula.

Practice Implications

Incorporating game-based learning into educational contexts, as evidenced by the implementation in the second-year introductory engineering design course at the University of Alberta by Alyona Sharunova, et al., requires a nuanced approach that prioritizes several key elements based on student feedback. Firstly, there's a crucial need to enhance the overall game outline and visual representation to captivate students' attention and foster engagement. Clear and concise game instructions tailored to individual quests are imperative to ensure comprehension and seamless navigation through the learning experience. Moreover, injecting humor and fun activities into the game can significantly elevate its appeal, making the learning process more enjoyable and immersive for students. Facilitating communication and collaboration within the game environment or enabling team-based gameplay can foster a sense of community and encourage peer learning and interaction. Additionally, integrating relevant course elements into the gamified format and offering them online can enrich the learning experience, providing students with a comprehensive educational journey. By focusing on these aspects, educators can effectively harness the potential of game-based learning to enhance student engagement, satisfaction, and ultimately, learning outcomes in engineering education.

Conclusion & Discussion

The aim for incorporating game play into engineering education is to enhance the understanding the importance of engineering design through an innovative and joyful way for students to experience and create a system that stick with students through their career. While conducting this research, it was found that many other articles outside of the nice articles frequently mentioned simulations in place of actual computer games geared towards engineering design and learning. In the future, there should possibly be more research on specific games or a push for more games that target game-based learning.

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Appendix A

Year	Authors	Motivations	Research design	Data collected	Population	Sample size	Framework	Notes
2015	Anastasio et al. [14]	Technical skills, motivation, feedback	Survey	Pre and Post Survey	First Year Engineer Students	62	Narrative Framework	Students had positive feelings towards comm., presenting projects, group work.
2017	Bodnar & Clark [15]	Technical/ Soft Skills, feedback			Second Year Eng. Students	282	Activity theory	
2019	Streinar and Bodnar [16]	Motivation,	Gamified Empowerment,		First Year Engineer Students	17 sections (# not specified)	Actor Network Theory	Framework to be used by professors
2018	Sharunova et al [17]	Motivation	PC Game: Game of Gears	Student Feedback, Surveys: Pre-Game and Post-Game	Second Year and up Eng. Students	111	Educational framework, Instructional design, social gamification framework	Students enjoyed game-based learning but were more comfortable with lecture-based class.
2013	Ranalli and Ritzko [18]		Simulation Game; Team-based, hands-on	Student Feedback; Survey	FY Eng. Student	267	NA	GBL was founded to be positive for students and allowed them to learn in a different way
2022	Delp and Okun [19]		RPG	Student feedback: Questionnaires standardized surveys	FY Eng. students	76	NA	Significant growth in understanding of basic electrical concepts and growth of interest
2022	Burkey et al. [20]		Student feedback; EERI		FY Eng. Students	250	Moral Dev. theory	Ethical decisions in a safe space.
2015	Nino and Evans [21]		Literature review		Engineering	NA	Constructivism Framework	Limitations: instructors may not be confident about the impact of digital GBL
2014	Franzwa et al. [22]		Games: Powerville, Gridlock, and Solaris One	utility and usability of game, interest in game learning, conceptual learning	Engineering Students	200+	GBL and Theoretical (?)	Results showed that the games were effective in promoting student learning.