Fostering 21st-Century Skills in Constructivist Engineering Classrooms With Digital Game-Based Learning

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***Abstract*— Video games can be considered constructivist instructional materials because of their potential to promote student-centered opportunities in the classroom. Since the emergence of this educational trend, called digital game-based learning, several studies have been conducted to evaluate the effect that learning or recreational video games have had on learners and on their mastery of learning objectives. Many of these studies have focused on specific sets of skills that specific video games can promote. Nevertheless, there is evidence that any type of video game, regardless of its learning or recreational nature, can help students develop certain knowledge, skills, and attitudes (KSAs) that could be useful for engineering courses and projects. This evidence also suggests that digital game-based learning contributes to 21st-century skills that are necessary for competitive engineering professionals. This literature review will describe the KSAs that could be promoted in constructivist-oriented classrooms when learners engage in any type of video game. This research paper will focus on how engineering students can develop 21st-century KSAs that are implicit in each gaming opportunity, such as high-order thinking and decision-making skills, persistence, socialization, leadership skills, self-confidence, and autonomy and self-regulation.**

***Index Terms*— Video games, constructivism, knowledge, skills, attitudes, digital game-based learning, engineering education.**

I. Introduction

ONE of the current goals of engineering education is to foster competitive 21st−century skills in students, as well as innovate traditional curricula [1]. Some examples of these skills are collaboration, self-regulation, creativity, high-order thinking skills, and decision-making skills [2]. In order to accomplish this goal, several projects have been carried out, such as the implementation of flipped classrooms and digital-game based learning, using video games [3], [4]. The use of video games in the classroom, also known as digital game-based learning, has taken place due to the evolution that video games have had in relation to education [5], [6]. At first, video games were widely known as a mechanism of entertainment [7], [8]. However, they have also been used in more intentional settings for educational purposes such as K-12 and higher education classrooms [9], [10]. As some studies have pointed out, the implementation of video games has positive outcomes in engineering students, such as higher levels of engagement and better understanding of complex topics [9], [11]. Based on these results, many video games have been designed and developed exclusively for learning purposes [12]. For instance, the game Times Engineer has been developed to help students apply civil, electrical, and mechanical engineering principles to solve problems [13].

Video games contribute to the development of several knowledge, skills, and attitudes (KSAs) in students in engineering fields. For example, some video games have been used to change attitudes and perceptions in learners about a wide variety of topics and situations, including engineering courses [14]. In other cases, it has been used to promote the learning of subjects relevant to engineering and pre-engineering, such as mathematics [12], [15].

On the other hand, it is possible to link the increasing use of video games and other social media in classrooms to constructivism [16], [17]. Many classrooms are changing their traditional structures to more constructivist ones, which gives a more relevant and independent role to the learner [18]. Since the intervention of teachers and instructors is limited when learners are playing video games, learners get to practice and develop many of the learning characteristics found in constructivism, such as self-regulation and autonomy [19]. These skills can be really useful for engineers, not only for their courses, but also for the transfer of knowledge that can take place in their professional careers [1].

De Grove *et al.* [20] have stated that students can effectively gain certain types of knowledge, skills, and attitudes (KSAs) when using video games in the classroom. Furthermore, there are studies that have addressed specific KSAs learners could master when engaging in specific video games [21]–[23]. The main goal of this literature review is to answer the two following research questions:

- What KSAs can engineering students acquire when playing video games in the classroom?
- Why can video games be considered constructivist instructional materials?

To provide answers to these questions, this paper will start with a theoretical framework that attempts to explain how the constructivist nature of video games fosters and promotes certain KSAs. The following section describes the findings and describes the KSAs that are common to video games. Finally, the paper provides conclusions and the significance of this review.

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II. Theoretical Framework

The literature presents several connections between video games and one or more learning theories, such as behaviorism, cognitivism, or constructivism. This can be related to the fact that the features and affordances of video games can fit into more than one learning theory [19]. For the purpose of this study, constructivism will be the main focus, since it is argued that video games are mainly connected to this learning theory. Constructivism places the learner in a more self-aware, self-regulated, and independent role in the learning process [24]. Instead of fostering a traditional learning environment, where the teacher or instructor is responsible for the instruction, constructivism is more focused on how learners connect new knowledge to prior knowledge and how they can determine their own learning goals, which can be negotiated [25]. In addition, constructivism focuses on sociocultural aspects of learning and how the environment and more knowledgeable people influence learning. This is especially true in the social constructivist theories of Vygotsky [26].

Constructivism is relevant in engineering classrooms because of the set of skills learners get to practice and how it helps engineering students build their own knowledge and solutions to problems [27]. The American Society of Engineering Education (ASEE) has defined engineers as "problem solvers" who use resources in an effective way to overcome challenges [28]. In constructivism, learners face authentic problems and they have to find solutions by themselves with a limited amount of guidance [29]. The use of constructivism in the classroom fosters the skills that fit the definition of the ASEE. In addition, the outstanding growth of online engineering programs and distance learning projects has allowed more room for constructivist approaches because of the student-centered practices they promote [30]. Furthermore, the globalization process in engineering education, the use of social media and technology to enhance communication, and the need to learn new information with a self-paced approach have given more ownership to the student in the learning process, which is one of the goals of constructivism [31], [32].

Using a constructivist perspective, current literature about video games, especially in educational settings, has been identified and evaluated. By assessing this literature, it was deducted that several of the skills that gamers engage in during video game play belong to constructivist processes. For instance, social negotiation and sense of self-regulation are skills that get to practice in video games, regardless of the topic or if it is a recreational or serious game [33]. In addition, participants in video games bring to the game many of the skills and knowledge they have previously acquired and they use the game as an arena to practice these skills and improve them [20]. After several hours of gameplay and several milestones, studies have shown changes in the knowledge, skills, and attitudes of gamers because they have constructed them throughout the development of the game [34].

Video games can be used as instructional materials and interventions that help students meet certain learning objectives [35]. When this occurs, students get to practice knowledge previously acquired to make progress throughout the game. Also, students acquired new knowledge throughout the game, as a result of the feedback they get from the game and the consequences of their decisions when playing. Therefore, video games help to construct new knowledge based on these foundations [5]. To some extent, the use of video games shape the knowledge of participants and help them build new perspectives about how they see themselves and how they see the things they already know [36]. Another evidence of the potential of video games in learning is the emergence of gamification. By definition, gamification is the use of the mechanics of game in a traditional scenario without it actually being a game [37]. If using the principles of a game promotes positive outcomes in the classroom, it is possible to infer that a video game can tremendously contribute to learning.

Based on this evidence, this study focuses on the KSAs that can be promoted in classrooms when video games are adopted and a constructivist approach is fostered. Even though there is a distinction between serious and recreational games, the purpose of the study is to demonstrate that when the teacher carries out an adequate evaluation, any type of video game can achieve this goal if the right features, affordances, and constraints are identified.

III. Methodology

To conduct this literature review, an iterative systematic review with different studies, especially in the field of engineering education, was conducted. This model for literature review has been suggested for the field of engineering education because of its complexity and its ability to incorporate all the necessary phases for a meta-analysis: planning, question formulation, search strategy, selection process, evidence, analysis, synthesis, and monitoring [38]. Using academic databases such as ERIC and EBSCOHost, the following keywords were used: "VIDEO GAMES," and "KNOWLEDGE," and "SKILLS," and "ATTITUDES, or 'VIDEO GAMES" and "ENGINEERING." The main search produced 2,958 results. From these results, only articles that focused on descriptions and outcomes of KSAs when using video games were used for the study.

IV. Findings

A. Knowledge, Skills, and Attitudes (KSAs)

One of the major challenges for the adoption of video games in the classroom was the assumption that video gamers tended to develop negative KSAs in gamers, such as aggression or isolation [39]. Even though there is evidence that certain video games can develop negative attitudes in learners, several studies have also pointed out the benefits of video games in the development of skills such as leadership skills, social skills, communication skills, and others [15], [21]. Gamers develop certain KSAs because "depending on the genre and individual game, players may be required to analyze, synthesize, and use critical thinking skills in order to play and execute moves" [8]. Teachers should evaluate how the affordances and features of

specific games can help students accomplish this purpose. The goal should be to align the game to the curriculum to promote these skills in the classroom [40]. Based on evidence in the video games literature, this study has found the following KSAs in classrooms that have adopted digital game-based learning: **high-order thinking and decision-making skills, persistence, socialization, leadership skills, self-confidence,** and **autonomy and self-regulation.**

1) High Order Thinking and Decision-Making Skills: In order for students to be successful when playing certain video games and achieve their ultimate goals, they should not only master basic principles, but they should also be able to infer, draw conclusions, and create a logical and sequenced logical mental models based on the knowledge acquired in the lessons [41]. In engineering courses, there is a need for transfer of knowledge; that is, students are required to apply facts, concepts, and principles into realistic scenario and to understand how certain processes take place.

This requires a high level of decision-making skills and analysis, which engineering students can experience in video games [9]. For instance, the game NIU-Torcs, developed by Northern Illinois University, has been used to develop complex problem-solving skills in mechanical engineering undergraduate students. Students find in this type of video games, scenarios that are even more challenging than the material covered in assignments and homework [9]. In order to make progress through the game (i.e. win a car race) students should be able to use pre-algebra and engineering principles, linked with strategies and decision-making skills.

Researchers have studied that many of the higher-order thinking skills, such as decision-making, intertextuality, and problem-solving, are not necessarily taking place in the classroom, but during the time students devote at home to playing video games [42]. This occurs because many of the scenarios in which students could practice these skills are not possible to be replicated in the classroom; for this reason, video games offer students unique opportunities to use high-order and critical thinking skills that could not be practiced and tested otherwise [12]. As a result, many instructors and teachers are using video games to allow students to face certain challenges and scenarios that cannot be seen on a daily basis [41]. Some video games have been used to simulate complex tasks and projects, in which the gamers have to interact with each other and make decisions that present consequences. For example, there are games that have been designed and developed to simulate a manufacturing company of circuit boards [43]. This also indicates that video games can be an adequate alternative when lack of resources and funding affect the learning experience of students. The use of video games can be cost-effective when trying to simulate an environment that would require too many resources and they could not be feasible and safe in the classroom. This translates in the ability that students have to make decisions in a safe environment without facing drastic and negative consequences, but still being aware of the cause-and-effect phenomenon of their choices.

Video games develop high-order thinking and decision-making skills in learners because the games can be personalized to the needs and level of skills of each gamer, especially when teachers and students engage in participatory design [44], [45]. In participatory design (PD), students also contribute to the design and development of a game and their feedback influences the final product [45]. Playing video games makes students apply knowledge previously acquired, but engaging in participatory design pushes them to the boundaries of proficiency because they should be able to create challenges and complex scenarios, knowing strategies and alternatives to succeed in the game themselves. In other instances, students can modify an existing game, which also is a high-order thinking skill process, since they have to find flaws or weaknesses in the game and suggest improvement or alternatives. This type of strategy is known as game modification or modding and has become an elementary part of many participatory design projects [47].

Higher-order thinking skills in engineering classrooms are also promoted through innovative assessments [1]. When implementing video games in the classroom, teachers have substituted conventional assessments such as research papers and ask students to create their own games in order to teach the content of a lesson to other students [41]. This type of assessments does not only show that students are able to master the content of a lesson, but they also have enough background to challenge others and build problem-based projects to which they know the answer or solution. It also gives more ownership to students in the learning process and makes it more student-centered [48].

It is relevant to point out that not only educational video games have been found to be beneficial for players in terms of acquiring high-order thinking skills. Some studies have also pointed out that even playing mainstream, controversial, and popular games such as Super Mario and The Sims can be beneficial for players. It has been concluded that players of these popular and commercial games "can handle more information, can synthesize more complex data, [and] solve operational design problems" [49].

Moreover, in engineering classrooms, the use of simulations has been used to illustrate processes and principles, such as inverse kinematics and workspace and singularities [50]. The use of these innovations has been necessary to increase the level of engagement in students, as some studies have pointed out [51]. However, many of these innovative tools do not give the same possibilities to students as video games do. In many of these tools, students have a more passive role, whereas when playing a video game, students are more active because they have to be constantly making choices and facing the consequences of these choices. Therefore, teachers who promote constructivism can find in video games a student-centered instructional intervention that allows learners to apply and evaluate, instead of simply memorizing.

2) Persistence: Obstacles and challenges in video games are overcome through persistence [52], [53]. Persistence is a skill that is developed and drastically tested in video games, especially at the highest levels of the games, since it can be very difficult to complete certain tasks and overcome some difficulties in a game [20], [33]. Video games are designed using different levels that gamers should master before moving

to the next one. Rewards are often presented at the conclusion of each level as motivators and they are an indicator that gamers are ready to move forward in the game [12]. However, as the gamer moves forward, persistence is sometimes the only skill that allows an individual to complete a task. In many games, it is not only a matter of mastering the content of the game or interacting with other participants, but of carefully planning and organizing [23]. This is a fact in video games; therefore, teachers who want to develop this skill in learners can use them.

Persistence is also linked to achievement. As a gamer moves forward in the game and obtains rewards, this is a motivator for his or her persistence to continue. In addition, feedback from the game and the instructors develop the persistence of the gamer and give additional information that is useful to face new challenges in the game [33]. Since engineering students are responsible for the completion of many projects, persistence is a skill that helps them succeed. Also, persistence is important for engineering courses, especially in group projects. For this reason, video games have been used in electrical engineering courses for students to test the complexities of working in teams and finding consensus when applying a solution or intervention [43]. Also, engineering video games, such as Internal Force Master, have taken into account these principles in their design to allow students to practice these skills.

3) Socialization: When video games were first developed, the level of interaction and collaboration was very limited [54]. Gamers could spend hours by themselves going through the game without the assistance or collaboration of other players. In some cases, there was the possibility to add certain players into the game by plugging their controls to the console of the games, thus creating a more competitive environment. As social media evolved and the interconnection of gamers using the Internet became a reality, gamers started to practice social skills with more frequency [55]. As a matter of fact, in order to experience success in certain games it is necessary to have high levels of social interaction and collaboration among gamers [56]. When playing video games, students are encouraged to use social skills in order to master and achieve goals in the game, by identifying the skills and knowledge of all members of the team. Social collaboration is necessary in today's video games because they are an efficient way of sharing information, tips, and ideas [57].

Finally, in many other instances, social relationships and friendships are developed after the interaction of players in these social platforms due to the high level of collaboration found in the games [58]. The internationalization of the field of engineering requires professionals to develop collaboration and relationships using social media and other forms of telecommunication [59]. This type of interaction, yet difficult, is required in today's competitive engineering market. Engineers are required to work in projects that might involve parties around the world. For this reason, engineering students need to be able to find in their classroom alternatives to practice this way of collaboration.

Additionally, when playing video games, learners tend to have a better performance when becoming part of a larger group, as pointed out in a study that was aimed at evaluating the skills acquired by people who have participated in video games tournaments [58]. Players also develop a sense of satisfaction and community when they are part of the group and they get to share the outcomes of the efforts in these group projects [33]. A study conducted with students of a electrical engineering course demonstrated that the socialization process of video games can foster a healthy level of competition in the classroom that increases their motivation and engagement. The video game used developed for this study was ISCARE [46].

4) Leadership Skills: Teamwork and collaboration can be considered two of the strongest skills developed in video gamers. In terms of socialization, it has been also reported that video gamers develop strong leadership skills [58]. These leadership skills are developed because gamers understand how a whole system works and how different parts need to interact in order to achieve a particular goal. Having a strong understanding of how each step, milestone, or member of the video game contributes to the overall performance allows a gamer to make more informed decisions and plan strategies to guide a team to success [21]. In engineering courses, these leadership skills can be useful because students need to manage projects and work in teams. For this reason, some games have been used to help students structure a fictitious organization in the game and analyze how the whole system works, based on the leadership skills in the team, such as Lean Manufacturing [43].

5) Self-Confidence: When teachers and instructors use video games in the classroom, members of a group benefit from all the variety of skills that each learner can bring to the game. As this collaboration progresses, each learner has the ability to be aware of the skills and knowledge that he or she is bringing to the group, thus building a strong sense of self-confidence [47]. One of the positive aspects of video games is that they offer something to everyone, regardless of the level or type of skill that he or she might have [20]. This is significant in the classroom because it means that any learner can develop self-confidence based on the skills already possessed.

On the other hand, video games provide feedback to learners about their actions. This type of feedback does not only offer an opportunity to point out areas for improvement, but it also focuses on the positive aspects of the performance of the player [60]. By being aware of the positive aspect of performance, learners build a sense of self-confidence about certain skills that can be transferred to other scenarios. For this reason, it is important for instructors to determine the set of skills that learners are going to be using during the game and they should not only let the game be the only source of feedback [39]. Feedback from instructors is also fundamental, especially when helping students be more confident. Another important source of feedback in games is observed through achievements in the game. As a gamer moves forward in the game and obtains rewards for doing so, there is an indication that he or she is having a good performance; therefore, a stronger sense of self-confidence would be developed [12], [60]. For instance, the game Minecraft is an example of how obtaining feedback and rewards through the game improves the situation

and conditions of the gamer; therefore, motivating them to continue a good level of performance [22].

Furthermore, feedback when playing a video game is extremely important because it gives a sense of accountability to the gamer. When a gamer receives feedback about his or her performance, they develop a sense of having power to change the situation of the game. This can have an impact on the self-confidence of the gamer because he or she would be able to link actions to outcomes [36].

6) Autonomy and Self-Regulation: Video games are an excellent tool to foster collaboration and teamwork, with the additional benefit that they allow gamers to be accountable for their own performance and progress [20], [61]. Gamers always need to have some sort of strategic planning, organization, and sense of direction when playing. This skill is enforced with the sense of choice in video games [8]. Throughout the development of a video game, players face several choices and opportunities for decision-making. In many instances, the choices they make are based on personal information and strategy and the consequences of this game will bring consequences that are related to their own performance, even if they are in a group environment. Because of these facts, players develop a true sense of autonomy and self-regulation that is always present in video games, regardless of the topic or nature [4].

B. Video Games as Constructivist Instructional Materials

Several of the KSAs found in this literature review are part of the learning conditions that should be promoted in constructivism. A constructivist environment is based on knowledge, rather than teaching [62] and this can be fostered through high-order thinking skills. In addition, social negotiation is an important aspect of constructivism [63]. Learners in constructivist classrooms are required to use social skills to acquire knowledge from other peers, which is a common practice when using video games. Also, one of the main points of constructivism is to develop a sense of autonomy and self-regulation [64]. Through the use of video games in the classrooms, learners are responsible for completing the tasks related to the game, to manage their time, and to make decisions on how to prepare them to face challenges. Teachers usually offer guidance, which gives more control to the student in the learning process.

Even though constructivism focuses more on the individual/learner than on the teacher or instructor, there is still a role for the instructor, as a facilitator or guidance [62]. In the case of video games, the instructor still has a role, since he or she will be deciding what type of video game should be played and how much time in class will be used for the game [65]. In addition, the instructor would provide general instructions, guidelines, and assistance when needed. However, the actual gaming experience and the decisions made during the game will depend on the student playing the game [63].

Using Vygotsky's principle of *zone of proximal development*, which is the difference between what a student can do and cannot do with help of a more knowledgeable person, it is possible to see why video games fit into the description of constructivism [66]. Students start with some guidance, and as they move forward through the game, the level of assistance or guidance can be drastically reduced. It is important to point out that in constructivism, the more knowledgeable person that assists in the zone of proximal development can be a human being or a machine [63]. Many video games are designed and developed, in such a way, that feedback is simply guidance, but the most relevant decisions of the game depend on the gamer. The type of feedback and assistance offered through the game is a fundamental aspect of the learning process, according to constructivism [64], [66], [68].

V. Significance and Conclusions

One of the limitations when adopting video games in the classroom is the fact that teachers and instructors might not be completely confident about the benefits and real impact they can have on engineering students [39], [65]. Research about the negative impact of video games has made the contributions of digital game-based learning unclear, promoting negative attitudes in teachers and parents [54]. However, the contributions of video games in engineering education have started to become more evident in the literature, as their potential is demonstrated [14], [67]. As education is re-evaluated and revamped to satisfy the current needs of 21st-century students, engineering education is also going through some significant changes. The need to promote 21st-century skills to give more competitive tools to students makes teachers consider the adoption and implementation of innovative instructional interventions, such as video games, to achieve this goal. Also, the focus on a more student-centered approach to allow students to be more accountable of learning has increased the adoption of constructivism [66]. The potential of video games to enhance learning in engineering is still unclear because there is lack of more empirical data to make more grounded evaluations [70]. For these reasons, the goal of this review is to advance the understanding of the benefits of video games as constructivist instructional tools in engineering classrooms.

Evidence from this review is relevant for teachers to make more informed decisions when considering the adoption of video games and their integration into their curricula. Video games have the potential to foster certain types of knowledge, skills, and attitudes in students, but teachers are responsible for identifying how the affordances and constraints of a particular game can promote these KSAs. Conventional instructional materials and assessments can limit the options of teachers and do not engage students in higher-order processes such as creating, evaluating, critiquing, or applying. The use of video games can be an alternative to integrate technology-based assessments that are very practical for engineering students, especially when they are meaningful to them and similar to instances found outside the classroom.

A significant challenge in engineering education is the lack of resources to represent or replicate scenarios or processes. Some of these processes can pose risks to students or be too expensive to develop in the classroom. However, these scenarios and processes are necessary for engineering students

to demonstrate the application of knowledge and how they can solve problems. The use of video games in the classroom can contribute to illustrate these processes and scenarios, in a safe environment. Students get the opportunity through video games of getting feedback, based on their decisions and choices, without having severe consequences. Also, video games can help students understand principles or processes that might seem too abstract.

One of the limitations of this review is that many studies are not empirical, but descriptive in nature. While this type of data is relevant, there is a need for more empirical evidence and rigor in the study of video games. This type of literature review can contribute to the field by giving a structure for engineering teachers of the type of KSAs they can assess in their students and how they can be connected to their lessons. Another limitation is that the design of many video games, especially learning games, are not instructionally sound and do not follow with rigor the principles of well-known learning theories [19].

Future research can focus on the transfer of knowledge of engineering principles in the workplace through video games and how engineering video games are connected to cognitive processes or learning theories.

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