Computational games in STEM courses: a systematic review of the literature

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***Abstract*—This full paper of Research Category presents the main results of a systematic review of the literature about the use of computer games in science, technology, engineering, and mathematics (STEM) courses. The concept of lifelong learning has often been encouraged in literature. However, it also reports students facing difficulties in exact sciences since elementary school: a significant challenge to overcome. Among the reasons for such difficulties are demotivation, disinterest, learning difficulties, and even the use of outdated teaching-learning methods. In an attempt to improve the relationship between students and exact sciences, schools are expanding the use of information technologies to offer the students interactive environments in order to enrich their classes. In this context, characteristics of digital games appear as a didactic resource that can benefit the students' learning process. If properly used, digital games can stimulate memory, creativity, socialization, and also incite curiosity. Due to the ease young students have with games and considering the benefits mentioned above, many institutions have been investing in digital games (or environments with some of their characteristics). However, these games can generate compulsive behaviors (WHO classified such disorders in 2018), and it is worth noticing that many articles reporting the use of games in education focus mainly on its acceptance instead of its teaching capabilities. In this article, we report the main findings, such as that technology is the area with the highest concentration of digital games. It is also observed that different guiding theories appear, such as those with a constructivist tendency. Among the arguments for using games stand out: the gain in cognitive skills, the possibility of using simulations, and the ease in understanding complex themes. The methods of didactic-pedagogical evaluation mostly used are questionnaires of acceptance or the student's perception. This review highlights the potential of digital games to promote learning. However, these games should not be focused solely on their ludic aspect, as they have a different purpose from regular games. Active methodologies mediated by information and communication technologies can make class more engaging as students actively participate in the construction of student learning.**

Keywords: ***Computational, Games, digital, Higher education, STEM education, Systematic review*.**

I. Introduction

In an attempt to improve student performance, schools are looking for new solutions to better the education scenario. New methodologies, teacher training, use of Information and Communication Technologies (ICT), and interactive environments as a support tool, are some examples of the actions taken by stakeholders.

In the last few years there has been a growing interest from committees created to discuss the role of digital games in science and engineering education. In North America, The Federation of American Scientists held in 2005 a conference called "Harnessing the power of video games for learning" and the National Academies Board on Science Education held a "committee on computer games, simulations, and education in learning science" [1]. In South America, The Brazilian Computer Society has supported SBGames since 2004; an event entirely focused on Games and Digital Entertainment, that since 2018 has a track dedicated to games and education [2].

In this context, some universities, aware of the new teaching methodologies, have started researching and applying digital gaming techniques to improve undergraduate students' learning, especially in science, technology, engineering, and mathematics (STEM) courses, as seen in [3], [4], [5]. In Brazil, for example, only 17% of students apply for STEM courses, while in countries in North America and Europe, this percentage reaches 24% [6]. Nevertheless, according to [7] engineering degrees, alongside mathematics and physics are among the courses with higher evasion rates.

Faced with the evasion and abandonment in exact science courses, the evidence that guides the hypotheses of the benefits of applying digital games in the teaching and learning process is guided by the important findings of researchers. In [8], the authors identified that the new generation of students, and the generation before it, has video games as an integral

part of their lives. That about 98% of teenagers play video games up to once a week. These generations will, in the future, be part of students from universities and educational institutions. Besides, in [9] it is reported that the use of video games increases learning in STEM courses by 7 to 40% when compared to the traditional lecture course approach.

In view of this context and aiming to contribute to the teaching-learning process in the STEM area, we conducted this Systematic Review of the Literature (SRL) aiming to investigate how computer games are being used in undergraduate courses in the STEM area. Its purpose is to obtain a panoramic view of the use of computer games in STEM and, from this view point, identify gaps, improvements and highlight successful strategies in the scenario. We are addressing STEM courses as it is the focus of our research group.

This paper is structured as follows: section II presents the protocol of the SRL, including Planning, Conducting and Reporting; Planning presents the five research questions, the selected databases and the inclusion, exclusion and quality criteria; Conducting presents the strings formatted according to each database standards and the list of selected papers to perform the SRL; Reporting presents the review in the form of answering the research question; section III presents some considerations and main findings regarding the research; section IV presents the conclusion to this review; section V presents acknowledgments.

II. Method/Protocol

This SRL is based on the methodology proposed by Kitchenham [10], which follows three stages: planning, conducting, and reporting. The planning stage consists of identifying the need for a review and defining a protocol. The conducting stage includes identifying research, selecting studies, evaluating studies, extracting data, and ultimately synthesizing data. Lastly, the reporting stage is one-step only.

The purpose of this research is to review publications to investigate how games are being used in STEM courses. That is, among other things, to find out which methods of evaluating the didactic effectiveness of the games. Thus, to conduct the research, selection criteria were developed to identify primary and secondary studies in the available research on the topic, to answer the general research question:

How educational games have been used in STEM courses?

A. Planning

To guide the research, the following questions were defined:

1) Research Questions:

- **Q1.** In higher education, which subarea of knowledge is most impacted by the use of computer games?
- **Q2.** What are the techniques used to measure the effectiveness of the game?
- **Q3.** What are the learning theories that support the use of digital games in STEM courses?
- **Q4.** What game dynamics are the most often used? and
- **Q5.** What are the most presented arguments for using games?

2) Databases: This study was conducted on two consolidated databases in the scientific scope: ACM Digital Library (dl.acm.org), IEEE Xplore Digital Library (ieeexplore.ieee.org). We selected these bases because they are notoriously associated with our research focus (engineering and computing education).

In order to use only articles that correspond to our research goals, Inclusion, exclusion and Quality criteria were adopted in some steps:

3) Inclusion Criteria: Were added to the review, primary studies within the following criteria:

- **I1.** Publications that address the use of games in STEM courses
- **I2.** Published in English or Portuguese;

4) Exclusion Criteria: Were removed from the review, primary studies within the following criteria:

- **E1.** Duplicated papers
- **E2.** Not accessible online
- **E3.** Not a book chapter, article or conference paper
- **E4.** A threat to method validity
- **E5.** Methodologies or final results.

The E4 exclusion criterion is related to the lack of methods to measure the effectiveness of using games to improve the learning of something. That is, studies that did not have a validation method for its learning effectiveness were excluded.

5) Quality Criteria: Papers published from 2015.

We decided to analyze only the most recent publications from 2015 to 2020. Thus, we can have a more updated view, taking into account the increasing technological insertion in the teaching-learning process in recent years.

B. Conducting

These search strings and their results are as follows:

- ACM: [[Abstract: comput*] OR [Abstract: digital]] AND [Abstract: game] AND [[Abstract: science] OR [Abstract: technolog*] OR [Abstract: engineering] OR [Abstract: math*] OR [Abstract: stem]] AND [[Abstract: "higher education"] OR [Abstract: undergrad*] OR [Abstract: course]
- IEEE Xplore: ((Comput* OR digital) AND game AND (scienc OR technolog* OR engineering OR math* OR stem) AND ("higher education" OR undergrad* OR course))

The application of the research protocol recovered 2,776 papers. Their title and abstract were analyzed using the selection criteria. When this was not enough, the conclusion was also analyzed. In the end, 48 papers were selected for complete analysis. The Table I shows the results with the final synthesis data extraction.

After applying the quality criteria, 26 papers were selected, as can be seen in the Table II.

C. Reporting

The two database searches returned a total of 2,776 papers, of with 12, only 0.94%, passed the quality criteria to be

Table I
SYNTHESIS DATA EXTRACTION

Database	Total	Inclusions	Exclusions
ACM	1,117	8	1,109
IEEE Xplore	1,659	18	1,641
Total	2,776	26	2,750

analyzed in this SRL (Figure 2). Most of them were conference papers and the few were journal articles. Just over half about 53.85% of the selected articles were produced or published in the years 2017 and 2018 (Figure 3). Figure 1 presents the total of search results in each database in relation to their selected papers.

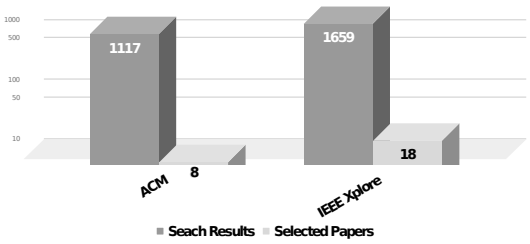

Figure 1. Relation between search results and selected papers in each database.

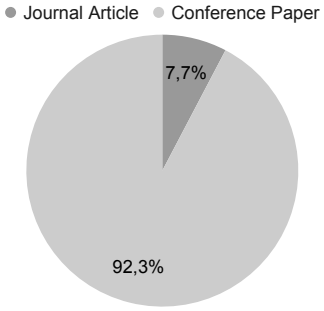

Figure 2. Publication types.

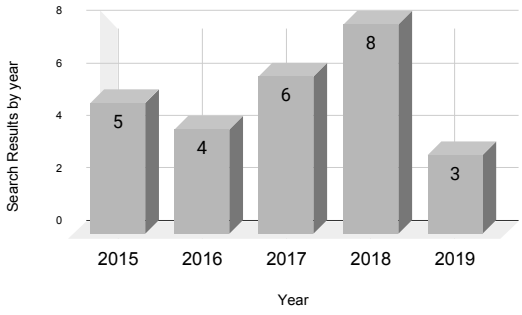

Figure 3. Research results by year.

The selected papers were fully read in order to extract answers to the research questions and the collected data was analyzed and condensed into answers to the research questions, as can be seen in the following.

Figures 1 and 2 are presented to provide a quick visualization of the context considering the bases used. Figure 1 shows which base presents more work on the researched topic and figure 2 the nature of these works, that is, the public IEEE plus works related to computer games in STEM courses and most of these works consist of conference articles. Thus, we have a few articles from journals published on the topic. This demonstrates the need for publications of this nature on the topic.

Q1. In higher education, which subarea of knowledge is most impacted by the use of computer games?

Considering the four STEM areas, technology is where the greatest use of games is concentrated in the learning process. Followed by Mathematics and Engineering. No science studies were found. This distribution is shown in Figure 4.

It is important to note that the papers that pointed out the use of games in the teaching of physics [21], [24] and math [25] were not classified in any STEM area, since they did not indicate in which course the experiment was applied. It just says that extension courses were offered, with freshmen from several undergraduate courses, designed to reinforce students' learning.

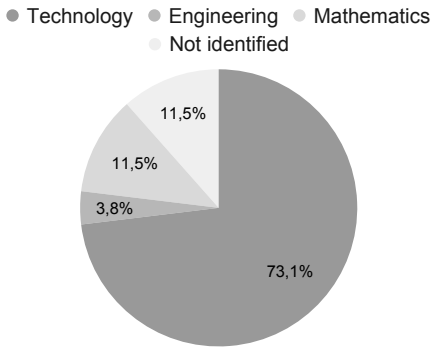

Figure 4. Impacted areas

In Technology, the computer science course is the one that most uses computer games for teaching. Focusing specifically on software programming [15], [17], [19], [26], [27], [30], [35] and engineering [11], [12], [14], [16], [22], [28].

Some others have addressed information security like [23] and [18]. Only [34] addressed the teaching of computer architecture and the [36] the teaching of operating systems. There are also interest in games in disciplines such as physics [21], [24], chemistry [33] and soil mechanics [31].

Q2. What are the techniques used to measure the effectiveness of the game?

As shown in Figure 5, a questionnaire is the most used technique to measure the efficiency of games. Followed by questionnaires and the application of tests and the evaluation model of the educational game MEEGA [28].

The questionnaires were applied with the most diverse objectives. In general, the studies analyzed sought to evaluate

Table II
ARTICLES LIST

Year	References	Title
2019	[11], [12], [13]	[Evaluating GSD-Aware: A Serious Game for Discovering Global Software Development Challenges], [Gamifying a Software Testing Course with Code Defenders], [LearnIt: A Serious Game to Support Study Methods in Engineering Education]
2018	[14], [15], [16], [17], [18], [19], [20], [21]	[GreaTest: A Card Game to Motivate the Software Testing Learning], [Active Learning through Game Play in a Data Structures Course], [Teaching Software Engineering Through Computer Games], [A Mobile Game to Teach AVL Trees], [Lord of Secure: the Virtual Reality Game for Educating Network Security], [A Gamified Approach to Achieve Excellence in Programming], [Let's learn with Kahoot!], [Videogames in teaching/learning Physics: A case study with "Portal 2"]
2017	[22], [23], [24], [25], [26], [27]	["2TScrum": A Board Game to Teach Scrum], [Using a Game to Teach About Phishing], [CocoGame: A funny app to learn physics and math], [Game based learning as a supplementary approach in teaching mathematics], [A propriety game based learning mobile game to learn object-oriented programming — Odyssey of Phoenix], [CMX: The Effects of an Educational MMORPG on Learning and Teaching Computer Programming]
2016	[28], [29], [30], [31]	[SORTIA 2.0: A Sorting Game for Data Structure Teaching], [Development of a Digital Game-Based Learning System with Graduated Prompting Strategy for Math Course], [Increase motivation in learning Java Programming Fundamentals using Gamified Moodle: Case: Central University of Ecuador], [Smart Quizzes in the Engineering Education]
2015	[32], [33], [34], [35], [36]	[Integrating Role-Playing Games into Computer Science Courses as a Pedagogical Tool], [Experimental development and implementation of computer-based quiz games in general chemistry for engineering], [An educational game for teaching computer architecture: Evaluation using learning analytics], [The effectiveness of digital game for introductory programming concepts], [Prototype of an educational game for teaching and learning in paged virtual memory]

everything from student acceptance for the methodology and software used to the acquisition of knowledge. Some articles carried out all these measurements [22], [25] while others were concerned with ascertaining only acceptance (methodology or software) [21], [28] or knowledge acquisition [12], [16], [19], [23].

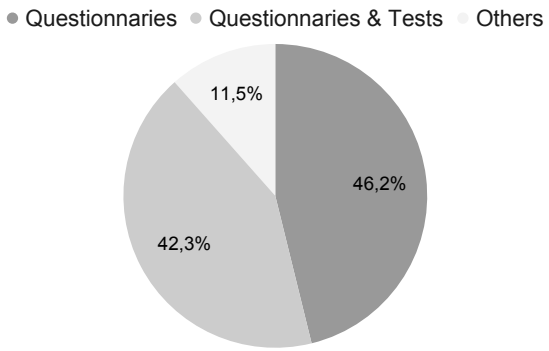

Figure 5. Most techniques used to measure the effectiveness of the game

The works that use tests as a metric of efficiency, were mostly evaluating, among other things, the acquisition of knowledge. Operability consisted of pre-tests applied to students before the insertion of games and post-tests applied as soon as the process was over [34]. Some works, in addition to the tests, applied questionnaires of acceptance and satisfaction to the students [15], [18], [21], [24], [26], [27], [29], [33].

In [34], for example, applied the pre-test and classified students into groups (Poor, Fair, Good, and Very good). Right after the game was used, the post test was applied and the students reclassified in the groups, so it was possible to observe if there was an improvement in the students' level of learning.

On the other hand, there were works that evaluated only the students' knowledge acquisition and they did this by observing the students' grades and performance during the course [19]. It is an exceptional case of [25] who used statistical Web metrics to measure student access and frequency in the game. They used the access *logs* to extract information, such as the time spent by each student.

Q3. What are the learning theories that support the use of digital games in STEM courses?

In all selected works, the principles of constructivist learning theory were found. In some works, constructivism has been mixed with cognitivism [11], [12], [23], [24], [33], [34], [35] or interactionism [16], [20], [30]. In others [13], [17], [18], [25], [26], [32] the principles of these three theories were applied.

Succinctly, Cognitivism says that knowledge is obtained through experience and reasoning, the way learners think is important to learn [37], [38]. Constructivism says the learners construct their own knowledge, that is based on the previous knowledge and experiences of the learners [39], [40] . While

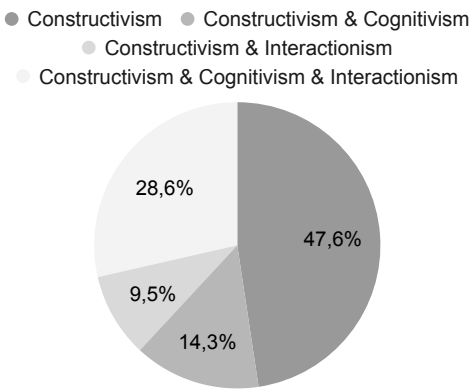

Figure 6. Theory of learning most used in computer games in STEM courses

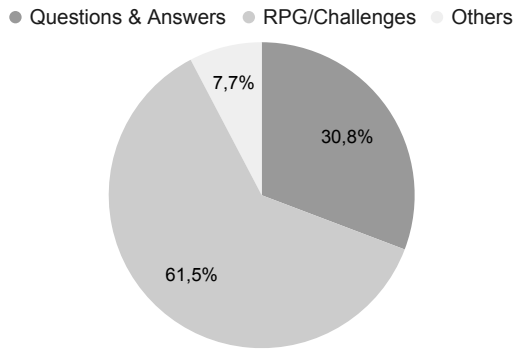

Figure 7. The most used dynamics

interactionism considers that the interaction between the individual and the environment in which he is inserted are essential to the learning process [41]. The most interesting is that all these theories postulate that knowledge is an objective/state to be achieved.

It is important to report that practically all works did not inform the theories used. None of them directly pointed out the theory and what specific principles they supported in the process. To build this information, it was necessary to connect the dynamics of the game and the way the game was used in the courses with the learning theories.

Another important threat to the selected works that evaluated the acquisition of learning in the absence of a method to balance the time and the natural knowledge associated with the game. Especially when the activities took place over several days (students can acquire knowledge elsewhere). This balance can be achieved by using a control group, that is, by applying another similar activity in a group where there is no use of games in learning.

The control group is a statistical treatment, which uses a single control variable, that is, the game is contrasted with another method - usually in terms of the motivational aspect. Control groups are often used in evaluation studies that use research and are also relevant to methodological research on research. Research that examines the effects of questionnaire design, item wording, or of other aspects of data collection often uses a classical “split-ballot” design or some variant [42].

Q4. What game dynamics are the most often used?

The most used game dynamics were based on Role-playing game (RPG) and challenges [11], [12], [14], [18], [23], [24], [25], [26], [30], [32], [34], [35], [36]. Followed by games that address questions and answers [13], [19], [20], [29], [31], [33]. The work classified in other dynamics focuses on environments where the student must explore skills such as management [21], [22] or code development [15], [16], [17], [28]. This is still a challenge, but it is not the most important feature of the game.

RPG is a type of game in which players take on roles of characters and create narratives collaboratively. The progress of a game takes place according to a predetermined system of rules, within which players can freely improvise. The players’ choices determine a direction the game will take [43].

Question & Answer (Quiz) is a form of game in which the players (as individuals or in teams) attempt to answer questions correctly. It is a game to test knowledge about a specific subject. In some countries, a quiz is also a brief assessment used in education and similar fields to measure growth in knowledge, abilities, and/or skills.

Q5. What are the most presented arguments for using games?

The most used argument in the works selected for the use of computer games focuses mainly on motivating students (50%), followed by more practical teaching (30.8%), and there were works in which the argument was only to take advantage of existing technological means.

Consider that the "practical" argument is directly linked to the "motivational / involvement" argument. For generally, the very theoretical teaching of concepts related to the STEM area discourages and disinterests students [12], [14], [17]. Therefore, more practical approaches are always seeking to arrest and encourage young people to venture in, to science, technology, engineering, and mathematics.

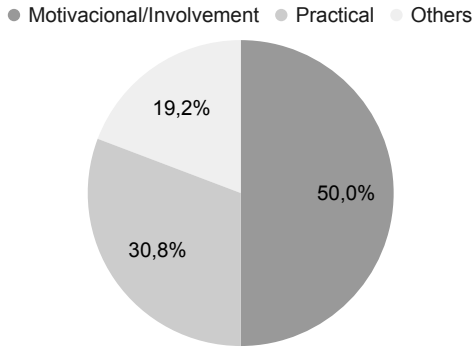

Figure 8. The most presented arguments for using games

The results presented in this research question validate the results presented in research questions **Q2**, **Q3** and **Q4**. Let's see:

In **Q2** the technique used to measure the efficiency of the games are the questionnaires. From them, it is possible to measure the level of acceptance of the students, and the data collection takes into account the students' direct opinion.

In **Q3** the theory of constructivism learning was unanimous among the works. In constructivism, the learning process occurs through interpretation and understanding gave the experiences lived by the learners, they are responsible for building their knowledge, trying to create meanings for their experiences, even recognizing that learning through real-life is complex [44]. This interaction between learners and the learning tool arouses more interest and encouragement for students [12], [15], [29], [32], [34], [35].

RPGs are typically more collaborative and social than competitive [45]. A typical game unites its participants in a single team that ventures as a group. Like novels or movies, RPGs appeal because they fuel the imagination, without however limiting the player's behavior to a specific storyline. This type of game takes advantage of its immersive and motivational nature to focus the player's attention on specific skills and competence development goals. This allows an interesting, useful, and efficient motivational process to take place. What corroborates with the information from **Q4**.

III. Main findings/Discussions

The main findings of our research are listed below:

A. We need more research on the application of computer games in the field of science

This SRL was carried out in two consolidated databases. The strings were tested, studied, and evaluated. As a database, more than 2 thousand articles were returned, and no study was found that used computer games in undergraduate courses in the area of science, specifically natural sciences.

It is at least intriguing that courses like Biology, Chemistry, Physics, Medicine, etc. are not researching the direct use of computer games in their pedagogical processes. The use of games in education plays is a significant role in the development of the student since they manage to evolve together with him. In the learning process, that is, of fundamental importance.

B. Democratize the use of computer games in the area of technology

It is possible to perceive the low democratization of the use of computer games in teaching, even within the area of technology, the area that most uses the resource. The research shows that most of the works were developed with an emphasis on programming. Few studies have covered sub-areas such as software engineering, operating systems and information security.

It is understood that programming is the most relevant knowledge in the area of technology, but there are knowledge such as networks and computational theories that can and should be practiced using games. This would make them less theoretical and more attractive. In addition to these, Artificial Intelligence and data analysis also lack this type of learning methodology.

In addition, studies like [46] show that in technology students, computing specifically has a deficiency in basic mathematical knowledge, such as fractions, algebra and so on.

C. Develop and test new ways to measure the efficiency of computer games in education

Only two studies were identified that used systematized efficiency metrics. In [28] To evaluate the game, use the MEEGA educational game evaluation model. In [33], the Freshman Engineering Chemistry Aptitude Test (FECAT) was used.

It is vital that the process that evaluates the efficiency of a given scientific experiment is based on theories explicitly developed for efficiency metrics. These theories must be consolidated, structured, and tested. This brings more credibility to scientific work.

D. Investigate why the technology area is the one that most uses games in the teaching-learning process

Computer games are currently a widespread concept. The revolution that technology has caused in the world is undeniable. Therefore, it is necessary to question why computer games are used on a larger scale in the area of technology.

Questions such as: are only technology players qualified to apply this type of methodology? Are educational games more easily developed to address technological knowledge? students and teachers from other fields not interested in games? Are games only a useful pedagogical tool within a technological context? How to expand this? These issues must be investigated to elucidate the teaching-learning process in a broadway.

E. Researchers must support the teaching-learning process through computer games on learning theories in a structured, planned and clear way

In all the analyzed articles, we observed a sub-information regarding learning theories. The theories addressed, and the principles emphasized were not explicitly described.

To Davidoff [47], learning is an activity that occurs within an organism, and that cannot be observed; in a way that is not entirely understood, the subjects of learning are modified: they acquire new associations, information, aptitudes, habits and the like. Based on this complex and continuous process that begins with the birth of the individual and ends with his death. Theories have emerged that try to explain how a person learns.

In this context, it is essential that scientific-educational experiences, such as those described in this research, be grounded, planned, and conducted in the light of learning theories. Even if it is necessary to achieve an interdisciplinary between technological and educational areas, thus, the tools and experiences will become more concrete.

F. We need more studies that support the evolution of games with technological evolution

According to Limberg and Silva [45], as the technology matures and games become more sophisticated, the industry grows and attracts a broader audience. There is also a concern to raise the quality of the plots, aiming to satisfy an increasingly demanding audience, whose average age is already over 30 years.

To better understand how computer games work, it is necessary to draw a timeline of the advancement of computing and its incorporation into games. It traces this historical evolution. It would help us to understand the initial contexts of games, the process of transition from simple games to machines, and their insertion in the educational context.

IV. Conclusions

The goal of this research was to investigate how computer games are being used to support STEM courses.

The systematic review returned 2,776, from which 26 were selected. Having STEM as focus, the reviews brought evidence about an emphasis on using games in **T**echnology courses and an absence on using them in **S**cience courses. In fact, the complete distribution of them among the STEM was: Technology (19 articles, 73.077%), followed by Mathematics (3 articles, 11.538%), Engineering (1 articles, 3.847%), and Not identified (3 articles, 11.538%).

The review pointed out that the area of technology is the one that most uses games to support the teaching-learning process, mainly focused on teaching programming. This could be explained by the domain of computational tools to produce software.

Another interesting conclusion emerged from this SRL, is that the most common argument for the use of games in education is justified to motivate and prioritize students' attention through less theoretical and more practical actions.

In accordance with this, it is interesting to note that all of them made reference to pedagogical support, indicating the focus on the learner as the center of the educational process.

Although constructivism is a unanimous learning theory in the selected works, there is the need to better structure and elucidate the theories in the development of this type of methodology.

However, since the games are analyzed in educational contexts, a major threat to the methods of all of the selected articles, are their learning impact. Some of them had used pre and post-tests, however, the time spent and content presents at the game are not considered. One solution could be the use of test and control groups, where the control group must adopt, at least, some interactive approach to teach the same content present in the game, to reduce the bias of using a more interactive/dynamic approach with the experimental group.

Another interesting question to be considered in future analysis is related to the privacy of the learners data. The articles did not explain with the students' data are hosted in private/secure school server or if they are "free" cloud servers.

V. Acknowledgments

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