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USING SIMULATION AND SERIOUS GAMES IN STEM EDUCATION

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Abstract. The use of serious games and simulation software in education is continuously increasing due to the availability of new computer software and the universalization of Internet-based learning environments. Such methodological and technological tools contribute the enhancement of the learning experience in the different areas constituting the Science, Technology, Engineering, and Mathematics education. This work reviews the current state-of-the-art in the use of simulation and serious games in higher education and, in particular, in the fields of STEM and Civil Engineering. Among others, the article explores topics such as the benefits and potential drawbacks of teaching practices based on the utilisation of games and simulations, the enrichment of the learning environment provided by simulation-based learning, or the analysis of collaborative interaction throughout digital games and simulation.

1 INTRODUCTION

A distinguishing aspect of the difficulties that students of the Science, Technology, Engineering, and Mathematics (STEM) cope with at present is the increasing complexity of their working environments. This is particularly true in the case of Civil Engineering students. The holistic perspective needed to tackle the new reality requires from these students a certain level of knowledge of many other engineering and social systems, and the understanding of the deep interrelation among these fields. The present complexity makes the learning process a very challenging one, in which multidisciplinarity, interdisciplinarity, and complex thinking should be achieved. The use of serious games and simulation in learning activities rises as an effective tool to address that challenge [1]. Understanding the potential pedagogical mechanisms of these tools and the associated tradeoffs of their implementation is crucial when developing an adequate roadmap of the educational STEM programs, including those related to Civil Engineering degrees. This paper reviews some existing work from the educational simulation and serious games fields. In particular, the focus is put on identifying best practices and emerging trends of these methodological tools. The learning simulation combines pedagogical, modelling and entertainment elements, presented either in a pure computer-based environment (without the intervention of human actors), or with the participation of drivers, competitors, teammates, and learning communities.

According to the role of entertainment elements, sometimes detrimental to the reality fidelity, the learning simulations can be classified into serious (educational) games and educational simulations. Educational simulations are representations of real phenomena aiming the practice for tasks in the real world, whereas serious games incorporate specific a priori pedagogical approaches, and are designed not only to train tasks but also to teach content. Also, in a simulation, the entertainment is a by-product of the actions and not necessarily the intention of the designers. Usually, motivation to perform any task or job is divided into two facets, intrinsic and extrinsic. Extrinsic motivation consists of behaviors that are performed because of a concrete or perceived consequence or reward, rather than because of the activity itself. On the contrary, intrinsic motivation is characterized by behaviors where people engage in activities that interest them, without the need for an external reward. There has been found to be a strong positive correlation between intrinsic motivation in learning activities and the learning effect of those activities [2]. In the last years, learning practices based on the use of simulation and serious games are attracting a significant attention within the pedagogical environments, as a large number of related publications evidence. Nevertheless, research addressing the topic under the perspective of the STEM and, in particular, Civil Engineering education is scarce. In that regard, this paper presents a focused study that can be used a baseline to design STEM-related programs.

2 GROWING IMPACT OF SIMULATION AND SERIOUS GAMES IN EDUCATION

The inclusion of simulation and serious games in education has received increased attention in recent years. Figure 1 shows a clear increase in Scopus-indexed publications including in its title the terms "education AND (simulation OR serious games)". Notice that the use of simulation in education is a topic that has been explored since 1980 (and even much before that date). Nevertheless, it is not until 2017 that the attention of the scientific community experiments a significant and constant growth. Also in the last decade, the use of serious games in education shows a noticeable increment in the number of related papers. Figure 2 illustrates the main areas of application of simulation methods in education. These include, in order of influence: medicine, social sciences, computer science, engineering, nursing, mathematics, and business & management.

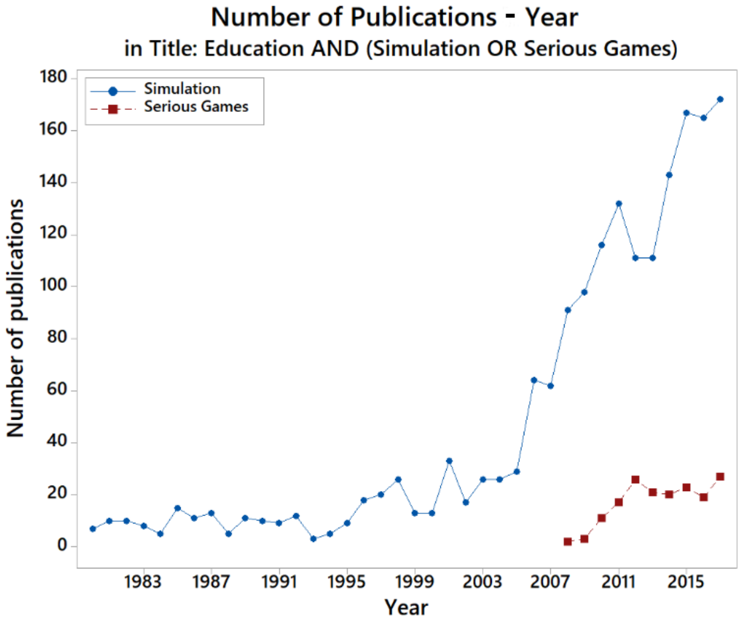

Figure 1: Scopus-indexed publications including the words Education AND (Simulation OR Serious Games)

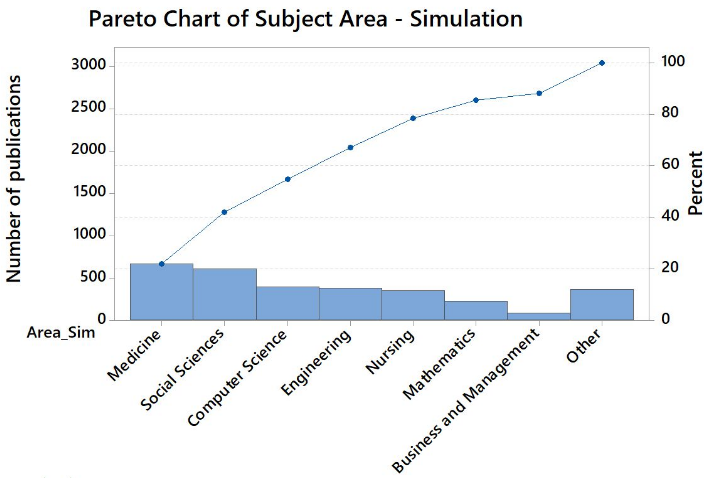

Figure 2: Subject area of Scopus publications including in its title the words Education AND Simulation

Similarly, Figure 3 illustrates the main areas associated with publications focused on the use of serious games in education. Not surprisingly, the main areas are almost the same as before, i.e.: computer science, social sciences, engineering, mathematics, and medicine. The diversity of these areas, ranging from medicine and nursing to social sciences or engineering, shows the outstanding potential of these methodologies when applied in higher education and the fact that a huge variety of professionals can benefit from their inclusion in the university academic programs.

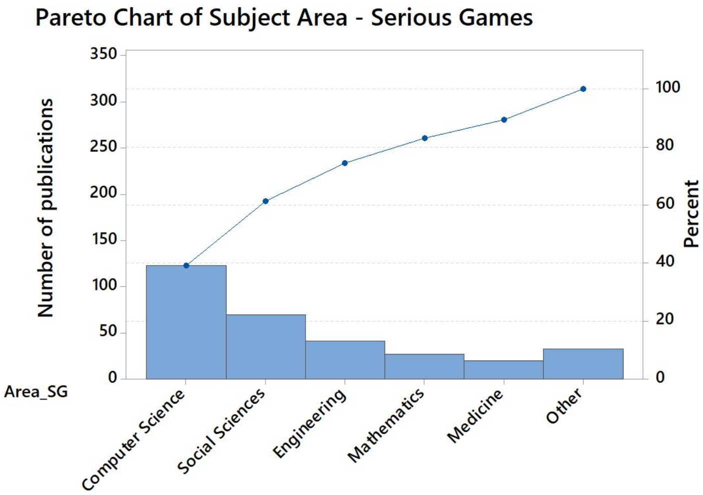

Figure 3: Subject area of Scopus publications including in its title the words Education AND Serious Games

3 BENEFITS OF SIMULATION-BASED TEACHING PRACTICES

Simulation is an interdisciplinary knowledge area that combines computer science, mathematics, statistics, and business management [3]. The rapid development of computer technology as well as the fast improvement of versatility in programming languages, has made simulation programs become such sophisticated tools that it is possible to reproduce reality with an excellent degree of precision [4]. Simulation games have been utilized as an educational tool in order to complement the traditional teaching methods for many years [5]. As pointed out by Clarke [6], there is not a common agreement on the specific meanings of the terms educational simulation and serious games. Authors such as Bloomer [7] define a game as any contest (play) among adversaries (players) operating under constraints and rules for an objective (e.g., winning the game). Simulation refers to a broad collection of methods and applications that allow the mimicry of the behaviour of real systems, usually on a computer with appropriate software. Simulation has been widely used to analyse systems and to compare proposed scenarios in order to improve the system performance, but it can also be adapted to constitute a game [8]. According to Adelsberger et al. [9], simulation games consist of two components, a description and a simulation model. Other authors define a simulation game as a series of “challenging interactive pedagogical exercises, wherein learners must use their knowledge and skills to attain specific goals, played within an artificial reproduction of a relevant reality” [8]. Simulation games can also be defined as a context or a competition-based problem-solving activity in a virtual reality.

As a learning tool, simulation games attempt to replicate various real world problems in the form of a game for various purposes of training, analysis, or prediction. Such types of learning methods can assist in the development of more effective personal transferable skills, such as teamwork, problem-solving techniques, or oral and written communication [10]. Simulation games indeed help students to learn and have fun simultaneously [11], and they have been applied for training purposes in diverse application fields, including: the military and the aeronautics industry, healthcare services (medicine, nursing, etc.), engineering, management, and several other fields. For example, Stanley and Latimer [12] evaluated the effectiveness and suitability of “The Ward” as a simulation game to promote and support nursing students understanding of decision making, critical thinking, and teamwork in clinical practice situations. Similarly, Deshpande and Huang [13] reviewed the different simulation games that have been applied in the education of science and engineering.

4 USING SERIOUS GAMES TO ENRICH THE LEARNING EXPERIENCE

Traditionally, researchers have artificially separated learning into three areas: affect, behavior, and cognition [14]. Current trends in educational measurement and psychometrics address the artificial disconnect that exists between these. For instance, automatic associative affect results from repeated contact with contexts not consciously under control. Also, within the so-called priming process, there are affective effects that take place prior to cognitive processes, fostering subsequent learning. In serious games the learner is exposed to complex representations, often requiring specific content knowledge and learning progressions to be completed in order to move the game forward toward the objective. Usually, the game adds a story as a means to drive game mechanics. In Lamb [15], the following characteristics of games are described: *(i)* emotional attachment to the outcome of the actions taken by the player; *(ii)* a uniform set of rules governing the actions players take; *(iii)* differential outcomes related to actions taken by players during play; *(iv)* differentiation of value for actions taken by players; *(v)* consequential actions resulting from actions the players take; and *(vi)* agents within the game for the player's characteristics to act upon. The efficiency of the serious games in the learning process will depend on the understanding of the structure and potential of the game. In that regard, Arnab et al. [16] provide a useful tool to analyse and support some serious games as means for fostering active learning. The tool provides the relation between the learning mechanics based on pedagogical theories and the game mechanics, as depicted in Figure 4. Rows present analogous mechanics from a general perspective. The central columns in each block show the core elements supported by the functional mechanics of the side cells. Colours allow a second classification based on the thinking skills acquired, according to Bloom’s theory [17]. In addition, abstract and concrete elements are indicated by cursive and bold fonts. For instance, the abstract learning objective of participation, which may be supported by concrete learning tasks and demonstrations activities (second row), is connected to the mechanisms of cooperation and collaboration allowed by serious games. The updated state-of-the-art publication by Turner et al. [18] summarises the many reported benefits of the online serious games, such as the increase of the level of motivation, engagement, critical thinking, and content proficiency of the students. As a complementing element of the educational program, they even foster the confidence and satisfaction of the students. It is also highlighted how serious games permit the experiential learning experience, real-life problem solving and training in decision-making processes. The construction of knowledge in a virtual environment is comparable to the construction of knowledge in an analogue environment (i.e., the real world) to take advantage of the engaging nature of video games by stimulation of the areas of the brain associated with attention and arousal. Engagement takes place as a psychological immersion in the game.

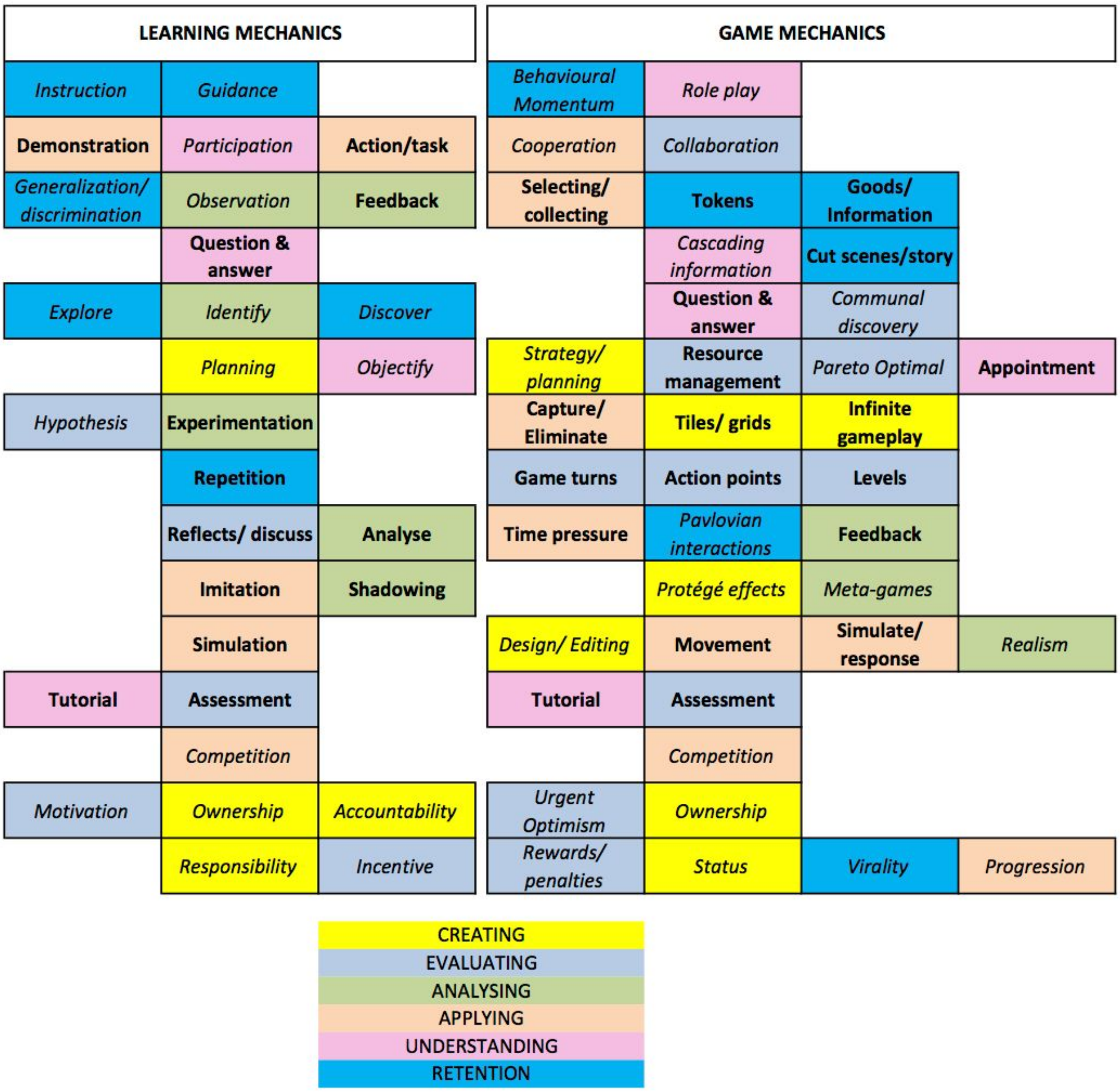

Figure 4: Relation between the learning and the game mechanics (Arnab et al.)[17]

Often, players experience a type of deep engagement known as flow. Flow is a highly energized state of concentration and focus that allows distractions to be excluded [19]. Flow is a concept first introduced by Csiksentmihalyi [20] in the 1990's, and it is also characterized as a psychological state that a person may enter, while being deeply involved with interactive and immersive learning environments that attract their attention for a period of time. This psychological state strongly fosters retention of contents and self-efficacy. Then, the challenge is to guarantee that serious games keep the student in the flow zone, that is, with a demand level neither too high that causes frustration, nor too low that causes tedium. Hainey et al. [21] claim that games support constructive, experiential and situated learning; these are all aspects that the modern theories of learning suggest as central for effective learning.

However, several drawbacks associated with the use of serious games in education have been identified too. For instance, Rondon et al. [22] note that serious games should be understood as a supportive tool of the contents learned in a lecture-based environment, not a means of replacing the lectures. Bellotti et al. [23] points out that the combination between entertainment and instructional purposes is not immediate, and must not be taken for granted. Integration of both must be designed carefully, avoiding situations where the game itself distracts the student from the learning goals. The learning process within the serious game requires a strong emphasis on guidance to the student. Otherwise, the serious game becomes less effective and may even lead to incomplete or disorganized knowledge. A “scaffolding” approach is needed to gradually build knowledge. It is important to avoid overloading the brain’s working memory, as saturation of short-term memory is known to inhibit learning. In addition, some students might feel anxiety when working in a computer-based environment [24]. However, this issue is becoming less likely within the digital natives that are already used to online learning environments. In fact, educators might find themselves more reluctant to implement serious games than students to use them, because of the generational gap. In either case, time is required by students and instructors to become familiar with the technology. The difficulty of the assessment of the effectiveness of serious games and the estimation of the correlation between game progression and curricular achievements may slow down the embracement of these tools for educational purposes. In that regard, the collaborative action of instructors and game designers during the phases of design and implementation is always recommended. Furthermore, the validation of the game, and refining if necessary, should be addressed based on the observed learning outcomes [25].

5 SIMULATION AND SERIOUS GAMES IN STEM AND CIVIL ENGINEERING

The multiple benefits of the use of simulation tools have been addressed in the literature. Some authors highlight the fact that the use of simulations for teaching and learning is becoming increasingly popular [26]. The value of simulation as supportive of the enhancement in learning that can occur has also been extensively discussed [27]. das Dores Cardoso [28] employ discrete-event simulation as a learning methodology in a course on automatic control systems. According to their tests, the use of such an environment allows students to gain experience in a variety of realistic scenarios. Curland and Fawcett [29] examined the problems with numerical skills applied in operations management and finance. They indicated that business simulations can be of value in overcoming fear of the use of numbers. In Balci et al. [30], the authors discuss the difficulties of teaching modeling and simulation courses in online learning environments, and provide some guidelines on how to develop an online course in this area. All in all, simulation is becoming a frequent pedagogical tool in many STEM courses, both in face-to-face as well as in online environments [31].

Regarding the specific fields of STEM and Civil Engineering, serious games allow the interaction with virtual environments that provide students with the interactive, digital, and multimedia skill sets required at the workspace. Usually, these skills cannot be learned by the classical lecture-based approach. In Cleophas et al. [32], the authors propose a framework for designing serious games in the area of revenue management. The framework makes use of simulation techniques to evaluate different revenue management strategies. As the authors point out, "simulation systems are well-suited to complement tutoring by allowing players to directly experience the effects of uncertain demand and to interact with realistic representations of complex revenue management systems without the risk and cost associated to real-world experiments." According to Ritterfeld [33], serious games is an important field of scholarship and practices focusing on the use of digital gaming platforms and technologies for purposes beyond pure entertainment. Examples of serious games actually being used, Schäfer et al. [34] show a collaborative-competitive serious game for learning mathematical logic in Computer Science at Aachen University (Germany). Rozkhova [35] uses a serious game for learning first-year Vector Algebra and Analytic Geometry, at the Elite Technical Education department of the National Research Tomsk Polytechnic University. Assessment can also be included in games. Students usually prefer questions that are included in games instead of traditional questions on paper. There are also interesting examples of serious games applied to the Civil Engineering field. For instance, the use of specific modules of the Sparksville 25 game program, which allow the operative learning of applications such as the management of natural resources and the control of energy systems [18]. Online games on virtual truss bridge have been also applied. The aim is to learn and practise the engineering mechanics, such as the estimation of the angles and spans of the bridge segments [36]. In most of the cases, students using this serious games obtained better grades than those who did not use them.

6 CONCLUSIONS AND FUTURE WORK

It is expected that graduate Civil Engineers are able to conceptualise engineering models based on a wide range of fundamentals on engineering, physics, and mathematics. Additionally, they should be able to identify the most appropriate techniques and tools, when facing the present complex engineering problems, with awareness of the available resources and existing limitations. These specific skills are sometimes barely acquired by the passive learning process provided in a lecture-based environment. For that reason, traditionally site training and secondments in engineering companies have been considered as an important part of the educational program. In that context, the learning simulation tools, that is, educational simulation and serious games, provide the students with a more holistic learning experience, allowing them to learn from mistakes and failures in a safe lab environment.

These learning simulation tools offer a number of clear advantages over traditional learning experiences, especially when properly combined with an online-learning environment in which students (even from different universities and countries) can interact among them as well as with instructors and industrial experts. Thus, simulation and serious games open new possibilities yet to be fully explored not only in Civil Engineering but also in the broader area of Science, Technology, Engineering, and Mathematics.

In future works, we expect to be able to extend this paper in different ways: *(i)* by discussing how the integration of learning simulation tools can be effectively and efficiently integrated with online learning environments; *(ii)* by completing a more exhaustive literature review on both successful and unsuccessful case studies regarding the implementation of these tools in real-life higher education; and *(iii)* by deploying our own case studies in different universities and measuring the effect of the introduction of these educational resources in different STEM-related degrees.

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