Extended Abstract

Evaluation of Virtual Reality Application as a Tool for Emergency Security Plans Execution

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1. Introduction

Fire drills and emergency plans are mandatory in every building. The outbreak of a fire in any kind of building puts the security of everyone inside at risk, in addition to their property. Moreover, not only the staff and emergency teams need to know that the established emergency plan is working, but also all those who use the building should know how to behave to maintain order and not to panic.

As a result of emergency evacuation plans being made only upon completion of a building construction, the detection and correction of these problems is later than it should be, thus resulting in more time and higher costs to solve them. This could be avoided if emergency plans were made much earlier. To this end, it would be necessary to build a virtual simulation system that could run a fire drill in a virtual, but realistic, model and immerse the users with some VR equipment in such a way they would really feel that the exercise represents a real situation.

2. Literature Review

2.1. Emergency Evacuation Plans and Fire Drills

2.1.1. Introduction

Besides the ambition to save lives and provide training that is characteristic of emergency plans, they also seek to preserve the main building and the assets inside. Moreover, they also have to protect neighbouring buildings and their users, as well as the pedestrians on the public highway. Lastly, they try also to protect the environment and the cultural and historical heritage. In buildings of the type under study (University or school), fire drills are mandatory at least once per year. With these exercises, authorities seek to [1]:

- Train both users of the building and professional staff;
- Evaluate the procedure and detect imperfections that may put people's lives at risk – detect critical points in the building;
- Practise the interaction between staff and emergency authorities;
- Ensure compliance with the law. Enforcement.

Within the scope of this paper, the first two reasons above are the most important, since the application of videogames and virtual reality to the execution of emergency plans will be applied directly to them.

2.1.2. Vulnerable aspects and Flaws of Emergency plans and Fire drills

Although the implementation of security plans is mandatory for the important role they play in emergency situations, discrepancies between the plan's goals and its outcomes frequently arise. The vulnerability shown by some emergency plans could be due to some of the following factors:

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- Design project errors – e.g. insufficient emergency exits;
- Structural design inaccuracies – e.g. small stairs for the number of people using the building;
- Construction imperfections and miscalculated details – e.g. wrong materials, unfinished details;
- Misinterpretation of human behaviour assumptions – misinterpreting or obliterating events such as flocking
- Other.

Furthermore, the majority of building users do not know where the emergency plans are exhibited or are even unable to read them. Additionally, the downsides of fire drills are rather obvious, such as the lack of accuracy during simulations, the difficulty people have in taking them seriously and to fully participate or even to learn how they should behave in emergency situations [**2**]. Videogames, as in serious games, have been regarded as a possible solution for this problem. They have been successfully applied in different areas such as education, health, politics and marketing, since they are able to transform tedious tasks into enjoyable experiences [**3, 4**].

2.2. Technology

2.2.1. Serious Games

If a game can be defined as *"A voluntary, interactive and competitive activity, artificially constructed, located in a specific context, with specific goals, a set of rules and constraints that restrain the player's behaviour and that ends in a quantifiable outcome"* [**5, 6**], a videogame would be *"a mental contest, played with a computer according to certain rules for amusement, recreation, or winning a stake"* [**7**], or *"a game played with a computer or other audio-visual platforms, that are able to provide a virtual or artificial environment.".* In line with the above definitions, serious games are no more than serious videogames, *"videogames applied to different purposes than that of entertainment, like supporting education, health, marketing or training activities"*. A serious game could be defined as *"a mental contest, played with a computer in accordance with specific rules, that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives."* [**7**].

The enjoyment and fulfilment sentiments experienced while gaming, the challenging situations, and the curiosity related to the uncertainty of the consequences of a player's actions during the game, are emotions that help users remain more focused and motivated on their tasks [**4**]. According to Freitas [**8**], other benefits of serious games are 1) learners' increased motivational levels, 2) higher success rate through engagement and enjoyment, 3) the ability to arouse new stakeholders, 4) use of collaborative activities and 5) accelerated learning periods by learning through doing and acquitting experience.

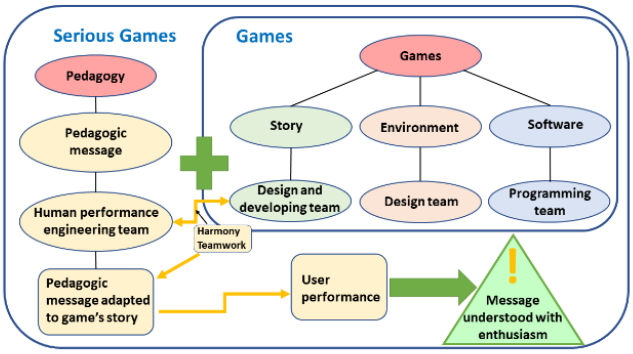


Figure 1 – **From Games to Serious Games**[**7**].

Serious Games can still be classified in five different categories such as **Edutainment**, **Advergaming**, **Edumarket Game**, **Political Games**, **Training and Simulation games** [**9**]. It is worth noticing that the same serious game is not exclusively classified with only one category, meaning that one serious game could have assign multiples classifications.

2.2.2. Hybrid Games – Simulation and Training games

Hybrid Games are *"Games compounded by different elements, not necessarily features from other games, whose final result is a game with considerably more far-reaching goals, rules and applications than the initial game"*. The definition of **videogame** has already been presented. According to Hays [**5**], and Leemkvil, et al [**10**], **simulations** are *"a method for implementing a model over time"*, and **case studies** are "*an actual or hypothetical problem situation taken from the real world"*. The relationship among these 3 concepts is displayed in Figure 2. As may be observed, these three concepts have their own context and may be related in pairs or in a trio, like the hatched part of the figure [**5**]. Consequently, according to the afore-mentioned Hybrid games definition, 3 Hybrid Games were obtained from these relations, namely *'Simulation Games', 'Games used as case studies'* and ***'Simulation Games used as case studies'***. The latter is the main focus of this paper.

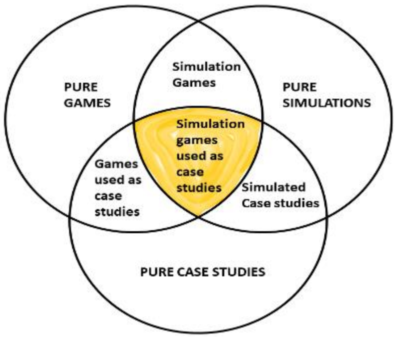


Figure 2 – **Relationship among 'Games', 'Simulations' and 'Case studies'[5]**

2.2.3. Pedestrian Simulation

Pedestrian simulation is a field of computing involving different areas, such as Artificial Intelligence, Crowd Simulation, Decision Making and Behaviour Analysis. Usually, this kind of technology is used for planning urban areas, studying the safety of buildings or open areas, but also in the evaluation of emergency systems and evacuation routes [**11**]. According to Ribeiro [**11**], the biggest difficulty in this area is to enhance the accuracy of the models used and to competently implement human behaviour. As reported by Teknomo [**12**], pedestrian simulation studies are divided in two different parts, Data Collection and Data Analysis, and regardless of the specific characteristics that may be under study, the final approach will always be geared towards an understanding of the pedestrian's behaviour (at a microscopic level – Individual pedestrians, or a macroscopic level – groups of people) [**11, 12**].

2.2.4. Crowd Representation Models & Crowd Behaviour

Crowd representation could be virtually simulated by means of a number of different approaches, however, 3 models clearly stand out: The **Cellular Automata Models**, the **Forces-based Models**, and the **Artificial Intelligence-based Models**. [**4**]

Groups and individuals behave in a totally different way. In emergency situations, differences in their pattern of behaviour are much greater. There are a variety of factors that can influence the decision process and people's behaviour. Helbing [**13**], and Ribeiro [**14**], have highlighted some attributes they consider to be imperative to simulate individuals' behaviour: **state**, **speed**, **field of vision**, **reaction time**, **collaboration**, **insistence**, **knowledge**. Additionally, when simulating large groups under stress or in emergency situations, certain phenomena like flocking (or herding) may also occur, and additionally influence individuals' behaviour [**15**]. Flocking occurs due to the uncertainty felt by some individuals as to what the best decision to make is (e.g. which route to take), and they instinctively follow other individuals instead of making their own choice. When visibility is low, or when the majority of people are not familiar with the building, this instinct may give rise to groups of wandering people, with no idea of where to go, thus increasing panic levels [**14**].

2.2.5. Virtual Reality

The approach followed in this paper is to mix the VR equipment with the 3D model and the game-based system in order to achieve a more realistic and effective experience than fire drills. Additionally, this paper seeks to validate the theory that with recourse to this VR connection, security plans may be established much earlier, enabling time and money to be saved as any flaws in the plan' can be detected before the construction is concluded. In order to utilize virtual immersive scenarios, the system in use must be connected to the VR equipment, such as HTC VIVE. HMD Vive will show the immersive environment created in the BIM software, and the Vive controllers will serve as the connection between the player and the game, so the he former can interact with the scene and the objects in a realistic simulation.

Immersive environment recognition is via a '*walkthrough'* mode, more precisely as a *First-Person Shooter*. This means that the player will be placed in the scene as if he were the avatar himself and will see everything through the eyes of the character. There is also the *Third Person Shooter* mode, where the player is placed in the scene as a third character that is watching the scene from a specific point in space and following the player's avatar moves, however, for an immersive and realistic experience, this would not be appropriate.

3. Methodology and Case study

3.1. Introduction

The main goal of this experiment was to show how VR technology and Serious Games can be applied to increase the efficiency of our security plans by reducing costs and time but achieving the same or even better results. The platform built recreated a virtual fire evacuation situation in a real building, in this case, the Civil Engineering, Architecture and Geo-resources Department's Building, in Lisbon, Portugal.

3.2. Setting up the platform

3D Model

Firstly, it is necessary to create a virtual scenario to be used in the simulations. A model of the IST Alameda campus was used, namely the ground and 1st floors of the Civil Engineering, Architecture and Geo-resources Department's Building. This model was created entirely from scratch, with the *Autodesk BIM software Revit 2018*, and the official plans of the building were used in order to ensure that it would be as real as possible. The initial step involved importing the official plans of the building to the *Revit*. These plans were in a *.dwg* file, which is an *AutoCAD* file and is perfectly compatible with *Revit*. The upload is a very simple process and

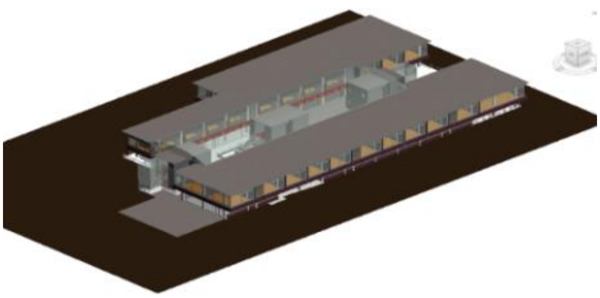


Figure 3 – **Revit 3D model used in this paper.**

preserves all the original properties such as geometry, dimension, thickness, etc. Although the outside of the building is an important feature to maintain and to recreate as accurately as possible, it's not enough to guarantee the realism of the model, as the interior layout and the materials play a fundamental role for this purpose. Revit has a library of materials (concrete, glass, wood, e.g.) but it's rather limited in the variety of its offer.

Game Engine

The game mechanism was built by adapting and customising the environment of a common game engine, in this case Unity 3D. This software acts as an intermediate between the BIM model and the virtual environment produced with it, while it is simultaneously the tool that allows the designer to build a virtual world with some action-reaction events. The Unity engine was chosen due to some characteristics, presented in Table 1, thus making it the perfect software for this purpose [**16**].

Table 1 – **Essential Unity's characteristics** [**16**]

Environment	2D e 3D and Audio playback
VR Hardware	Vive, Oculus Rift, Samsung Gear VR, others
Operating System	Windows PC, Android e IOS
Scripts / Programming Language	C#, JavaScript, Boo
Physics Engines	Included in Unity itself; Adapted by scripting
Complexity	Low. Simple engine and easy to start
Objects Importation	Allows objects import.

In order to ensure the interoperability between the BIM model and Unity, the imported objects must be saved in a specific format, .fbx ('*Filmbox file'*) or .obj ('*Object file'*). Within these two files, Unity can guarantee that all the original geometric properties are kept, on the other hand, materials and textures are not preserved. Usually, a designer can solve this problem by using a rendering or image processing and animation software, like *Autodesk 3DS Max*, however, this is not a simple software to use, nor is it cheap, so in this study another solution will be presented. The plug-in referred to as "Export to Unity" (available in *Autodesk store)* transforms all the visual objects into a .fbx or .obj file and exports them to the *Assets folder* of the Unity project, preserving the geometric properties. At the same time, it generates a folder with all the textures in *.mtl* files so that Unity can open and read them (Figure 4).

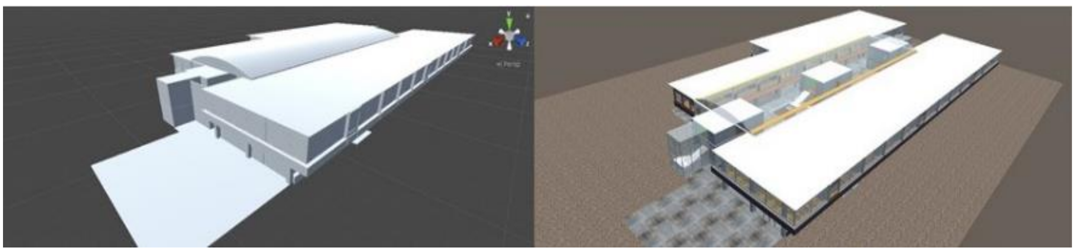


Figure 4 – **Unity project. Model without and with correct materials.**

Apart from making the realistic environment with the BIM model and assembling the correct materials for every part of it, the scenario would not be a truly realistic scene without some interactivity between the user and the game. To recreate the real experience of a fire emergency evacuation, he needs to open doors, see other people and where they' are moving, see were the fire is, etc (Figure 5). The 'open' and 'closing' doors movements, players movements and all other features of the game were made through C# Scripts. The other absolutely crucial asset for this experiment to work is the generation of AI Agents. AI Agents are characters in the scene that can intelligently move through a mesh generated by Unity, as a result of our predefined settings. They are capable of avoiding collisions with obstacles or other agents and will try to reach a defined point in space through the shortest path possible. A very common algorithm to find the shortest path is A*, which is what Unity uses, because it combines two other methods of path finding in only one algorithm. A* algorithm associates the information of Best-First method that searches for a path through vertices close to the goal, with the Dijkstra's algorithm that searches for a path through vertices near the starting point [**17, 18**].

Figure 5 – **Civil Engineering, Architecture and Geo-resources Department's Building. Real vs. VR models.**

Virtual Reality

After finishing the game-based system, it is necessary to assure that it will be compatible with VR equipment. For this experiment, the Vive VR equipment (HMD and Wands) was used so that the player's movements were made by the touchpad, and for opening doors the trigger button was used in order to accomplish a fully immersive scenario and a realistic experiment.

Figure 6 – **Virtual Reality equipment. HTC Vive – HMD and Wands. Adapted from [**19**]**

3.3. Experimental Setup and Simulations

Implementation

Each user plays the game twice. The first scene simulates the building exactly as it is in the real world, while the second scene is just like the first but with more emergency signs and a new emergency exit closer than the existing one. Before playing, users were unaware of the difference between the two scenes, only that they would play twice. All the players had a few moments to try to adapt to the HMD and to try the controls of the wand, for that purpose, it was built a starting scene (Figure 7). Additionally, all the users received a tour from the entrance of the building to the room in which the simulation would start. When the game starts, a fire breaks out somewhere in the building, the fire alarm rings and users gain control of an avatar in a predefined room. As soon as the timer starts to count, players must evacuate the building by taking the route they think is the shortest (Figure 8). They can go on the basis of their intuition, stick with the other AI Agents that are trying to leave the building too, or look for some emergency signs to decide which way they should go. It is important to note that not all the AI Agents choose the shortest exit. This was predefined in order to simulate the real situation where not everyone inside the building knows where they must go.

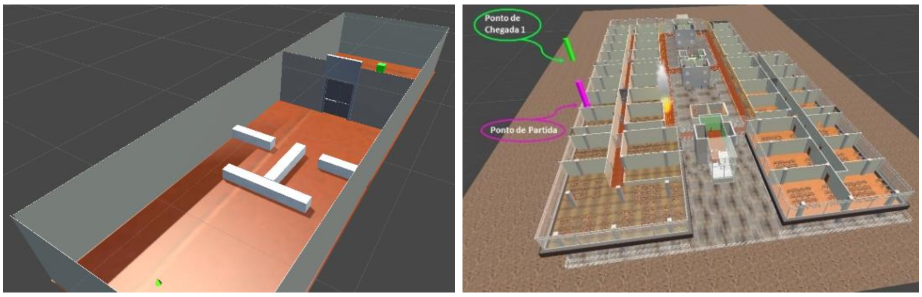


Figure 7 – **User playing one Simulation and virtually evacuating the building.**

The starting point of both simulations is the same, and it was chosen because it was a location in the area from which a person would take longer to evacuate the real building. The aim of this choice is to show that the additional signs make a lot of difference in the evacuation time and that a new emergency exit would drastically decrease the time people take to leave the building. After the experiment, each user answered a short questionnaire discussing how they felt during the simulations, evaluating the game-based system and the experiment, and giving their views on how useful this platform could be.

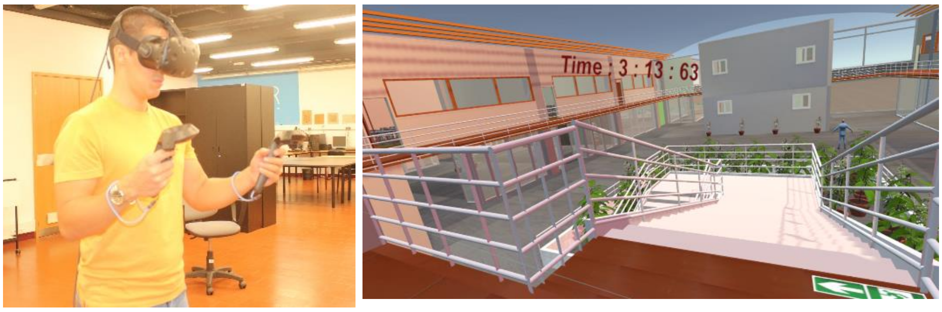


Figure 8 – **Starting scene and Simulation I starting and finishing point.**

Model calibration

Calibration of the model was a fundamental issue to guarantee the reliability of the results. For this purpose, the real model was compared to the virtual one, and the evacuation time in the two distinct worlds. Each floor had a path near the emergency exit (Zone I) and another further away (Zone II). Using the same method as Ribeiro [**11**], the model's calibration was made using equation (1), in order to attain an approximate value for the player's speed in the game, and to ensure the errors were acceptable.

$$1-\frac{Virtual\ Evacuation\ time}{Real\ Evacuation\ Time} \qquad \textbf{(1)}$$

Table 2 – Model's calibration

Path	*Floor 0 + Zone I*	*Floor 0 + Zone II*	*Floor 1 + Zone I*	*Floor 1 + Zone II*
Distance (m)	52	65	93	124
Real Evacuation Time (s)	37	44	67	91
Real Individual's Speed (m/s)	1,41	1,48	1,39	1,36
Virtual Evacuation Time (s)	35	43	62	83
Error (%)	5,4	2,3	7,5	8,8

As may be observed in Table 2, the Real Individuals Speed is consistent at around 1.36 and 1.48 m/s, so the speed value used in the game was an acceptable value. It should also be noted that the error is low (always $\leq 10\%$) and, as expected, is higher in the routes of the first floor. This was already expected as these routes involve stairs, where the Player's Speed does not decrease in the game as it does in real simulations, reducing the 'Virtual Evacuation Time' and increasing the error associated with that path [**11**].

3.4. Results

To test this new prototype, and to guarantee a balance among the sample, a total of 18 individuals were distributed according to Tables 3 and 4 [**14, 11**]. This value was chosen in line with Forza [**20**], as the correlation between the variables were fixed as with a large effect, i.e., the variables were treated from a macroscopic perspective, therefore a sample of 12 individuals would be enough. These individuals were selected and distributed according to their age and gender, in order to equalise these variables. Moreover, in an attempt to receive as many different approaches as possible, and to minimize the impact these two variables may have on the results if poorly distributed, testers were classified into two important categories [**14, 11**]:

- Previous Knowledge of the building;

- Videogame skills (Frequent video Game players).

Table 3 and 4 – Classification and distribution of the sample

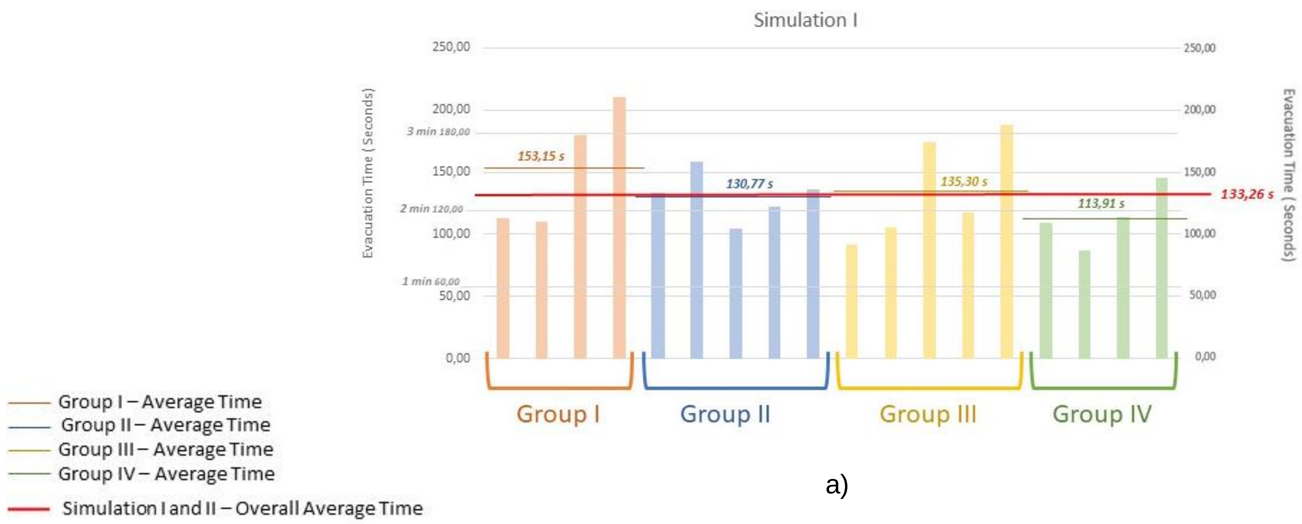
Group	Videogame Skills	Previous Knowledge of the building	Sample
I	No	No	4
II	No	Yes	5
III	Yes	No	5
IV	Yes	Yes	4

		Age	
		(18 - 35 years)	(> 35 years)
Gender	Male	6	5
	Female	4	3

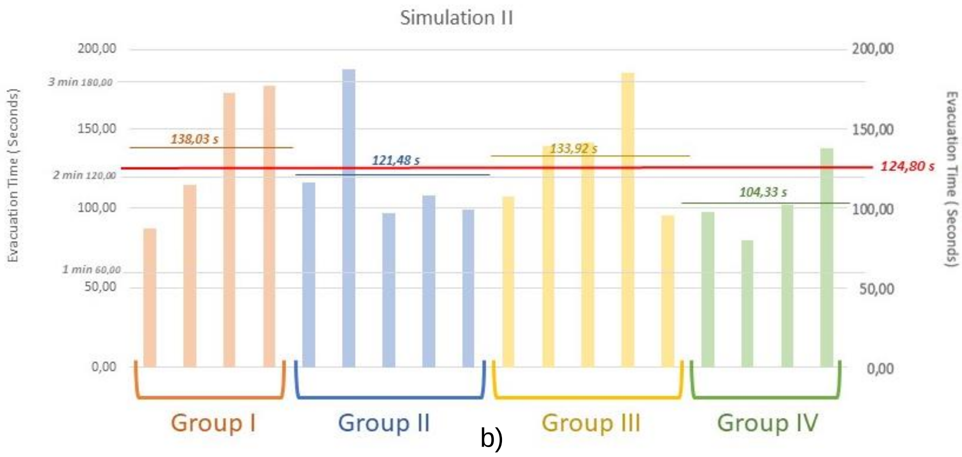
Naturally, individuals' familiarity with videogames is a very important variable to keep, as frequent players would obviously get used to the equipment and the immersive environment more rapidly. On the other hand, familiarity with the building may also constitute crucial knowledge so that simulation of the evacuation may be accomplished in the least amount of time. Once users have some familiarity with the building, they will more efficiency detect where they are in the virtual scenario, and where they have to go to avoid wasting time. They would not feel tempted to follow other people or even to look for emergency exit signs. The main measured value during the simulations was the evacuation time of every user in each scenario. Figure 7 depicts the time each player took to evacuate the building in each scenario. In the graphs, a red line may also be observed, measuring the average time, and four colored lines illustrating the average of each one of the four groups.

Individuals from Group IV were already expected to achieve the best result, as they had previous knowledge of the building and were frequent game players, while those from Group I were expected to have the worst performance because of their poor or total lack of familiarity with the building and of videogame experiences. To analyse Groups II and III, Table 5 introduces some important data.

At first glance, both **Group II** and **Group III** could achieve better results. Whilst individuals from **Group II** had previous knowledge of the building, which could be crucial to accomplish the minimum time in the evacuation simulation, but little experience controlling the avatar, elements from Group III had videogame experience to naturally control the avatar but no familiarity with the building, thus taking longer to decide where they should go. According to Figure 7, between these two groups, the one with the better performance was Group II. This may be explained by the number of individuals choosing the shortest path, which was higher in Group II than Group III as shown in Table 5. This concludes that between the two variables "regular game player" and "familiarity with the building", the latter is the most crucial. According to Frey, et al. , the equipment is easily mastered after a few times playing, unlike familiarity with the building [**21**].



a)



b)

Figure 7 – Evacuation time of each individual and mean value in: a) Simulation I, b) Simulation II. Division by group

Table 5 – Path chosen by each group

Simulation I			
Group	**Shortest path**	**Building's entry path**	**Sample**
I	No	No	1
	No	Yes	1
	Yes	No	1
	Yes	Yes	1
II	No	No	0
	No	Yes	2
	Yes	No	2
	Yes	Yes	1
III	No	No	2
	No	Yes	2
	Yes	No	0
	Yes	Yes	1
IV	No	No	1
	No	Yes	0
	Yes	No	1
	Yes	Yes	2

Simulation II			
Group	**Shortest path**	**Same path Chosen on Simulation I**	**Sample**
I	No	No	0
	No	Yes	3
	Yes		1
II	No	No	0
	No	Yes	1
	Yes		4
III	No	No	1
	No	Yes	1
	Yes		3
IV	No	No	0
	No	Yes	0
	Yes		4

The total number of individuals choosing the shortest path was substantial, representing 50% in **Simulation I** and 67% in **simulation II**. Obviously, in the second scene, this number is higher due to the increase in emergency signs and the extra emergency exit.

4. Discussion and Final Considerations

The intention of this paper is to improve the way fire emergency evacuation plans are made in order to anticipate the conclusions that, nowadays, are only drawn after completion of the building construction and the execution of the mandatory evacuation drills.

It is clear that the second simulation obtained much better results than the first, and that is essentially due to the higher number of emergency signs and their better distribution. The new emergency exit also contributes to this better performance. If this simulation had been made before the building was constructed, the security experts could have alerted the project leader to this fact and another emergency exit could have been constructed. Furthermore, the emergency signs problem would not have even existed because all the signs would have been put up from the beginning. These deductions are only an example of what would be possible to conclude with a VR game-based simulation in some random building, since this emergency exit would be dificult to build in the real Civil Engineering, Architecture and Geo-resources Department's building.

However, there are many other conclusions that could effectively be made in this case study. In both simulations, it is possible to see that most of the players and the AI Agents chose the central stairs as the fastest way out, even if it is not. This happens because most individuals use the same entry path (and usually, when entering the building, people use these stairs to go up and down), or the most used path by other people (instead of making sure that it was really the closest exit, people just 'go with the flow'). Therefore, it was not hard to predict that these would be a critical point of the building, with a lot of influx and agglomeration, thus delaying the evacuation process. In the fire drills building's reports of 2017 and 2018, this same situation is reported, and these stairs are classified as a critical point, calling for some kind of intervention. Another conclusion from the reports, that could also be seen in the virtual simulations, is the small passageway between the stairs and the elevators on the main floor. The evacuation route does not go through there, but the majority of people try to leave the building that way. As only one or two individuals can pass at the same time, this delays the whole process and creates even more confusion on the stairs. Within the simulation, it is possible to see that every player chooses exactly that pass instead of the real evacuation route. In the real building, these two cases are still being studied and hypothesis testing is being conducted in order to find the best solution with the least costs. The report even says that nothing has been done so far due to the high cost of the intervention. Therefore, if these problems had been discovered sooner, prior to the building construction, they would not even exist now.

To conclude, with these simulations it was possible to discover that the central stairs and the small passageway on the main floor are critical points, the lack of emergency signs is enormous and there is only one emergency exit in the building, making effective evacuation difficult. All of these problems were discovered in the VR game-based simulation and acknowledged with the fire drill reports, so they could have been avoided. Moreover, this system also provides the possibility of using some sort of 'open project discussion' to be experimented by others and receive some input from security experts or from the final users of the building. It should be noted that this tool does not replace fire drills (to test or train people) or on-site investigations and studies, it merely seeks to provide a system that could help save time and money and improve the execution of emergency plans. Moreover, fire drills are a very important complement of this preliminary study of the Civil Engineering building's users' behaviour. Ultimately, this platform could also be a helpful tool in the instruction and training of evacuation behaviours due to its connection with videogames and the enjoyment experienced during a VR game.

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