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Computer Simulation and Fire Drill in an Educational Building

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Abstract *— Despite the evolution of computational models for evacuation simulations, there's still some doubt if they can generate accurate results. The objective is to analyze and compare the evacuation times of a fire drill and a computer simulation in an educational building. The method consisted of a fire drill with prior notice of a 4-floor building with classrooms in a public university. A computational model was developed for the same building and population using the evacuation simulation software Pathfinder. The results were that the evacuation times observed in the computer simulation were slightly lower than the times of the fire drill because people covered smaller distances due to the random distribution performed by the Pathfinder software and because in the drill some time was spent for the start of the movement toward the exit, which was estimated at around 30 seconds, while the software was configured for a pre-movement time equal to zero. The use of the computer simulation, therefore, proved to be an effective solution to replace the fire drill, since it allows for the identification of design failures and for the simulation of different scenarios in less time and without the need to mobilize people.*
Keywords— Computer Simulation, Evacuation Time, Fire Drill, Fire Prevention, Human Behavior, Means of Egress.

I. INTRODUCTION

In Brazil, the emergency exit system and other fire protection systems follow the prescriptive methods defined by federal and state standards. With regard to the design of the emergency exits in buildings, NBR 9077 [1] considers the capacity method, which specifies the minimum dimensions for the accesses, corridors and doors in relation to the floor with the largest population. These prescriptive systems have limitations as they don't consider such variables as those related to human behavior during a fire, which is also subject to the heat, smoke and toxic gases arising from the fire. Codes based on performance usually take these conditions into account [2].

The variables used to design emergency exits are directly related to the evacuation time of the building, because the dimensions of the exits must allow for a certain population to leave a site before environmental conditions reach a critical point. The option of designing exits using computational evacuation simulation models enables designers to design buildings based on the performance of exits. With the computational models, it is possible to model the building and the population, enabling the estimation of the time required for the occupants to safely evacuate a building still in the design phase.

However, there's still some doubt if a computational evacuation simulation model can produce accurate results, bearing in mind that the assumptions may lead time to overly optimistic or conservative estimates. In addition, studies carried out in educational buildings are scarcer than studies in residential buildings.

As such, the objective of this article is to analyze and compare the evacuation times of a simulated evacuation drill and a computer simulation in an educational building.

II. EVACUATION OF BUILDINGS IN EMERGENCY SITUATIONS

2.1 Human behavior in emergency situations

In order to develop a fire safety design, the designer must not only study passive and active fire protection systems, but also human behavior in an evacuation situation.

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According to Kuligowski [3], human behavior in fire situations is the study of human response, including the attitudes, decisions, behaviors and strategies used by people exposed to fire and in other similar emergencies. The main focus of the research in this field is to minimize the risk to people during an emergency situation.

According to Gwynne [4], the studies focusing on human performance in fire situations considering psychological and sociological factors are overshadowed by the emphasis given to research focusing on physical fire safety sciences . This fact is due to the lack of and difficulty in obtaining data related to human performance in fire situations.

For Kuligowski [5], the currently used assumptions in the calculation techniques regarding human behavior in an emergency situation can produce inaccurate results. In cases in which the assumptions lead to overly optimistic or conservative evacuation times, buildings and safety procedures may be designed too leniently on the one hand, or too burdensome and costly on the other.

For Kuligowski [6], the integration of the different fields of social sciences, such as sociology and psychology, would allow the expansion of knowledge in the field of human behavior in fire situations. As a consequence, buildings would become safer, benefiting the practice of engineering and preserving the lives of the people affected by the fire.

2.2 Evacuation time

The time taken for the complete evacuation of a building depends on several factors. According to Purser and Bensilum [7], the evacuation time depends on the time required for the detection of the emergency, the alarm system, the response to the alarms (pre-movement time), the profile of the occupants (such as age, physical and mental ability, asleep or awake, population density), the pre-egress behavior (such as looking for information, gathering belongings, the choice of exit and other activities), the egress (including guidance, movement toward an exit, the flow of the crowd and other factors), the design of escape routes, the number and width of exits, and the psychological and physiological influence on the flight behavior of the exposure to heat and smoke.

For the BSI (British Standards Institution) [8], the time required for safe evacuation (RSET - Required Safe Escape Time) must be less than the time available for safe evacuation (ASET - Available Safe Escape Time), i.e., the time required to evacuate a building must be less than the amount of time in which environmental conditions become unsustainable.

One of the first definitions of the times that take a fire into account includes the following definitions, according to the BSI (British Standards Institution) [8]:

- Detection time of the fire: the elapsed time since the ignition until the detection of the fire by an automatic system or by the first person to notice the fire. It depends on the type of fire detection system installed. An automatic detection system is the most recommended;
- Alert time: time between detection and the general alarm. This time can vary from 0 seconds (when the detection system is automatic) to several minutes (when the alarm system works in stages or is manually activated).
- Recognition time: the time interval between the time the fire alarm is sounded and the first person to respond to the stimulus;
- Response time: the time interval between the time when the first person notices the alarm and the moment when the first movement toward an exit is carried out. At this stage, people perform such tasks as investigating the situation, alerting others. The sum of the recognition and response times is called the pre-movement time;
- Travel time: The time starting with first movement and ending when the person reaches a safe place. Several factors influence this time, such as the physical and mental characteristics of the occupants.

2.3 Real Evacuation Simulations

The legislation dealing with the emergency plan, whether it is the national standard ABNT NBR 15.219/2005 [9], or state standards as the IT 016/2011/CBMSP [10] and the IN 031/2014 DAT/CBMSC [11], includes recommendations on fire drills in buildings, which should be performed periodically and recorded in documents including an assessment of the drill and the respective correction of the occurred failures.

In the particular case of higher-education buildings, the frequency of the fire drills is essential due to the entry of new students. Preferably, fire drills should be scheduled at the beginning of each semester to familiarize new students with the emergency procedures.

Peacock et al [12] reported that real emergencies provide realistic information about human behavior in fire, but also that data on such emergencies are harder to obtain than the data of fire drills. The data obtained through fire drills provide approximate results of human behavior in an emergency situation, making it possible to verify the efficiency of the exit systems in a building.

According to Gwynne et al. [13], the evacuation of a building on the real scale involves a drill that is representative of the evacuation of a target population, an approach that brings financial, ethical and practical problems regarding its viability. The ethical problems are related to the behavior of the persons involved and the lack of realism of the simulation, since people will not be subject to the heat, smoke and gases generated by a real fire. The practical problems are related to the fact that the

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implementation of only one fire drill will not provide satisfactory answers to draw conclusions. The financial problem is related to the high cost to perform several fire drills, since one single simulation won't provide sufficient information. It is also clear that the fire drills are conducted after the construction of the building and if modifications to the building prove necessary, these can be expensive.

Kuligowski et al. [14] used fire drills to observe the speeds of people with reduced mobility on stairs. According to the authors, this data will assist in the development of computational models that engineering professionals can use to determine the time required for a safe evacuation in performance-based designs. Sano et al. [15] performed fire drill in a 25-floor building and obtained various information related to human behavior in an evacuation situation, more specifically on stairs, such as the walking speed, density and flow rate of people.

Although they don't present enough data for the design of emergency exits, fire drills are very important for the population of the building, the fire brigade and fire fighters. The people who participate in a fire drill put the emergency plan of a building into practice in order to verify whether the plan is working satisfactorily, and they provide relevant information for professionals who develop fire prevention designs [16].

2.4 Computational Models for Evacuation Simulations

Computational models for evacuation simulations are computer programs that assist fire engineering professionals in the design of emergency exits through mathematical models. Figure 1 shows the classification of evacuation models proposed by Kuligowski [17].

According to Kuligowski [18], in the behavioral models the occupants perform actions during the evacuation, in addition to moving to a safe location. These models can assign decision power to the occupants regarding the performance of actions as a result of the conditions existing in each design.

The movement models are those in which the occupant moves in the direction of the exit or to a safe location. This model is important to check areas of congestion and bottlenecks in the simulated building. The partial behavior evacuation models begin to simulate the behavior of the occupants. It is possible to represent pre-evacuation times, insert occupant characteristics, smoke effects.

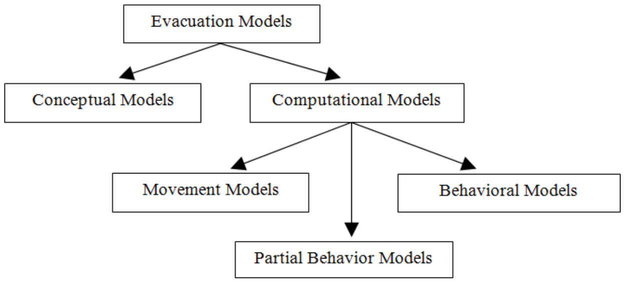

Fig. 1: Organization of Evacuation Models

In order to guide users in selecting the best computational model for the evacuation simulation, Kuligowski et al. [18] analyzed 26 currently used computational models. In this study, the models were separated into categories, such as availability of use, modeling method, display type and compatibility with CAD (computer-aided design). The categorization of the models makes the user's decision regarding the model more appropriate for the design in question.

III. METHODS AND PROCEDURES

The object of study of this research is a 4-floor classroom building, called Bloco A, of a public university located in the Southern region of Brazil. Bloco A has a total area of 5,344 m2. Table 1 presents the characteristics of the building Bloco A (Figure 2 and 3) and Table 2 show the number and the dimensions of the existing emergency exits.

Table 1: Characteristics of Bloco A

Total Constructed Area	5,344 m²
Ground Floor Area	1,945 m²
First, Second, Third Floor Area (each)	1,133 m²
Classrooms	27
Administrative Rooms	8
Number of Elevators	3
Height between the exit floor and the last floor	11.20 m

Table 2: Emergency exits in Bloco A

Emergency Exit	Quant. (un)	Dimension (m)
Corridors	2	2.50
Protected Stairs	2	2.20
Stair doors	2	1.40
Auditorium doors	2	2.00
Exit floor doors	2	2.00
		1.65

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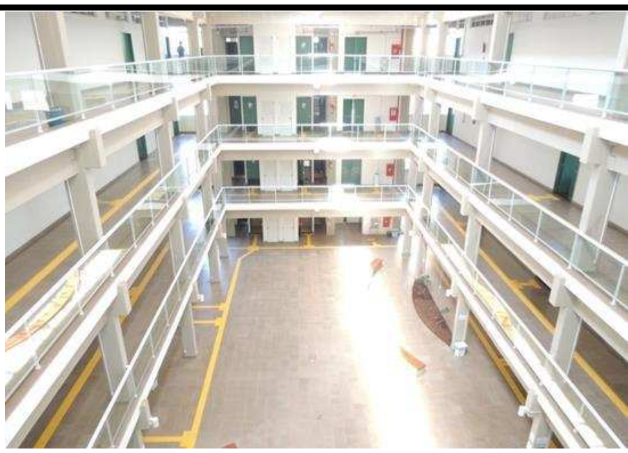

Fig. 2: Picture of the classrooms of Bloco A

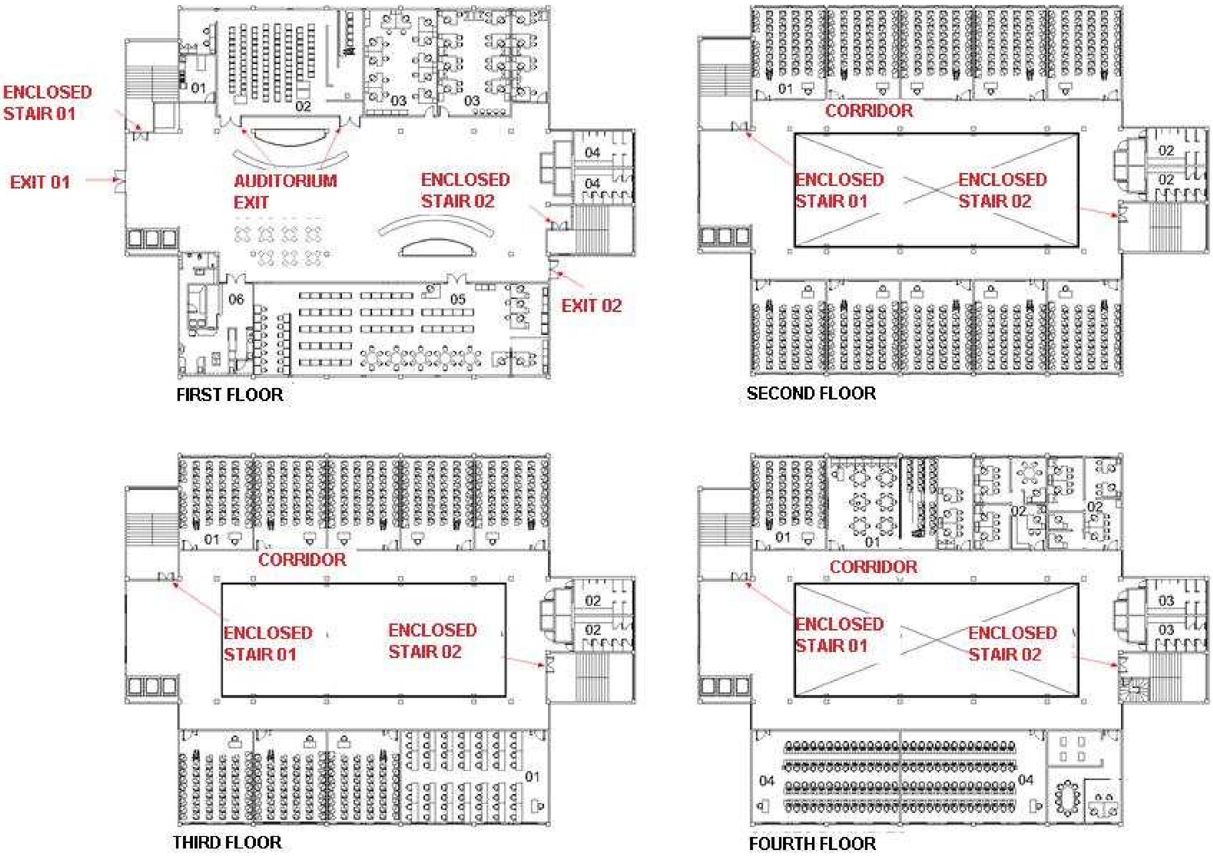

Fig. 3: Floors, Bloco A

3.1 The Simulated Building Evacuation Drill

The simulation drill was held in the context of a university that has an active emergency plan for all buildings on the campus. In case of an emergency, the users of the buildings should follow the emergency procedures as defined in the plan. To assist and signal the escape routes and installed fire protection systems, the buildings have emergency layouts displayed in all the rooms. Next to the two emergency exits on the ground floor, the emergency layouts of the building are displayed signaling the meeting points in case of an emergency.

A simulated drill was performed to observe the performance of the emergency exits of Bloco A, in addition to the behavior of people during the evacuation of the building. The drill was coordinated by the fire brigade and trainees from the university and it counted with the participation of the local Fire Department.

The coordination team consisted of 12 people with the following functions during the drill: five people pointing out the exits on the floor and checking for the presence of people inside the rooms; two people pointing out the exits on the ground floor; two people pointing out the meeting

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points outside the building; three people filming the building's evacuation, two of which focusing on the ground floor doors and one inside of the protected staircase 1. Three firefighters of the Fire Department also observed the drill.

The drill was performed with notice, i.e., all students, teachers, technicians and contractors were warned about its occurrence. The notices were sent via email and also announced twice in the classroom: a week before and on the day of the drill. In the classroom, the fire brigade not only informed the day and time that the exercise would be carried out, but also gave a brief training on the evacuation procedures of the building. The drill began at 9h25min with the activation of the fire alarm system consisting of a visual and audible warning. The drill counted with the participation of 329 people.

3.2 Computer Simulation

A computational model was developed for the same building and population of the simulated drill using the evacuation simulation software Pathfinder 2017, revision 2017.1.0116 [19], developed by Thunderhead Engineering Consultants, Inc., based in Manhattan, Kansas, USA.

The movement environment in Pathfinder is a triangular 3D grid that can be entered manually or automatically based on the imported data. Individuals are represented by a vertical cylinder on the movement grid. The movements of each individual are calculated independently, using an agent-based technique called inverse steering. Each person in the model operates with his own profile (size, speed) and own behavior (leave, wait). Based on his characteristics, each person uses his location to take decisions on the exit paths.

The Bloco A scenario was modeled with the emergency exit dimensions existing on the site. The population of 329 people used in this model was the same that participated in the drill.

Since the fire drill was performed with notice, the population of the building began the evacuation immediately after the alarm was triggered. For this reason, the pre-evacuation times, such as the fire detection an alarm times, were disregarded in the computational simulation. A pre-evacuation time equal to zero was considered.

The profile of the people used in the computer simulation included only persons without disabilities in accordance with the real-life simulation, with dimensions equivalent to a circle of 45.58 cm in diameter and 182.88 cm in height. These values refer to the standard profile used by the software. The walking speed varied between 0.95 and 1.55 m/s. This speed range is proposed by Korhonen [20] and is valid for adults of both sexes.

As for the behavior, the profile of the people without disabilities had independent behavior, moving directly to the nearest exit.

The simulations performed in this study used the "Randomize" option of the Pathfinder software. This option is used before running a new simulation, and it distributes the population with its different profiles and behaviors in a random manner in the scenario to be simulated. Using this option, each simulation of a given scenario provides a different result. The goal was therefore to run multiple simulations for the scenario to check the variation of the results. Based on the 15 first simulations, it was observed that the result of the simulations didn't alter the mean by more than 2%.

The result of the software generates a data output summary indicating the maximum, minimum and mean times for the exits through the doors and from the rooms, the mean flow at the doors and also the individual times for each occupant.

IV. RESULTS

4.1 The Simulated Building Evacuation Drill

The simulated drill had a total duration of 173 seconds. The time count began with the triggering of the fire alarm and ended with the exit of the last occupant from the building through emergency exit 1.

With the aid of the film footage, it was possible to determine the number of participants, the distances travelled and the evacuation time. Table 3 shows the number of participants per floor in the drill.

Table.3: Number of participants in the simulated evacuation drill

Floor	Number of people
Ground floor	78
2nd floor	151
3rd floor	87
4th floor	13
TOTAL	329

The second floor had the greatest number of people since it has the classrooms with the highest concentration of students. The 4th floor had the lowest number of people with two administrative buildings occupied. The computer laboratories on this floor were not being used.

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Fig. 4: Inside of the protected staircase 1

Table 4 shows the number of people who used each emergency exit in the building. The vast majority of the population used exit 1 (Figure 4).

This is explained by the higher concentration of people in the west side of the building, who should use exit 1 in case of an emergency according to the emergency plan. Another fact that may have interfered to increase the use of exit 1 is the familiarity of the population with this exit path, since it is the main entrance, which the occupants use every day to enter and exit the building.

Table 4: Use of emergency exits

Emergency Exit	Number of people	Percentage
Exit 1	257	78.1%
Exit 2	72	21.9%
Total	329	100.0%

Table 5 shows the time spent to leave the building, both through exit 1 and exit 2.

Table 5: Time to evacuate the building

Description	Time spent (s)
The first to leave through exit 1	19
The first to leave through exit 2	33
The last to leave through exit 1	173
The last to leave through exit 2	127
Total evacuation time	173

As for the distances traveled to the exit of the building, the shortest distance (11.50 m) was covered by a person who was sitting in the courtyard of the ground floor. The person who traveled the greatest distance (46.95 m), on the other hand, was working on the fourth floor. He only had to go 23.60 meters to reach a safe place, however, which in this case was the protected staircase 1, which is fire resistant for 2 hours.

The second floor of the building is attended by a student using a wheelchair to move around. This person routinely uses the elevator to move vertically. On the day of the simulation this student was not present, but he was previously instructed to stay in a reserved space within any one of the two existing protected staircases in the building until the firefighting volunteers could carry him down the stairs. In addition to the wheel chair user, all other occupants of the building were given instructions to not use the elevator in emergency situations.

Figure 5 shows that the occupants went down through the central region of the stairs without using the handrails to guide them, and that they occupied the entire staircase, in 3 rows of people, enabling a good flow of people. This situation was identified in the fire brigade report, which suggested that the population should use the external side of the staircase, leaving the inner side for the rescue teams.

Fig. 5: Inside of the protected staircase 1 - Second floor level

Figure 6 was taken outside the building, showing the displacement of occupants until the meeting point.

Fig. 6: Population moving to the meeting point

4.2 Computer Simulation

Table 6 shows the distances traveled and the evacuation times for the simulation of scenario. The maximum total evacuation time of the building was 146.2 seconds.

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Table 6: Distances traveled and total evacuation times

Profile	Distance traveled		Journey time	
	Minimum (m)	Maximum (m)	Minimum (s)	Maximum (s)
People without disabilities	0.3	80.6	0.8	146.2

Table 7 shows the results of the simulation of scenario, per floor. A significant difference in the values of the mean flow can be observed in the second floor, where the door to stairs 1 had a mean flow of 82.80 persons/min and the door to stairs 2 had a mean flow of 49.80 persons/min. This difference occurred because the door to stairs 1 was congested at 39.7 s and some of the occupants who were near these stairs went to stairs 2, which had no agglomeration of people, generating a larger interval of time for the last occupants who used stairs 2. Consequently, the mean flow at the door for stairs 2 was lower than at the door for stairs 2.

Table.7: Results of the simulation of scenario, per floor.

Floor	Exit		Number of people who used the exit	Time (s)		Mean flow (people/ min)	Specific flow (people/ min.m)
	Description	Effective width (m)		First to pass through the exit	Last to pass through the exit		
Exit floor	Exit 1	2.00	197	1.90	146.20	82.20	41.10
	Exit 2	1.65	132	0.80	94.70	84.60	51.27
Second Floor	Door stairs 1	1.40	99	5.10	77.00	82.80	59.14
	Door stairs 2	1.40	52	11.40	74.30	49.80	35.57
Third Floor	Door stairs 1	1.40	60	6.80	47.40	88.80	63.43
	Door stairs 2	1.40	27	9.60	35.30	63.00	45.00
Fourth Floor	Door stairs 1	1.40	9	8.90	25.20	33.00	23.57
	Door stairs 2	1.40	4	9.20	16.40	33.00	23.57

Pathfinder provides a 3D view of the results (Figure 7). With this option you can follow the movement of the occupants, rewind or fast forward the progress of the simulation, zoom the view of the occupants in and out.

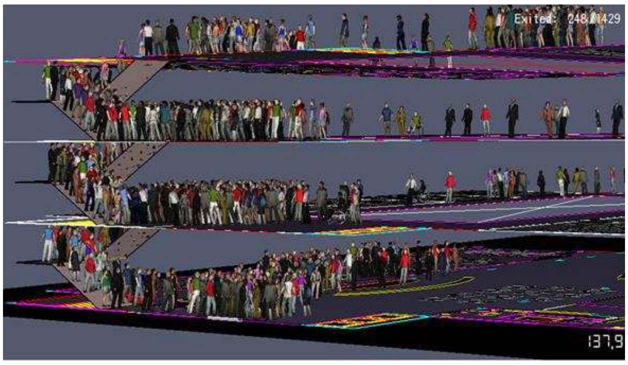

Fig. 7: 3D visualization showing the congestion of people near the stairs of building

4.3 Discussion of the Results

Table 8 shows a comparison of the number of people who used each one the two exits in the simulated drill and computer simulation.

Table 8: Comparison of the use of the exits between the simulated drill and the computer simulation

Emergency Exit	Simulated Drill		Computer Simulation	
	Number of people	Percentage	Number of people	Percentage
Exit 1	257	78.1%	197	59.9%
Exit 2	72	21.9%	132	40.1%
Total	329	100.0%	329	100.0%

The computer simulation had a different distribution of the use of each exit, 59.9% of the population used exit 1, while in the simulated drill 78.1% of the population used this exit 1. This increased concentration in exit 1 during the fire drill can be explained by the familiarity that the occupants have with this path because it is the main entrance of the building. Although some of the occupants of the upper floors were closer to exit 2, they went for exit 1 because they were familiar with it.

Table 9 compares the distances traveled until the exit in the fire drill and the computational simulation. Both the shortest and longest distance traveled in the computer simulation can be explained by the selection of the randomize option in the software, which distributes the

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occupants at random in the movement grid. Another factor is that some of the occupants of the third floor decided to walk to the protected staircase 2, which was free, after waiting to get on the protected staircase 1, which was congested. This displacement resulted in this longer path.

Table.9: Comparison of the distances traveled in the simulated drill and the computer simulation

Description	Distance (m)	
	Simulated Drill	**Computer Simulation**
Shortest distance traveled until the exit	11.50	0.30
Longest distance traveled until the exit	46.95	80.60

Table 10 shows the results of the evacuation times identified in the simulated drill and in the computer simulation. Since scenario was simulated in the Pathfinder software with the pre-movement time equal to zero, the exit time of the first occupants were much lower when compared with the times of the first to exit in the fire drill. Although the participants of the fire drill were aware of the day in which it would be held, there was still a pre-movement time toward the exit. This observed pre-movement time consists of the time people needed to identify the alarm, assimilate the situation and initiate the movement toward the exit.

Table 10: Comparison of the times spent between the simulated drill and computer simulation

Description	Time spent (s)	
	Simulated Drill	**Computer Simulation**
The first to leave through exit 1	19.00	1.95
The first to leave through exit 2	33.00	0.80
The last to leave through exit 1	173.00	146.20
The last to leave through exit 2	127.00	94.70
Total evacuation time	173.00	146.20

This delay to begin moving was reflected in the times of the last people to leave the building, 26.80 and 32.30 seconds more, respectively, than the last occupants in the computer simulation of scenario, as seen in Table 5. The pre-movement time was therefore estimated with a mean of 29.5 seconds.

V. CONCLUSION

This article presented the evacuation times of an educational building in Brazil using two methods: a simulated drill and a computer simulation. The evacuation times observed in the computer simulation were slightly lower than the times in the simulated drill. Two situations led to this difference in the times. The first situation was due to the shorter distance traveled by the people in the computer simulation as a result of the random distribution performed by the Pathfinder software. The second situation is the fact that there was a pre-movement time toward the exit in the simulated drill even with the participants being aware of the day in which it would be held. This time was estimated at around 30 seconds, while the software was configured for a pre-movement time equal to zero.

When considering the simulated evacuation drill, the importance could be observed of developing and applying emergency plans in buildings. For a safe evacuation, the population must know the emergency plan and the escape routes, and participate in trainings through fire drills, among other actions to facilitate the evacuation of the building in the case of an emergency. Despite being the best way to train the building occupants for a fire situation and to identify the strengths and weaknesses of the emergency plans, fire drills require an extensive mobilization of people and a great expenditure of time to organize and carry them out.

To improve the emergency plans, the use of the computer simulation proved to be an effective solution to replace the simulated drill, since it allows for the identification of design failures and for the simulation of different scenarios in less time and without the need to mobilize people. When complex buildings like university campuses, multipurpose arenas and shopping centers are considered, the use of computer simulations are essential for the evaluation of emergency plans, since fire drills in these spaces become infeasible. In addition, the use of computer evacuation simulations becomes even more advantageous when it comes to the development of the design, since it enables the analysis in its initial phase.

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