SIMULATING EVACUATION OF BUILDINGS

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ABSTRACT

High rise buildings are a smart way of multiplying space in limited and expensive areas, but it brings safety issues which must be addressed. In order to keep its employees safe, Petrobras commissioned a study on the evacuation of the buildings occupied by its workforce. This study's scope covers the analysis of escape routes and floor abandonment sequencing strategies from every populated area of the buildings to the exits on the street level. Since it is not feasible to test all possibilities in all the buildings, simulation was used to test and evaluate evacuation options. The study model and the the simulation tools used (one of which was specially made in-house) are presented in the paper.

KEYWORDS. Simulation, Building evacuation, Safety.

Main area: Simulation, OR in Services.

1. Introduction

High rise buildings are a smart way of multiplying space in limited and expensive areas. Unfortunately, this brings safety issues that, unless correctly addressed, can cause tragedies. World experience has demonstrated that proper escape routes combined with periodic evacuation drills can save lives.

In order to keep its employees safe during a period when it is quickly expanding and spreading to new buildings (both old and newly erected), Petrobras commissioned a study on the evacuation of the buildings occupied by its workforce. This study's scope covers the analysis of escape routes and floor abandonment sequencing strategies from every populated area of the buildings to the exits on the street level. Although different routes and strategies have been already tested in annual safety drills, they were limited because there were too many possible strategies to test and because testing different strategies caused confusion among the employees as to what the real evacuation plan was. Computer Simulation presented itself as a solution for these problems, since it would make possible to evaluate all the strategies and adopt the best one. The drills are still important to train the employees and to corroborate the simulation results. Past drills were comparatively used to validate the simulation model.

The next section will present how an evacuation happens. The following ones will describe the conceptual model for the simulation and the two-part implementation of the simulation. The tool developed for stairs simulation will have a dedicated section and the last sections will show some test results and conclusions.

2. Evacuation process

In high rise buildings, an evacuation must be carefully planned. Escape routes must be defined and clearly indicated with signs. Bottlenecks must be removed whenever possible and people must be informed and trained according to the predefined plan.

When an emergency happens and it is necessary to evacuate a building, people must be warned and follow predefined escape routes to safe areas.

High rise buildings allow several evacuation strategies. The most flexible is sequencing the alarms by floor. In this strategy, floors are notified of an emergency at different times.

The basic evacuation process is shown in Figure 1. When an emergency is detected, the alarm is activated. This can be done at once for the whole building or, on high-rise buildings, the alarm can be sequenced by floor. Once they hear the alarm, people leave their work stations and follow the escape route towards the staircase access designated for them. Upon arriving, they are met by a safety brigade volunteer who helps them form a queue and lets them enter the stairs at the right time. Inside the stairs, the queues are expected to keep together, unless instructed to split to allow people who are on the floors to enter the stairs.

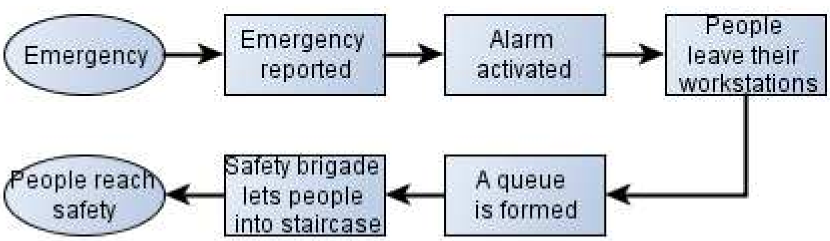

Figure 1. Evacuation process flowchart.

The floor sequencing can be done in many ways. One floor at a time is the most extreme version and all floors at the same time is effectively no sequencing. In between, the floors can be grouped in waves and each wave released sequentially.

3. Evacuation conceptual model

The evacuation comprises the analysis of the path from the populated areas of a building to the exits on the street level. In buildings with more than one floor level, this means people will move in horizontal paths (on the floors) and also in vertical paths (the stairs).

In horizontal paths, it is important to avoid obstructions and bottlenecks that can slow down people movement.

Modern stairs in high-rise buildings are enclosed corridors with safety devices (fire-resistant walls and doors, air injection compressors, etc) which aim to keep the evacuees safe for relatively long times (ABNT, 1993). In these safe vertical paths, it is important to make sure there is enough room to receive as many people as possible, as fast as the horizontal paths will allow.

In low buildings, the most important part is the horizontal, since the stairs are quickly traversed and either do not cause blocks or they are brief. In high-rise buildings, however, the relative importance of the vertical and horizontal paths moves towards the stairs, which can be blocked by too many people and seriously impede people from leaving dangerous areas.

Another aspect that arises from high building height is that people on floors which are distant from the source of the problem are safe for a longer time. It is possible, with adequate signaling systems, to sequence the evacuation by floors in order to speed up the evacuation of those closer to the danger (by evacuating them first and therefore avoiding blocks in the stairs) and to take advantage of opportunities to improve overall evacuation time (if a problem happens on the 15th floor, it is probable that evacuating the first floor in the first wave will speed up the complete evacuation without causing blocks for the people closer to the danger).

To enable sequencing, the alarm system must be prepared to be activated by floor and the people must be trained to form queues at stair accesses and wait for instructions from volunteers to enter the stairs.

The value of sequencing the evacuation cannot be perceived in small buildings or in areas open to a public that cannot undergo training drills, such as sports arenas or transport stations.

4. Evacuation simulation

Physically experimenting all possible strategies for evacuation of a high rise building is not practical. It involves too many people who must stop their activities and the drills actually present some danger of real accidents. Drills are performed annually for each Petrobras building. In order to make these tests possible, it was decided to use a simulation tool to find the most promising strategies and use the past drills to validate it and future drills to corroborate the expected results.

First, a list of possible scenarios was made with the help of safety experts in the company. From this list, a set of necessary attributes of the simulation tool was derived. Many commercially available software tools were evaluated and none was found that had all the attributes. The main drawback in all of them was that they were not built with the idea of sequencing in mind. Their main focus was short buildings or public areas occupied by untrained people. Some provided work-arounds for emulating the sequencing, but it was decided that it would be more productive to split the study in horizontal and vertical parts. In the horizontal studies, the floor-plans for each floor would be evaluated and the evacuation times would become inputs for a stairs simulation software. For the horizontal simulation, Simulex (IES, 2012) was chosen based on its good results, ease-of-use, cost and support. The next section will detail the stairs simulation software.

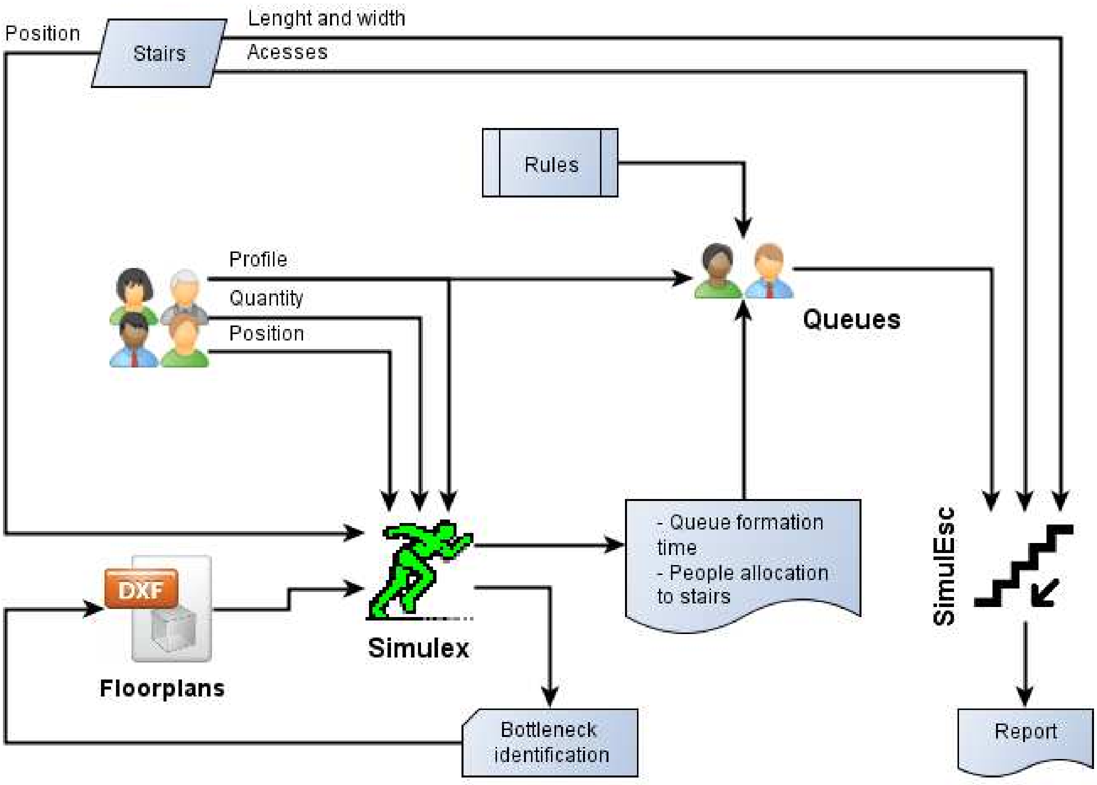

Figure 2. The proposed study scheme.

The proposed study scheme is depicted in Figure 2. Along with information, such as number of people, their workstation's position and profile (male, female, special needs, etc), about the population of that floor, the floor-plans are input into Simulex one at a time (no stairs are necessary) and obstructions and bottlenecks can be detected by watching the animation and observing the results. Figure 3 shows a simulation under way. Whenever possible or desirable from a study point of view, the detected problems can be removed and the updated floor-plan re-simulated. Among other information, Simulex provides, for each stair access, a table of how many people reached the stairs (considering it is unblocked) at each 5-second time interval (Table 1 shows an example). From this table, the necessary information for the input of the stairs simulator can be inferred. How this is done is covered in the next section.

5. Stairs simulator

Since the evaluated commercial tools didn't provide straightforward options to simulate evacuation with floor sequencing, it was decided to develop a stairs simulator, called SimulEsc. Figure 4 shows a simulation underway.

Stairs are modelled as long corridors. The length of the corridors represents the distance travelled by someone on a walkline in the centre of the stairs and the width is given in width units, the necessary width for a one-person-wide queue to walk. The corridors are divided in a grid of cells which are one width unit wide and one metre long. Some of these cells are identified as accesses; points associated with floors through which people enter the stairs.

The main entity of the stairs simulator is the queue. Since people are organised in queues at each entrance to the stairs in order to organise the evacuation, it is expected that they descend the stairs as a group.

Each queue is defined by the quantity and group of people who will form it and associated with two accesses: one for entrance and one for exit.

Table 1. Simulex results for a floor with two staircase accesses.

Time (s)	Number of people over 5-second periods through:		
	All exits	Exit A	Exit B
5	0	0	0
10	0	0	0
15	1	0	1
20	9	4	5
25	13	5	8
30	12	6	6
35	13	5	8
40	15	7	8
45	12	5	7
50	13	5	8
55	12	5	7
60	11	4	7
65	13	6	7
70	13	6	7
75	10	6	4
80	6	6	0
85	5	5	0
90	6	6	0
95	5	5	0
100	7	7	0
105	4	4	0
110	6	6	0
115	7	7	0
120	2	2	0

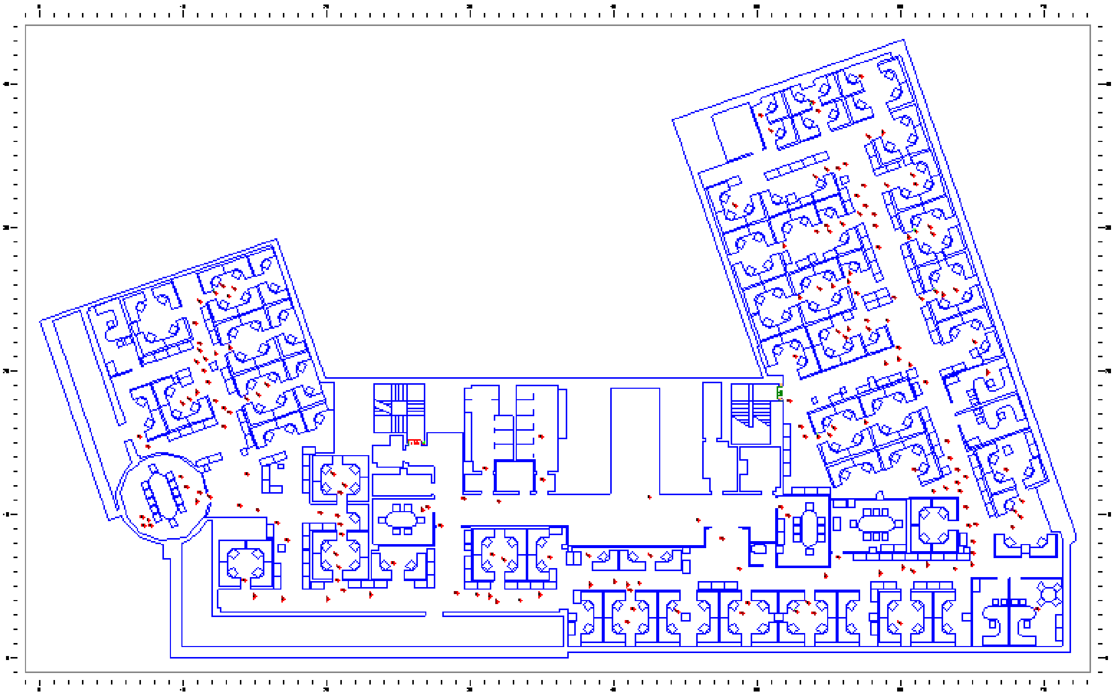

Figure 3. Simulex simulation underway. Red dots are people.

Queues also have a formation time. This is the minimum time it takes for the first person to be allowed to enter the stairs assuming there is the expected queue behind this person. This time is counted from the point when the alarm is triggered and includes the people's reaction time and horizontal movement time. It does not include hold ups due to blocked stairs.

Formation time is derived from the horizontal simulation. It was established that a queue which is not blocked can enter the stairs at any time between the arrival of the first person and the arrival of the last person. The experts explained that the volunteers, unless specifically instructed otherwise, usually let the queues into the stairs when 75% of the people arrive. This works in such a way that the last person to arrive neither waits nor is separated from the queue while the whole process of entering the stairs is accelerated. These three values from the horizontal simulation (arrivals of the first person, of 75% of the people and of the last person) were used to determine a triangular distribution which is the basic formation time of the queues.

People groups are defined by their movement speed in the stairs. This speed is empirically determined.

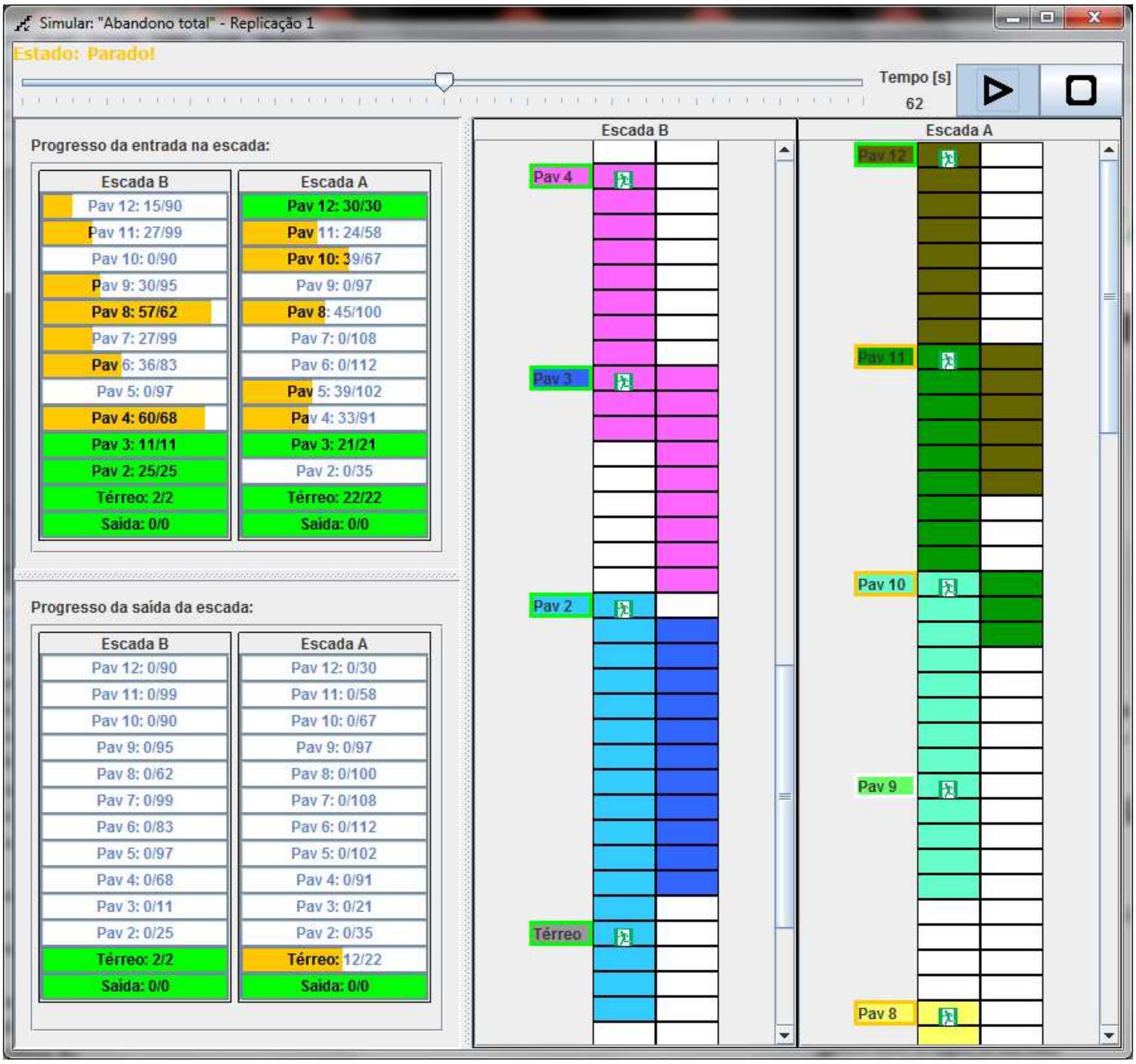

Figure 4. SimulEsc simulation underway.

There are situations when a queue can be split to allow another to enter the stairs. This situation is emulated in the simulation by assigning priorities to queues. When two queues with different priorities meet and vie for the same space in the stairs, the lowest priority queue splits and its tail part stops to allow the other queue to move.

In order to enable the sequenced simulation, the simulator has a trigger mechanism which allows the alarm of for one queue to depend on a time delay or on events happening to other queues. There are three trigger types:

- time trigger, which makes the alarm for one queue to be delayed for a time;
- head trigger, which makes the alarm for one queue to be delayed until another queue reaches one access;
- tail trigger, which makes the alarm for one queue to be delayed until every person from another queue has passed one access.

One queue can have as many triggers as necessary and they can be arranged in AND and OR groups, which allows alarms which are triggered only when all conditions of one set of triggers are met but multiple sets are possible.

Moving people tend to keep a larger distance from each other than stopped people. To emulate this, each queue has a dynamic packing of the people in it. This means that a queue's length changes during the simulation depending on whether it is moving or it is stopped.

6. Tests and validation through a case

The simulation process was tested on a 12-story building. Although not the tallest building in the company, it was sufficiently tall that a complex, sequenced the evacuation made sense and sufficiently simple that the results could be easily checked. The choice was further advanced because updated floor-plans were already available and there had been a drill recently, which provided reliable, comparable results.

The building has two stairs and is regularly occupied by 1,664 people.

First, all the floors were simulated on Simulex. The results used as input in the stair simulator are provided in Table 2. Since the goal was to simulate the current situation of the building in order to compare the results with the recent drill, identified bottlenecks were not removed for the study. The allocation of people to the stairs was left to Simulex, which determines that based on the smallest distance from the initial position of each person to each stair access on the floor.

Table 2. SimulEsc input based on Simulex results.

Staircase A												
Floor	**G**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
First person (s)	15	25	25	15	20	20	20	20	25	25	20	25
75% of people (s)		50	40	70	75	95	90	90	80	65	55	50
Last person (s)		60	50	95	110	120	115	115	100	80	70	60
People quant.	22	35	21	91	102	112	108	100	97	67	58	30
Staircase B												
Floor	**G**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
First person (s)	25	15	20	10	20	20	20	20	15	15	20	25
75% of people (s)		30	30	45	75	60	70	50	65	60	70	80
Last person (s)		35	35	60	100	75	90	60	80	75	85	105
People quant.	2	25	11	68	97	83	99	62	95	90	99	90

Three scenarios were tested in the stairs simulator. In all of them, the emergency is considered to be on the 6th floor.

- **Scenario I, Total evacuation:** the alarm is triggered simultaneously on all floors one minute after the emergency. Queue formation times are the triangular distributions from

Table 2, except for the 6th floor which does not wait for the alarm nor forms a queue (as soon as the first person arrives at the stairs, it enters: formation time is, therefore, constant at "First person" time).

- **Scenario II, Endangered floors first:** The evacuation happens in three waves. People from the 6th floor evacuate immediately without waiting for an alarm nor forming a queue. After one minute, the alarm is triggered on the most endangered floors: 5th, 7th and 8th floors (one below, two above the emergency). When everyone from these four floors is in the stairs, the alarm is triggered in all the other floors. Floor 5 through 8 do not form a queue before entering the stairs.
- **Scenario III, Endangered floors first, with priorities:** this is the same scenario as scenario II, but queues from higher floors which are already in the stairs can be split to allow people from the 3rd and 4th floors to enter the stairs.

A Monte-Carlo simulation with ten replications was run for each scenario. The main average results are in Table 3.

Table 3. Simulation results (times in "minutes:seconds" format)

Scenario		I		II		III	
Staircase		A	B	A	B	A	B
Evacuation time (total in **bold**)		**26:11**	26:07	**26:53**	26:29	26:54	**26:36**
First person enters the stairs		00:22	00:22	00:22	00:22	00:22	00:22
Last person enters the stairs		11:18	10:32	17:07	14:00	15:12	12:25
Time with people in the stairs		25:49	25:45	26:31	26:07	26:32	26:14
Max. quant. of people in the stairs		446	489	356	412	374	424
Evacuation time in the endangered floors	5	09:58	08:06	02:18	02:15	02:18	02:16
	6	01:25	01:09	01:28	01:11	01:27	01:10
	7	08:06	09:39	06:43	05:24	07:32	06:00
	8	09:49	04:47	06:23	02:52	06:19	02:51
Wait time to enter the stairs in the endangered floors	5	01:56	02:24	00:01	00:01	00:01	00:01
	6	00:01	00:01	00:01	00:01	00:01	00:01
	7	02:31	02:31	00:01	00:01	00:01	00:01
	8	02:49	01:53	00:01	00:01	00:01	00:01
Time until the alarm is Triggered in all floors		01:00	01:00	07:34	05:25	07:33	06:01

In the drill, performed according to the total evacuation scenario, the building was evacuated in just under half an hour. The safety experts considered the simulation time of 26 minutes and 11 seconds adequate, arguing that, although it was slightly less than the observed time during the drill, people act differently when a real emergency arise and, in general, are more concerned and move faster than in drills.

The scenarios with floor sequencing (II and III) have a slightly higher total evacuation time than scenario I. However, the time necessary for people from the endangered floors to reach the safety of the stairs was reduced (drastically in the 5th floor) and the wait time for the 5th, 7th and 8th floors was eliminated, which helps prevent panic. This is a much safer result overall and demonstrates the value of sequencing the evacuation.

Sequencing the evacuation also reduced the amount of people simultaneously in the stairs, which also improves safety, since there is less chance of accidents in them due to excess of people.

Prioritising the queues from lower floors (scenario III) doesn't seem to be a good idea. Not only it is much harder to implement, the results are actually worse for some endangered floors than in scenario II.

The alarm system of the building is not prepared to sound based on event triggers (head or tail triggers), so the simulation can be used to determine the expected time when the conditions for triggering the alarm are met and this time can then be used by the safety team to determine when to sound the alarms during real emergencies.

7. Conclusions

Simulating different strategies for building evacuation allows a wider set of options to be evaluated before drills are performed with people. This removes the experimentation angle from drills, reduces confusion among people as to what is the correct evacuation plan and, consequently, improves safety.

Commercial evacuation simulation tools are very focused on public-access, low buildings and don't have all the necessary parameters to allow a complete evaluation of the scenarios in high-rise buildings with a mostly permanent population that can be trained through drills.

This limitation has been overcome by developing a stairs simulation tool which is used in combination with a commercial tool (Simulex) that provides the results for the horizontal part of the evacuation.

Test results demonstrated how the simulation can be used to evaluate different strategies and measure the improvement potential from proposed options.

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