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Evacuation modelling – benchmark analysis of input parameter sensitivity of simulation software

Quentin Jullien[1], Virginie Dréan[2], Camille Le Compagnon[3], Nicolas Trévisan[4], Bertrand Maury[5], Huy-Quang Dong[4], Amirouche Sadaoui[1], Anastasiya Burdun[1], Mathieu Blouin[2], Etienne Pinsard[5,6], Romain Hourqueig[3], Jean-Luc Paillat[6], Bachar Kabalan[7], Sylvain Faure[5], Aurélie Wyzgolik[2], Steve Gwynne[7]

[1]CSTB
84, Avenue Jean Jaurès, Champs-sur-Marne
77447 Marne-la-Vallée cedex 2, France
quentin.jullien@cstb.fr

[2]EFECTIS France
Espace Technologique – Bât. Apollo, Route de l'Orme
des Merisiers 91193 Saint Aubin – France
virginie.drean@efectis.com

[3]STUDIO FAHRENHEIT
128 rue la Boétie, 75008 Paris, France
camille.lecompagnon@studio-fahrenheit.com

[4]CNPP
Route de la chapelle Réanville, 27950 Saint-Marcel
nicolas.trevisan@cnpp.com

[5]Université Paris-Saclay, CNRS, Laboratoire de
Mathématiques d'Orsay, 91405, Orsay, France
bertrand.maury@universite-paris-saclay.fr

[6]LCPP
39bis Rue de Dantzig, 75015 Paris
jean-luc.paillat@interieur.gouv.fr

[7]Movement Strategies, A GHD Company
10, Fetter Lane, London EC4A 1BR, UK
bachar.kabalan@ghd.com
steve.gwynne@ghd.com

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ABSTRACT

Numerical simulation is one of the tools available for emergency evacuation planning. Its main advantage is its ability to represent the impact of dynamic factors related to people movement on outcomes across different incident scenarios. The appropriate use of a simulation tool allows examining multiple scenarios in a more cost-effective way compared to real-life exercises – potentially representing scenarios beyond the reach of exercises given ethical concerns. Tools and methods that can be used for emergency evacuation planning are usually governed by each country's regulatory structure. A collaboration between seven French institutes and a UK-based consultancy was started in 2018 to evaluate the use of simulation tools for evacuation planning during coming major events in France - especially the 2023 Rugby World Cup and the 2024 Summer Olympic Games. The first stage of this collective work involved collecting data from an evacuation drill that provided a benchmark for comparison of different numerical tools. In order to investigate more deeply the outcomes of this benchmark, the sensitivity of key model input parameters is discussed in this paper (walking speed, occupant diameter and reaction time). The sensitivity analysis was conducted with four numerical tools: Pathfinder, FDS+EVAC, buildingEXODUS and Cromosim. The impact factor of each input parameter was evaluated via a general sensitivity analysis as well as with use of a variance-based analysis (Sobol's sensitivity indices).

INTRODUCTION

The complexity of modern infrastructures and the size of crowds have created a need for advanced tools to help design facilities and plan for major events. Professionals from architects and transport planners to fire engineers and security advisors are now using crowd models to evaluate the maximal densities and to estimate evacuation times for different emergency scenarios for various types of facilities. They make it possible to investigate complex problems that could be beyond straightforward analysis. However, the use of crowd models still varies significantly between different sectors and countries [1][2].

To date, there is no international standard on procedures to assess the verification and validation of numerical evacuation models. The first guidance made available was the guidelines for maritime evacuation analysis for passenger ships, namely the MSC/circ.1238 [3], developed by the International Maritime Organization. Then the NIST Technical Note 1822 [1] and RIMEA guidelines [4] expanded and modified the tests listed in the MSC/Circ.1238 in the context of building evacuation.

Standard guidance providing information on evacuation engineering methods to be used in the application of fire safety engineering in buildings already exists in some countries (such as BS 7974-6 [5] in UK or the Verification Method C/VM2 [6] in New Zealand) or are emerging (such as ITM-SST 1553.2 [7] in Luxembourg or DIN 18009-2 [8] in Germany).

In France, building regulations are mainly prescriptive. The use of simulation tools is restricted to specific fire engineering aspects, such as assessing the performance of smoke ventilation systems or performing structural calculations. Furthermore, evacuation modelling is not yet acknowledged in the building sector – likely influenced by the absence of a performance-based requirement. However, managing crowds, especially during major events, is increasingly challenging for public safety in the current context – given the scale and complexity of the situations faced. France is preparing to host several major events such as the Rugby World Cup 2023 and the Olympic Games 2024. These events have triggered a number of large-scale construction projects, often requiring innovative designs that fall outside regulatory capabilities. Changes to the French regulatory structure regarding evacuation may now be necessary and inevitable to allow new innovative designs.

A collaboration between seven French institutes and a UK-based consultancy was started in 2018 to evaluate the ability of simulation tools to reproduce real evacuation exercises in a project called EVAC2024. These institutes are laboratories, such as LCPP, CSTB, EFECTIS France and CNPP, universities (Université Paris-Saclay, Université de Lorraine – LEMTA), and specialist consultancies (Studio Fahrenheit, Movement Strategies). The consortium also includes firefighters (SDIS 39, BSPP) who were mainly involved in conducting the reference evacuation drill.

There are several objectives in the project. The first objective is to make an inventory of models and calculation codes that can reasonably be used to estimate crowd movements in various situations (with or without crisis, in or out of buildings, etc.). The models need to be able to represent the movement of evacuees from the beginning of evacuation until they reach the building exits or the physical limits of the assembly points if they exist. The second objective of the project is to select appropriate input parameters common across most of the evacuation models and tools available, to study their impact on the egress time. Certain simulation tools may have specific parameters that are not available in others. These software-specific parameters are not reviewed in this study, which instead focuses on the most recurrent assumptions in evacuation modelling that may cause congestion and increase egress time.

The third objective is to build an analysis methodology that allows to conduct meaningful comparison between the chosen models.

In a previous work [9] simulations of the drill of an existing 9-storey office building in Paris were conducted using multiple tools (FDS+EVAC [10], Pathfinder [11], buildingEXODUS [12] and Cromosim [13]). Since each tool relies on its own set of input parameters that may be different for other models (or have a different impact on the model's results), the authors endeavored to identify tool-specific input parameters and common input parameters, i.e. shared by the majority of the chosen models. Tool-specific parameters were set to their default values. For the selected universal inputs, common values were chosen to be applied across all tools. Despite this consistent implementation, a large dispersion of results (mainly on the total egress time) was observed. One of the main reasons for these discrepancies might be the way each tool models the impact of congestion on crowd movement. In the present study, a sensitivity analysis was conducted on three input parameters (walking speed, occupant's size and reaction time that appeared in most of the models examined) in order to evaluate their influence on congestion phenomenon and hence the total egress time. The impact factor of each input parameter was evaluated via a general sensitivity analysis as well as with use of a variance-based analysis (Sobol indices [14]). This statistical method evaluates the individual weight of an input parameter (while all others are kept constant) and the correlated weight of several parameters together.

CASE STUDY – DESCRIPTION

An evacuation drill was conducted in 2019 for benchmark purposes, in a 9-storey office building, comprising one basement level, located in Paris, France. The authors used several evacuation modelling tools to reproduce the evacuation drill conditions. Simulation results were used to evaluate the variability of simulated egress times with respect to those produced during the evacuation drill. [9].

The building, of modern construction, is used as an office space and is classified accordingly under the French Workplace fire regulations. Local authorities approved a design occupancy of 3,366 people. The building is fitted with a category A fire detection & alarm system, meaning that automatic fire detectors are installed along the circulation routes, corridors and high-risk rooms. Fire alarm sounders are located all around the building.

An overview of the building's geometry is shown in Figure 1. The premises comprise of a basement, a ground floor and eight levels, accommodating essentially a mix of office desks and meeting rooms. The dimensions of a typical floor are circa 61 m long and 44 m wide for a total floor area of 20,600 m^2 across all 10 levels. At each floor, the building is typically fitted with 8 egress stairs, including two scissor stairs, with clear widths varying from 1.4 m to 1.8 m. A central atrium space, fully glazed, accommodates passenger lifts.

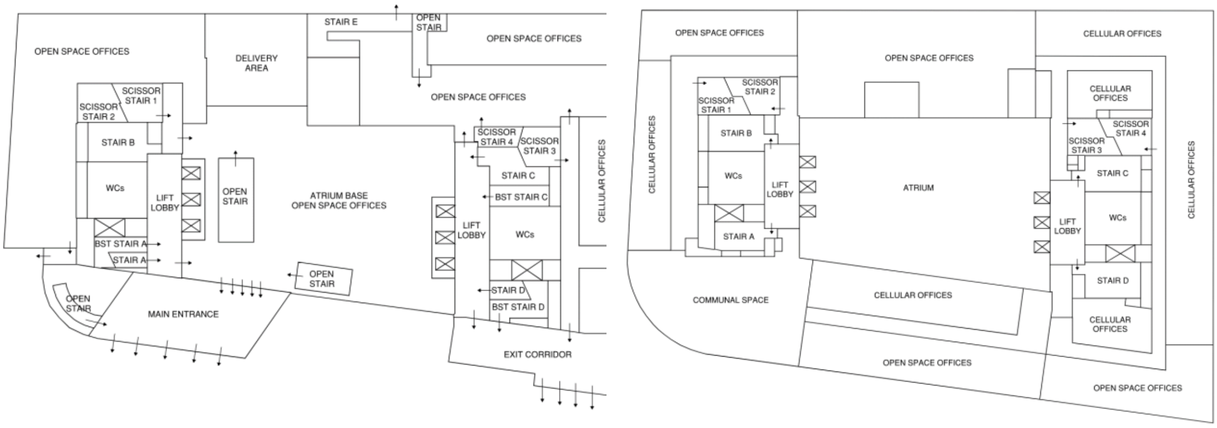


Figure 1: Schematic views of the ground floor (left) and a typical upper floor (right)

The evacuation drill detailed in [9] took place in November 2019. Approximately 1,350 people were involved, representing around 40% of the overall means of egress capacity of the building (the overall maximum capacity being circa 3400 people). Occupants knew of the occurrence of the drill on that day but did not know at what time the drill was going to occur.

In order to collect data from the evacuation drill, 20 members of the working group spread across the building at key locations and moved with the crowd as people were evacuating. The main measurements and behavioral observations were focused on premovement times, the number of people escaping along certain routes, and each observer's floor evacuation time after all other evacuees have left. Time was logged at every point the observer would reach (i) a stair level landing, (ii) the final exit of the premises and (iii) the assembly point located in a street close to the building. The total evacuation time was approximately 7.0 minutes and the time for all to reach the assembly point was around 8.5 minutes. Further data such as usage of the egress stairs, flow rate through stair C (see Figure *1*) and the number of people using final exits was collected using the extensive network of CCTV installed throughout the building. Additionally, three mobile cameras were installed inside Stair C (deemed to be the busiest stair as per building operator's experience) at different levels in order to observe the movement, density and behavior of people inside the staircase.

The collected results were analyzed alongside the simulation results in [9]. A variety of tools were examined - from a simple analytic approach provided by French regulations to commercial software, and academic tools.

The building design and occupancy in this preliminary study were used as the design basis in the simulations of this study as well. The occupants were distributed across each level to match their position the day of the drill. The floor occupancy is synthetized in Table 1.

Table 1: Number of occupants per level of the building during the drill

Level 8:	133 people	Level 7:	169 people
Level 6:	193 people	Level 5:	249 people
Level 4:	218 people	Level 3:	146 people
Level 2:	0 people	Level 1:	137 people
Ground:	65 people	Basement:	39 people

The occupants' path during evacuation and the usage of egress stairs were set in the numerical models to match the drill evacuation routes. To achieve this, specific pathways have been assigned to certain occupants, some doors have been "closed" or virtual walls have been added depending on the software.

SOFTWARE SPECIFICITIES

In this section, we provide information on the main characteristics of the software examined (see Table 2). Refer to [9] for a more complete discussion of the models and the individual user guides for in-depth technical aspects. Both microscopic and macroscopic models were examined. They differ in the sense that microscopic models track the movement of an individual within and between rooms or spaces, while macroscopic models typically focus on population flows between rooms or spaces.

buildingEXODUS [12] is a microscopic model for evacuation simulation, based on a fixed discretization of the space into nodes connected by links (or arcs). Pedestrians can move between connected nodes and each node can be occupied by a single agent. The software relies on a potential field to assign the nearest exit for each agent. The user can also assign probabilities to choose a certain exit or assign exits to agents. When a conflict occurs between several agents at a node, a leadership individual parameter is used to resolve it. The resolution of conflicts as well as other additional modelling ingredients are stochastic, and it is therefore necessary to perform several simulations and to interpret the results statistically.

FDS+EVAC is a microscopic evacuation module [10] linked to the CFD code FDS. The tool is based on Helbing's social force model [15]: agents are represented by ellipses and their interactions are represented through a set of forces of physical or social nature. These enable to account for close contacts as well as long-range anticipating behaviours of agents trying to minimize their exit time whilst avoiding congested areas. Random force terms are also present which make results have statistical variations that should also be treated.

Pathfinder is a microscopic agent-based model where individuals move in a triangulated 3D mesh used to compute desired velocities and estimate exit times [11]. Movements can be computed using two modes. The first one uses SFPE's flow-based egress modelling techniques, which focuses on computing flows through doors depending on their width, and agents are authorized to collide. The second mode uses the 'locally quickest' approach to plan each agent's route. This method assumes that the agent has local information about its current room (including queues at doors) and global knowledge of the building.

The **compartment model** is a macroscopic approach of egress implemented in the Open Source Library Cromosim [13]. It relies on a simplified vision of evacuation as a skeleton graph of the building, where doors are represented by nodes connected by directed edges to represent paths between rooms. During an egress simulation, individuals move from one room to another with a transit time given by the length of a path and a fixed speed. They can accumulate upstream doors, where the flow is limited by a given capacity, chosen as passage units. The resulting model only has the geometry, door capacities and path speeds as parameters. The compartment model of Cromosim shall be referred to as Cromosim hereafter.

Table 2: Main characteristic of studied tools

	Pathfinder	**buildingEXODUS**	**FDS+EVAC**	**Cromosim compartment model**
Micro/Macro	Micro	Micro	Micro	Macro
Space representation	Space grid mesh (triangular)	Space grid mesh	Space grid mesh (rectangular)	Network (skeleton of the building)
Agent representation	Cylinder	One agent per cell (0.5 m x 0.5 m)	Ellipsis*	N.A.
Characteristic dimension of agent	Diameter	Cell size	Major axis length	Via door capacities

*: The shape of the human body is approximated by a combination of three overlapping circles.

SENSITIVITY STUDY

A sensitivity analysis was conducted on the office building case study described above to determine the influence of key parameters on the output produced by the simulation tools. It should be noted that the design of the building may have had some impact on the sensitivity of the models to parameter variation, meaning that different building complexity (where congestion does not govern the egress time) may lead to different sensitivities of output to input parameters. The examined output in this study is the final evacuation time (i.e. the time for the last occupant to leave the building).

The first step in conducting this sensibility analysis was to quantify the part of intrinsic variability in each numerical tool. This would allow to discard this variability and to only take into account the one induced by the variation of the chosen input parameters.

Indeed, FDS+EVAC and BuildingExodus rely on probabilistic elements to govern human behaviour (conflict resolution, random social forces) and this would lead to getting different outcomes for the same initial conditions.

In Pathfinder, this stochasticity does not exist. However, the Monte Carlo method was used to randomize the starting position of occupants across several simulation instances for testing the sensitivity to this positional input. This position randomisation has been replicated in other tools too: the occupants were redistributed in each simulation to stay in their original rooms (to match the drill conditions). This sensitivity to occupant position is separated from the variability of other parameters as this data cannot be determined accurately during the concept design phase of a building.

In order to separate the "natural" variability caused by stochastic elements and positional inputs from the variability associated to the studied parameters (speed, size, premovement time), the mean value of evacuation time is taken from a number of simulation instances for a set of fixed parameters.

The calculated number of simulations instances N is based on achieving a standard deviation approximating 2% of the mean value of the output (i.e. the building evacuation time), with a confidence interval of 95%. This is calculated as follows

$$0.02 * \bar{X} = \frac{1.96 * \sigma}{\sqrt{N}}$$

With:

- N: Required number of simulations
- N0: initial estimation of the required number of simulations
- $x_1, x_2, \dots x_{N0}$: Output of each simulation
- $\bar{X}$: the mean value of simulation outputs: $\bar{X} = \frac{(x_1+x_2+\cdots+x_{N0})}{N0}$
- σ: Empirical standard deviation: $\sigma = \sqrt{\frac{1}{N0-1}\sum_{i=1}^{N}(x_i - \bar{X})^2}$

It must be noted that the sample size N, is dependent on the building model (geometry, complexity). Therefore, it should be recalculated for each project.

When applied to the case-study, the tools showed different variances in the evacuation times across simulations, when all parameters were fixed. The N number of simulations, meeting the deviation requirements set out above, is indicated for each tool in Table 3.

Table 3: Number of simulations to perform in order to meet the standard deviation requirement for the case studied

	Pathfinder	BuildingExodus	FDS+EVAC	Cromosim
N simulations to perform	5	10	10	1

The sensitivity to the velocity, the size of occupants and the premovement time is analysed in the following section. The input velocity is set to a fixed value that corresponds to the maximum horizontal travel speed. This occupant's speed then varies during simulation according to the environment, obstacles and changes of level. The size of an occupant is determined by the shoulder width (for example the diameter of cylinder (Pathfinder) or the axis of ellipse (FDS+EVAC)). Premovement time corresponds to the delay between simulation start and the beginning of an occupant's movement. These three inputs parameters are deemed important as they affect three key aspects of evacuation performance: travel movement, population density with its impact on speed and flow, and the delay to initiate movement. To facilitate comparisons on velocity, the travel speed down the stairs is a fraction of horizontal speed (66%).

All other input parameters are kept constant throughout the study and are set to their default values.

Some parameters do not make proper sense for certain tools, and they may not be directly tunable. In particular:

- In Cromosim, the size of individuals is an indirect parameter, in the sense that it affects the capacity of an exit, which is the tunable parameter. Increasing the size can thus be done by reducing the capacity.
- Cromosim does not follow individual positions, so that setting a premovement time simply induces an offset on the computed solution, which is of little interest. Thus, this parameter is disregarded for this tool.
- BuildingEXODUS, which is based on the so-called Cellular Automata approach, relies on a grid made of fixed-size cells (0.5 m by 0.5 m), each of which may contain 0 or 1 individual. Therefore, no size change is possible with this tool.

The intervals studied, indicated in Table 4, are constituted of five values (velocity and diameter) or ranges (premovement times) for each parameter with one used as reference (1 m/s for velocity, 0.5 m for agent diameter and 0 s for premovement time interval). Indeed, a single value for the premovement time implies an offset of evacuation time. The distribution over intervals is uniform.

These parameter intervals were chosen to cover the most common values found in literature and user guides of the studied tools, both being closely linked.

Table 4: Values of input parameters for sensitivity analysis

Parameter	Values	Reference value
Velocity in m/s *	0.6, 0.8, 1.0, 1.2, 1.4	1.0
Diameter of a person in m	0.40, 0.45, 0.50, 0.55, 0.60	0.5
Premovement time interval in s**	0, [0-5], [0-15], [0-30], [0-60]	0

*: Speed does not follow any distribution and is fixed for all agents.
**: Values are attributed to occupants using a uniform distribution over the time intervals.

RESULTS

Individual impact of variables on total evacuation time

First-order sensitivity is examined for each of the selected input parameters. Figure 2 presents the variation of evacuation time with respect to variation of velocity. The reference value (0% of variation) corresponds to 1 m/s. Results show that evacuation time is highly sensitive to variation in occupant's speed. Two global trends are observed: (i) one for lower speeds (0.6 m/s to 1 m/s) and (ii) another for higher speeds (1 m/s to 1.4 m/s). These two trends are almost linear. The slope of the linear regression is steeper for lower speeds compared to higher speeds: the slope varies from -0.69 to -2.25 for low speeds across numerical tools and from -0.33 to -0.85 for high speeds.

It can be explained by the presence of congestions that disrupt the evacuation. Indeed, the higher the occupants' speed is, the sooner they arrive at the bottlenecks or the landings. Then more occupants find themselves in the stairwell at the same time, hindering the otherwise smooth movement. Evacuation is therefore governed not so much by the occupants' speed itself but by the congestion that limits it.

Moreover, even though trends seem to be similar for the tools studied, the magnitude of the influence varies. It is related to the manner in which staircases and interactions between people in merging flows are taken into account.

Figure 2: Influence of speed variation on evacuation time in percent

Figure 3 presents the sensitivity of evacuation time to occupants' size. As already mentioned, buildingEXODUS is not considered here as size is not a tunable parameter. Two trends can be observed on each side of the reference value of 0.5 m (agent diameter). For small diameters (0.4 to 0.5 m), the sensitivity of evacuation time to variations in agent size is low (evacuation time decreases by 7% for a 20% reduction in agent size). This is due to the flow of agents through doors being at or near maximum capacity.

Figure 3: Influence of agent size variation on evacuation time in percent

In Pathfinder and FDS+EVAC, a reduction of the agent diameter has little impact on achieved flow rates and thus on evacuation time. For larger diameters (from 0.5 m to 0.6 m), evacuation time is sensitive to agent diameter.

This is due to higher space requirements at doors and stairs leading to lower flow rates and lower evacuation times.

Indeed, as an example in a simulation performed with Pathfinder, average flow rate in stair A on 6th floor is of 0.74 person/s for 0.4 m diameter of an agent, while it is 0.53 person/s for 0.6 m diameter agents. Therefore, at t = 250 s, it can be seen that for agent's diameter of 0.4 m almost all occupants have evacuated through the stair (Figure 4), whereas occupants are still queuing at the stair entrance in the case where agent's diameter is 0.6 m (Figure 5).

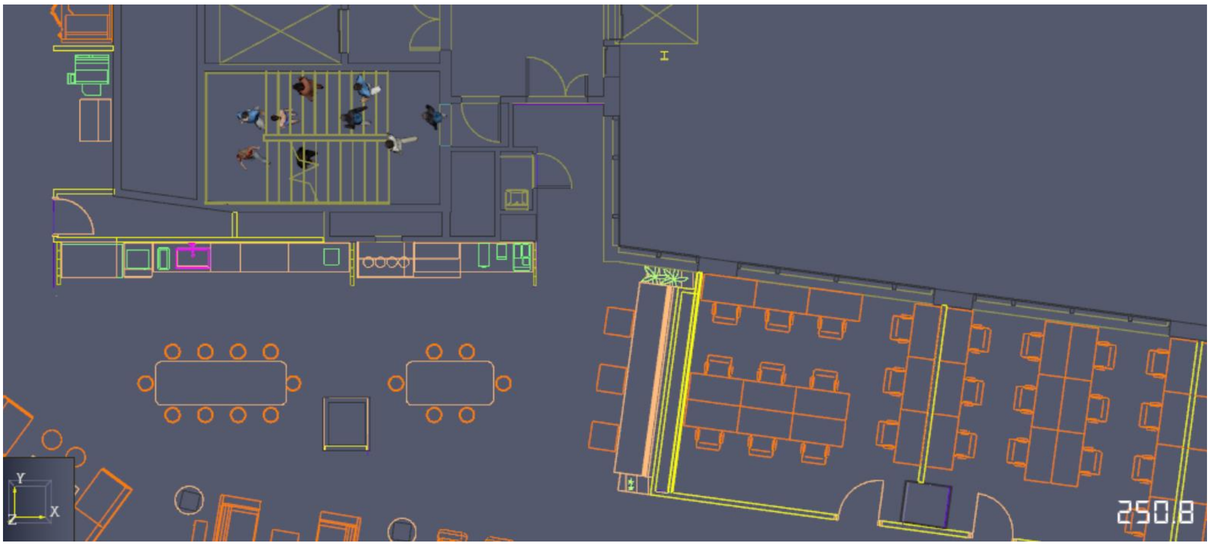


Figure 4: View of the Pathfinder simulation with [speed, size]=[1 m/s, 0.4 m] at t=250 s, floor 6, staircase A

At t=250s, occupants have already evacuated through the stair A. It took 253s to evacuate 179 people through Stair A on 6th floor.

Figure 5: View of the Pathfinder simulation with [speed, size]=[1 m/s, 0.6 m] at t=250 s, floor 6, staircase A

At t=250s, occupants are queuing at the stair entrance. The last person enters the Stair A on 6th floor at 350s.

In Cromosim, evacuation time has low sensitivity to agent diameter: a 20% increase in agent diameter leads to a 3.2% increase in evacuation time. Indeed, conflicts are managed differently in Cromosim. As explained before, agent size does not exist as a parameter in Cromosim *per se*. The variation of size is done by modifying door capacity. So, occupant movement resolution is of a different kind, less impacted by conflict phenomena or door capacity, especially in stairwells.

Figure 6 presents the variation of evacuation time with respect to premovement time. Longer premovement times (up to 120s) were modelled in buildingEXODUS and Pathfinder to explore the influence of this parameter up to the maximum premovement times observed during the drill.

For all simulation tools, evacuation time has low sensitivity to premovement time (close to 5% variation in evacuation time for a variation of premovement time between [0 – 60] s).
This is because the egress time in the building is largely governed by the flow in the stairs, which represent the bottleneck of the system. Indeed, even if occupants are delayed before starting their evacuation, they will eventually reach a stair that is already jammed.

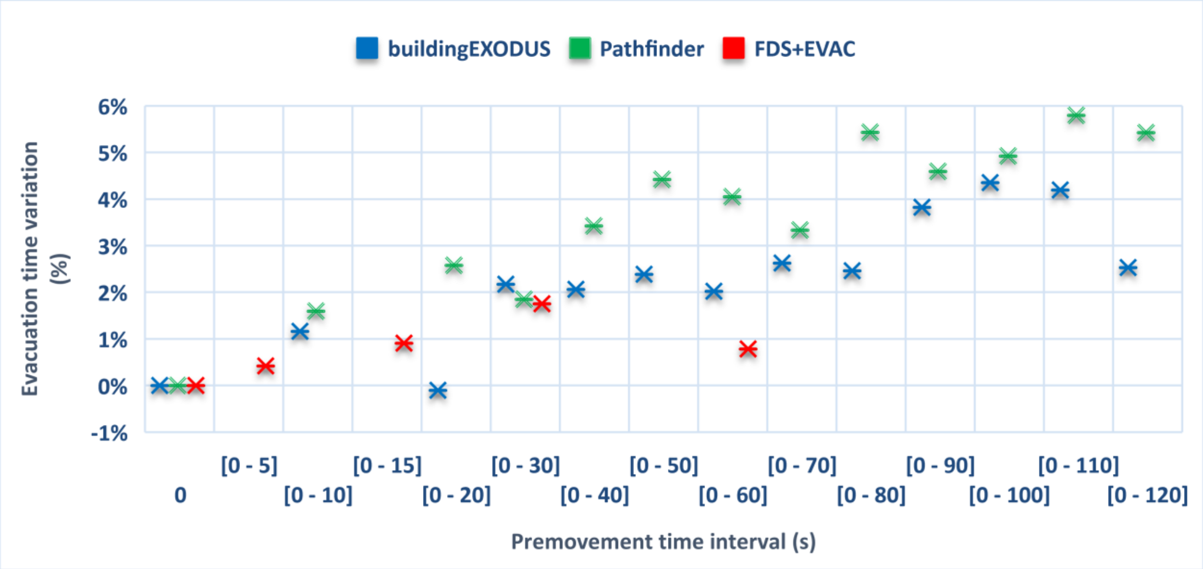


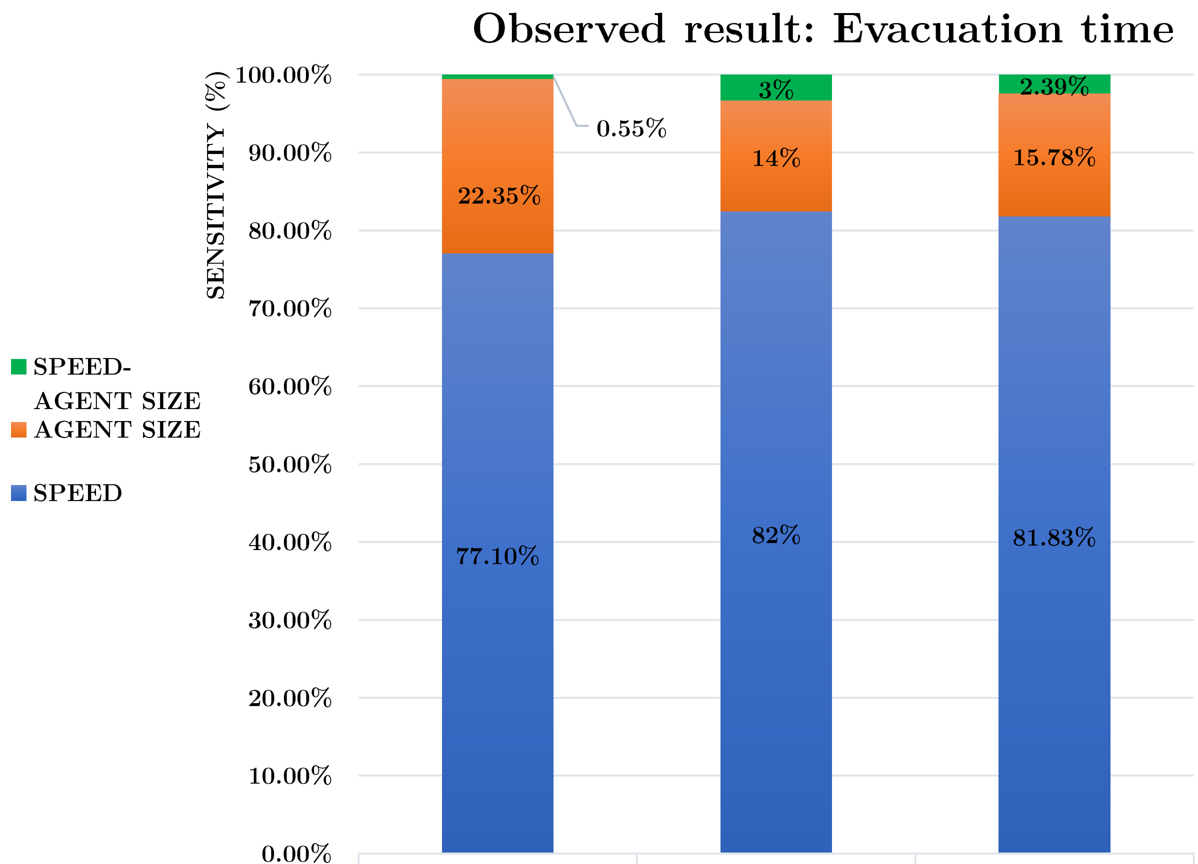
Figure 6: Influence of premovement variation on evacuation time in percent

Influence of speed, agent size and their second-order interactions on evacuation time using Sobol indices

Sobol method [14], otherwise referred in literature as variance-based sensitivity analysis, consists in breaking up the variance of the output into fractions, thus showing its sensitivity to different input parameters. Sobol indices of higher orders represent, accordingly, an influence not of a single parameter but rather of a combination of those.
In the following section, the Sobol method is used to quantify the influence of two parameters at a time. In order to reduce the number of simulations, the study was limited to the evaluation of two parameters. Indeed, when only two parameters are analysed, it already implies to perform simulations for each combination of values for the two parameters including simulations done for standard variation purposes (Table 3), i.e. 250 simulations (5 x 5 x 10 simulations) for buildingEXODUS for example. Therefore, applying the Sobol method to three parameters would increase the number of simulations excessively. Indeed, simulation time for FDS+EVAC is significantly higher than for other tools which is not suitable for a large number of simulations.
Hence, only a maximum of two parameters' interaction were studied, such as speed-size and speed-premovement time interactions. For same reason (to limit the number of simulations), the size-premovement interaction has not been studied, as well as the speed-premovement time sensibility for FDS+EVAC.

It must be noted that Sobol indices are dependent on the length of parameter intervals and the discretization over these intervals. Therefore, the following results are only valid for the values and intervals indicated in Table 4.

Figure 7 illustrates the influence of the occupants' speed on the variance of the total evacuation time is predominant (around 80% of evacuation time variation is due to speed). Agent size alone is responsible of 14% to 22% of evacuation time variation. The interactions between speed and size of agents are responsible for less than 3% of the evacuation time variation. This shows that there is no relationship between the speed and the size of occupants, meaning that the effect of the occupant's speed on the output does not depend on the value of the occupant's size and vice versa.



	Pathfinder	FDS+EVAC	Cromosim
🟩 SPEED-AGENT SIZE	0.55%	3%	2.39%
🟧 AGENT SIZE	22.35%	14%	15.78%
🟦 SPEED	77.10%	82%	81.83%

Figure 7: Sobol's indices for agents' speed, agents' size and their crossed interactions on evacuation time.

Sensitivity of the total evacuation time to the speed and premovement time with Sobol method

Figure 8 presents the weight of speed, premovement time and their interaction on evacuation time for buildingEXODUS and Pathfinder. For both tools, the influence of speed is strongly predominant in the case studied (responsible for more than 90% of the variation in evacuation time). In buildingEXODUS, premovement time (from 0 to 60s) is responsible for 5% of variation in evacuation time and the interactions between both parameters of about 4%. In Pathfinder, the effect of premovement time or the interactions of combined speed and premovement time on the result are negligible.
This means that the premovement time does not have individual impact on the evacuation time in this building and that speed and premovement time are independent variables that do not affect each other's state.

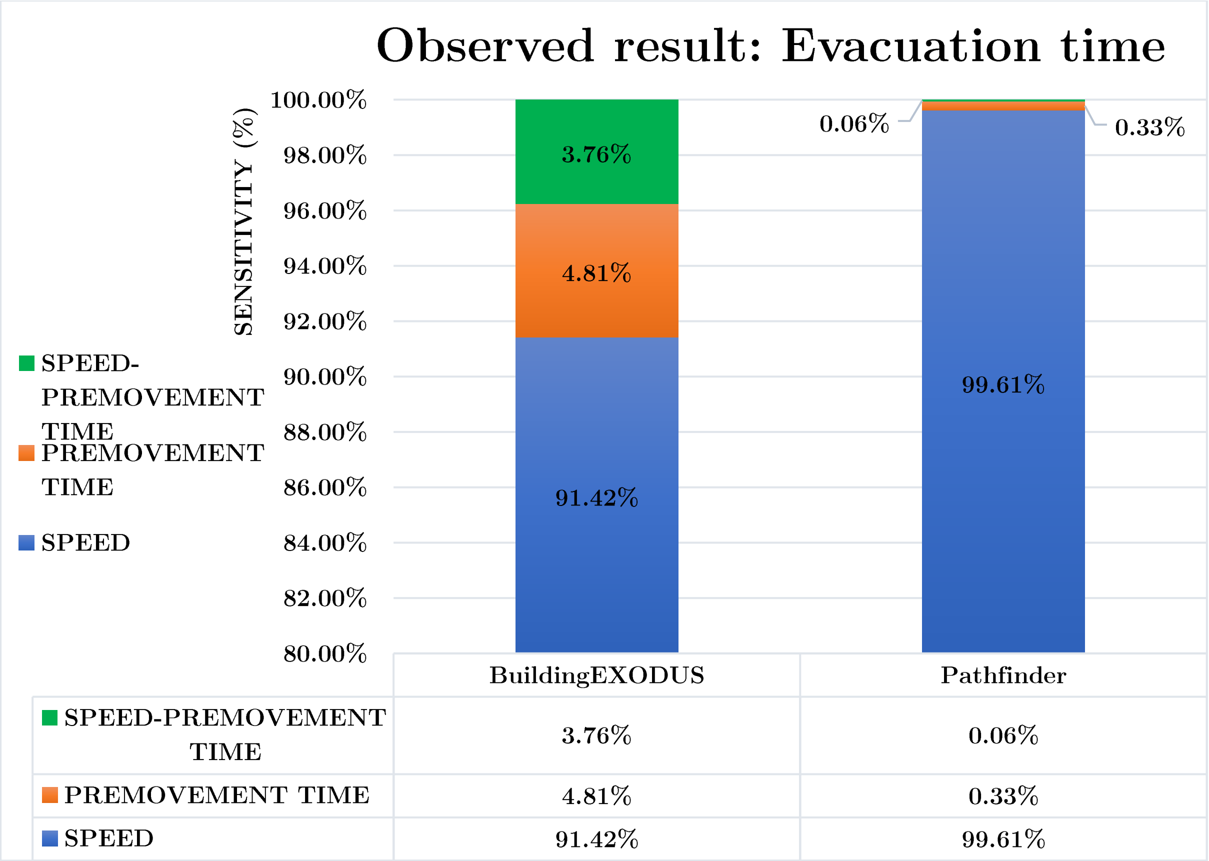


Figure 8: Sobol's indices for speed, premovement time and their crossed interactions' effect on evacuation time

SYNTHESIS AND DISCUSSION

The sensitivity study focused on three main parameters of an evacuation simulation (speed, size of an agent and premovement time). According to the findings of this study, speed is the primary cause of variations in evacuation time for all of the tools analysed in the given scenario. It should be noted that these results are dependent on the geometry, the number of agents and the intervals studied. It is therefore strongly recommended to be cautious while attempting to extrapolate these results to other cases.

The influence of input parameters on evacuation time is consistent across the studied numerical tools because the speed is the main influencing factor when compared to size and premovement time.

The main difference across the chosen simulation tools is in the amplitude of effects of input parameters on evacuation time variation. This is particularly observed at doors and at merging flow points between levels. This raises the practical question about how the priority of access to the stairs is managed, and whether people coming from higher storeys impede evacuation of lower storeys. Additionally, the different solutions of conflict resolution implemented in the tools may affect the merging of flows.

The values used by default for the speed and the diameter of an agent appear as a point of bifurcation between two linear operating regimes.

This implies that, when performing a simulation, the occupants' size parameter can be fixed to its default value in the various tools, (i.e. equal or close to 0.5m) as it will not generate significant variations in evacuation time. Increasing occupants' size above 0.5 m intensifies congestion at bottlenecks resulting in longer evacuation times as conflict resolution between occupants at narrow points becomes more complicated and time-consuming. However, speed cannot be fixed in the same way as its variation are often a key part of a scenario.

The speed is therefore a crucial parameter and is primarily responsible for the output variations. The default value of occupants' speed (i.e. maximum horizontal speed) is greater than 1 m/s in all chosen numerical tools, which results in faster evacuation but greater congestion (this is consistent with what is observed in road traffic). Only fixed speeds have been studied in this article, however the occupants' speed can be set using a distribution law (uniform, normal, log-normal) that may be more relevant to model the diversity of the occupants (sex, age, disability, luggage, etc.).

The influence of premovement time on evacuation time variation is minimal in this case study. Adding a premovement time has the effect of delaying the start of the movement of the occupants and therefore their arrival at the level of the bottlenecks. However, as the building evacuation is governed by the flow through doors and stairs, a time-wise gradual arrival at stair entrance does not result in a more efficient evacuation as congestion has already formed in stairs.
Moreover, the occupants' paths during evacuation and the usage of egress stairs were set to match the evacuation drill routes. This implies that the distribution of occupants in relation to the existing stairwells is not optimal. Thus, for the case studied, the delay created by the premovement time is outweighed by the congestion present at storey exits and in the stairwells.

Finally, the results presented in this paper are exclusively associated with evacuation time, which is a key result of evacuation engineering. The impact of the selected input parameters on different outcomes (such as congestion) remains to be investigated.

CONCLUSION

The overall objective of our working group is to lead to regulatory changes, which are planned in the medium term.
The work presented in this paper concerns a sensitivity study carried out on three key input parameters of an evacuation simulation: the speed, the size of the agents and the premovement time. This study has been carried out on four evacuation simulation tools: buildingEXODUS, Pathfinder, FDS+EVAC and Cromosim.

The results show a preponderant influence of the speed compared to the other two parameters via the Sobol indices on the evacuation time for all the tools used. In addition, variations in speed alone are responsible for a variation in evacuation time between 10% and more than 90% in the selected simulation tools. The variations in evacuation times are not proportional to the variation in speed. Large variations in evacuation times are obtained for speed values varying below the reference value of 1 m/s). This implies that congestion limits the variation of the evacuation time when the speed increases.

Regarding the influence of the agents' size on the evacuation time, micromodels (FDS+EVAC and Pathfinder) are much more sensitive than macro-model ones such as Cromosim. It should be reminded that it is not possible to evaluate builingEXODUS on this point due to a fixed mesh size coupled with the fact that a mesh can only contain one agent.
The ease with which occupants navigate bottlenecks in FDS+EVAC and Pathfinder is directly related to the diameter of the occupants. A 20% increase in diameter implies an increase in evacuation time for Pathfinder of the order of 25% and of the order of 40% for FDS+EVAC.
Attributing a premovement time to occupants following a uniform distribution over intervals up to [0s, 60s] has a negligible influence on the evacuation time for buildingEXODUS, Pathfinder and FDS+EVAC. Same outcome was observed for intervals up to [0s, 120s] in buildingEXODUS and Pathfinder. We deduce from these results that congestion outweighs the average delay generated by the premovement time interval. Premovement interval sensitivity is not applicable to Cromosim.

It is important to note that these results are valid for the intervals and case studied (building geometry, occupancy etc.). Finally, it emerges from the various points above that the quantification of congestion and the knowledge of conflict resolution in software is necessary because it has a strong impact on the results. In addition, conflict resolution management is specific to each tool and is more or less accessible depending on the case.

PERSPECTIVES

Based on the results of this study, the way of modelling the stairwells must be the subject of particular care. Indeed, in the French regulations, the exit capacities of a building are assessed as widths of passageway called "units of passage". So, for example, a landing door which is 0.9 m wide provides one "unit of passage" because it can only accommodate single lane movement. A 1.4 m stairwell provides two "units of passage" because it can accommodate two-lane movement. Each tool discretizes the space differently and manages the merging flows (e.g. which group of people amongst those going down the stairs and those arriving from the landing has the highest priority) in its own way. Future work will be carried out specifically on stairwells in order to formalize the good practices associated with their modelling.

In addition, the evacuation time is an essential result of an evacuation simulation but is not the only outcome to be taken into account. It is necessary to have means to quantify the congestion during an evacuation. Indeed, areas of heavy congestion are areas of potential danger for people: propensity to anxiety, trampling and crushing. The congestion can be quantified by studying the density of people/m^2 over time (this involves knowing where and how to determine the areas to be studied), the individual waiting time of people or other indicators such as the PEE (Personal Egress Efficiency) characterizing the efficiency of the evacuation of a person.
Other case studies, including drills, will be carried out to compare the observations made in this study with those obtained with a different building geometry and occupancy.

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REFERENCES

[1] Ronchi E., Kuligowski E.D., Reneke P.A., Peacock R.D. and Nilsson D.. The Process of Verification and Validation of Building Fire Evacuation Models. NIST Technical Note, 2013.
[2] SFPE Guide to Human Behaviour in Fire, Edition Number 2, 2019, DOI 10.1007/978-3-319-94697-9
[3] International Maritime Organization. Guidelines for evacuation analyses for new and existing passenger ships. Technical Report MSC/Circ.1238, 2007.
[4] Directive relative aux analyses microscopiques de l'évacuation, RiMEA e. V. , version 3.0.0, March 2016.
[5] PD 7974-6 :2019, The application of fire safety engineering principles to fire safety design in buildings – Part 6: Human factors: Life safety strategies – Occupant evacuation, behaviour and condition, BSI, last amended in March 2019
[6] C/VM2 Verification Method: Framework for Fire Safety Design, Ministry of Business, Innovation & Employment, last amended in July 2014

[7] ITM-SST 1553.2 Instruction technique : Simulation d'évacuation de personnes à l'aide d'une approche performancielle, Direction, Département Sécurité et Santé Luxembourg, November 2014

[8] DIN 18009-2, Brandschutzingenieurwesen – Teil 2: Räumungssimulation und Personensicherheit, June 2021.

[9] Jullien Q., Dréan V., Wyzgolik A. et al. Evacuation modelling –application to an office building using several simulation tools - FEMTC 2020

[10] FDS+EVAC version 2.5.2, VTT, Fire Dynamics simulator with evacuation: FDS+Evac technical reference and user's guide, VTT Working Papers, February 2018

[11] Pathfinder 2019, https://www.thunderheadeng.com/pathfinder/

[12] Galea E.R. P.J. Lawrence P.J., S. Gwynne S., Filippidis L., Blackshields D. and Cooney D., buildingEXODUS v6.3, User Guide

[13] CROwd MOtion SIMulation (Cromosim) user guide, www.cromosim.fr

[14] I.M. Sobol. Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. Mathematics and Computers in Simulation, 55(1-3) :271–280, 2001.

[15] Helbing, D., and Molnár, P., "Social force model for pedestrian dynamics", Physical Review E 51, 4282-4286,1995