Evacuation modelling – application to an office building using several simulation tools

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ABSTRACT

Numerical simulation is one of the tools available for emergency evacuation planning. Its main advantage is its capability to represent the impact of dynamic factors related to people movement on outcomes. These include walking speeds, travel times, and variations in the use of circulation space based on route choice, local navigation and interactions with the building and other pedestrians. The appropriate use of a simulation tool allows examining multiple scenarios in cost-effective approach compared to real-life exercise. Tools and methods that can be used for emergency evacuation planning are usually governed by each country's regulatory structure. In France, regulation is mainly prescriptive and currently does not require the use of simulation tools. A predominantly French collaboration between seven institutes and a UK-based consultancy was started a year ago to evaluate the capability of simulation tools to reproduce a real evacuation exercise. At this stage, the tools that are used are FDS+EVAC, Pathfinder, buildingEXODUS, Cromosim, and an analytic (code compliant) approach based on the French regulations. To provide a benchmark for comparison, an evacuation drill was carried out in a ten-storey office building in Paris, France. Data on various aspects of evacuee performance was collected for comparison. This paper focuses on comparing the results of the drill to the results obtained by the different simulation tools. The ability of the different models to reproduce certain phenomena, such as exit congestion, are examined and their limitations are discussed.

INTRODUCTION

The complexity of modern infrastructure 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 maximal densities achieved and estimate evacuation times for different emergency scenarios for different types of facilities. However, the use of crowd models still varies significantly between different sectors and countries [1]-[17]. The main challenge facing the wide use of pedestrian simulation tools is the absence of regulatory guidance and standards. Two exceptions are the guidelines for maritime evacuation tools, namely the MSC/circ.1238 [18], developed by the International Maritime Organization and the NIST Technical Note 1822 [1] that expanded and modified the tests listed in the MSC/Circ.1238 in the context of building evacuation. In France, regulation is mainly prescriptive and does not require the use of simulation tools. Furthermore, evacuation modelling is not yet acknowledged in the building sector. However, managing crowds, especially during major events, is becoming a real problem for public safety in the current context. 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 to allow for new innovative designs.

A predominantly French collaboration between seven institutes and a UK-based consultancy was started a year ago 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 design offices (Studio Fahrenheit, Movement Strategies). The consortium also includes firefighters (SDIS 39, BSPP) who were mainly involved in conducting the evacuation drill.

The objective of the project is to make an inventory of models and calculation codes that can be used to estimate crowd movements, in various situations (with or without crisis, in or out of buildings, etc.), from the start of the drill to the exit of the building or the physical limits of the assembly points if they exist.

To simulate the evacuation drill, both analytical and numerical approaches are used. For the analytical approach, an analytic method from the French analytical model GA 23 (French fire regulations) [19][20] is used. In this method, the evacuation time is defined as the time interval between the time of alarm and the time at which occupants are able to enter a place of safety [20][21]. This evacuation time is calculated using simple hand calculations detailed in the regulations.

In the numerical approach, simulation tools, such as agent-based models, are used. These allow to include individual characteristics and behaviours such as physical dimensions, walking speeds etc. However, these tools require several simulation runs to obtain reliable results.

The examined simulation tools are FDS+EVAC [22][23], Pathfinder [24], buildingEXODUS [25] and Cromosim [26]. Some of these models are commercial (such as buildingEXODUS, FDS+EVAC and Pathfinder) while others are under development by academics, such as Cromosim. The latter, although less commonly used in design offices or by the evacuation community, allows to compare to a research-based model and contribute to its development.

To provide a reliable benchmark for comparison of the selected tools, an announced evacuation drill was carried out in a ten-storey office building in Paris, France. Data on various aspects of evacuee performance were collected such as egress time, walking velocity, flow, and congestion in high traffic areas.

This paper focuses on comparing the results obtained by the different modelling tools to that of the evacuation drill. The ability of the different tools to reproduce certain phenomena, such as exit congestion, are examined and their limitations are discussed.

CASE STUDY – DESCRIPTION

The project used a real evacuation drill for benchmark purposes. The drill was conducted in 2019 in a ten-storey building located in Paris, France. The premises comprise of a basement, ground floor and eight levels, accommodating essentially a mix of office desks and meeting rooms.
The building is of modern construction and used uniquely for office purposes. It is therefore classified under the French Workplace fire regulations. The local authorities have approved a design occupancy of 3,366 people and its means of egress designed to accommodate for such occupancy. Figure 1 presents the geometry of the building.

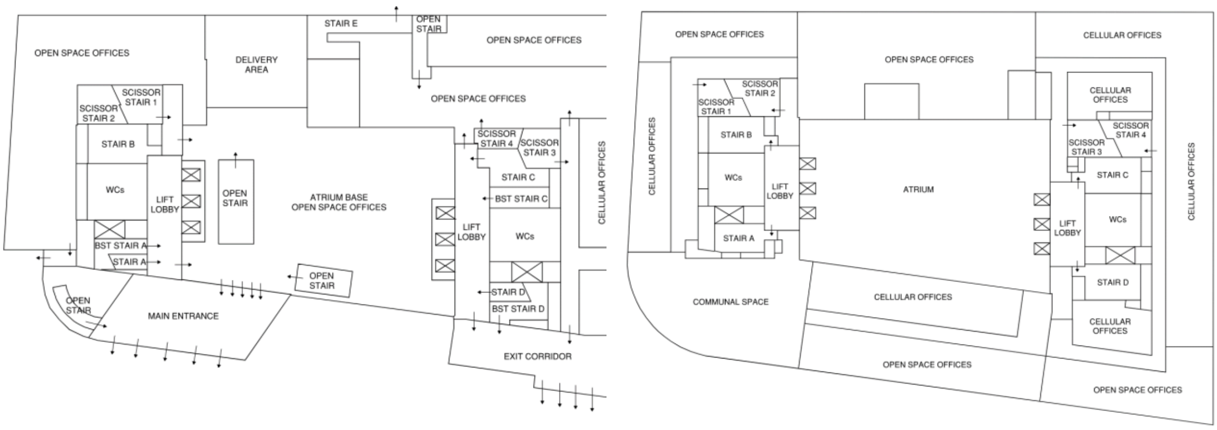


Figure 1: Schematic views of the ground floor (left) and a typical upper floor (right)

The building is circa 61 m long and 44 m wide for a total floor area of 20,600m^2 across all 10 levels. On a typical floor, the building is fitted with 8 egress stairs, including two scissor stairs. These have clear widths varying from 1.4 m to 1.8 m. As the building is located on a sloping site, its exits at ground floor are located on the South-West elevation and at basement on the North-East elevation. The building is organised around a central atrium space that is fully glazed and accommodates passenger lifts.
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 evacuation drill took place in November 2019 that involved the participation of circa 1,350 people. This is 40% of the overall means of egress capacity of the building. Occupants knew of the occurrence of the drill on that day but did not know at what time. Occupants of the building were spread across the levels as follows (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

In order to collect data from the evacuation drill, 20 members of the working group spread across the building at key locations. Each member observed behaviours to determine pre-movement times, counted the number of people escaping and then timed their own respective evacuation after all occupants have left their designated floor. This involved a chrono-measure each time the person reached a stair level landing, reached the final exit of the premises and then reached the assembly point located in a street close to the building. All results were then collected and analysed. These are presented in the following paragraphs of the report alongside the simulation results. The total evacuation time was recorded to circa 7 min and the time for all to reach the assembly point was 8.5 min.

The individual counts and time measurements allowed the working group to determine an average pre-movement for the building's occupants of around 50 seconds. Literature indicates pre-movement times of approximately 1 min for office buildings, which reflects what has been observed during the drill.
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 were collected using the extensive network of CCTV installed throughout the building. Footage recordings remained accessible for 1 month after the drill and was fully utilized. Finally, 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 behaviour of people inside the stair.

MODELS AND SOFTWARES

Modelling crowd movement: an overview

Most commercial software relies on a microscopic / agent-based description, where each agent is represented. Macroscopic models represent crowds as a continuum and are under numerous theoretical investigations. Their use in practical applications is less common.

The seminal model of Helbing [15] is of the microscopic type. It describes the movement of inertial physical particles evolving according to a modified Newton's Law. The forces in action comprise a driving term to the desired velocity, a short-range repulsion force to reproduce mechanical interaction preventing agents from overlapping and so-called *social forces* designed to encode the tendency of people to stay away from each other. The last term is in fact an asymmetric force depending of the cone of vision of an agent, breaking the law of action-reaction. The code FDS+EVAC, for example, is based on this approach.

Cellular automata (CA) models rely on a cartesian grid. Pedestrian movements are restricted to hop between cells, such that each cell can be occupied by one agent at a time. Hopping movements between grid cells are drawn randomly at each step. A set of rules is prescribed to bias the expected direction toward the desired one and to handle short-range interactions. buildingEXODUS shares with these models the Cartesian grid, and uses heuristic rules to determine movement, handle congestion and choose local and global exit routes [25].

Recent models from the computer graphics and robotics communities explicitly treat interactions as individual decision processes made by each agent. In collision-avoidance models, agents seek to choose the route minimizing a local cost function among a predefined set of directions, possibly accounting for the local density of people. In Pathfinder [24], this local path-finding strategy, or *steering behaviour*, is coupled with a global wayfinding algorithm and heuristic arguments to include exit choice.
Another recent model introduced in [16] is based on a *hard congestion constraint* on agents: they are regarded as rigid disks with a desired velocity and their effective velocity is defined as the closest one (in a global least square sense) among all feasible velocities, which preserve non overlapping. The resulting interactions are of a mechanical type and are especially adapted to account for clogging effects. Some additional rules can be introduced to handle congestion in a weaker sense and to account for social and psychological effects. The Python library Cromosim [26] contains a numerical implementation of this model.
In addition to these agent-based models, we implemented another model recently introduced in [27]. It is based on simpler arguments: for evacuation scenarios, we see the building as a set of compartments in which the crowd flows through doors with a fixed maximum rate and travel times between rooms. The required input data includes the capacities, travel times (which can be computed from a given walking speed and building plans) and the global route of each group of pedestrians to the exit.

The Cellular Automata approach is based on random hopping movements; it is therefore stochastic by nature. As for the other microscopic models that we presented, they are based on deterministic principles, yet they may integrate stochastic effects in a weaker sense. FDS+EVAC integrates a random force in the social force model. A final source of randomness lies in the definition of initial and individual characteristics. The initial positions of individual agents can be randomized while headcounts in rooms are specified for all the models that are considered in this paper. Individual characteristics of agents, which often depend on the specific model or software, can be randomized with specific distributions in Pathfinder, FDS+EVAC, buildingEXODUS and the granular model of Cromosim.

Detailed software presentation

The software described below are used in this project. Further details can be found in each dedicated user guides.

buildingEXODUS [25] is an evacuation simulation software developed by the University of Greenwich. It is a microscopic model where each occupant has its own characteristics. This software is based on a multi-level interpretation of buildings. A building is therefore represented as a collection of different levels linked together by connecting elements (stairs, escalators, elevators, etc.). Within each level, the space is discretized into nodes and arcs. Nodes are interconnected according to Moore's model (each node is connected to 8 adjacent nodes).
By default, buildingEXODUS calculates a potential map to determine the distance to an exit for each node of the model. Occupants seek to minimize their travel time and thus optimize their trajectories. buildingEXODUS solves conflicts by assigning a leadership parameter to each occupant. The occupant with the greatest leadership comes first. A conflict resolution time is applied for each conflict and randomly drawn in one of the two-time ranges. A shorter duration is provided for conflicts involving very different leadership, as opposed to conflicts with close leadership involving longer resolution times. Conflict resolution contributes to generate stochastic aspects. Although normally low, this randomness requires statistical processing in order to be able to present representative results. Usually the most influent parameter on results are the speeds and pre-movement time which are fixed here for comparison purpose. Since the approach is fully stochastic by nature, the outcome is a random variable. Our protocol was the following: we carried out 10 trial computations and extracted all values from the trial that lead to the median value of the evacuation time.

FDS+EVAC. The CFD code FDS [22] and its evacuation module EVAC [23] is also investigated (an example of geometry is presented in Figure 2b). This code has been used for many years, and has been verified and validated according to dedicated methodology [28]. The FDS+EVAC model is more thoroughly described in [23][29].
FDS+EVAC treats each evacuee as a separate entity, or an 'agent', which has its own personal properties and escape strategies. The basic algorithm behind the egress movement solves an equation of motion for each agent in a continuous two-dimensional space representing the floors of buildings (e.g., a horizontal xy-plane) and time, i.e., FDS+EVAC, uses an approach based on molecular dynamics to model the movement of agents. In FDS+EVAC, the agents will observe the actions of others and will select the target exit that minimizes evacuation time. For each agent, the evacuation time is based on distance to final exit and the waiting time due to congestion in front of the exits. Exit visibility and the fire related conditions near exits are criteria that also affect the decision, as well as the familiarity with the different exits.

Pathfinder [24] is an agent-based model that simulates people movement in 3D space. Hence, agents change their desired speed depending on the element they are walking in (e.g. level surface, stairs, escalator, etc.). To reach the final exit, each agent evaluates a number of paths and chooses the one that minimises a cost function. At every step of the itinerary, agents estimate the current conditions in the element they are in to choose the exit that minimises the total travel time. A number of factors is included such as queueing time for each available exit in the current room, walking distance, etc. To model avoidance behaviour (with other occupants and obstacles), a combination of steering mechanisms and collision handling is used to modify occupants' desired velocity. Pathfinder also offers the option to model occupant movement using SFPE mode which implements SFPE's flow-based egress modelling techniques [17]. In this mode, occupants are allowed to collide. In addition, walking speeds are determined by occupant density within each room and flow through doors is controlled by door width. Pathfinder has performed several verification and validation tests to reproduce experimental findings related to the fundamental diagram. The verification and validation tests recommended by the IMO and the NIST documentation has also been reproduced.

Cromosim [26] is an Open Source Library written in Python. It proposes implementations of various crowd motion models. As for the present project, two types of simulations have been carried out: the granular approach and the compartment model.
As previously mentioned, the **granular** approach is especially adapted to highly crowded evacuations, with people pushing against each other. In the basic form of this model, at every time step, the global velocity is defined as the closest one (in a mean square sense) to the set of admissible velocities, i.e. velocities which do not lead to overlapping. In the present case of a fire drill, we integrated social tendencies of individual to keep apart from neighbors, to avoid unrealistic clogging phenomena upstream doors. In this setting, the actual flux of pedestrians through egress doors is not prescribed, it is a raw outcome of the computation. Also proposed in the Cromosim library, the **compartment** model obeys to fully different principles. It is based on a skeleton of the building, that is defined as a directed graph. The nodes of this graph are all the doors, seen as bottlenecks at which people are likely to accumulate, together with points of interest, like abrupt changes of width in corridors, or turning points in stairs. The edges correspond to paths between these nodes. The main parameters are the capacities of the doors, and the lengths of edges. Unlike microscopic approaches, the model computes the evolution of a limited number of quantities (much smaller than the actual number of individuals), which are the number of people gathered at each node, and also the number of people travelling from a node to the next one. Typical capacities range between 2 and 4 passage units, depending on the local width.

Setting the parameters

As detailed in the previous section, the numerical tools rely on different sets of parameters (see Table 2 for a synthesis of parameters used for simulations). We describe here our efforts to set up the various implementations in a consistent manner. This parameter set-up has been carried out in a blind manner: experimental data were not used in the process of adjusting parameters. Before describing the most important parameters / data, it is important to note that some quantities are input parameters for some approaches while being an outcome of the computation for others (e.g. fluxes though exit doors).
In the list below, the first group of 3 corresponds to universal input parameters (their value is set for all tools). The 2 elements of the next group are mutually exclusive, i.e. depending on the model, one parameter can be set as an input parameter while the other one is an outcome. The last value (flow rate of pedestrians per unit width of an exit) has a dual nature: it is a computable observable for some models, and an essential input parameter for some others (see details below).

Walking velocity (m/s): velocity to which people tend to walk (on a flat level) in the absence of external constraints.
Walking velocity in stairs (m/s): same as the previous one but in the case of stairs for going up and down.
Initial people location: how people are distributed in the different areas of the domain at the start of the simulation.

Maximum density (pers/m^2): maximum number of people per unit area.

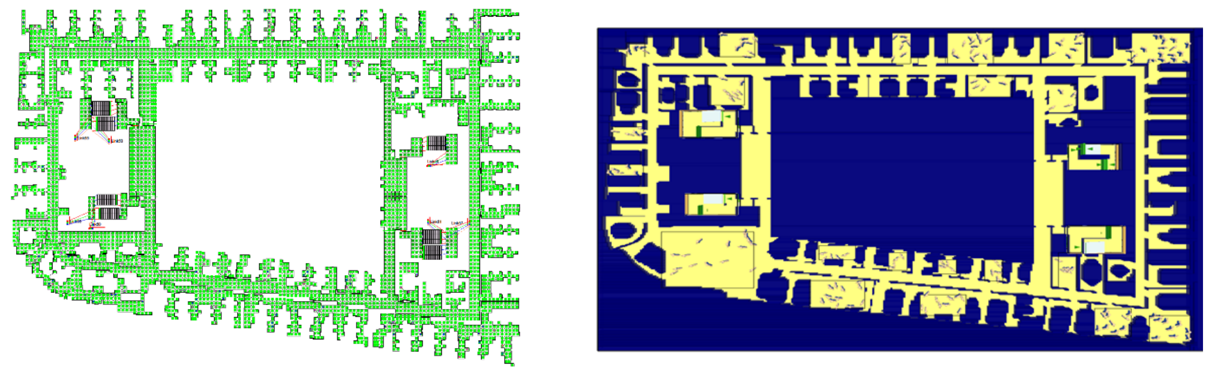
Agent characteristic size (m): size of the agents (when applicable). In case of non-circular individuals, this size is taken as the diameter, which is the largest dimension of a person seen from above.

Maximum flow rate at doors, or capacity (pers/m/s): maximum number of persons allowed to pass a door (by unit of length) simultaneously.

Walking velocities and initial positions are common input parameters for all numerical tools. Similarly, the initial distribution of people has to be specified for all approaches. For microscopic models, they are randomly distributed over each zone in order to respect the available initial conditions as defined in the Case-Study section above (Table 1).

Maximum density and agent characteristic size can be considered as mutually exclusive parameters: the shape and size of agents determines in an indirect way the maximum packing configuration, and thus the maximal density. The standard choice for the shape of agents is a simple disc, but ellipses can also be considered (as in FDS+EVAC, where ellipse like shapes are defined has the union of 3 overlapping discs with different sizes, and based on the shoulder radius Rd of the agent). A so-called *reduction factor* can be added to modify the size of agents in the case of high congestion to avoid complete clogging. buildingEXODUS uses a grid of cells of side length 0.5 m (Figure 2a), and thus has a maximal density of 4 pers/m^2. In macroscopic models, the maximal density is a more natural way to define maximal congestion, but some agent-based models take into account the density and may then define a "weak" maximal density, i.e. a density at which no movement occurs but the packing of agents is not maximal. For the compartment model a maximal density per room or corridor can be specified but has not been used in this simulation.
The maximum flow through doors is crucial, and its nature is ambivalent: for microscopic models is essentially a result of the simulation. Note that a maximal value can be prescribed in some of the tools that we used, but this feature has not been activated in the presented simulations. For the compartment model, the door specific capacity is a key input parameter of the simulation. As for buildingEXODUS, its value results in reality from other parameters: the number of cells in an exit door depends on the size of the cells (each which contains at most an individual), which indirectly fixes the maximal number of pedestrians which can go through a door during a time step.

Let us add that the pre-movement time was set to 0 for all computation: people start to evacuate at the beginning of the simulations. As indicated in the case study description above, an average pre-movement for the building's occupants of around 50 seconds was observed during the drill. This pre-movement time is addressed as an initial offset in the simulations egress time.



a) **b)**

Figure 2: Example of 7th floor modelled with a) buildingEXODUS and b) FDS+EVAC

Table 2: Synthesis of the main input data used in every evacuation tool investigated

	Pathfinder* User 1 and 2	FDS+EVAC	building EXODUS	Cromosim Granular	Cromosim Compartment	Analytic GA 23
Walking velocity (m/s)	0,9	0,9	0,9	0.9	0.9	1
Walking velocity in stairs (m/s)	0,6	0,6	0,6	0.6	0.6	0.4
Maximum density (pers/m^2)	4	4	4	no	no	no
Maximum flow rate at doors (pers/m/s)	1,33	no	1,33	no	1,66	0,92
Initial agent location Y/N How	Randomized per room	Randomized per room	Randomized per room	Randomised per room	Uniform per room	Per floor with a horizontal and vertical distance to do
Agent diameter(m)	2xRd*** = 0.45	2xRd*** = 0.51±0.07	0.5 x 0.5 m^2**	0.40±0.01	NA	NA
Space meshing	Triangulated navigation mesh	Cartesian mesh	Space grid mesh	Cartesian mesh	NA	NA

*: modelling software Pathfinder was used by 2 entities **: relative to cell size
***: shoulder radius of an agent

Analytic approach

The French fire regulations are of a prescriptive nature when it comes to designing escape routes. Train stations (called type GA premises) are the one exception to that rule. As these involve large crowds and the use of escalators, travellators and upward use of stairs, the code compliant approach to designing means of escape is based on flow rates and escape time calculations [20]. The code provides a detailed breakdown of the flow rates at each element (door, corridor, escalator, etc.) for harmonization purposes across all such premises in France. Hand calculations have therefore been carried out using this approach to see how they compare with the computer simulation tools and the real case study.
The hand calculations are carried out on a floor by floor, from the furthest point to the egress stairs/doors. The first step consists in calculating the travel time of the furthest person; then, the designer calculates the overall egress flow rate across all available exits and calculates the escape time of the floor based on its occupancy. The vertical travel time is then calculated and the horizontal to the final exits. All these times are added together to form the maximum evacuation time from that floor. The process is repeated floor-by-floor or zone by zone. Results are compared to define the overall maximum evacuation time of the building.

RESULTS

The results below are presented starting from the building boundary then going back inside to the different interior elements (main entrance, stair cores, etc.).

Figure 3 represents the cumulative number of people that left the building versus time during drill and for each tool applied. Due to some difficulties to count precisely the occupants leaving the building (e.g. some CCTV did not work), the number of simulated occupants is deemed to be slightly higher than the drill's population. The numbers used in the tool was estimated by measuring the number of occupants going into the building at the end of the fire drill. There is an offset on simulated curves corresponding to the mean pre-evacuation time measured during the test (i.e. 50 s). This initial delay was reflected in the tools employed through the addition of a set value after the simulation.

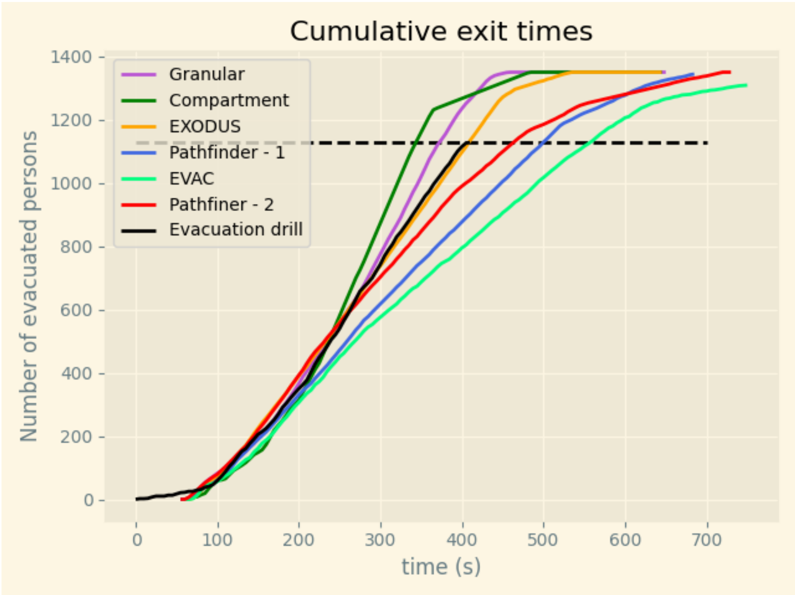


Figure 3: Cumulative curves for number of agents evacuated for trial and simulation tools

It appears that the simulation results are consistent with the experiment during the first four minutes. Then, some differences appear in the simulated results. Compared to the evacuation drill, the total evacuation time is lower for Cromosim and higher for Pathfinder and FDS+EVAC. buildingEXODUS provides median results compared to the other models. A corollary observation is the difference between the slopes after 210 s between the tools used. It implies that the simulated movement on the stairs is not equivalent across the models. For instance, given the different tools used, it is expected that congestion does not appear at the same place and with the same magnitude between the tools studied.
To investigate this point, Figure 4 and Figure 5 present respectively the flux through Door 2 (one of the main entrance doors at ground floor) and the numbers of persons in Area 1 (area in front of the main entrance doors at ground floor) in function of time.

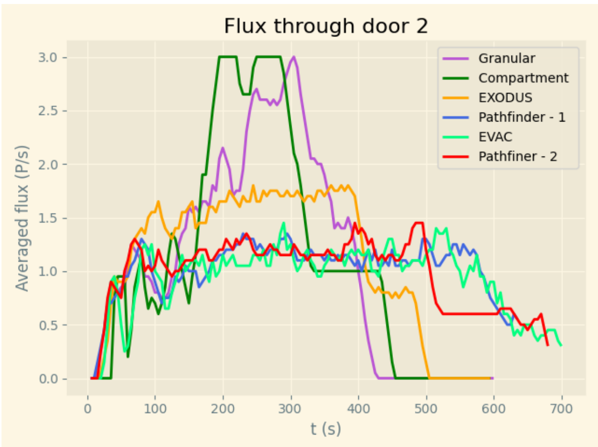


Figure 4: Flux through Door 2 versus time

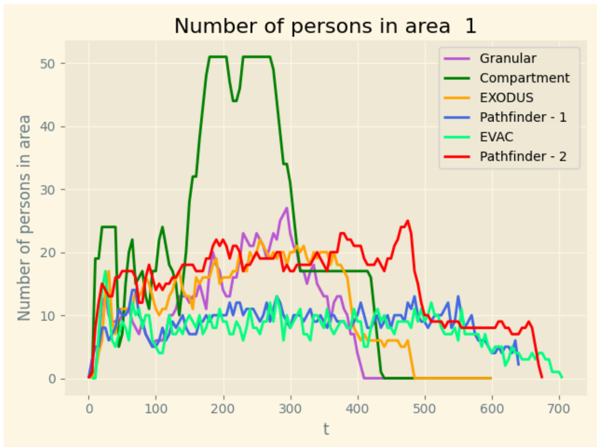


Figure 5: Number of persons in Area 1 vs time

Unsurprisingly some differences appear. The number of persons present at the same time in the area 1 at steady state is of 10 persons for Pathfinder (user 1) and FDS+EVAC, 20 persons for buildingEXODUS, Pathfinder (user 2) and the granular model of Cromosim and 50 persons the compartment model of Cromosim.
Consequently, people do not arrive at the same time at the feet of the egress stairs. Figure 6 to Figure 9 present the number of persons respectively in areas number 7 (left landing of the 3rd floor), 14 (right landing of the 6th floor), 17 and 18 (respectively left and right landings of the 8th floor).

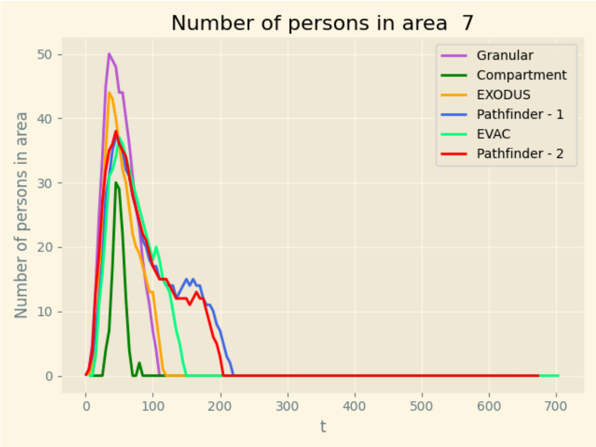


Figure 6: Number of persons in Area 7 vs time

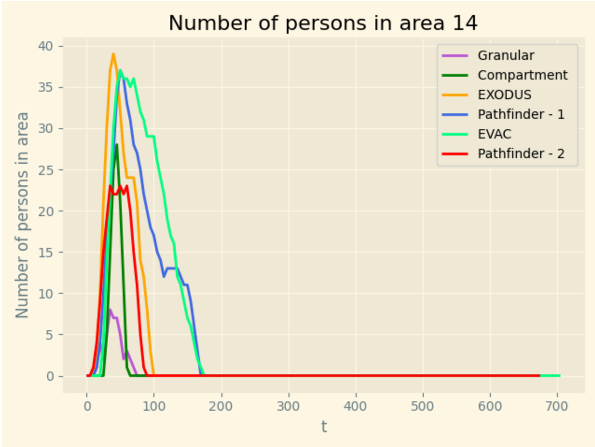


Figure 7: Number of persons in Area 14 vs time

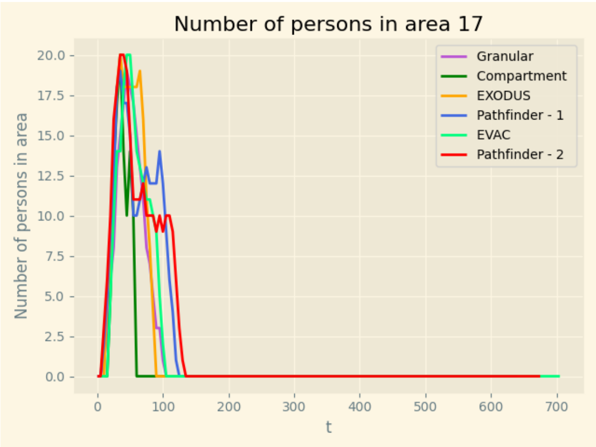


Figure 8: Number of persons in Area 17 vs time

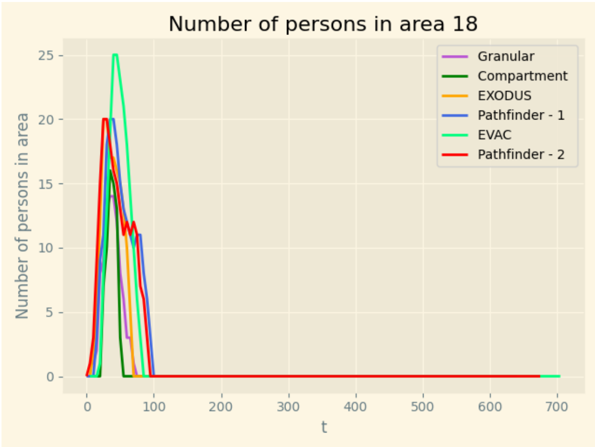


Figure 9: Number of persons in Area 18 vs time

For areas 17 and 18 (8^{th} floor), there was no congestion recorded on the stairs as there were no converging flows (top floor). The maximum number of persons is equivalent for the set of tools as well as the egress rate. It is not the case for areas 7 and 14. For these areas, the maximum number of persons recorded, and the egress rate varies between tools. It probably implies differences in how the tools resolve merging flows/conflicts entering the stair.

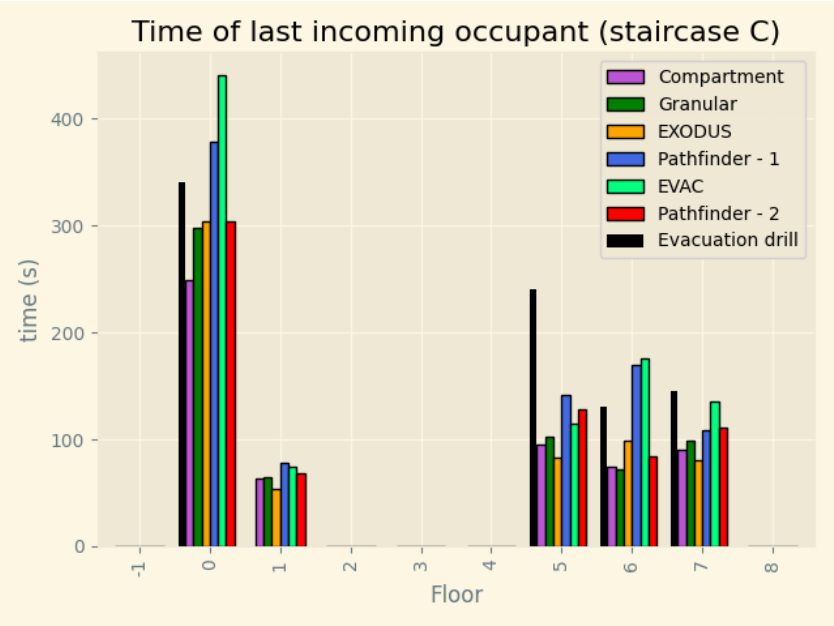


Figure 10: Time for the last occupant to enter in each level of the staircases C (time to exit at the ground floor) – Note: this figure does not include the pre-movement time in the simulation results

This tendency is confirmed by the Figure 10 for staircase C. This staircase is not used on all floors. Two categories of tools in terms of time to exist the landing appear at high densities. The two models of Cromosim (compartment and granular ones) and buildingEXODUS are faster than Pathfinder and FDS+EVAC. This point is to be nuanced because at the 6th floor, one of the two users of Pathfinder obtains a time comparable with Cromosim and buildingEXODUS. This kind of difference occurs occasionally on other staircases. But the tendency stated above applies to most cases and is confirmed by the Table 3 for the main staircases. Moreover, in the scissor stairs 3 and 4 (see location in Figure 1), there are fewer occupants than for staircases A to D and it observed that the variability on the time to exits is lower.
Consequently, the following hypothesis is raised and discussed in the next section: the manner in which each tool models movement and congestion on the stairs, landings and entrances varies and generates consequent differences on the total time to evacuate.

Table 3: Egress time for the last occupant to reach the bottom of the stairs for different tools Note: this table does not include the pre-movement time in the simulation results

	Egress time of the last occupant (s) to reach the bottom of the stairs						
	Pathfinder User 1	Pathfinder User 2	FDS+EVAC	building EXODUS	Cromosim Granular	Cromosim Compartment	Drill
Staircase A	483	405	680	413	343	283	385
Staircase B	614	630	560	459	311	389	335
Staircase C	379	304	440	315	298	249	340
Staircase D	442	418	560	410	353	265	355
Scissor stair 3	147	140	165	124	136	192	175
Scissor stair 4	150	148	185	121	146	199	-

Results from the analytic approach are presented in Table 4.

Table 4: Results of floor by floor calculations using GA 23 analytic approach

Level 8:	**177 seconds**	Level 7:	176 seconds
Level 6:	174 seconds	Level 5:	165 seconds
Level 4:	142 seconds	Level 3:	117 seconds
Level 2:	N/A	Level 1:	92 seconds

The longest evacuation time calculated is at level 8 with a total of 177 seconds (~ 3 minutes). This does not include a pre-movement time.

SYNTHESIS AND DISCUSSION

The initial objective of this research project was to assess a number of evacuation engineering tools (numerical and analytic) using a real case study to create a common base of works. In no way, was the objective to validate a tool over another or to reproduce the case study. This is a first step exercise that paves the way to further evacuation drills' attendance and subsequent modelling. Once the working group is satisfied with the number of data collected and consideration of sufficient parameters, more concrete conclusions will be drawn.

In the Results section above, pre-movement time was added as a simple 50-seconds value to each numerical model. The value was taken from observations made during the evacuation drill. The reason for this is that all models are not able to cater for pre-movement time in a similar manner, therefore creating discrepancies when comparing their results. The method of integration of the pre-movement time in each model will form part of the set of parameters for further studies.

Despite the divergence of the results obtained, the different tools are able to reproduce the evacuation drill with a certain number of fixed input data obtained from on-site observations. The main differences observed for the results are directly linked to the intrinsic differences of the simulation tools.
The softwares broadly represent the inputs provided by the user in terms of maximum crowd density, flow at exits and walking velocities. All tools investigated are able to reproduce specific effects observed during the drill such as congestion, exit selection and queuing at exits.
However, attention must be paid to the interpretation of the results:

- The pre-movement times observed during the evacuation drill vary from a few seconds to slightly more than 1-min; whilst the pre-movement time considered for the numerical models was a fixed value. This means that the models slightly emphasize the congestion phenomena at doors and stairs compared to reality.
- The walking velocities in corridors and stairs provided as inputs were those observed from the drill. Thus, local congestion phenomenon was already included in these reduced velocities although they are comparable to those found in the literature [17]. However, this can cause an accumulation of congestion phenomena in the simulations linked with an additional reduction of the walking velocities. The low travel speeds imposed on the models may therefore already take into account the congestion evident on the stairs – it may therefore have a greater impact on travel speeds than might have originally been the case.

Regarding FDS+EVAC, the agents always try to take the shortest route. Therefore, in the stairs, the agents will all follow this directive and force the passage to follow the interior walls of the stairs. This leads to an inefficient use of available space.
As for buildingEXODUS, the user has chosen to convert egress width of the staircases into a number of lanes. By default, occupants are staggered in stairs leading to an optimal use of the full stair widths. In Pathfinder, FDS+EVAC and buildingEXODUS, localized congestion appears at the entrances of the stair cores due to a narrowing from a circa 1.6m wide stairs to a 0.9m wide door. This leads to lower flow rates that vary across these tools as movement in dense areas is modelled differently. For Pathfinder, the speed-density profile (set by default to SFPE profile) could have a significant impact on the obtained results. Although inputs and geometries were imposed for each tool, the two Pathfinder simulations done by different users lead to slight differences across all levels. This can be related to the geometry implementation, the initial people location or the way of defining exits or stairs.

As for the Cromosim Compartment Model, door capacities are defined as parameters, so that congestion is in some way circumvented, which mechanically leads to smaller egress times than other tools. The Cromosim Granular Model, in spite of its microscopic nature, also produces smaller egress times. This is due to the following fact: with the standard size of individuals and no politeness effects, static jams were observed, leading to infinite egress time. Parameters (size and politeness tendencies) were adjusted to recover realistic capacities, in a way that tends to overestimate them, thereby reducing the computed egress times.

The analytic approach using "Type GA" hand calculations concludes with a maximum evacuation time of circa 3 minutes, which is 43% of the case study evacuation time. Considering a 1 min pre-movement time, this still equates to 57% of the real evacuation time.
This is an important difference that can be explained by what has been witnessed during the evacuation drill as well as in the computer simulation results: merging flows inside the stairs. Whilst queuing at the floor exit access doors is theoretically considered by the flow rates imposed by the code, merging flows inside the stairs and subsequent queuing is not. These effects are seen to create important delays in the evacuation process as they hinder occupants' movements. For that reason, the results of the analytic approach have not been directly compared with those of the case study and computer models. In conclusion, applying "Type GA" calculations to design the egress capacities of an office building is therefore not considered as an appropriate approach.

CONCLUSION, FUTURE PROSPECTS

The presented work is part of a larger study to lay the foundations for good evacuation engineering practices in France. The overall objective of this study is to lead to regulatory changes, which are planned in the medium term.

A variety of tools have been studied, from a simple analytic approach provided by French regulations to full embedded commercial softwares, and also academic tools. The parameters were set in a **blind manner**, i.e. no effort was made to fit the computational results to experimental data by adjusting parameters. Generally, default settings were used unless stated overwise.

The analytical approach largely underestimates the egress time. The results obtained with the other simulation tools range from approximately 450 to 760 seconds, while real drill data falls between those two values. Since some discrepancy could be expected from a drill experiment to another, even under identical conditions, a certain amount of dispersion among numerical results is acceptable. Yet, in the present case of such a simple scenario (there is no fire, no perception of risk, building occupancy is far from being full), the dispersion can be expected to be quite small, much smaller than the observed dispersion among numerical results. This dispersion of values, which is the main outcome of the present work, can be explained by the variety of implementations, which leads to different evolutions of densities. Our opinion is that most discrepancies come from the way clogging in bottlenecks, especially in staircases, is accounted for.

The comparison of numerical results and real-world CCTV footage indeed shows that congestion phenomena around staircases occur too soon when using microscopic simulation tools. This is deemed to be due to an improper accounting of the social interaction and the fact that pre-movement was not accounted for at the start of the simulation. In the drill, the distribution of pre-movement times has led to a faster dispersion of occupants, hence reducing congestion at narrow and merging points.
Indeed, with simple models like the Compartment model or builingExodus that handle door fluxes as input parameters, flow rates do not drop when congestion occurs, therefore the egress time tends to be underestimated. On the other hand, egress time is generally overestimated with more complex microscopic models, where door egress capacity drops when the density around the doors increases. The aforementioned results show that the computation of realistic egress times

mainly relies on a proper account of congestion at bottlenecks / staircases. The handling of these phenomena is quite sensitive to the chosen parameters, in a way that depends on the specific method that is considered, so that dispersion of results is inevitable.
However, anticipating the large gatherings, which will take place in the years to come, the development of accurate and robust predictive models is mandatory. The basic GA23 analytical tool seems to be restricted to basic configuration, and sophisticated approaches to account for topographic or behavioural specificities will be needed. Indeed, merging flows are not adequately considered in such approach.

In view of this objective and in terms of next steps, we will refine our benchmark study by integrating pre-movement times and modifying the speed values. Once our benchmark is consolidated, each model user will investigate the input parameters that have the most impact on the identified elements that lead to differences between the different simulations. We will then attempt to reproduce the experimental results. This will require statistical processing, in particular for stochastic models requiring a certain number of simulations.

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