ISRG PUBLISHERS

ISRG Journal of Engineering and Technology (ISRGJET)

Abbreviated Key Title: ISRG J Eng Technol
ISSN XXXX-XXXX (Online)
Journal homepage: https://isrgpublishers.com/isrgjet/
Volume – Volume – I Issue -I (January- February) 2024
Frequency: Bimonthly

OPEN ACCESS

Modelling and numerical simulation of a building under fire and optimal regulation

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| **Received:** 31.12.2023 | **Accepted:** 03.01.2024 | **Published:** 11.01.2024

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Abstract

This paper proposes an optimal control scheme for the evacuation and fire prevention of a structure, such as ships, high-rise buildings, industrial buildings, or warehouses, that is subject to fire. Large structures present unique challenges for fire prevention, protection, and firefighting due to factors such as increased potential heat load and fire spread, limited access and evacuation, and the height of the structures which can cause significant thermal stress on facades and load-bearing structures leading to ruptures or collapses. Additionally, large structures can have significant environmental and social impacts, particularly in terms of atmospheric pollution, and can disrupt economic activities. It is important to adapt fire safety measures to address these specific characteristics. Controlling the risk of fire in structures with a large number of premises is a significant challenge. This has consequences for people, property, structures, activities, and the environment. Although the stakes may vary, the goal is always the same: to prevent and contain fires, detect them quickly and accurately, evacuate people efficiently, optimize mitigation and extinguishing efforts, and preserve the integrity of the structure and functional networks. There are no simple solutions to these issues. Instead, we propose a hybrid multi-scale approach that combines a fire model at the compartment scale with a network model. This allows us to simulate the spread of fire and smoke throughout the structure in real-time, while also quantifying the time required for safe and efficient evacuation. Currently, the network model calculates smoke transport using a basic filling model. The system was applied to a multi-storey office building to provide real-time disaster mapping, risk forecasting, and assessment of sensitive and vulnerable areas to be defended.

***Keywords:** Modelling, numerical simulation, fire propagation, network model.*

INTRODUCTION

In case of a fire, the safety and well-being of the building occupants is of utmost importance. According to the French Construction and Housing Code, exits and internal clearances leading to them must be designed and distributed in a manner that allows for quick and safe evacuation. Evacuation engineering, which is already widely used internationally, is becoming increasingly important due to the rise in complex construction projects. Given the importance of objective evaluations, there is a growing interest in mastering the different approaches used in evacuation and their limitations. In a fire situation, the effectiveness of this action is generally quantified by an evacuation time, which corresponds to the time interval between the fire alarm being sent to the occupants and the moment when the occupants of a specific part of a building or the whole building are able to enter a safety zone. This article describes a people flow model based on a macroscopic representation of individuals and integrating specific constraints linked to the development of a fire. The main points to be studied with a view to modelling and the different strategies used to optimize the evacuation of people will be identified.

Overview of the network model

The model is based on a network of polydisperse rooms, meaning that the rooms can be of different sizes, and amorphous rooms, meaning that there is no geometric regularity. This enables the model to support a realistic arrangement of rooms with varying complexity. By using information about the connectivity of the rooms, it is possible to define a graphical representation of the existing paths between the different rooms in the structure. Graph theory is a branch of discrete mathematics that deals with networks, such as social networks, communication networks, and

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road networks. The use of network models to solve problems related to the movement of people is a natural application of graph theory. It involves representing a problem as a graph, which consists of nodes connected by arcs. The arcs in question can be assigned both a capacity, which represents the maximum quantity that can be transported along the arc, and a cost. One classic problem in graph theory is connecting two nodes with a path of minimal cost. In evacuation simulation network models [7], nodes typically represent different rooms in a compartment and are associated with their maximum and initial capacities. The language used is clear, concise, and objective, adhering to formal register and conventional structure. Technical terms are explained when first used, and the text is free from grammatical errors, spelling mistakes, and punctuation errors. No changes in content have been made. The arcs represent the passages from one room to another. They are characterised by their maximum capacity, which is the maximum flow of people that can pass from one room to another, and their cost, which is generally the passage time between rooms. Figure 1 shows an example of a connectivity graph for a three-storey building using EVACNET+ software.

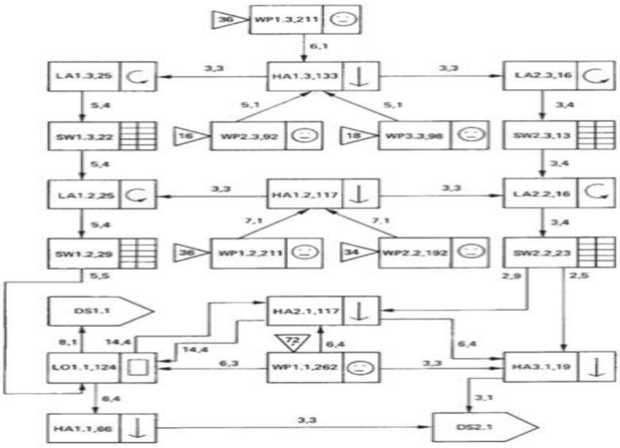

Figure 1: Diagram of the network structure and connectivity graph.

Network models are based on graph theory algorithms, such as shortest path search and minimum cost flow problems, to solve the routing problem. The objective is to calculate the minimum evacuation time required to transport people to a safe area as quickly as possible.

Hypotheses of the model

The proposed model is based on important assumptions and principles that enable a simplified representation.

Flashover occurrence in a room, fire transmission through a barrier, and propagation between rooms are represented by normal probability distributions. Each distribution depends on two parameters: the mean value and the standard deviation. The standard deviation typically represents a fraction of the mean value, usually between 10 to 15 percent.

The probability of transmission through an open door or trap door is always equal to 1. Ignition of a target room, marked 2, adjacent to a burning room, marked 1, only occurs if the fire in room 1 is fully developed and there has been transmission from room 1 to room 2. Fire can transmit through a barrier when the temperature in the target space surpasses a predetermined critical value.

During the decay phase of a fire, the probability of transmission is zero.

Preliminary calculations indicate that the decay phase does not affect fire propagation. For propagation to occur from room 1 to room 2, ignition must take place in room 2 and the fire in that room must be fully developed.

The average flashover time is the time interval between ignition and the moment when the gas temperature in the room reaches a critical temperature, typically between 500 and 600°C.

The zone model determines the average times of flashover occurrence, fully developed fire and decay, as well as fire transmission through barriers, based on room characteristics such as partition type and material(s), heat load, dimensions, insulation or ventilation conditions. These times are calculated for each room in the structure beforehand.

The probability of barrier transmission during the fully developed fire phase is also considered. The probability density function for fire transmission from source room 1 to target room 2 through barrier b during the fully developed fire phase ($0 \le t - t_{fo} \le \tau_{fd}$), where t_{fo} is the time of flashover and τ_{fd} is the duration of the fully developed fire, can be expressed as follows, using σ_b and μ_b to represent the standard deviation and average duration of fire resistance of barrier b:

$$p(1 \to 2) = \frac{1}{\sigma_b\sqrt{2\pi}} e^{\left[-\frac{(t - t_{fo} - \mu_b)^2}{2{\sigma_b}^2}\right]}.$$

The corresponding cumulative probability is :

$$p_b(1 \to 2) = \int_{t_{fo}}^{t} \frac{1}{\sigma_b\sqrt{2\pi}} e^{\left[-\frac{(t - t_{fo} - \mu_b)^2}{2{\sigma_b}^2}\right]} dt$$

In addition to $t_{de} = t_{fo} + \tau_{fd}$, the probability is assumed to be nil.

The error function method is used to calculate the integral, expressing the cumulative probability at time t as follows:

$$p_b(1 \to 2) = \frac{1}{2}\mathrm{erf}\left(\frac{(t - t_{fo} - \mu_b)}{\sigma_b\sqrt{2}}\right) + \frac{1}{2}\mathrm{erf}\left(\frac{\mu_b}{\sigma_b\sqrt{2}}\right).$$

Immediately after flashover, the fire in room i has the potential to become fully developed. The cumulative probability of this occurring is defined by:

$$p_{fd(i)} = \begin{cases} \int_{t_{ig}}^{t} \frac{1}{\sigma_{fo}\sqrt{2\pi}} e^{\left[-\frac{(t - t_{ig} - \mu_{fo})^2}{2{\sigma_{fo}}^2}\right]} dt & if \quad t_{ig} < t < t_{de} \\ 0 & otherwise \end{cases}$$

where σ_{fo} and μ_{fo} represent the standard deviation and the mean time taken to flash over.

Ignition probability

A random number, R_{fd}, between 0 and 1 is generated and compared with the calculated cumulative probability.

$R_{fd} < P_{fd}(i) \to$ fire fully developed

$R_{fd} > P_{fd}(i) \to$ no fully developed fire

If $R_{fd} < P_{fd}(i)$, then the flashover time is equal to the current time, $t_{fo}(i) = t$.

Assumption 3 states that ignition of target location 2 only happens when the fire in source location 1 is fully developed and the fire has spread from location 1 to location 2 through barrier b. Therefore, we can express this in terms of probability:

$P_{ig}(1 \to 2) = P_b(1 \to 2) \times P_{fd}(1)$

The statistical approach involves generating a random number R_{ig} between 0 and 1 and comparing it with the probability of ignition.

$R_{ig} < P_{ig}(1 \to 2) \to inflammation$

$R_{ig} > P_{ig}(1 \to 2) \to$ no $inflammation$

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If ignition occurs, the ignition time of location 2 will be equal to the current time, $t_{ig}(2) = t$.

Probability of spread

When a fire spreads through a building, the heat generated can cause glazing to break. In some cases, the flames can then spread to the floors above. This occurs when the fire in the source room is fully developed and under-oxygenated. The zone model enables determination of the fire's combustion regime, controlled by either ventilation or fuel, and identification of conditions that allow for vertical propagation between floors. Assuming 6, the probability of the fire spreading from room 1 to room 2 is equal to the product of the probability of ignition in room 2 and the probability of a fully developed fire in that room. $P_{fs}(1 \rightarrow 2) = P_{ig}(1 \rightarrow 2) \times P_{fd}(2)$.

Transport of smoke

The model is based on a simple filling approach that assumes the invasion of smoke into the structure is solely dependent on the structure's geometric configuration and the fire's development. This implies a weak coupling between the fire and the structure, assuming that the natural or mechanical ventilation of the structure has no significant impact on the smoke flow.

- The smoke does not affect the burning premises, especially if the smoke can spread over a large area.
- Smoke from the room(s) on fire spreads to connected rooms through open doors or hatches.
- The simplified model uses data from the zone model to calculate changes in smoke flow, density, and temperature for each room on fire, based on the conservation of mass equation. $\frac{d}{dt}(\rho V) = q_f$

The density and volume of the smoke layer are represented by ρ and V, respectively, while q_f denotes the smoke flow rate that accumulates in the room.

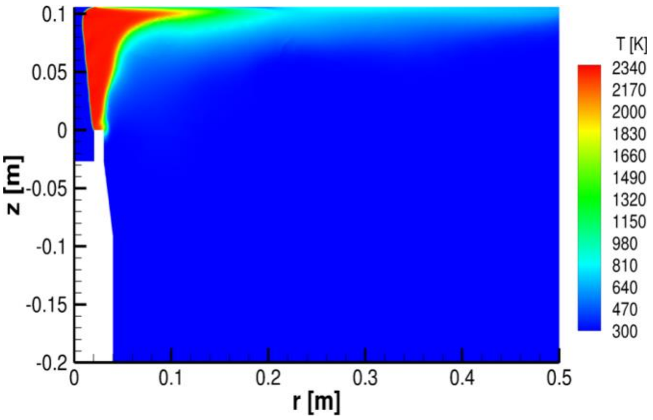
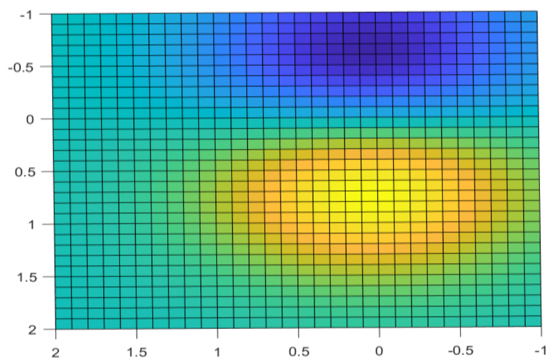


Figure 2: Simulation of the impacting flame concentration field.



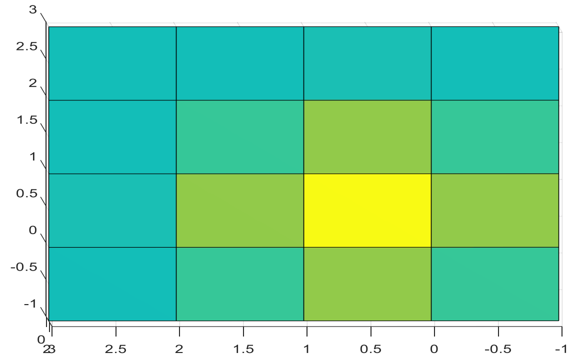


Figure 3: map of the disaster zone

Modelling the movement of people in a structure during a fire

The theoretical foundations and mathematical formulation of the path model are presented. The formulation is dedicated to the case of high population densities and includes a conservation equation with a convection term.

Basic assumptions and mathematical formulation

This article presents a continuous macroscopic model for the transport of people density in a 2D domain. The model follows three simple rules:

Firstly, people move at their free walking speed in the absence of constraints.

Secondly, the walking speed of people is a function of the density of people in their vicinity. Individuals aim to reduce their travel time to the exit and avoid congested areas when necessary.

The issue is presented as a conservation equation for the density of people (represented as ρ) transported in a velocity field ($\vec{v}$). This equation is similar to the continuity equation in fluid mechanics (conservation of mass equation). The equation considers the correlation between an individual's walking speed and the density of people in their surroundings, as determined by the density-velocity relationship.

$$\begin{cases} \frac{\partial \rho}{dt} + div(\rho \vec{v}) = 0 \\ \vec{v} = V(\rho)\vec{U} \end{cases}$$

where $\vec{U}$ corresponds to a velocity field that has been scaled.

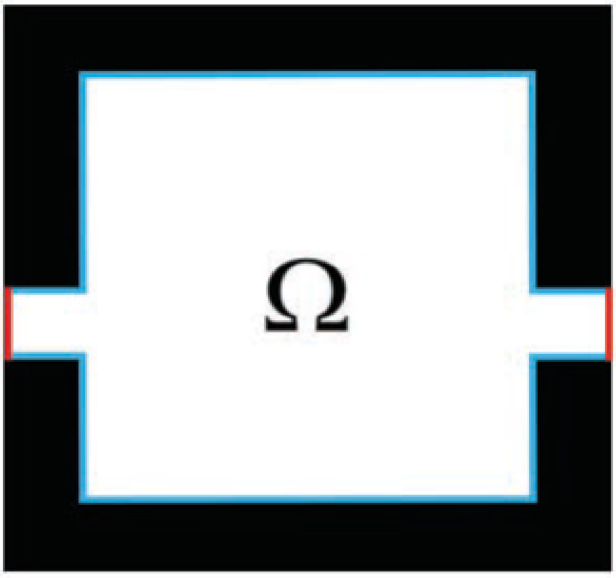


Figure 4: illustrates the calculation domain and its two types of boundary.

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The system of equations is solved in a 2D domain, denoted Ω, which corresponds to the surface on which people move. The boundary of the domain Ω, denoted ∂Ω, can be of two types:
impassable walls and obstacles, denoted $\partial\Omega_w$ (drawn in blue in Figure 2).
- outputs, denoted $\partial\Omega_s$ (drawn in red)
The boundary $\partial\Omega_w$ is an impermeable wall. It is therefore characterised by a "zero flow" type boundary condition: individuals cannot "re-enter" obstacles. The boundary condition at the edge $\partial\Omega_w$ is therefore written as follows: $\rho V(\rho)\vec{U}.\vec{n}|\partial\Omega_w = 0$ where $\vec{n}$ refers to the outgoing normal.
However, the boundary condition at the edge $\partial\Omega_s$ is unrestricted, and no specific limitations on the flow of people are imposed at the exits. Therefore, the flow of people through an opening depends on the density of people present at the exit, any resulting decrease in speed, and the width of the clearance.: $\rho V(\rho)\vec{U}.\vec{n}|\partial\Omega_s = \rho_s V(\rho_s)$ where ρ_s is the density of people at the exit.
The problem at hand necessitates the introduction of an initial condition. The user is responsible for defining the initial distribution of the density of people, i.e. the distribution of people at the start of the evacuation. This distribution must consider the specificities of the compartment under study, particularly the fact that certain areas are more likely to be occupied than others. When the initial distribution of people in a room is unknown, or when dealing with an average scenario, it is advisable to assume a uniform distribution of people over the area. This distribution should be equal to the ratio of the initial number of people (N) to the surface area (S) of the compartment: $\rho(x,y,t=0) = \frac{N}{S}$, $\forall (x,y) \in \Omega$.
Consider a set consisting of N_{pop} different populations characterised by respective densities ρ_1, ..., $\rho_{N_{pop}}$ and respective directions of migration $\overrightarrow{U_1}$, ..., $\overrightarrow{U_{N_{pop}}}$. We note that:
– $\overrightarrow{v_1}$, ..., $\overrightarrow{v_{N_{pop}}}$ are the real velocities of the different populations;
– V_1, ..., $V_{N_{pop}}$ the density-velocity laws characteristic of each population. :

$$V_i(\rho) = V_{0i}\left(1 - \exp(-1{,}913(\tfrac{1}{\rho} - \tfrac{1}{\rho_c}))\right)$$

where V_{0i} is the free running speed for population i.
The convective model can then be written as :

$$\begin{cases} \frac{\partial\rho_1}{dt} + div(\rho_1\overrightarrow{v_1}) = 0 \\ \overrightarrow{v_1} = V_1(\rho_t)\overrightarrow{U_1} \\ \quad \dots \\ \frac{\partial\rho_{N_{pop}}}{dt} + div\left(\rho_1\overrightarrow{v_{N_{pop}}}\right) = 0 \\ \overrightarrow{v_{N_{pop}}} = V_{N_{pop}}(\rho_t)\overrightarrow{U_{N_{pop}}} \end{cases}$$

The total density of people is represented by $\rho_t = \sum_{i=1}^{N_{pop}} \rho_i$
The desired speed of a person at a given point is the speed that allows for the fastest exit, defined as the opposite of the potential gradient. This potential is generally the time required to reach an exit from that point. The direction of the desired speed at point $(x,)$ is determined by: $U(x,y) = -\frac{\vec{\nabla}\gamma(x,y)}{\|\vec{\nabla}\gamma(x,y)\|}\gamma(x,\ y)$
The potential γ(x,y) corresponds to the minimum time needed to walk from point (x,y) to an exit. It is assumed that people have perfect knowledge of the premises, the location of the exits, the density of people they will encounter on their way and the resulting slowdowns. They are therefore able to estimate the minimum time $T_{out}(x,y)$ they will need to reach an exit.

$$U(x,y) = -\frac{\vec{\nabla}T_{out}(x,y)}{\|\vec{\nabla}T_{out}(x,y)\|}$$

The evacuation speed is obtained using the relationship :

$$\vec{v}(x,y) = -V(\rho_t(x,y))\frac{\vec{\nabla}T_{out}(x,y)}{\|\vec{\nabla}T_{out}(x,y)\|}$$

In this study, we examine how individuals adjust their travel speed based on the perceived density of people in their surroundings. Diffusive terms may arise in the model as a result. In the multi-population model, groups of individuals with varying walking speeds and objectives coexist, leading to interactions between populations such as crossovers, overtaking, and counter-currents, which can result in conflicts or annoyances. The walking speed components at the centre of each cell (i,j) are determined.

$$\vec{v}_{i,j} = -V(\rho_{t_{i,j}})\frac{(\vec{\nabla}T_{out})_{i,j}}{\|(\vec{\nabla}T_{out})_{i,j}\|}$$

The finite volume method involves integrating the conservation equation over all cells in the domain for a given population, which are finite 2D 'volumes'. Integrating the equation over a cell $C_{i,j}$ provides:

$$\frac{1}{h^2}\iint_{C_{i,j}}\left(\frac{\partial\rho}{dt} + div(\rho\vec{v})\right)dS = 0 \qquad \text{posing } \vec{\Phi} = \rho\vec{v}$$

$$\Rightarrow \frac{1}{h^2}\iint_{C_{i,j}}\left(\frac{\partial\rho}{dt}\right)dS + \frac{1}{h^2}\iint_{C_{i,j}}\left(div(\vec{\Phi})\right)dS = 0$$

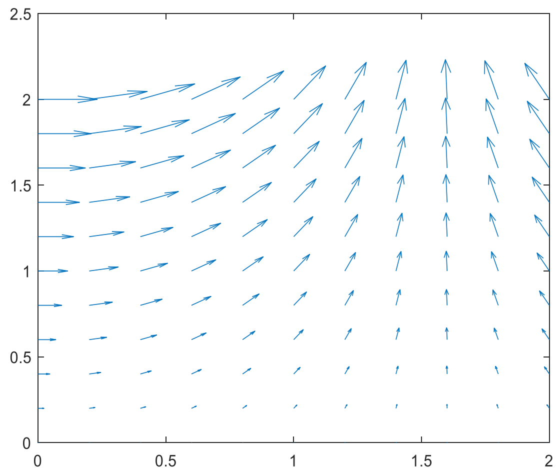
The theorem of flux-divergence enables us to write: $\frac{\partial}{\partial t}\left(\frac{1}{h^2}\iint_{C_{i,j}}\rho dS\right) + \frac{1}{h^2}\iint_{\partial C_{i,j}}\vec{\Phi}.\vec{n}dl = 0$
We will note $\rho_{i,j}$ the value of ρ at the centre of a cell $C_{i,j}$, which corresponds to the average value of the density of people on the cell $C_{i,j}$: $\rho_{i,j} = \frac{1}{h^2}\iint_{C_{i,j}}\rho dS$, we then have

$$\frac{\partial}{\partial t}(\rho_{i,j}) + \frac{1}{h^2}\iint_{\partial C_{i,j}}\vec{\Phi}.\vec{n}dl = 0 \qquad \textbf{(E)}.$$

To discretise equation (E), we will opt for an explicit time scheme: the people density field at time n +1 is a function only of the magnitudes of the problem at time n.
The discrete form of equation (E) can be written as :

$$\frac{\rho_{i,j}{}^{n+1} - \rho_{i,j}{}^{n}}{\Delta t} + \frac{1}{h}\left(\Phi_{i+\frac{1}{2},j} - \Phi_{i-\frac{1}{2},j} + \Phi_{i,j+\frac{1}{2}} - \Phi_{i,j-\frac{1}{2}}\right) = 0$$

$$\Rightarrow \rho_{i,j}{}^{n+1} = \rho_{i,j}{}^{n} + \frac{\Delta t}{h}\left(\Phi_{i+\frac{1}{2},j} - \Phi_{i-\frac{1}{2},j} + \Phi_{i,j+\frac{1}{2}} - \Phi_{i,j-\frac{1}{2}}\right)$$



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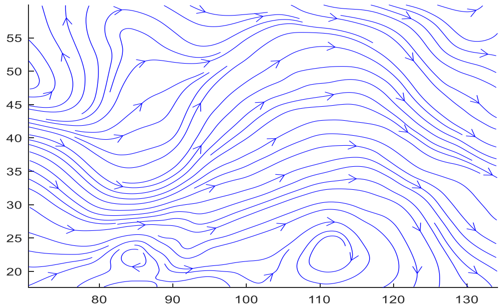

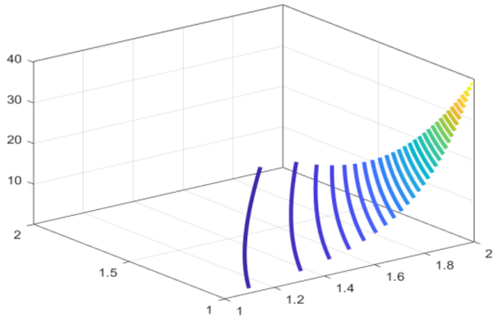

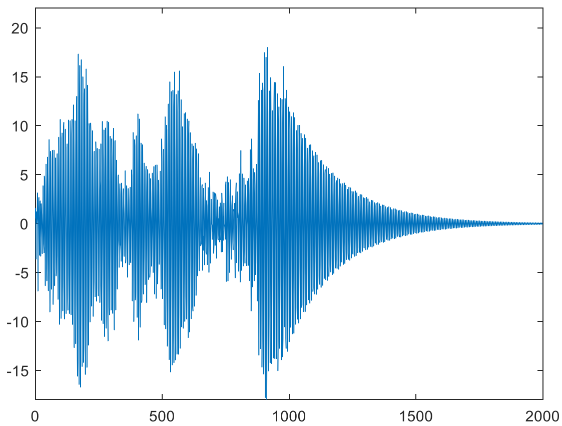

Figure 5: People flow at the outlet over time.

To evaluate convective flows at cell interfaces, velocities must be introduced at those interfaces. These velocity components can then be used to assess the flow of people between neighbouring cells.

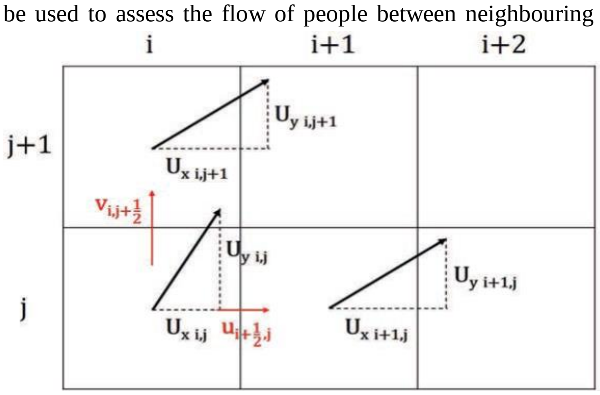

Figure 6: Speed components at cell centres and edges

The component $u_{i+\frac{1}{2},j}$ is calculated in the following way:

$$u_{i+\frac{1}{2},j} = \frac{1}{2}(U_{x\ i,j}V(\rho_{t\ i,j}) + U_{x\ i+1,j}V(\rho_{t\ i+1,j}))$$

The boundary condition between the calculation domain and obstacles must be respected.

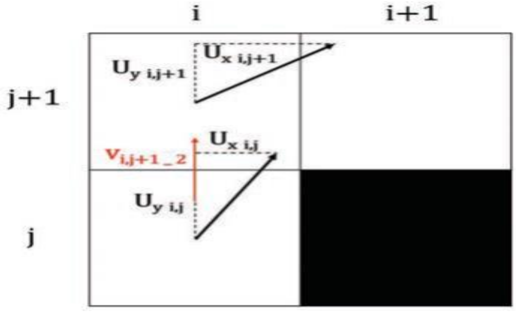

Figure 7: - Evaluation of speeds at interfaces with obstacles

As in the case of the notations in Figure 4. where the cell (i +1,j) is an obstacle, this boundary condition is expressed by: $u_{i+\frac{1}{2},j} = 0$

We seek to determine the expression of the diffusion term in the case of the multi-population model, taking the case of a population i $\in[1, N_{pop}]$. Consider the following Figure 5

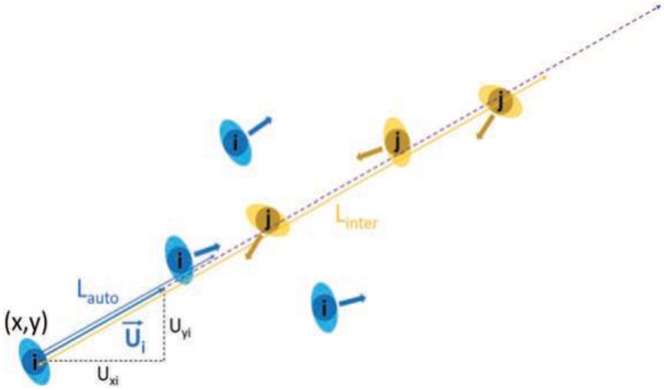

Figure 8: Perception zone of an individual in the multi-population case

The individual adjusts their speed based on the perceived density of people in the direction they are looking $\vec{U_i}$ In the multi-population model, groups of people with varying walking speeds or objectives coexist, leading to interactions such as crossings, overtaking, and counter-currents that may result in annoyances or conflicts. To optimize the exit route, it is necessary to anticipate the evolution of the wider population, rather than assuming everyone is walking in the same direction. This means that the interaction distance L_{ij} between individuals from different groups is greater than the interaction distance L_{ii} between individuals from the same population. The walking speed of population i at point (x,y) and time t is:

$$v_i(x,y,t) = V_i(\sum_{j=1}^{N_{pop}} \rho_j(x + L_{ij}U_{xi,y} + L_{ij}U_{yi,t}))$$

The system of equations for population i is then written:

$$\begin{cases} \dfrac{\partial\rho(x,y,t)}{\partial t} + div(\rho_i(x,y,t)\vec{v_i}(x,y,t)) = 0 \\ \vec{v_i}(x,y,t) = V_i(\sum_{j=1}^{N_{pop}} \rho_j(x + L_{ij}U_{xi,y} + L_{ij}U_{yi,t}))\vec{U_i} \end{cases}$$

Experimental set-up to validate the model

Consider a rectangular room measuring 102 square metres (8.5 m wide and 12 m long), with a single passageway unit 2 m wide (Figure 6).

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Figure 9.1 Photo of the room

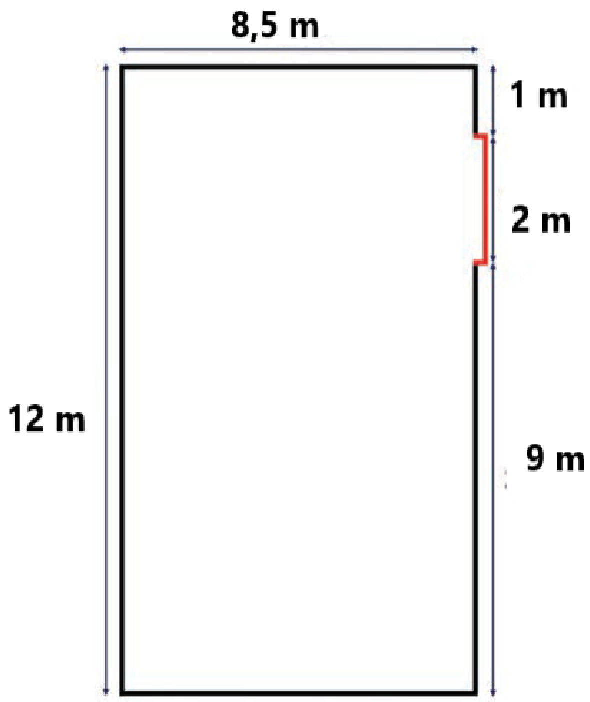

Figure 9.2: Configuration Diagram

The experiment proceeds as follows:
Each person is positioned according to their assigned initial position and orientation, which is chosen randomly from one of the 40 cells on the grid drawn on the floor.
One person, designated at random, gives the signal for the evacuation to begin. This enables the stopwatch to be started and the reaction time to be taken into account for video analysis. The people then leave the room**.**

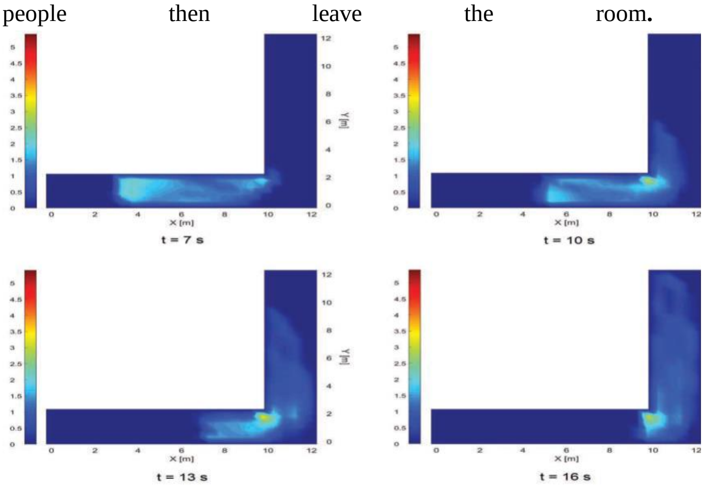

Figure 10: Spatial distribution of population density at four different points in time

Results analysis

The numerical and experimental results indicate two important findings (**Figure 5)**. Firstly, there is a significant difference between the experiment and the simulation regarding the exit time of the first person. According to the numerical simulation, the density of people begins to leave the compartment approximately 3.5 seconds after the start signal. This is because the simulation assumes that the reaction and pre-movement times of the people are zero and that the acceleration phase does not exist. From time t=0, it is assumed that people are travelling towards the exit at speed V_0. In practice, participants have a reaction time of approximately one second, followed by a brief phase of orientation towards the exit and acceleration. It is important to note that, unlike the simulated scenario where the density of people is uniform throughout the room, individuals tend to leave an empty space of 1 to 2 metres around the door at the start of the experiment. This partially explains why the first people to leave the compartment did so about 6 seconds after the start of the sound signal. However, the experimental observation of the average flow of people at the exit 0,59$m^{-1}.s^{-1}$ differs from the value predicted by the code 0,91 $m^{-1}.s^{-1}$. This discrepancy may be due to the parameter set used for the simulation (V_0 = 1,25 m. s^{-1}, ρc = 5,4 m^{-2}) not being the most suitable for characterising our population sample.

Conclusion

The primary concern in the event of a fire is the safe evacuation of individuals. Therefore, during building construction, the layout of the premises and emergency exits are of utmost importance as they can facilitate the swift and secure evacuation of occupants. To this end, evacuation engineering tools have been developed to simulate the movement of people in a given configuration and optimize the size of evacuation resources. In light of future developments in evacuation engineering, it is necessary to master evacuation modelling. The language used is clear, objective, and value-neutral, with a formal register and precise word choice. This article aims to establish a reliable model for simulating the evacuation of people from a building during a fire. The structure follows a logical progression with causal connections between statements. The text is free from grammatical errors, spelling mistakes, and punctuation errors. No changes in content have been made. The project's approach can be broken down into several stages. Firstly, a model for the movement of people based on a macroscopic approach was developed. Secondly, the impact of fire on people was considered, including toxic effects such as asphyxiation, irritation, or narcosis, thermal effects such as heat flow and temperature, and optical effects mainly caused by soot particles. Finally, evacuation procedures were analysed.

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