

EVACUATION MANAGEMENT IN MIXED INDUSTRIAL BUILDINGS THROUGH DYNAMIC HUMAN FLOW MODELING

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Abstract: Ensuring safety in complex industrial environments requires a transition from static evacuation plans to dynamic models. This paper aims to optimize evacuation flows within a mixed-use production facility, employing an advanced digital approach to identify zones of vulnerability. The methodology combines architectural reconstruction in AutoCAD with computer simulations of fire scenarios in Pyrosim and evacuation flows in Pathfinder. The computational model reproduces the complexity of human behavior by integrating varied reaction times, adapting movement speeds based on the occupants' demographic profile, and modeling their tendency to use familiar access routes rather than the nearest emergency exits. The results demonstrate that implementing a phased evacuation strategy, through the temporal staggering of alarms across levels, eliminates critical congestion phenomena. By prioritizing the evacuation of the ground floor and intermediate levels, followed by a controlled delay for the upper floors, vertical flow fluidization and a significant reduction in total egress time are achieved. The study thus validates that the strategic planning of alarm sequences can replace costly structural modifications, providing an applied solution for eliminating bottlenecks and optimizing the evacuation process for occupants in mixed industrial structures.

Keywords: simulation, fire, evacuation, alarming, congestion

1. Introduction

Occupant safety in industrial settings is a critical aspect of operational management and occupational health and safety. Unlike residential or commercial buildings, industrial structures are characterized by complex designs, the presence of hazardous materials, and an inherent risk of major accidents, such as gas leaks, explosions, or rapidly spreading fires. In the face of these risks, the ability to evacuate personnel quickly and safely becomes vital, where effective planning can prevent loss of life.

2. The importance of using computational simulations to evaluate occupant evacuation scenarios

Traditionally, evacuation plans have been based on prescriptive regulations and periodic practical drills. Although these

methods remain fundamental, they have limitations. A routine drill cannot accurately replicate the stress, panic, potential physical bottlenecks, and unpredictability of a real-life crisis situation. For this reason, computer-based evacuation simulations have become an indispensable planning and analysis tool.

Accurately assessing the health consequences of an accident depends on realistically anticipating the movement of exposed individuals, especially when evacuation is the primary safety measure. A well-founded evacuation model precisely indicates the distribution of the population in space and time. By correlating this data with the evolution and intensity of the hazards triggered by the accident, an objective and clear estimate of the actual impact on human health is obtained [1-2].

Live evacuation drills are a cornerstone of safety protocols, but the ability to objectively analyze and optimize them has often been constrained by human limitations. In this context, computer simulations, integrated with other technologies such as virtual reality, smart sensors, and video analysis tools, represent a technological solution that is revolutionizing this field [3].

These tools are used to estimate the time required to evacuate people to a safe area, while also analyzing the factors that influence the efficiency of the process (travel times and population density), as well as the environmental conditions to which occupants are exposed [4-5].

3. The risks to which occupants of an industrial building are exposed

In the event of a fire in an industrial building, occupants are exposed to a range of major risks, which can be classified as direct risks (physically caused by the fire) and indirect risks (associated with the evacuation process, human behavior, and the specific characteristics of the environment).

Direct risks to health and life:

- Inhalation of smoke and toxic gases: When people are trapped inside a building during a fire, they are at risk of suffocation due to exposure to harmful smoke. Smoke inhalation is a major cause of injury.
- Thermal burns: Direct contact with flames or exposure to extreme temperatures can cause minor or severe burns, which often require medical treatment [6].
- Death: Due to the harsh industrial environment, fires can be fatal.

Indirect risks to health and life:

- Crowding and crushing: In panic-stricken and life-threatening situations, people's normal behavior changes radically. During an evacuation, people may be pushed, struck, or crushed by the rest of the crowd. This psychological behavior (which includes pushing and panic

reactions) often leads to stampedes and is a major secondary cause of injury and death.

- Slowing down the evacuation flow: Extreme psychological reactions, such as screaming, shouting, and the tendency to form groups, can dangerously slow down the overall evacuation process, prolonging the time spent exposed to danger [7].
- Quickly spread of fire and blocked exits: Industrial fires (often caused by electrical short circuits or gas leaks) can spread extremely quickly over large areas, blocking escape routes and trapping occupants inside the building [8].

4. Analysis of factors influencing the evacuation process in an industrial setting

Modeling and optimizing the evacuation process requires a systemic approach capable of integrating the complex interactions between the physical environment, hazard dynamics, and the characteristics of the exposed population. The analysis of evacuation performance is based on the assessment of three major categories of influencing factors.

4.1 Factors resulting from the dynamics of the fire

The progression of a fire determines the level of danger in the environment and directly affects the "mobility" (ability and speed of movement) of the occupants. This progression is indicated by the following parameters:

- Thermal radiation: The amount of heat emitted by burning surfaces and materials.
- Smoke dynamics: Temperature variations and the descent of the smoke layer into the passageway.
- Air toxicity: Concentrations of asphyxiant and irritant gases, such as carbon monoxide and carbon dioxide, which rapidly impair occupants' motor and orientation functions.

4.2 Human factors

Beyond environmental conditions, variables related to traffic volume fundamentally alter actual travel times:

- **Occupancy density:** This refers to the degree of crowding in a space and has been identified as the human factor with the greatest impact on the overall efficiency of an evacuation.
- **Age composition:** This is the second most important variable, directly influencing the group's physical agility and initial walking speed—parameters that decline in proportion to advancing age.
- **Gender:** The ratio of men to women introduces variations in the average weight, height, and agility of the simulated population [9].

5. Computer simulation of the evacuation process

This chapter presents an evaluation of the exhaust system's efficiency using a series of computational modeling tools. The analysis was conducted on an industrial building

consisting of a ground floor dedicated to production processes (where the main fire source was simulated) and four administrative floors.

The implementation of the 3D space used for the simulations involved drafting the basic geometry in AutoCAD (2D), followed by the use of Thunderhead Engineering software suites for the advanced stages. The three-dimensional model and fire dynamics were created in PyroSim [10], while human behavior and evacuation times were calculated using Pathfinder.

For a realistic simulation in PyroSim, the combustion intensity was defined using the HRRPUA parameter (Heat Release Rate per Unit Area), whose curve is shown in Figure 1. The set value was 550 kW/m², corresponding to polyurethane. The choice of this material is justified by its widespread use in the industrial sector, where it is found both in building structures (panels, insulation) and in technological and logistical processes.

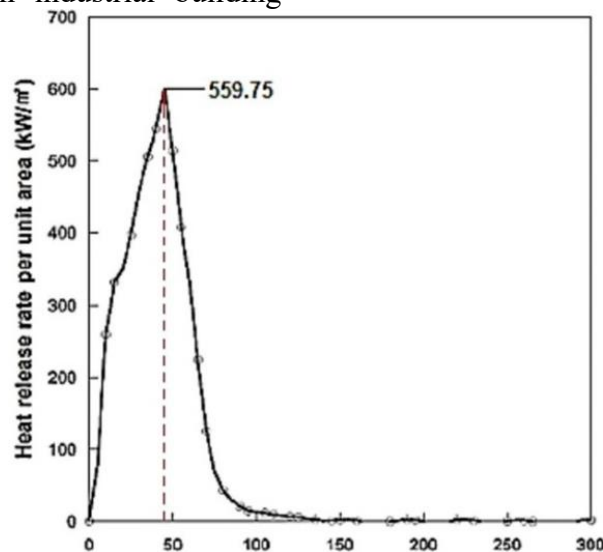


Figure 1: Heat release rate for polyurethane [11]

Pathfinder is evacuation simulation software developed by Thunderhead Engineering that uses agent-based modeling to accurately replicate human behavior in emergency situations, enabling precise estimates of evacuation times from a building [12]. To perform the analysis in the Pathfinder

program, two scenarios were defined involving the evacuation of 169 people, located throughout the building. The modeling was based on assigning unique movement profiles, defined according to each individual's characteristics (age and gender). Additionally, the velocity dynamics

were established in relation to the type of movement, distinguishing between

horizontal movement (Table 1) and vertical movement (Table 2).

Table 1. Horizontal travel speed

Age	Gender	Travel speed [m/s]
< 29 years old	M	1,77
< 29 years old	F	1,64
30 - 50 years old	M	1,87
30 - 50 years old	F	1,75
> 50 years old	M	1,42
> 50 years old	F	1,35

Table 2. Speed of movement on stairs

Age	Gender	Travel speed [m/s]
< 29 years old	M	0,82
< 29 years old	F	0,59
30 - 50 years old	M	0,69
30 - 50 years old	F	0,50
> 50 years old	M	0,56
> 50 years old	F	0,47

6. Scenario analysis

The first scenario involves the uncoordinated evacuation of occupants in the event of a fire breaking out on the ground floor (which houses the production area), with no specific order; each person moves quickly toward the nearest exit. The second scenario involves implementing a phased evacuation process to streamline the evacuation. In the event of a fire breaking out in the production area, occupants are

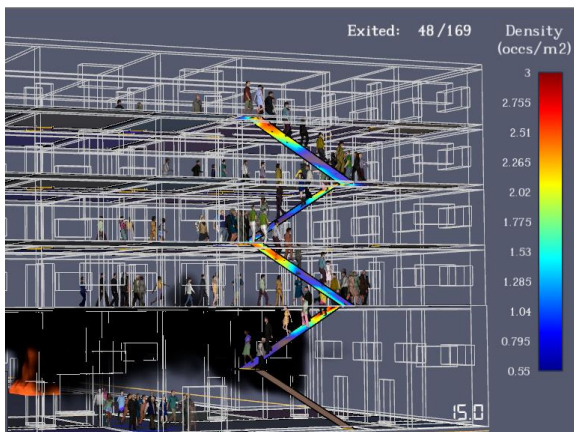
instructed to follow specific procedures based on their floor location: people on floors 1 and 4 begin moving within the first few seconds of the fire breaking out, occupants on floor 2 start the evacuation process after 55 seconds, and those on the 3rd floor begin moving after 80 seconds. The difference between the two scenarios lies in the phased evacuation, with all other parameters remaining unchanged.



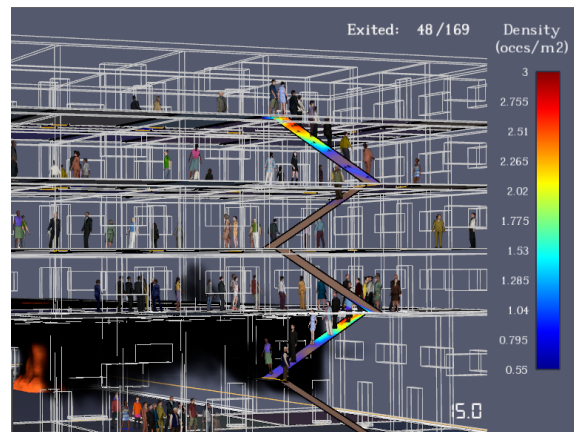
Figure 2: Illustration of the evacuation process for occupants on the ground floor after 10 seconds for both scenarios

In the first 10 seconds after the fire broke out (Figure 2), for both scenarios, we observe both the exposure of personnel in the production area to extreme conditions and the rapid spread of the fire in its initial phase. This demonstrates a complex evacuation process, especially for people on the upper floors, with the simulation indicating that

only 28 of the total 169 people were evacuated during this time. Furthermore, this number consists entirely of occupants from the lower level, as it is observed that the occupants from the upper floor who were in the stairwell had not yet reached the lower level.



a



b

Figure 3: Illustration of the evacuation process after 15 seconds for Scenario 1(a) and Scenario 2(b)

In the first scenario (Figure 3a), a free and simultaneous evacuation leads to an increase in density at all access points to the stairwell within the first 15 seconds. In contrast, the phased evacuation strategy in the second

scenario (Figure 3b) prevents the early formation of bottlenecks, keeping the intermediate landings completely clear to allow occupants on the upper floor to descend smoothly.

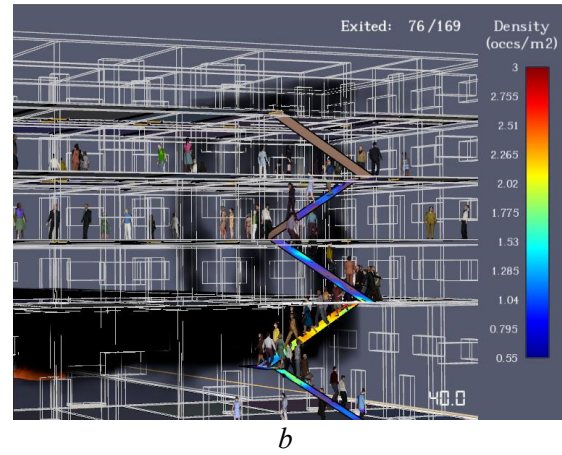
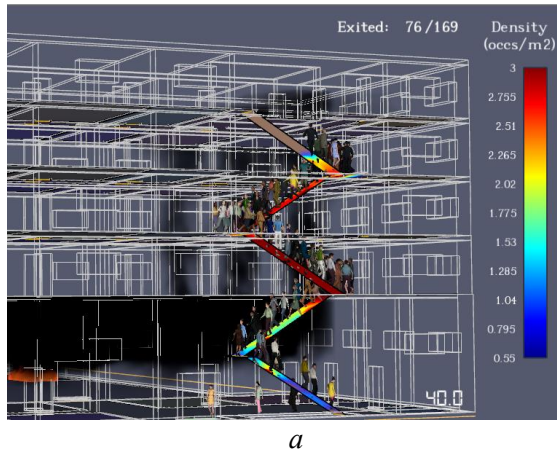


Figure 4: Illustration of the evacuation process after 40 seconds for Scenario 1(a) and Scenario 2(b)

At the 40-second mark of the simulation (Figure 4a), a free-flow evacuation causes a bottleneck in the stairwell, reaching critical crowding levels of up to 3 people per square meter, with occupants exposed to smoke.

In contrast, the phased evacuation strategy (Figure 4b) prevents overcrowding of the route, maintaining a smooth downward flow for occupants on the top floor, with optimal density values of 1–2 people/m².

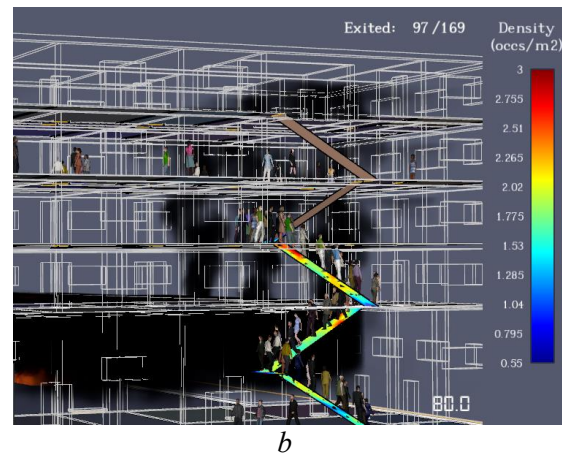
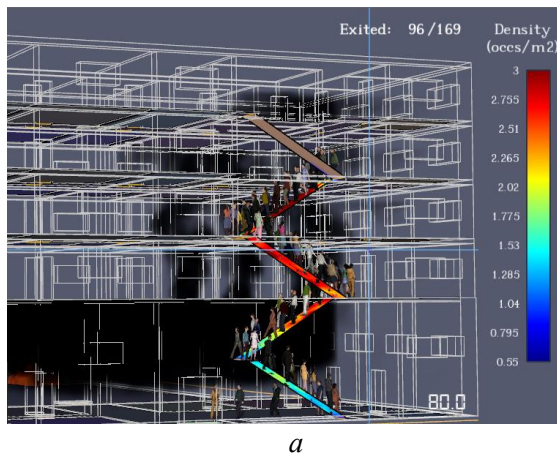


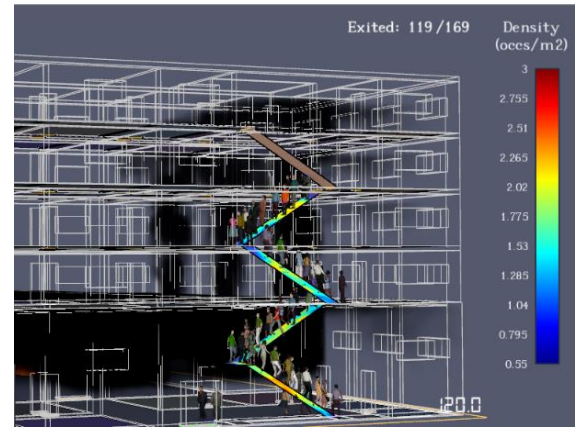
Figure 5: Illustration of the evacuation process after 80 seconds for Scenario 1 (a) and Scenario 2 (b)

At the 80th second of the simulation, it can be seen how a free evacuation (Figure 5a) prolongs the critical congestion phase, maintaining a high density (values around 2–3 people/m²) throughout the entire stairwell, slowing the progress of all occupants. In contrast, the phased evacuation strategy demonstrates the effectiveness of controlled decongestion (Figure 5b): although

occupants on the 3rd floor are just beginning to move at this point, the upper levels are already cleared, and the lower flights of the stairwells show a continuous flow, with optimal densities of no more than 1–2 people/m², with minimal exposure to smoke and temperature conditions for each individual.



a

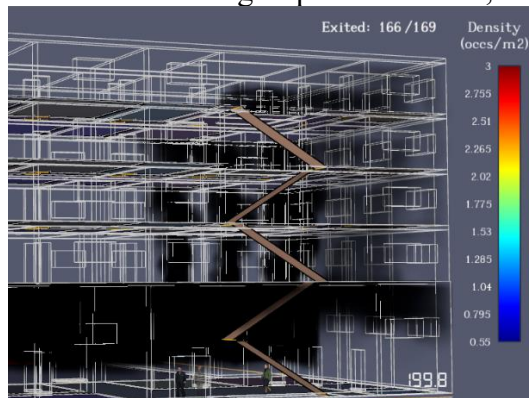


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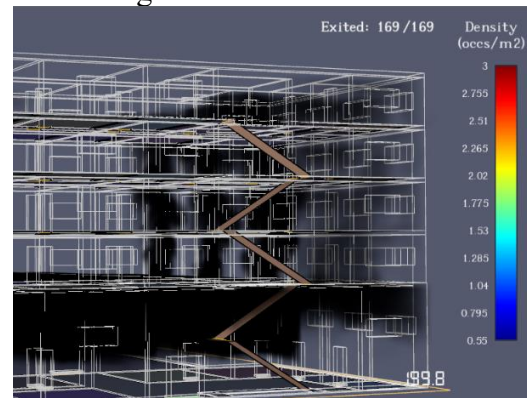
Figure 6: Illustration of the evacuation process after 120 seconds for Scenario 1(a) and Scenario 2(b)

At 120 seconds, free evacuation (Figure 6a) maintains congestion zones at the base of the staircases, with densities reaching the threshold of 3 people/m², thereby blocking the exit of the last groups. In contrast, the

phased evacuation strategy (Figure 6b) ensures a much more uniform movement, with most sections exhibiting optimal density values, which confirms the smoothing of the evacuation flow.



a



b

Figure 7: Illustration of the evacuation process after 199.8 seconds for Scenario 1(a) and Scenario 2(b)

At 199.8 seconds, the phased scenario completes the evacuation of the entire group of 169 people, with the stairwell and circulation areas completely cleared (Figure 7b). In contrast, the first scenario (Figure 7a) requires a total of 205 seconds to complete, with this delay caused by severe congestion and density bottlenecks that occurred during the process.

7. Conclusions

A comparative analysis of the two scenarios highlights that implementing a phased evacuation process is a technically superior solution to a free-flow evacuation, with a

direct impact on occupant safety. While simultaneous evacuation caused severe congestion in the stairwell, with critical densities of up to 3 people/m², the strategy based on delay times allowed for the segmentation of the flow of people. By keeping the intermediate floors on standby, an optimal density of approximately one person/m² was ensured, facilitating a smooth and steady movement. Although the final time difference was approximately 5 seconds (199.8 seconds versus 205 seconds), the major benefit of phasing lies not only in the total duration but in eliminating the risk of a stampede and reducing the physical and

psychological stress caused by prolonged blockages in the evacuation routes.

The dynamics of vertical evacuation in the stairwell revealed a bottleneck in the flow, with the overall speed being determined by the occupants with the lowest mobility (0.47 m/s). This deceleration is caused by the restrictive geometry of the space, which limits the possibility of overtaking and forces each person to match the walking speed of the individual in front. To capture and analyze these complex pedestrian dynamics, simulations conducted in environments such as Pathfinder and Pyrosim prove to be fundamental tools for fire safety engineering, offering a quantitative perspective impossible to obtain

through conventional field exercises. These systems allow for the precise modeling of building geometry and the individual behavior of occupants based on real-world parameters, such as age and gender. The importance of these simulations lies in their ability to anticipate congestion points and areas of dangerous density before they manifest in a real-world scenario. Thus, authorities and designers can validate complex evacuation strategies, optimizing spatial configurations and intervention protocols to demonstrate that, in the event of a fire, the evacuation process exhibits a high degree of reliability, minimizing risks to occupants and keeping evacuation times within regulatory tolerance limits.

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