NUMERICAL SIMULATION ANALYSIS OF THE IMPACT OF SPRINKLER SYSTEMS ON THE EVACUATION PROCESS IN PRODUCTION FACILITIES

Andrei-Cătălin CARAGEA

"Transilvania" University of Brasov, Romania (a.catalyn@yahoo.com)

DOI: 10.19062/2247-3173.2026.27.13

Abstract: *The paper analyzes the efficiency of sprinkler systems during the evacuation process in the event of a fire occurring in a production hall. The research employs computational modeling to evaluate in parallel two comparative scenarios: the development of a fire source in an unprotected hall and an equivalent scenario equipped with active suppression systems. The results demonstrate that the presence of these installations is decisive for ensuring occupant safety. In the absence of active protection, toxic gases and high heat flux rapidly invade access routes and vertical circulation spaces, compromising visibility and survivability limits. In contrast, the activation of sprinkler systems facilitates environmental cooling and the maintenance of smoke stratification at ceiling level. Thus, thermal values along exit routes remain within safe limits, preventing occupants' exposure to extreme temperatures. Even under conditions of pedestrian congestion along evacuation routes, fire control through cooling ensures the time interval necessary for safe egress from the enclosure. In conclusion, the research demonstrates that the utility of sprinkler systems extends beyond the protection of structural integrity, representing the critical element for safeguarding the physical integrity of occupants and ensuring viable evacuation conditions. Beyond their fundamental role in protecting infrastructure and limiting fire spread, the efficiency of these systems may constitute the determining factor in maintaining occupant survivability limits.*

Keywords: *simulation, fire, sprinklers, evacuation, management.*

1. INTRODUCTION

The integration of advanced technologies and the automation of complex industrial processes have significantly altered the risk profile in the production sector. A major accident within a production facility can generate severe consequences for the health and safety of personnel, the integrity of material assets, and the economic continuity of the organization [1]. In practice, companies with a complex organizational structure or multiple operational sites often face a lack of uniformity in protective measures, with safety levels varying from one section to another, even when the industrial activities are of the same nature.

2. FUNDAMENTAL ELEMENTS OF FIRE IN THE PRODUCTION SECTOR

From a fire safety perspective, it represents a self-sustaining combustion process that develops uncontrollably in time and space, exceeding safety limits and endangering personnel and the integrity of assets within the affected perimeter.

A fire is dependent on and sustained by three vital elements: an ignition source, fuel, and an oxidizer (oxygen in the air). In the absence of any of these elements, the fire cannot be initiated or maintained [2].

The ignition source is defined as a release of heat, flame, or spark capable of raising the temperature of materials to the point of ignition and represents a triggering element of the fire. In industrial environments, these sources are closely linked to daily activities, organized into the following defining categories: mechanical and thermal (welding operations, heating equipment, friction), electrical (overloading of equipment, defective wiring and electrical networks), and chemical (residues, industrial materials).

Fuel is represented by any substance capable of sustaining combustion, influencing the intensity and rate of fire development. In a production facility, it belongs to various categories depending on its intended use, such as: raw materials (solvents, liquefied gases, reagents), materials for logistics and storage (plastics, rubber, packaging), as well as materials specific to the construction of the hall (finishes, thermally insulated panels with combustible cores, fine powders resulting from the manufacturing process).

Oxygen is a vital chemical element that supports the combustion process and is present in the air within the hall. In certain production environments, this oxygen supply is amplified by the presence of oxidizing chemical substances, as well as by industrial activities that generate oxygen. In the case of a fire initiated in a hall, its rate of development is conditioned by the volume of oxygen within the enclosure.

3. CLASSIFICATION OF FIRE PROTECTION SYSTEMS IN THE INDUSTRIAL ENVIRONMENT

Maintaining an optimal level of fire safety in the industrial environment is directly conditioned by the implementation of active protection systems, such as sprinkler installations and automatic detection and alarm systems. Their use plays a fundamental role in reducing response time through early-stage fire detection and in limiting its development [3]. In this context, through early detection and control of combustion, personnel safety is ensured, facilitating optimal conditions for evacuation.

At the industrial level, fire safety architecture is based on three main categories of active protection: fire detection, smoke management, and automatic suppression.

The first category is represented by detection and alarm systems, whose role is to identify the fire source at an early stage. The technologies employed range from smoke detectors (optical or aspirating) to temperature, flame, and flammable gas sensors. The primary function of these devices is to activate acoustic and visual warning systems, thereby facilitating the rapid initiation of occupant evacuation procedures.

The second category consists of active systems for controlling the spread of smoke and hot gases (smoke extraction), intended to protect the building and ensure evacuation routes [4]. These installations (with natural draft through vents or mechanical draft through fans) operate in synergy with the building's passive protection elements (compartmentation systems). Thus, upon alarm activation, elements such as fire-resistant doors and curtains or dampers on ventilation ducts close automatically, physically isolating the affected sector and preventing the migration of flames and smoke to other sections of the production facility [5].

The third category includes automatic suppression systems, which act directly on the combustion process by cooling the fuel material or by reducing the concentration of the oxidizer. The standard option for industrial buildings is represented by water-based installations, such as sprinkler networks.

In the case of specific hazards where water may trigger secondary chemical reactions, alternative technologies are employed, such as mechanical foam systems for flammable liquids and inert gas systems for the protection of sensitive electronic equipment, acting by reducing the oxygen concentration below the threshold required to sustain combustion.

4. ROLE AND OPERATING MECHANISM OF SPRINKLER SYSTEMS

Within production facilities and industrial warehouses, automatic sprinkler systems represent the central element of the active fire protection strategy. Their role is to detect and act rapidly on the fire source in its incipient phase, limiting flame propagation, reducing temperatures, and protecting both the structural integrity of the building and personnel safety.

The operation of a standard sprinkler system is strictly local, individual, and is based on a direct thermodynamic principle. Each sprinkler head functions as an independent temperature sensor, being equipped with a thermosensitive locking element consisting of a glass bulb containing an expandable liquid or a fusible element made of a metallic alloy. When the hot gases generated by a fire rise to ceiling level and reach a specific critical temperature (for example, 68°C or 93°C), the liquid inside the bulb expands until it breaks the glass or until the fusible element melts.

In the case of a fire within a production hall, it is necessary for the sprinkler suppression system to fulfill a series of complex functions in managing the emergency situation, acting beyond simple fire extinguishment. Through its intervention, water absorbs a significant portion of the energy released by the fire source, leading to a rapid decrease in temperature and a reduction of the thermal load within the enclosure. This direct action also ensures the isolation of the fire strictly at its point of origin, as localized activation above the affected area immediately blocks fire migration. The efficiency of the entire process relies on functional interdependence with smoke extraction systems, where, concurrently with flame suppression, the sprayed water cools the volume of generated smoke, facilitating the extraction and removal of toxic gases before they spread throughout the building.

Beyond the direct control of flames, the operation of sprinkler systems supports the maintenance of a layer of clean air at a tolerable temperature in the lower part of the hall. Preserving visibility at an optimal level beneath the smoke layer is an essential condition both for the safe completion of operator evacuation and for facilitating access and intervention by professional firefighting crews.

5. ANALYSIS OF THE EFFICIENCY OF SPRINKLER SYSTEMS ON THE EVACUATION PROCESS

To evaluate the efficiency of sprinkler installations, the case study employs the numerical modeling of a fire in a modern industrial building arranged over four levels. The conceptual model reflects a mixed architectural configuration, commonly encountered in practice, where the ground floor combines the production area with administrative spaces, while the following three floors are exclusively designated for offices. This geometry was specifically chosen to analyze a critical safety issue concerning the evacuation process of occupants from the upper floors in the event that a fire breaks out at ground level, within the production area, thereby directly threatening evacuation routes.

5.1 Input data. The computational analysis was based on the use of a set of dedicated software programs. In the first phase, the basic geometry of the structure was modeled in 2D format using AutoCAD software. For the subsequent stages, the software suite developed by Thunderhead Engineering was employed. Thus, the PyroSim program was used to construct the 3D model (FIG. 1) and to simulate fire dynamics, including sprinkler activation [6], while the Pathfinder program was used to model human behavior and to calculate evacuation times [7].

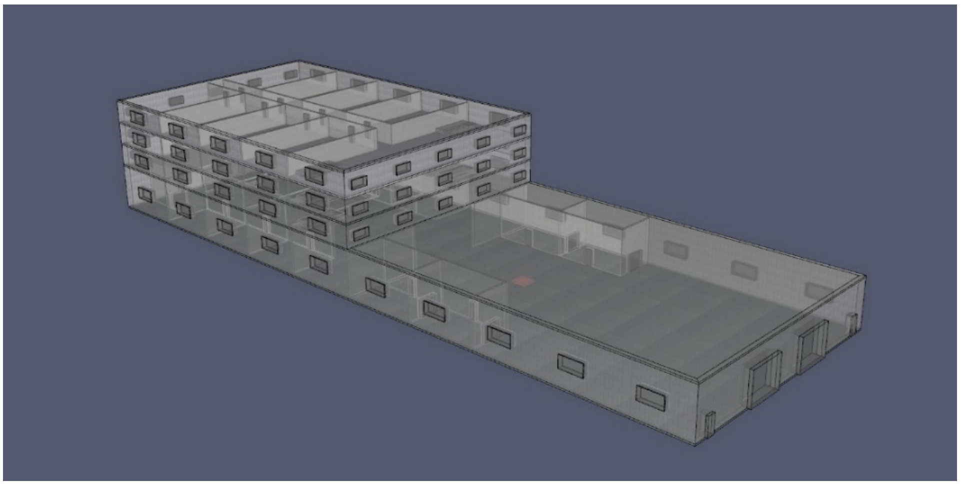


FIG. 1 Illustration of the industrial building in 3D format in PyroSim

In order to achieve an analysis faithful to reality, each program was assigned specific input data. In the PyroSim environment, the fire source intensity was defined through the HRRPUA (Heat Release Rate Per Unit Area) parameter, whose evolution curve is illustrated in FIG. 2.

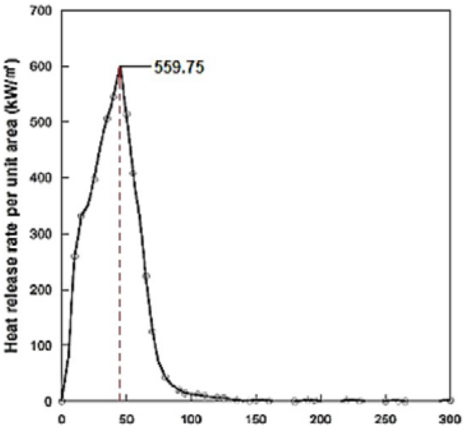


FIG. 2 Heat release rate per unit area curve for polyurethane [8]

The value selected for this parameter was 550 kW/m², reflecting the specific combustion characteristics of polyurethane. This is one of the most widely used materials in the industrial production sector, being utilized both in the structure of halls (sandwich panels and thermal insulation foams) and in technological processes (packaging materials, insulation, furniture components).

In the Pathfinder simulation environment, the analyzed scenario included a total of 168 occupants, distributed across all levels of the building.

The evacuation dynamics were modeled based on specific biometric parameters (age and gender). Thus, each occupant was assigned an individualized movement profile, ensuring realistic variability of speeds throughout the simulation. At the same time, the software algorithm allowed for the automatic adjustment of transit speed depending on the geometric characteristics of the route, making a clear distinction between horizontal movement speed (whose values are detailed in Table 1) and the specific evacuation speed on stairs (illustrated in Table 2).

Table 1. Horizontal movement speed

Age (years)	Gender	Movement speed (m/s)
< 29 years	M	1,77
	F	1,64
30 - 50 years	M	1,87
	F	1,75
> 50 years	M	1,42
	F	1,35

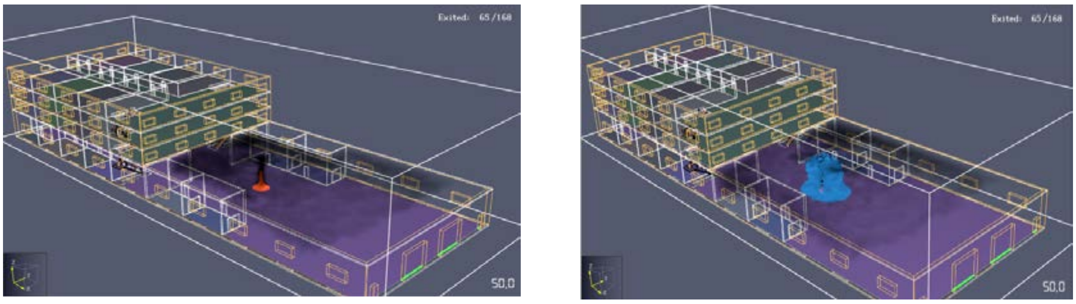
Table 2. Movement speed on stairs

Age (years)	Gender	Movement speed (m/s)
< 29 years	M	0,82
	F	0,59
30 - 50 years	M	0,69
	F	0,50
> 50 years	M	0,56
	F	0,47

Based on these input data, two analysis scenarios were constructed. The first scenario involves simulating the fire in a situation where the sprinkler system is completely deactivated. Its objective is to observe the natural dynamics of combustion, the manner in which smoke propagates within the industrial platform, and to determine the time interval in which environmental parameters become critical for survival. The second scenario maintains constant the ignition source and the building geometry, but introduces into the model the sprinkler network installed at ceiling level. The purpose of this simulation is to record the response time of the thermal sensors (calibrated at 68°C) and to demonstrate how water discharge halts the increase of the heat release rate (HRR curve), cools the layer of hot gases, and limits fire propagation. In order to highlight the impact of sprinkler systems, the evaluation of results is based on a parallel analysis of the two scenarios, directly comparing survivability parameters and evacuation efficiency.

The analysis of results was structured along two main directions: visual and thermal. The visual analysis examines the manner in which the smoke layer propagates within the building and along evacuation routes, highlighting the imminent risk of inhalation of combustion gases. For the thermal analysis, the “2D slices” (two-dimensional sections) function was used. This tool facilitates the monitoring of temperature variations in relation to simulation time, thereby enabling an objective evaluation of occupant evacuation conditions.

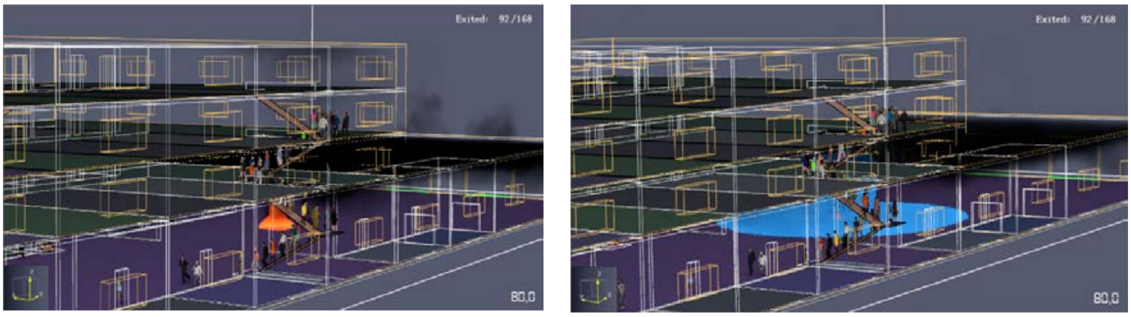
5.2 Visual analysis. To facilitate comparative evaluation, simulation frames were extracted at predefined time intervals, thus highlighting the key stages of smoke layer development in both scenarios.



(a) (b)

FIG. 3 Smoke development stage after 50 s with the sprinkler system deactivated (a) and activated (b)

After 50 seconds, in the scenario with inactive sprinklers (FIG. 3a), a stratification of smoke concentration above the fire source can be observed, migrating toward the stairwell. In the case of the scenario with an active system (FIG. 3b), 10 seconds after sprinkler activation, they isolate the fire source and reduce the amount of smoke generated by the initiated fire. At this analyzed moment, occupants located on the upper levels are not directly affected by the release of hot gases.

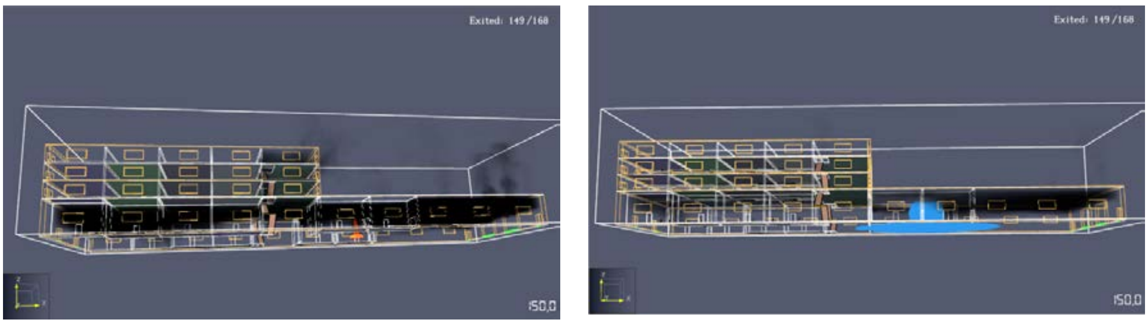


(a) (b)

FIG. 4 Smoke development stage after 80 s with the sprinkler system deactivated (a) and activated (b)

At the moment recorded after 80 seconds, the simulation (FIG. 4a) captures the formation of a congestion of occupants at the intermediate level of the stairwell. A major difference between the two scenarios is represented by the dynamics of smoke migration. In the first scenario, the smoke layer rapidly rises to the breathing zone of individuals engaged in the evacuation process. Due to the reduced movement speed induced by the blockage at the stairwell level, occupants are exposed for an extended period to a mixture of hot and toxic combustion products, leading to the loss of motor coordination.

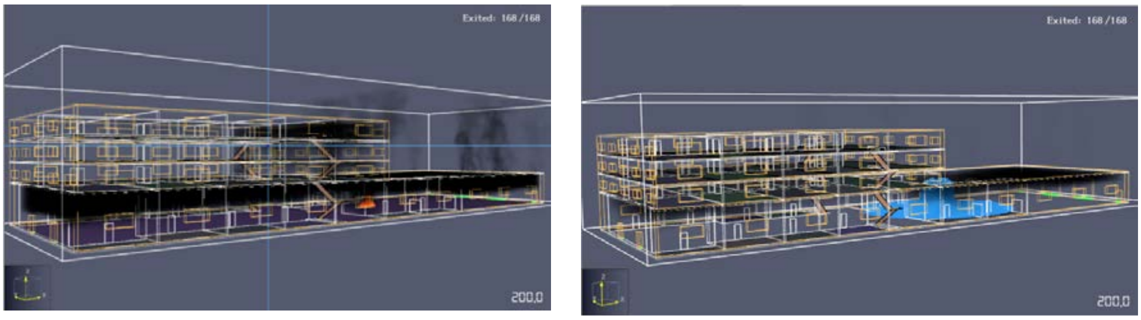
In contrast, the activation of the sprinkler system (Fig. 4b) limits the spread of smoke strictly to the fire source area, allowing for safe evacuation even under conditions of sustained physical congestion along the evacuation route.



(a) (b)

FIG. 5 Smoke development stage after 150 s with the sprinkler system deactivated (a) and activated (b)

At 150 seconds after the outbreak of the fire, the analysis highlights, in the case of inactive protection systems (FIG. 5a), the complete smoke inundation of the ground floor level, as well as the penetration of smoke to the top level of the stairwell, compared to the other scenario in which the quantity of smoke occupies half of the ground floor area and the stairwell, respectively. For a total of 168 occupants (representing a minimum number relative to the number of spaces), the movement of the last 19 occupants is carried out exclusively through smoke in the first scenario, compared to the other scenario (FIG. 5b), in which the smoke layer is thin and present only in the area where the fire occurred, the evacuation being performed under optimal conditions.



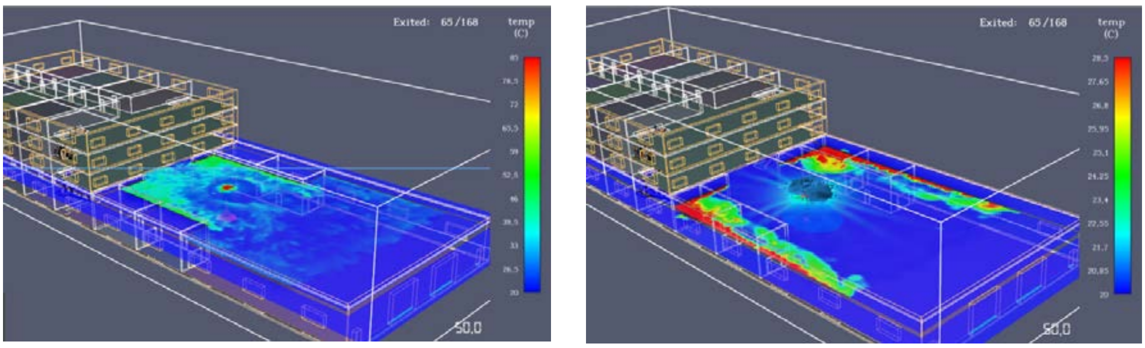
(a) (b)

FIG. 6 Smoke development stage after 200 s with the sprinkler system deactivated (a) and activated (b)

The moment marked by the 200th second represents the final phase of evacuation of the 168 occupants. By comparison, in the first scenario (FIG. 6a), the penetration of smoke at the level of all circulation routes is visible, conditions that endanger the safety of workers, especially in the case of a larger number of occupants.

In the second scenario (FIG. 6b), the fire source is inundated with water and no longer generates smoke. Additionally, in this scenario, the smoke that entered the stairwell has been naturally removed, which would have allowed for a prolonged evacuation of occupants if their number had been significantly higher.

5.3 Thermal analysis. This section analyzes the direct impact of temperature variation during the evacuation process, evaluating the physiological consequences on occupants, ranging from simple thermal discomfort to the risk of burns.



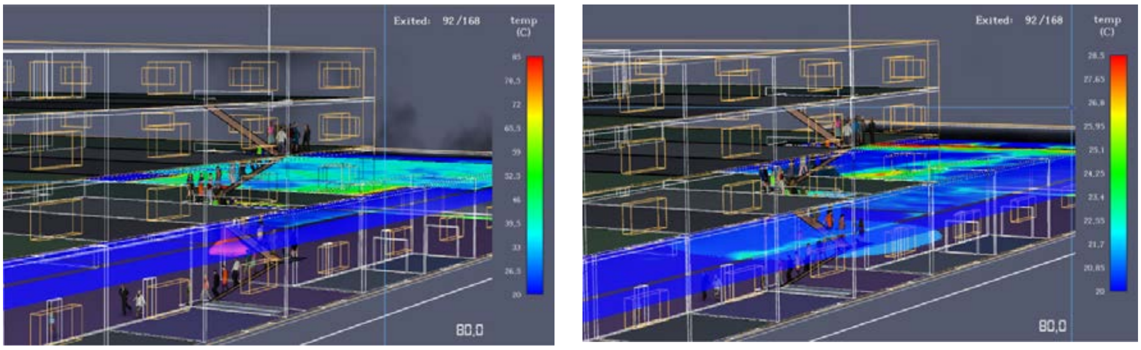
(a) (b)

FIG. 7 Temperature level after 50 s with the sprinkler system deactivated (a) and activated (b)

At the 50-second interval, the thermal analysis of the scenario with the sprinkler system deactivated (FIG. 7a) indicates the propagation of a front of gases with temperatures ranging between 35°C and 50°C toward the stairwell.

This thermal gradient generates immediate discomfort, the values being directly perceived by individuals engaged in the evacuation process.

In contrast, in the scenario with an active suppression system (FIG. 7b), the temperatures recorded at the level of emergency exits vary within a much safer range (25°C–28.5°C), with heat dissipation occurring in a controlled manner through these openings. Moreover, along the main evacuation routes, thermal values remain at an ambient level of approximately 20°C, allowing occupant movement to take place under normal thermal conditions.

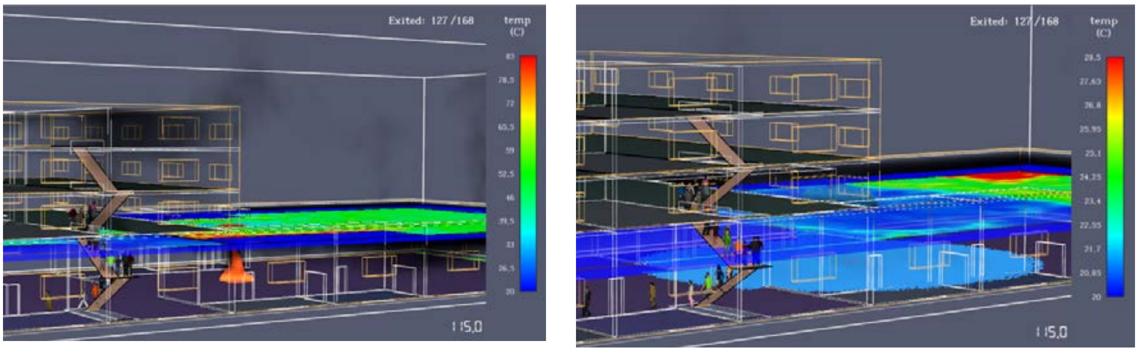


(a) (b)

FIG. 8 Temperature level after 80 s with the sprinkler system deactivated (a) and activated (b)

At the interval of 80 seconds from the initiation of the fire source, the thermal analysis of the reference scenario (FIG. 8a) highlights the propagation of a front of gases with temperatures ranging between 40°C and 65°C toward the evacuation routes. This thermal mass interacts directly with occupants whose movement speed is already reduced due to congestion, generating pronounced thermal discomfort and triggering the first respiratory difficulties.

In contrast, in the scenario protected by active systems (FIG. 8b), a dispersion of the warm air mass is observed exclusively toward the peripheral areas of the hall (in proximity to windows). Along the main circulation routes, thermal values remain below the threshold of 24°C, ensuring the continuation of the evacuation process under maximum safety conditions.

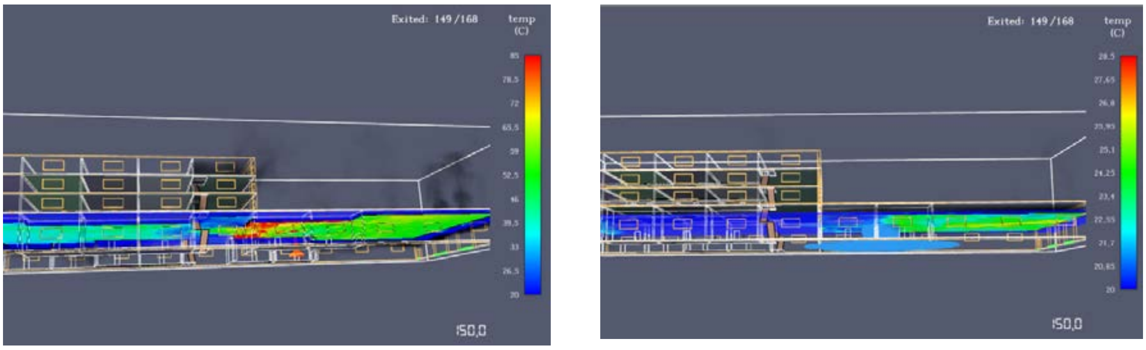


(a) (b)

FIG. 9 Temperature level after 115 s with the sprinkler system deactivated (a) and activated (b)

After 115 seconds, in the case of inactive systems (FIG. 9a), a temperature variation of 50–70°C is recorded, predominantly at ceiling level within the fire-affected compartment. The temperatures present at the stairwell level are slightly lower compared to previous values; however, prolonged exposure may cause thermal discomfort and minor burns.

The activation of the sprinkler system (FIG. 9b) controls temperature variation, with the analyzed areas presenting an average value of 25°C, indicating occupant safety during the evacuation process.

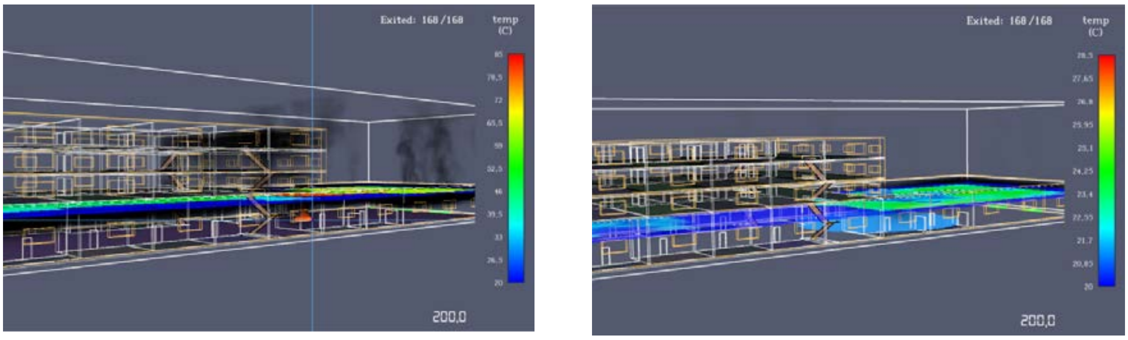


(a) (b)

FIG. 10 Temperature level after 150 s with the sprinkler system deactivated (a) and activated (b)

At the 150-second interval, the thermal analysis of the reference scenario (FIG. 10a) indicates a severe degradation of the environment, with the area in the immediate vicinity of the stairwell recording temperatures of 85°C. Simultaneously, within the stairwell, thermal values exceed the threshold of 60°C. This exposure to acute thermal stress severely compromises the tenability limits for the last occupants along the evacuation route, generating an imminent risk of heat exhaustion and burns.

In contrast (FIG. 10b), in the scenario protected by active systems, the temperature in the vicinity of the evacuation route remains at ambient values of 20°C. Moreover, the combustion gases stratified beneath the ceiling register a thermal maximum of only 26°C within a limited perimeter of the ground floor, confirming the system's efficiency in absorbing thermal energy and maintaining a safe transit environment.



(a) (b)

FIG. 11 Temperature level after 200 s with the sprinkler system deactivated (a) and activated (b)

The end of the simulation finalizes the scenarios from the perspective of safety regarding the thermal exposure of personnel within the building. For the first scenario (FIG. 11a), an average temperature of 85°C is observed in the fire source area, while at ground floor level a uniformly distributed temperature of approximately 70°C is recorded. Along the evacuation route at ground floor level, the temperature ranges between 50–55°C.

For the second scenario (FIG. 11b), at the level of the production area the temperature does not exceed 27°C, while along the ground floor evacuation route the temperature reaches maximum values of 22°C.

CONCLUSIONS

The analysis of visibility and fire dynamics demonstrates that the operation of sprinkler systems has a significantly greater influence on building safety than the mere control of flames. By absorbing the thermal energy of the fire source and limiting the propagation of combustion products, active protection directly supports the maintenance of a safe transit environment. This environmental stabilization has a dual fundamental value, ensuring both the completion of occupant evacuation within tenability limits and the preservation of clear routes for the access and effective intervention of professional response teams.

A critical aspect highlighted by the simulation results is the direct dependency relationship between the number of occupants, building architecture, and the time available for safe evacuation. Although the analyzed scenario evaluated a minimum flow of 168 occupants, the occurrence of congestion at the stairwell level was observed, which extended the time required for evacuation. By extrapolation, it can be concluded that, in the case of a higher occupant load, the probability of safe evacuation would be compromised in the absence of active protection.

By synthesizing these concepts, the paper validates the fundamental importance of risk assessment through advanced computational simulations (FDS and Pathfinder). The modeling of these particular scenarios provided an analytical perspective on the interaction between fire dynamics and crowd behavior. Digital evaluation enabled the quantification of vulnerabilities, demonstrating that computational simulations represent a fundamental tool for testing and optimizing modern fire safety strategies.

REFERENCES

[1] *** Parliament of Romania, *Law no. 307 of July 12, 2006 on fire protection*, Official Gazette no. 633 of July 21, 2006;

[2] ***HM Government. *Fire safety risk assessment: factories and warehouses*, London, Department for Communities and Local Government Publications, 2006;

[3] A. M. Jones, Jr., *Fire Protection Systems*, ed. 3. Burlington, MA: Jones & Bartlett Learning, 2021;

[4] A. G. S. Doğuç, Z. Şimşek and N. Yamankaradeniz, „Smoke Evacuation in Industrial Buildings”, *International Journal of Applied Science and Technology*, vol. 4, nr. 3, pp. 184-191, 2014;

[5] K. Kempna et al., „Fire Safety Protection Assessment of Industrial Technologies”, *IOP Conference Series: Journal of Physics*, vol. 1107, 042036, 2018;

[6] *** Thunderhead Engineering. *PyroSim User Manual*, Version: 2022-1, Manhattan, KS, USA, 2022. Available at www.thunderheadeng.com, accessed on 20 Apr. 2026;

[7] *** Thunderhead Engineering. *Pathfinder User Manual*, Version: 2021-4, Manhattan, KS, USA, 2021. Available at www.thunderheadeng.com, accessed on 20 Apr. 2026;

[8] P. Setyadi and D. Muflihah, *Analysis of fire simulation on polyurethane foam using FDS in a university meeting room*, Journal of Applied Engineering and Technological Science, vol. 4, no. 2, pp. 644-654, 2023.