

Article

Integrated Performance of Sprinkler and Natural Smoke Ventilation Systems in Warehouses: A CFD-Based Evaluation Using PyroSim

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Abstract

This study examines the interdependent performance of fire detection systems, automatic sprinklers, and natural smoke ventilation in warehouse environments. Using computational fluid dynamics (CFD) simulations with PyroSim and FDS, four operational scenarios were analyzed to evaluate system activation sequences and suppression effectiveness. Results show that ceiling-only sprinklers may limit fire growth but fail to achieve extinguishment, while integrated in-rack sprinklers with coordinated venting provide full suppression and optimized thermal control. The findings underscore the importance of performance-based, integrated design strategies to enhance fire protection and minimize property losses.

Keywords: fire protection; warehouse fire safety; smoke control; sprinkler systems; natural smoke ventilation systems



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1. Introduction

Modern warehouse facilities, often characterized by open floor plans, tall storage racks, and substantial combustible loads, demand rigorous fire safety design methodologies. While prescriptive codes provide baseline requirements for active suppression and smoke control systems, performance-based design (PBD) approaches allow greater flexibility and optimization through simulation-based validation.

Among the critical components of warehouse fire protection systems are automatic sprinkler systems, responsible for active fire suppression, and natural smoke ventilation systems (NSVS), tasked with managing smoke stratification and maintaining tenable conditions. The performance of these systems, however, is not independent. Instead, their interaction can either enhance or compromise safety outcomes depending on the degree of integration during the design phase [1,2].

The existing scientific literature reveals a limited number of studies that independently investigate the performance of sprinkler systems and natural smoke ventilation systems, with comparatively little attention given to their mutual interactions. The complex dynamics between these two safety mechanisms play a crucial role in determining the overall efficiency of fire protection strategies within large enclosures. A comprehensive understanding of their interdependent behavior is therefore essential to optimize fire safety design,

improve evacuation conditions, and enhance the resilience of building infrastructures during fire events.

Yaxin, T. et al. [3] investigated the influence of hollow floor panels in mezzanine shelving systems on fire dynamics and the performance of automatic sprinkler systems in logistics warehouses. Using Fire Dynamics Simulator (FDS), the research evaluates smoke temperature distribution and establishes a quantitative relationship between sprinkler activation temperature and the hollowing rate, modeled as $Y = a(1 - e^{-bx})$. The results indicate that increased hollowing rates elevate smoke temperatures and accelerate sprinkler activation, while the strategic placement of sprinkler heads directly above hollow panels is critical for effective fire suppression. These findings offer valuable insights for optimizing sprinkler system design and enhancing fire risk mitigation in warehouses equipped with mezzanine flooring. In addition to internal warehouse configurations, external environmental factors can also strongly influence smoke behavior and fire protection performance. For instance, Wegrzynski, W. et al. [4] demonstrated how wind conditions and surrounding architectural features affect smoke control and dispersion near buildings using 25 CFD simulations conducted with ANSYS Fluent (version R12.2). Their results show that wind velocity and direction can significantly alter the effectiveness of building smoke venting systems, sometimes enhancing exhaust flow through façade inlet–outlet arrangements, while also modifying the shape and spread of smoke plumes. Urban canyon effects and vortices around tall structures may lead to smoke accumulation in distant areas, impacting visibility and traffic safety. These findings underscore the importance of coupled wind–fire modeling for accurately assessing fire risk, enhancing urban preparedness, and mitigating the environmental impacts of large-scale fires.

Ho H. et al. [5] conducted research to analyze fire protection challenges in Automatic Storage and Retrieval System (ASRS) warehouses, which feature increased storage height and density. Field surveys and experiments in Taiwanese ASRS facilities revealed that while most in-rack sprinkler systems comply with existing standards, their fire suppression performance is often inadequate under standard design parameters. Improved effectiveness was achieved through optimized sprinkler positioning, discharge pressure, and spacing from stored goods. The study provides practical recommendations and a flowchart for designing efficient in-rack sprinkler systems to enhance ASRS warehouse fire protection. Building upon this, recent experimental and modeling efforts achieved by Han, D. et al. [6] have aimed to develop a new approach for estimating sprinkler protection requirements in warehouse storage. This methodology integrates predictive models for water penetration effectiveness, critical delivered flux, and fire plume/ceiling jet dynamics to determine the optimal sprinkler discharge density and number of activations for various storage configurations. Large-scale fire tests using solid-stacked plastic pallets validated the model, showing good agreement with experimental data and less than 20% error. These findings contribute to a more reliable and cost-effective framework for designing and optimizing warehouse fire protection systems.

A study conducted by Trapp A.C. et al. [7] introduces an optimization-based tool for enhancing fire protection design in warehouses by simulating fire behavior and evaluating the effectiveness of different sprinkler configurations, both in-rack and ceiling-mounted. The research demonstrates that fire control efficiency depends not only on the number of sprinklers but critically on their placement. Through simulation optimization, the study identifies minimal and effective sprinkler configurations, emphasizing the importance of strategic positioning. Future research aims to extend this model to more complex storage geometries and analyze cost-performance tradeoffs in sprinkler system design. Expanding on previous research focused on optimizing sprinkler configurations for effective fire

suppression, the study conducted by Suhaimi N.S. et al. [8] examined smoke behavior in high-rack warehouses using computational fluid dynamics through the Fire Dynamics Simulator (FDS). The work highlights the significant risk that smoke poses to human life and explores how factors such as building height, ventilation, and fire source type influence smoke temperature and dispersion. By modifying the model across multiple fire scenarios, the study finds that greater building height and natural ventilation lead to lower smoke temperatures, while the type of fire source has a notable impact on smoke dynamics. These findings result in three key recommendations designed to guide engineers and architects in creating safer and more resilient warehouse and atrium designs. This study aims to quantify the interdependence between these systems through CFD simulations using Smokeview, a visualisation tool for FDS. The simulation models fire growth, smoke behavior, and system response in a warehouse environment, enabling engineers to assess efficiency, compliance, and robustness.

Given the complex interaction between fire dynamics, system response, and architectural configuration in warehouse environments, this study seeks to advance the understanding of how fire detection, suppression, and smoke management systems perform under realistic operational conditions. Emphasizing the importance of integrated, performance-based design approaches, the research combines numerical simulation with engineering analysis to assess the efficiency and coordination of fire protection systems. Accordingly, the main contributions of this work are summarized as follows:

- i. Demonstration of the “umbrella effect” generated by the upper racks on fires occurring on the lower racks, within realistic storage configurations, and its influence on fire and smoke behavior.
- ii. Provision of quantitative data through CFD simulations regarding the delay time in sprinkler system activation, as a function of space configuration and organized natural ventilation.
- iii. Evaluation and optimization of natural smoke ventilation systems, with the potential to formulate recommendations applicable to the practical design of commercial and industrial spaces.
- iv. Establishment of a preliminary step toward proposing a replicable methodology aimed at addressing existing legislative gaps, which can be applied to the evaluation and design of other fire safety systems.

2. Materials and Methods

2.1. Warehouse Fire Safety Context

Warehouses constitute large-volume enclosures with high storage densities, making them particularly vulnerable to rapid fire growth and smoke accumulation. The architectural features relevant for fire safety analysis include:

- High fire load density due to stored goods, packaging, and plastic commodities.
- Vertical heat and smoke stratification in tall-rack storage arrangements.
- Delayed detection and suppression caused by ceiling height and plume entrainment.
- Extended evacuation times resulting from large floor areas and occupant distribution.

These conditions require integrated fire safety systems that address both active suppression and smoke management simultaneously.

The reference building represents a modern logistics warehouse, characterized by large unobstructed spaces, tall storage racks, and a high combustible load. The geometry (Figure 1) was modeled as a rectangular enclosure of $66\text{ m} \times 25\text{ m} \times 12\text{ m}$ ($L \times W \times H$). The roof was assumed to be a lightweight steel construction, with negligible thermal inertia.

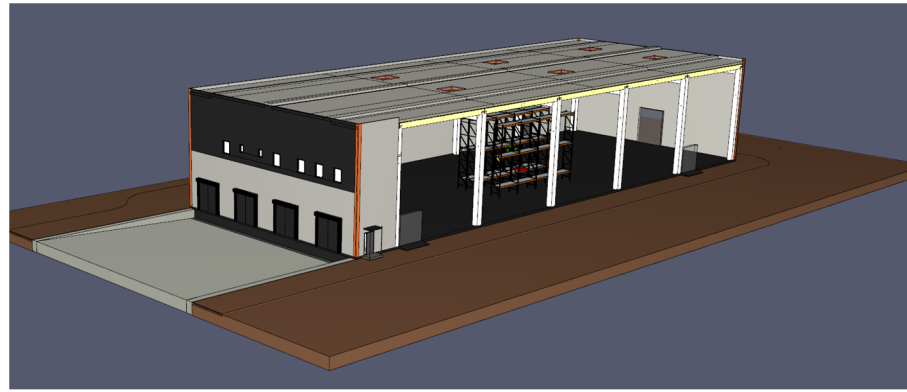


Figure 1. Warehouse building model.

Internally, high-rack shelving units were arranged in parallel rows, extending to 8 m in height. Stored commodities were modeled as plastic materials, cardboard and wood pallets, a representative high-hazard fuel load in warehouse fire safety engineering. This configuration ensured both vertical and horizontal continuity of combustible material, generating a conservative basis for smoke production and heat release.

The fire ignition source was positioned at the central aisle to represent a worst-case condition for smoke stratification and evacuation, given its symmetrical distance from vents and external boundaries. A custom fire growth curve was applied, with a design heat release rate per unit area (HRRPUA) of 1900.82 kW/m^2 , in the absence of suppression, based on experimental data [9].

Figure 2a is a schematic representation of the warehouse rack array, indicating the burner positioned on the lower rack, which serves as the ignition source in the simulations, and Figure 2b illustrates the fire development curve applied in the modeling process, representing the fire development profile for all simulated scenarios.

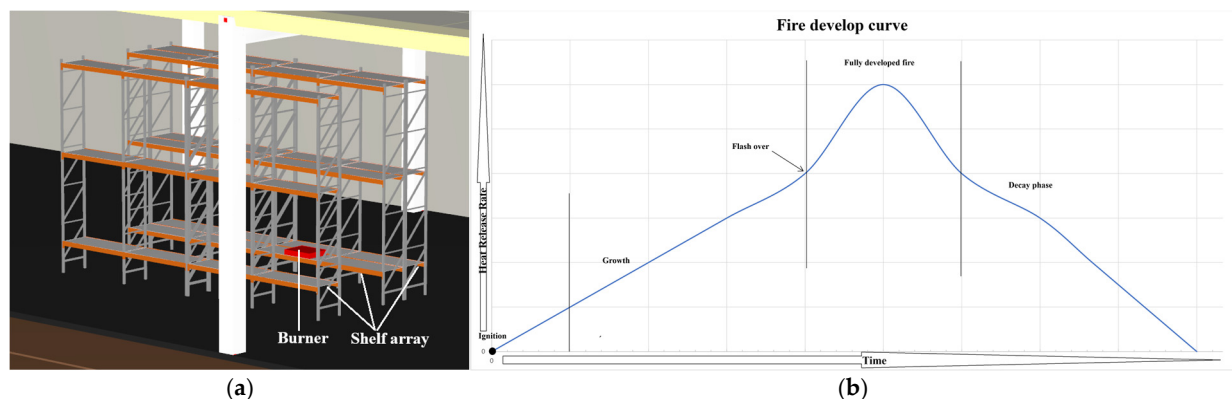


Figure 2. (a) Shelf array, (b) Fire develop curve.

Three primary protection systems were integrated into the model:

- **Sprinkler System:** Ceiling-level sprinklers were placed across the storage area, with an activation temperature of 68°C . In one scenario, in-rack (shelf) sprinklers were additionally modeled to assess local suppression efficiency.
- **Natural Smoke Ventilation System (NSVS):** A total of 6 roof-mounted vents were distributed uniformly across the roof surface, each with an effective free area of 4.5 m^2 , consistent with building design recommendations. These vents were modeled to operate under different activation logics depending on the scenario, either triggered by heat detectors, coordinated with sprinkler discharge, or remaining closed.

- **Fire Detection System:** An automatic fire detection system was included to provide early identification of fire development and to initiate control logic for other systems. The detection system was modeled using thermal and smoke sensitivity parameters consistent with EN 54 standards [10], capable of triggering smoke vent activation in scenarios where ventilation precedes sprinkler discharge. Its integration allowed evaluation of how detection-driven early ventilation affects smoke stratification, sprinkler activation timing, and overall tenability conditions.

The potential interaction mechanisms between sprinklers and NSVS were explicitly modeled:

- **Positive coupling:** Sprinkler-induced reduction in HRR limits smoke production.
- **Negative interference:** Premature venting delays sprinkler activation by reducing ceiling gas temperatures.
- **Buoyancy disruption:** Sprinkler spray cooling alters plume momentum, influencing smoke vent efficiency.

This interdependence formed the basis for the CFD evaluation.

Figure 3 is an illustration of the simulation setup showing the placement of ceiling sprinklers, one of the smoke detectors, and a thermocouple. These components were positioned to monitor fire detection, activation timing, and thermal conditions within the warehouse during the CFD simulations.

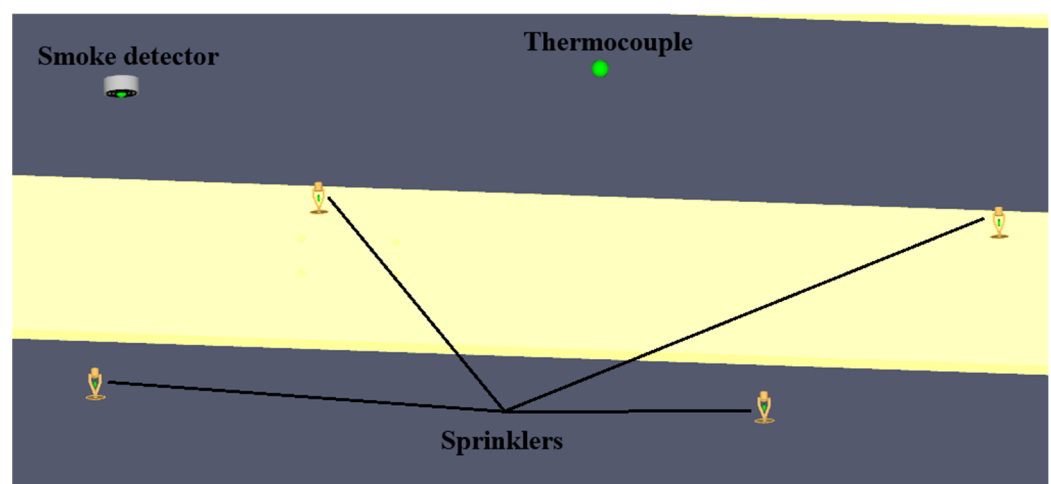


Figure 3. Fire protection systems models.

2.2. Warehouse Model Configuration

The fire scenarios were simulated using PyroSim 6.9.1 (Thunderhead Engineering, Manhattan, KS, USA) [11], a graphical preprocessor for the Fire Dynamics Simulator (FDS, NIST). FDS employs large-eddy simulation (LES) to resolve turbulent flow, heat transfer, combustion, and sprinkler-water interaction.

- **Geometry:** 66 m × 25 m × 12 m;
- **Fuel load:** Plastic materials, cardboard and wood pallets;
- **Mesh resolution:** Uniform grid with 0.25 m cell size in the model;
- **Ventilation:** Roof-mounted vents modeled per design parameters;
- **Fire scenario:** Centrally located fire, free-burn HRRPUA of 1900.82 kW/m² without suppression, total simulation time 140 s.

System Implementation

- Sprinklers modeled using thermal activation algorithms based on RTI and activation temperature.

- Water spray dynamics included droplet size distribution, spray cone angle, and cooling effects.
- NSVS vents implemented as pressure-dependent flow boundaries, with opening triggered by thermal conditions.

3. Results

The performance of fire safety systems in large warehouse enclosures is strongly dependent on the activation sequence and interaction between sprinklers and natural smoke ventilation systems (NSVS). While each system individually contributes to life safety and property protection, their combined efficiency is shaped by dynamic fire conditions, system design parameters, and operational coordination.

To assess these interdependencies, four distinct computational fluid dynamics (CFD) simulations were carried out using PyroSim, each representing a different system configuration and activation strategy [12]. The scenarios include fire development with all smoke vents closed (sprinkler-only condition), vents opened by fire detection prior to sprinkler activation, vents activated with a short delay after sprinkler operation, and shelf-level sprinklers combined with vents activated by sprinkler spray discharge [13].

In all cases, the HRR initially increased until the activation of the suppression system. After sprinkler discharge began, the HRR was reduced and subsequently maintained at a limited value. Specifically, in all scenarios, the HRR rapidly decreased to a quasi-steady level corresponding to the value reached 5 s after sprinkler activation.

The analysis focuses on three primary performance indicators:

- Heat Release Rate (HRR) suppression dynamics—Reflecting the efficiency of fire control.
- Smoke layer interface height—Monitoring smoke layer height as an indicator for maintaining tenable conditions for occupants, and for efficient functionality of NSVS.
- Time to sprinkler activation.

By comparing these parameters across the four cases, the study aims to identify both synergies and conflicts between sprinklers and NSVS, thereby informing performance-based design strategies for warehouses [14].

3.1. Scenario 1: Fire with All Smoke Vents Closed

In the baseline case, all smoke vents remained closed throughout the fire event, and only sprinkler activation governed fire suppression. The absence of smoke exhaust led to the rapid accumulation of hot gases beneath the ceiling, accelerating the reduction in tenable conditions at the occupant level [15]. Sprinklers activated relatively quickly due to the sustained ceiling temperature rise, reducing the HRR after approximately 84 s.

Sprinkler activation reduced the HRR significantly and confined the burner dimensions; however, the fire did not self-extinguish, persisting at a reduced intensity.

Heat Release Rate (HRR) curve over time for Scenario 1 is represented in Figure 4. The chart illustrates the evolution of fire intensity and the effect of ceiling sprinkler activation on limiting, but not extinguishing, the fire. The HRR stabilizes after sprinkler activation, indicating partial control of the combustion process without complete suppression. This behavior highlights the limitations of ceiling-mounted sprinklers in obstructed rack configurations, where water distribution to lower storage levels is restricted.

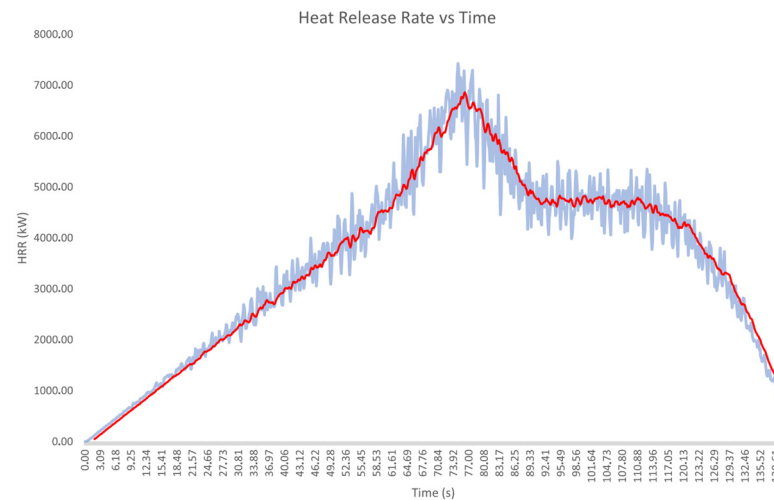


Figure 4. HRR vs. time for Scenario 1 (sprinkler-only conditions).

3.2. Scenario 2: Vents Opened by Fire Detection, Sprinklers Activated by Temperature

In this configuration, vents were triggered by the fire detection system prior to sprinkler activation. The early venting promoted the stratification of smoke and initially improved visibility conditions by exhausting combustion products. However, the reduction in ceiling gas temperature delayed sprinkler activation by several tens of seconds compared to Scenario 1. This delay permitted the fire to grow to a larger HRR before suppression initiated, resulting in higher thermal exposure and a more significant descent of the smoke layer, from a height of approximately 8 m (7.98 m) when the sprinkler system was activated, to a height of 6.5 m at the end of the simulation. Although visibility was partially maintained, the delay in suppression increased the overall risk of structural fire escalation.

A comparison between Scenarios 1 and 2 showing the variation in sprinkler activation times is presented in Figure 5. The chart highlights the influence of smoke vent activation on the thermal environment near the ceiling, which in turn affects the responsiveness of the sprinkler system [16]. The earlier vent opening in Scenario 2 resulted in slightly delayed sprinkler activation due to reduced ceiling temperature rise. Figure 6 is a visualization from the CFD simulation illustrating the smoke height profile for Scenario 2. The figure depicts the distribution and movement of smoke within the warehouse following vent activation, showing the formation of a stable smoke layer near the ceiling and the efficiency of natural smoke extraction under active ventilation conditions.

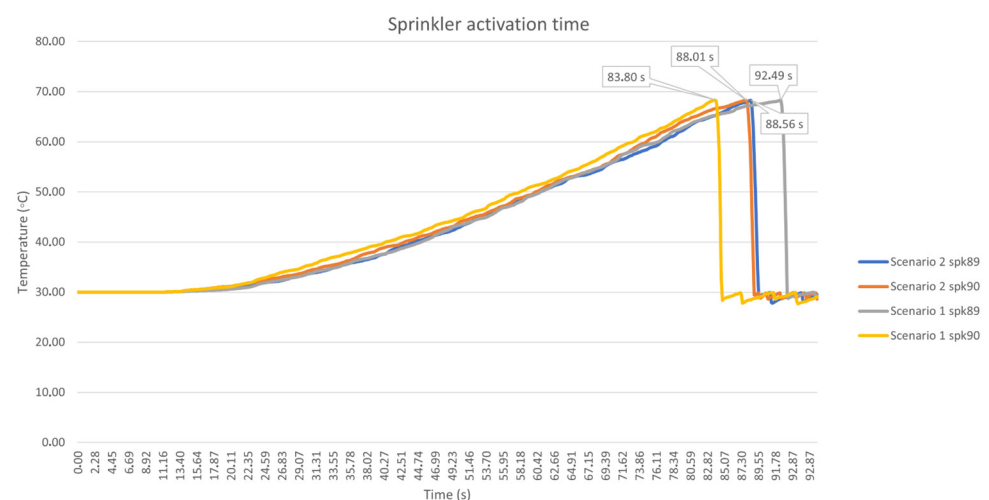


Figure 5. Comparison of sprinkler activation times between Scenario 1 and Scenario 2.

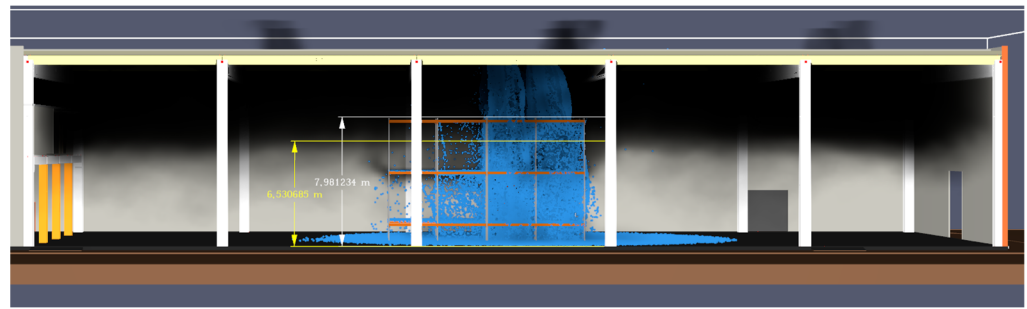


Figure 6. Smoke layer height profile for Scenario 2 (ventilation-before-sprinkler).

3.3. Scenario 3: Vents Opened 10 s After Sprinkler Activation

The third case introduced a controlled delay, with vents opening shortly (10 s) after sprinkler activation. This sequencing allowed the sprinklers to activate promptly under higher ceiling gas temperatures, while subsequent venting assisted in stabilizing the smoke layer. HRR was suppressed in a timeframe comparable to Scenario 1, but tenability conditions were significantly improved compared to both Scenario 1 and Scenario 2.

Although full fire extinction was not achieved, the system succeeded in confining the fire to its area of origin, preventing horizontal flame spread to adjacent racks. As a result, the scenario demonstrated improved effectiveness in limiting fire spread and thereby reducing the potential for goods losses, compared with the first two cases [17].

The chart (Figure 7) shows that Scenario 2 reached the highest peak temperature, primarily due to the early activation of smoke vents, which intensified the burning rate through increased oxygen supply. Scenario 1 displayed a slightly lower overall temperature curve, with values comparable to Scenario 3 during most of the simulation. However, in Scenario 3, the temperature decreased more rapidly in the final 50 s, indicating a more effective control of the thermal environment following delayed vent activation.

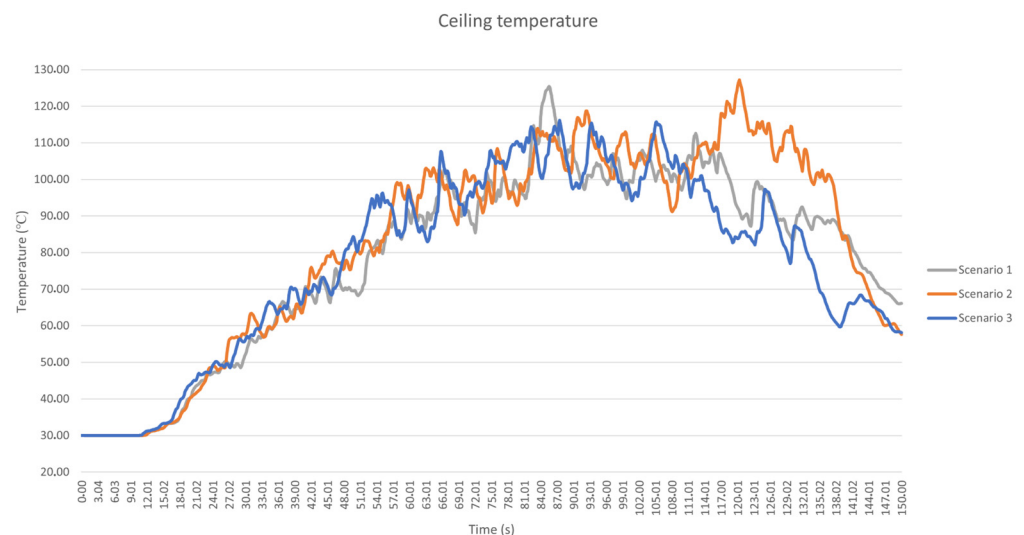


Figure 7. Ceiling temperature comparison between Scenarios 1, 2 and 3.

The chart (Figure 8) illustrates how local temperatures evolve relative to the sprinkler response, showing delays due to thermal inertia and the influence of rack configuration. It highlights the effect of different venting strategies on ceiling temperatures and the resulting timing of sprinkler activation, demonstrating their role in controlling fire intensity. The data reveal that early venting can increase peak ceiling temperatures by enhancing combustion, while delayed venting moderates the thermal rise. This comparison emphasizes the importance of coordinated system design to optimize sprinkler performance. Over-

all, the figure provides insight into the interplay between fire dynamics, detection, and suppression efficiency.

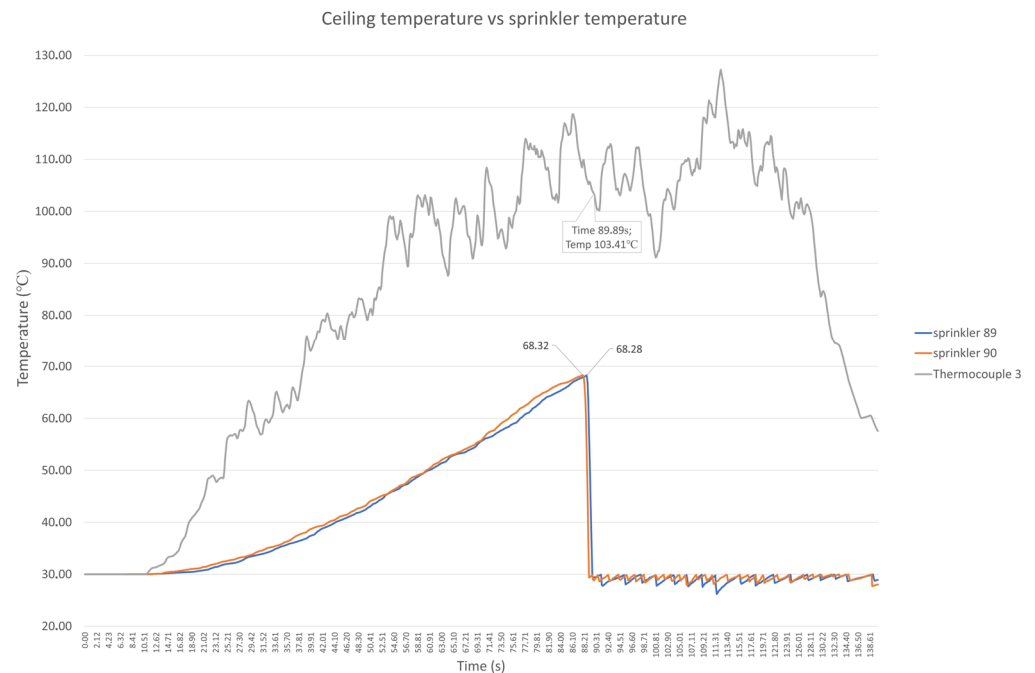


Figure 8. Ceiling temperature vs. sprinkler temperature chart.

3.4. Scenario 4: Shelf Sprinklers with Vents Activated by Sprinkler Spray

The final scenario combined shelf-level sprinklers with coordinated vent activation triggered by sprinkler spray discharge. This configuration achieved the most effective fire suppression and smoke management performance among all cases. Shelf sprinklers limited fire growth locally, reducing the HRR at an earlier stage, while venting efficiently exhausted smoke without significantly impacting sprinkler activation [18].

As a result, the fire was fully extinguished 37 s after burner ignition (Figure 9), marking the fastest suppression time among all simulated scenarios. The simultaneous operation of in-rack sprinklers and coordinated vent opening ensured that the heat release rate rapidly decreased to zero, while smoke concentrations were maintained at minimal levels. This prevented significant thermal degradation of stored commodities and eliminated the risk of smoke accumulation within the occupied zone.

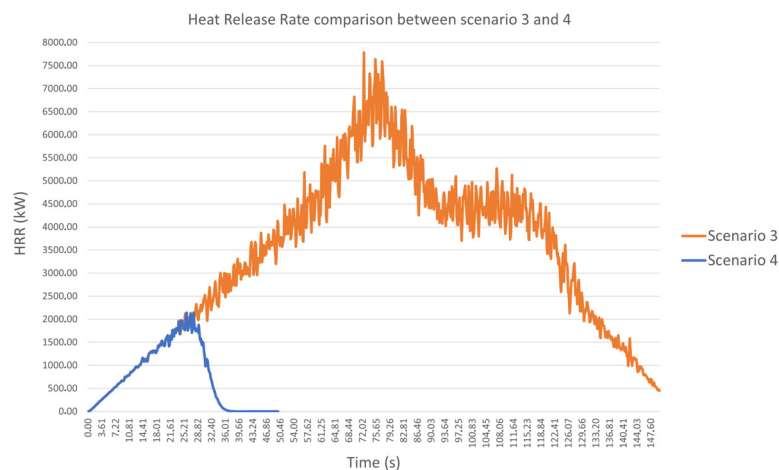


Figure 9. Heat Release Rate comparison between scenario 3 and level.

Unlike the ceiling-only sprinkler configurations, this integrated arrangement ensured that water droplets directly reached the burning materials, avoiding shadowing effects caused by higher shelves. Consequently, the scenario clearly demonstrated the advantages of integrated system design, where active suppression and smoke management functioned synergistically rather than competitively, resulting in superior fire control, protection of goods, and preservation of safe conditions for potential occupants and emergency responders.

Figure 10 illustrates how local temperatures near the racks evolve relative to the response thresholds of the in-rack sprinklers, highlighting the effectiveness of localized water application in achieving timely fire suppression. It also demonstrates the reduced delay in activation compared with ceiling-only sprinklers, emphasizing the role of in-rack systems in controlling fire growth and protecting stored goods.

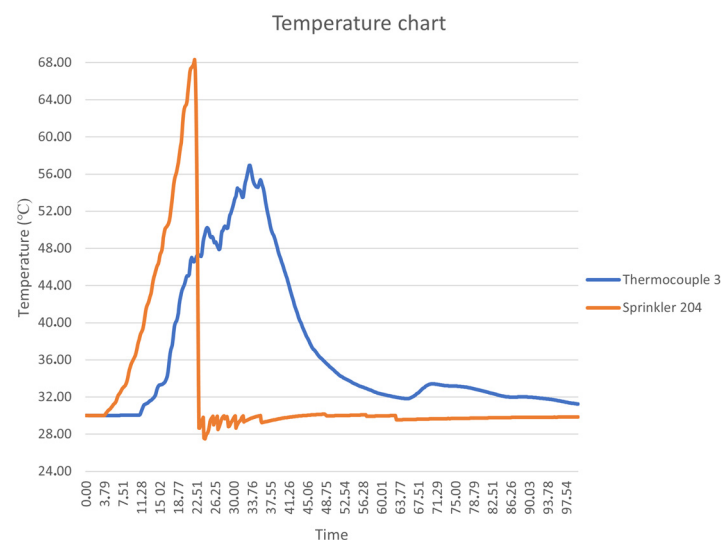


Figure 10. Temperature comparison between ceiling-level thermocouple and in-rack activated sprinkler.

3.5. Comparative Analysis

A cross-scenario comparison highlights the critical interdependence between sprinklers and smoke ventilation systems. Scenario 1 ensured timely suppression but resulted in rapid smoke accumulation; Scenario 2 improved smoke clearance but delayed suppression; Scenario 3 provided a balanced approach, enabling both prompt suppression and efficient smoke exhaust; and Scenario 4 demonstrated the most robust performance, combining localized suppression with synchronized ventilation.

From a performance-based design perspective, the results underline that system efficiency cannot be evaluated in isolation. Instead, activation sequencing, fire load characteristics, and system interaction must be considered holistically. Among the tested configurations, Scenarios 3 and 4 provided the best outcomes in terms of both life safety (tenability) and property protection (faster HRR suppression and fire extinguishment).

Figure 11 illustrates how different system configurations and activation sequences affect fire intensity, showing that Scenarios 1–3 reduce HRR without achieving full extinguishment, whereas Scenario 4 achieves complete suppression with in-rack sprinklers and coordinated venting. Figure 12 presents the corresponding temperature evolution, highlighting the impact of sprinkler placement and vent timing on ceiling and rack temperatures. Together, these figures provide a clear overview of how system interdependencies influence fire dynamics, thermal conditions, and overall suppression performance.

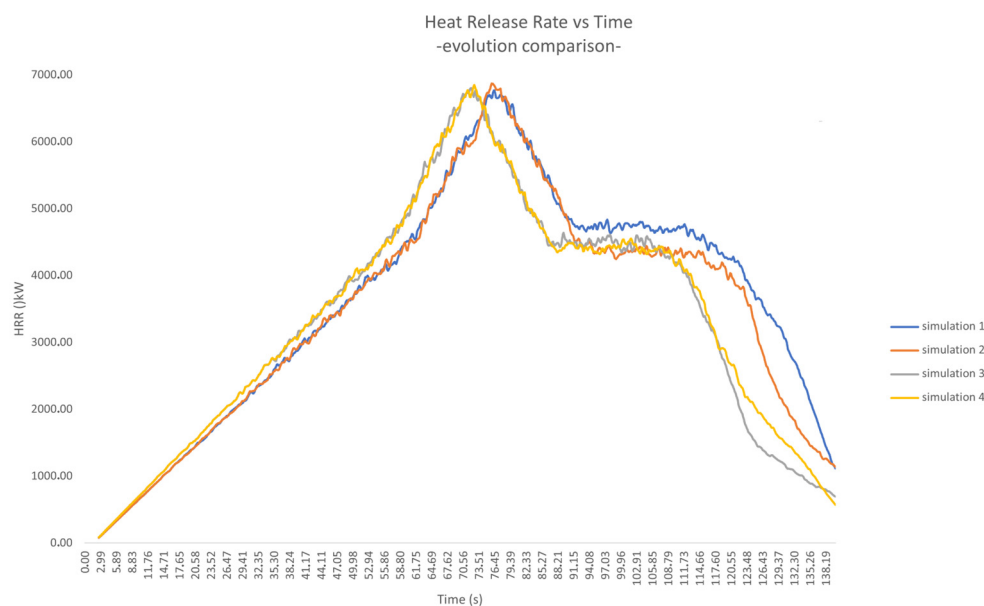


Figure 11. Comparative chart of heat release rate trendline vs. time across all four scenarios.

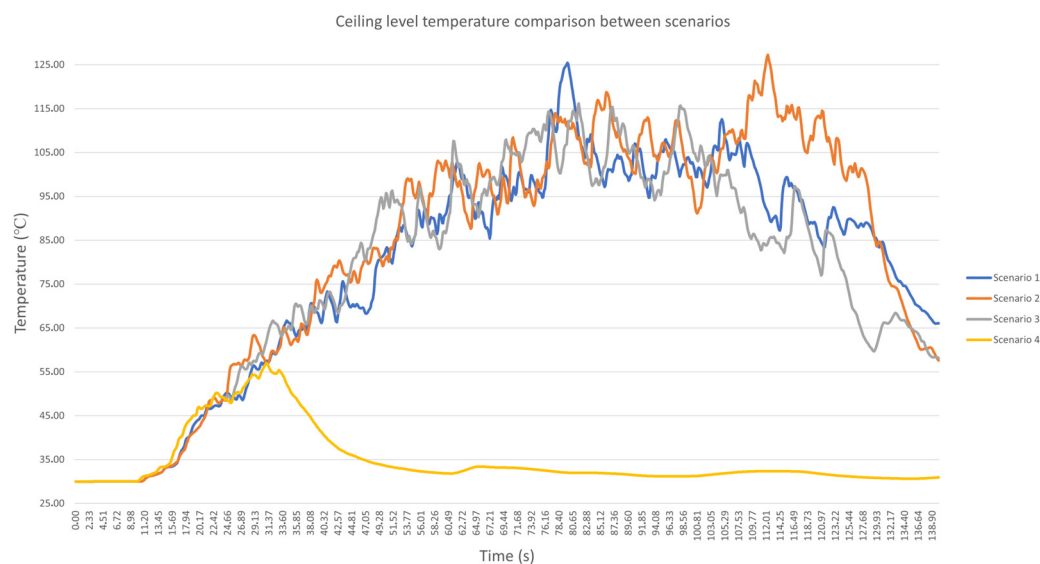


Figure 12. Temperature evolution comparison between scenarios.

4. Conclusions

This study investigated the combined performance of sprinklers, natural smoke ventilation systems (NSVS), and fire detection systems in a large-scale warehouse environment using CFD-based simulations in PyroSim. Four operational scenarios were modeled to assess how coordination strategies and system configurations influence fire development, suppression efficiency, and potential losses. Based on the results, the following conclusions can be drawn:

Ceiling-level sprinklers alone are insufficient for full fire extinguishment [19]. In Scenarios 1–3, sprinkler activation reduced the HRR to a stable, controlled level but failed to achieve complete suppression. The fire was contained but continued to burn in a limited state, maintaining the potential for damage to goods and prolonged firefighting intervention.

Ventilation sequencing influences suppression effectiveness. Early activation of smoke vents prior to sprinklers (Scenario 2) did not provide significant advantages compared with delayed venting (Scenario 3) [20]. However, delayed vent opening ensured timely

sprinkler operation under higher ceiling gas temperatures and supported better fire spread limitation.

In-rack sprinklers enable complete fire extinguishment. In Scenario 4, the use of shelf-level sprinklers resulted in full fire suppression after 37 s from the onset of sprinkler discharge. The localized application of water directly to the burning fuel bed proved decisive in extinguishing the fire.

Storage configuration plays a critical role in determining sprinkler system performance. In particular, the presence of upper-tier shelving can obstruct water distribution from ceiling-mounted sprinklers, effectively acting as “umbrellas” that prevent water from reaching fires on lower storage levels [21]. This obstruction helps explain why ceiling-only sprinkler systems failed to achieve extinguishment in Scenarios 1–3. In contrast, in-rack sprinklers were able to mitigate this limitation by delivering water directly to the fire source. Integrated system design minimizes fire spread and goods losses. Coordinated activation of sprinklers, smoke vents, and detection systems demonstrated the ability to prevent horizontal fire propagation and reduce the volume of damaged stored goods, even in cases where extinguishment was not achieved [22].

CFD simulations are a valuable tool for performance-based design. The results highlight the importance of simulation-based validation for understanding system interdependencies, optimizing activation sequences, and informing warehouse fire safety strategies beyond prescriptive design codes.

5. Future Research Directions

Future research should aim to extend the current investigation toward a more comprehensive, performance-based assessment of warehouse fire safety. A key direction involves the integration of additional safety criteria, including tenability indicators such as visibility, carbon monoxide (CO) concentration, and ambient temperature, to better evaluate occupant survivability and overall environmental safety. Furthermore, subsequent studies will address occupant evacuation dynamics and safety parameters, enabling the development of a holistic framework that integrates both system performance and human-centered outcomes.

Another promising avenue concerns the detailed examination of flame propagation and fire spread mechanisms within complex storage geometries. Future studies should explore how different rack heights, storage densities, and combustible materials influence flame behavior, heat transfer, and the effectiveness of sprinkler and ventilation systems. Such analyses will contribute to refining predictive fire models and improving the accuracy of simulation-based fire safety design.

Finally, further research should incorporate economic and operational aspects through cost–benefit analyses, maintenance strategy evaluations, and reliability assessments of integrated suppression and natural smoke ventilation systems in real warehouse environments. Combining these technical and practical considerations will support the formulation of optimized, sustainable, and evidence-based design strategies.

Collectively, these research directions will advance the development of a holistic, performance-based fire safety framework, promoting safer, more resilient, and economically efficient warehouse designs aligned with future regulatory and engineering standards.

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Abbreviations

The following abbreviations are used in this manuscript:

NSVS	Natural Smoke Ventilation System
FDS	Fire Dynamics Simulator
CFD	Computer Fluid Dynamics
HRR	Heat Release Rate
HRRPUA	Heat Release Rate per Unit Area
NIST	National Institute of Standards and Technology

References

1. Morgan, H.P.; Hansell, G.O.; Ewer, J. *Design Methodologies for Smoke and Heat Exhaust Ventilation*; BRE Report 368; BRE Electronic Publications: London, UK, 1999; ISBN 1 86081 289 9.
2. Klote, J.H.; Milke, J.A. *Principles of Smoke Management*; American Society of Heating Refrigeration and Air-Conditioning Engineers: Atlanta, GA, USA, 2002.
3. Tan, Y.; Li, J.; Li, Y.; Huang, Y. Study on the response of sprinkler system in logistics warehouse under the influence of the hollow floorboard. *Case Stud. Therm. Eng.* **2019**, *14*, 100427. [\[CrossRef\]](#)
4. Węgrzyński, W.; Krajewski, G.; Kimbar, G.; Lipecki, T. Fire smoke dispersion inside and outside of a warehouse building in moderate and strong wind conditions. *Fire Saf. J.* **2023**, *136*, 103760. [\[CrossRef\]](#)
5. Ho, H.-H.; Chen, C.-F.; Sung, M.-H.; Shen, T.-S.; Chen, Y.-J. Experimental investigation of in-rack sprinkler parameters for ASRS warehouse protection. *J. Loss Prev. Process Ind.* **2025**, *98*, 105760. [\[CrossRef\]](#)
6. Han, D.; Krisman, A.; Gopala, Y.; Zhou, X.; White, J.; Xin, Y. A model-based approach to estimate sprinkler protections for warehouse storage. *Fire Saf. J.* **2023**, *140*, 103875. [\[CrossRef\]](#)
7. Andrew, C.T.; Rangwala, A.S. Analyzing the impact of in-rack sprinklers in a warehouse fire: A demonstration of the role optimization has in mitigating damage. *Fire Saf. J.* **2015**, *73*, 55–62. [\[CrossRef\]](#)
8. Suhaimi, N.S.; Mohd Idris, M.F. Prediction of Smoke Temperature in a Warehouse Using Fire Dynamic Simulator. *Curr. Sci. Technol.* **2024**, *4*, 5–10. [\[CrossRef\]](#)
9. McGrattan, K. *Heat Release Rates of Multiple Transient Combustibles*; Technical Note (NIST TN); National Institute of Standards and Technology: Gaithersburg, MD, USA, 2020.
10. EN 54-7:2018; Fire Detection and Fire Alarm Systems, Part 7: Smoke Detectors—Point Smoke Detectors Using Scattered Light, Transmitted Light or Ionization. European Committee for Standardization: Bruxelles, Belgium, 2018.
11. McGrattan, K.; Hostikka, S.; McDermott, R.; Floyd, J.; Vanella, M.; Mueller, E.; Paul, C. *Fire Dynamics Simulator Technical Reference Guide (FDS 6.10.1)*; NIST: Gaithersburg, MD, USA, 2025. [\[CrossRef\]](#)
12. Beyler, C.; Cooper, L. Interaction of Sprinklers with Smoke and Heat Vents. *Fire Technol.* **2001**, *37*, 9–35. [\[CrossRef\]](#)
13. Hinkley, P.L. The effect of vents on the opening of the first sprinklers. *Fire Saf. J.* **1986**, *11*, 211–225. [\[CrossRef\]](#)
14. Zhang, C.; Chow, W. Numerical Studies on the Interaction of Sprinkler and Smoke Layer. *Procedia Eng.* **2013**, *62*, 453–462. [\[CrossRef\]](#)
15. Yang, P.; Tan, X.; Xin, W. Experimental study and numerical simulation for a storehouse fire accident. *Build. Environ.* **2011**, *46*, 1445–1459. [\[CrossRef\]](#)
16. Rundle, C.A.; Lightstone, M.F.; Oosthuizen, P.; Karava, P.; Mouriki, E. Validation of computational fluid dynamics simulations for atria geometries. *Build. Environ.* **2011**, *46*, 1343–1353. [\[CrossRef\]](#)
17. Ertugrul, A.; Michalowicz, R. Modeling of a Warehouse Fire—A Case Study. In Proceedings of the 2005 AIChE Spring National Meeting, Cincinnati, OH, USA, 30 October–4 November 2005.
18. Pandey, A.K.; Mishra, M.K. Application of Fire Dynamics Simulator in Warehouse Fires: A Case Study. *Int. Res. J. Eng. Technol.* **2020**, *7*, 5457–5461.

19. EN 12845:2015+A1; Fixed Firefighting Systems—Automatic Sprinkler Systems—Design, Installation, and Maintenance. European Committee for Standardization: Bruxelles, Belgium, 2019.
20. EN 12101-2:2017; Smoke and Heat Control Systems—Part 2: Natural Smoke and Heat Exhaust Ventilators. European Committee for Standardization: Bruxelles, Belgium, 2017.
21. *Regulations on Fire Safety of Buildings, Part II—Extinguishing Installations, Reference P 118/2-2013*; Order of Minister of Regional Development and Public Administration, No. 2,463/2013; Ministry of Regional Development and Public Administration: Bucharest, Romania, 2013.
22. VdS. *Interaction of Water Extinguishing Systems and Smoke and Heat Exhaust Ventilation Systems (SHEVS)*; Fire Protection Leaflet; VdS Schadenverhütung GmbH: Cologne, Germany, 2018; VdS 2815en:2018-05(03). Available online: <https://shop.vds.de/en/publikation/vds-2815en-> (accessed on 22 August 2025).

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