RESEARCH PAPER

A Case Study on Fire Safety Challenges in Automated Warehouses

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Abstract
Automated warehouses have become an essential component of modern logistics systems due to their ability to improve operational efficiency, storage capacity, and inventory management through advanced technologies such as automated storage and retrieval systems, robotics, and conveyor networks. However, the integration of high-density storage, electrical equipment, and lithium-ion battery systems creates fire safety issues such as fire propagation speed, detection delay, and inefficiencies in fire suppression systems. The study aims to assess the fire hazards and the efficacy of the fire safety measures in the automated warehouse system. The study uses the quantitative case study approach, including fire load density calculations, Fire Risk Index modeling, fire detection system evaluation, and sprinkler fire suppression system evaluation. The study collected primary data from alarm logs, maintenance logs, and expert questionnaire responses, and secondary data from engineering standards and design documents. The findings indicate that the fire load density is 1800 MJ/m² in the battery charging area, the fire risk index is 100, showing high fire risk, the fire detection system efficiency is 96.7%, and the sprinkler fire suppression system efficiency is 78%. The study concludes that there is an urgent need for fire safety strategies in automated warehouse systems.

Keywords: Automated warehouses; Fire risk assessment; Fire load density; Fire detection systems; Warehouse fire safety **Keywords:** Automated warehouses; Fire risk assessment; Fire load density; Fire detection systems; Warehouse fire safety.

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1. Introduction:

Warehouses are very important in the contemporary supply chain systems as they guarantee to facilitate efficient goods storage, management and distribution in diverse industries. Automated warehouses have been developed in recent years as a result of technological progress and the increasing necessity to conduct logistics activities at a higher speed [1]. These processes employ hi-tech technologies like automated storage and retrieval systems (AS/RS), robotics, conveyor systems, as well as computerized inventory management, to improve its operation and minimize human involvement [2]. E-commerce companies, manufacturing companies and providers of logistics services widely use automated warehousing as it enhances productivity, lowers labor expenses and maximizes capacity. Nevertheless, although automation is associated with significant operational advantages, it also raises some novel safety issues, in particular, in respect of fire risks and risk management [3].

The safety of the fire has always been a rather crucial issue of industrial infrastructure, particularly in warehousing where the massive amounts of the merchandise, the packaging material, and the equipment are stacked in the enclosed areas [4]. The existing warehouses already have significant fire hazards in form of large fire loads, the presence of flammable paper and plastic materials, electrical operation and machinery used in moving materials. The introduction of automation technologies has complicated the task of fire safety to an unprecedented extent [5]. Automated warehouses are also characterized by high bay rack storage system, narrow aisles, compact stocked inventory as well as electrical and electronic integrated systems. Such features may increase the speed at which a fire may spread and complicate the process of fire detection, suppression, and evacuation relative to the most traditional warehouses [6].

Concentration of combustible materials in the vertical storage systems is one of the greatest concerns in the automated warehouses. High-bay racks enable goods to be stored at a height that is much higher than a matter of several meters, which increases the degree of storage density, but also forms a vertical route through which fire can propagate [7]. As soon as a fire breaks out in such a setting, it might rise very fast due to the arrangement of commodities and package materials atop one another producing a lot of heat and smoke. The use of conveyor belts, robotics, and automated machinery also adds to the complexity of fire because these systems might still be in use even during an incident, which might also foster the expansion of fire or make their response to the incident challenging [8, 9]. Moreover, automated facilities are usually run with limited human input and may take time before the occurrence of a fire outbreak in its early stages is detected.

The other important challenge occurs due to the wide use of electrical equipment and energy systems in the automated warehouses. Storage Automated storage systems are based on electrical motors, sensors, control panels and battery-operated devices like “Automated Guided Vehicles (AGV)” and forklifts [10]. Specifically, the growing popularity of lithium-ion battery as a charging station and robotic equipment poses a new risk of fire because of the possibility of thermal runaway, overheating, or electrical malfunctions. Any electrical problems, short circuiting or equipment malfunction will be simple sources of ignition in a setting that has combustible materials [11]. Since the automation technologies are going to keep on changing, it is important to make sure that these electrical systems are reliable and safe to eliminate fire accidents.

Automated warehouses also have special engineering problems related to fire detection and suppression. The use of conventional fire protection systems in the high-density automated storage environments is not always effective [12]. Indicatively, a typical sprinkler system may not be able to penetrate deep rack storage or fire that is at a high elevation. The ceilings are also high with large open areas and tangled air movement patterns formed because of ventilation and machinery which may interfere with the function of smoke detection system [13]. Therefore, more specific fire protection measures, such as high-quality detection systems, in-rack sprinklers, and smart monitoring software are frequently needed to provide proper fire protection in automated plants.

Moreover, the emergency response and evacuation planning in automated warehouses can be complicated as compared to that in traditional warehouses where the storage facilities are not as complicated [14]. Robotic equipment, conveyors, and the limited access zones can be the factors that prevent the firefighters and the emergency service members capable of responding to the fire source as fast as possible. Besides that, automated warehouses are usually designed to move machines but not to be convenient to the human, so it can be a barrier to the rescue or suppression efforts [15]. These operational limitations help to place emphasis on the need to address the consideration of fire safety in the process of designing and planning automated warehouse facilities. Due to the growing use of automation technologies in the logistics and industrial storage, it is necessary to discuss the problem of fire safety that is inherent to the modern storage facilities. Knowledge of the risks, vulnerabilities and constraints of current fire safety measures can assist organisations to come up with more efficient safety techniques and legal frameworks. The systematic review of practical situations and operation practices is of special value in the detection of gaps in fire safety management in automated settings.

As such, this paper is a case study of the fire safety issue in automated warehousing. The study will examine the possible risks of fire, current safety provisions, and the risk factors that are critical to automated storage system. Investigating the structural, technological and operation components of automated warehouses, the study aims at helping to enhance the concept of setting up a fire safety, risk evaluation and building a more resilient warehouse infrastructure. It is assumed that the results of the present study could have multiple valuable implications on the professionals of the industry, safety engineers, and policy-makers towards achieving safer and more sustainable automated storage facilities. The following are the research objectives:

- To quantitatively assess fire risk levels in automated warehouses using fire load density and Fire Risk Index (FRI) analysis.
- To evaluate the operational effectiveness of fire detection and suppression systems under automated warehouse conditions.

2.Literature Review

In the recent past, the technological, structural and strategic factors of automated warehouses have been considered more and the benefits on operations as well as emerging issues of fire safety have been highlighted. Kembro et al. (2025) [16] were conducting a study on the strategic decision making of adopting large “Automated Warehouse Systems (AWS)” by taking the form of an abductive multiple case study with eight Swedish retailers. In a study, four strategic intent profiles were also proposed also showing how automation investments relate to the wider organizational goals. Inevitably, Fogarty et al. (2023) [17] also studied the role of automation of warehouses in business resiliency in the UK logistics industry. Their results indicated that the speed at which they have expanded their warehouses and automated it after the Brexit and the COVID-19 outbreak have placed them in a more vulnerable situation when it comes to fire incidents, and fire safety management and regulatory awareness must be more indemnifiable throughout the sector. Much of the recent literature is concerned with fire modelling, structural performance and engineering design strategies in order to deal with fire risks in automated storage facility.

The methodology that was suggested by Autiero, et al. (2025) [18] involves the integration of fire modelling and structural thermo-mechanical to assess “Automated Rack Supported Warehouses (ARSWs)”. The study was analytical, applying analytical models, using software (Computational Fluid Dynamics) simulations of vertical and horizontal fire propagation caused by localized ignition sources and evaluating potential structural collapse using SAFIR and ABAQUS modelling software. As well, Okur et al (2025) [19] used “Fire Dynamics Simulator (FDS)” modelling in exploring the performance of steel-framed warehouse racking systems to a fire under different ignition sources. They found that the intensity of the fire is particularly dependent on the place of ignition and the type of stored commodity, and the temperatures were able to reach 970OC causing intense structural strain and drift on the steel members. Crosti et al. (2025) [20] also noted the constraints of traditional prescriptive fire design techniques towards “Automated Vertical Warehouses (AVWs)”, suggesting a performance-driven interdisciplinary design of the structures, i.e. combining structural engineering and fire protection techniques. In addition to these, Stochino et al. (2025) [21] proposed a superior structure of post-fire damage analysis, which integrates CFD simulation and a finite-element structure analysis to measure structural degradation of warehouse buildings. This work showed that combinations of computational modelling and diagnostic facilities like laser scanning and non-destructive testing can have a large effect in regard to the enhancement of accuracy of damage discovery and structural resilience planning. The other researches have been centred on fire risk analysis, fire detection system, fire evacuation strategy as well as smart fire safety measures in warehouse settings. Qualitative research by Nadararajah et al. (2026) [22] based on interviews with experts revealed that the most significant components include a poor maintenance of fire protection systems, inappropriate storage setups, and excessive combustible loads, which cause most shortcomings in warehouse fire. The authors Suhaimi et al. (2024) [23] used CFD modelling to study the smoke spread in high-rack warehouses and prove that building height, ventilation conditions, and characteristics of the sources of fire matter greatly to realize smoke temperature and distribution.

A multi-source data-driven system, which is proposed by Sun et al. (2024) [24], to evaluate fire danger through evidential reasoning and artificial fish swarm algorithms enables the dynamic evaluation of fire risk in logistic warehouses with real-time environmental measurements like temperature and carbon monoxide concentration. Studies related to structural design and fire protection planning have been conducted earlier, e.g., Kátai-Urbán et al. (2023) [25] compared properties of steel and timber structural beams of different warehouses storing hazardous materials in terms of fire resistance and assessed the output using the regulatory fire codes framework, and Hassanain et al. (2022) [26] suggested the implementation of a systematic fire risk assessment strategy based on the regulatory fire codes framework. Moreover, Sharyy et al. (2022) [27] have created the empirical models of the optimal location of fire detectors in warehouses with better prevention time results than the traditional code-provided methods. Other works encompass probabilistic fire protection analyses of automated storage systems Cifuentes-Cante et al., 2021 [28], adaptive ICT-based fire protection systems in smart factories Tricomi et al., 2021 [29], and the use of fire dynamics and decision analysis in evacuation planning Chanthakhot et al., 2021 [30]. Taken together, these investigations indicate that fire safety issues in automated warehouses have become rather intricate and that such trend requires comprehensive technological, structural and management-related solutions to be effective in the mitigation of fire risks. In the current literature, there are some gaps in research in spite of the massive developments in fire modelling, the structural analysis and the automated technologies of the warehouse. Majority of inquiries dwell on the simulation-based fire behaviour, structural resistance or technological structures, but few studies offer the real-world case-based analysis concerning the presence of fire safety issues in operational automated warehouses. Further, structural, operational, and safety management combined perspectives are yet to be integrated. Thus, the present study requires in-depth research that could be posed through the use of case studies to determine real-world fire risk, safety precautions, and control measures in automated warehouses.

3.Materials and Method

This study employed a quantitative case study research design in exploring the issue of fire safety challenges in automated warehouse environments. The use of a case study is relevant in this study as automated warehouse systems constitute a complex engineered system in which fire safety is subject to many influencing factors, including structural, storage, mechanical, and electrical considerations.

This study employed a quantitative research methodology, which incorporates various analytical perspectives in addressing the issue of fire safety challenges in automated warehouse environments. The methodologies employed in this study include fire safety engineering principles, quantitative risk analysis, statistical performance analysis, and engineering efficiency evaluation. The research process employed in this study was divided into the following stages:

- Identification and classification of warehouse operational zones
- Quantification of fire load in different storage areas
- Calculation of Fire Risk Index (FRI) values
- Evaluation of fire detection system performance
- Assessment of automatic sprinkler system efficiency
- Statistical analysis and interpretation of collected data

This structured methodology enables a systematic evaluation of both fire hazard severity and fire protection performance in automated warehouse systems.

3.1 Description of Case Study Warehouse

The case study occurred at a high-bay Automated Storage and Retrieval System (AS/RS) warehouse, which serves as a model for Industry 4.0 logistics operations that depend on automated storage systems to handle high storage capacities. The key characteristics of the selected facility include:

- Maximum storage height: 28 meters
- Rack configuration: Steel multi-depth rack system
- Storage density: 4 pallets per square meter
- Commodity type: Mixed combustibles including plastic packaging, cartons, and consumer goods
- Material handling systems: Automated Guided Vehicles (AGVs) and conveyor belt systems
- Battery charging zone: Lithium-ion battery charging infrastructure

The warehouse is equipped with multiple fire protection systems designed to mitigate fire risks:

- Ceiling-mounted automatic sprinkler system
- In-rack sprinkler system

- Smoke detection sensors
- Heat detection sensors

This configuration reflects the structural and technological complexity commonly observed in modern automated logistics warehouses.

3.2 Data Collection

i.Primary Data: Primary data were collected directly from operational records and technical monitoring systems within the warehouse facility. The primary sources included:

- Fire alarm logbooks
- Sprinkler system maintenance records
- Battery temperature monitoring sensors
- Structured questionnaires completed by fire safety engineers

Parameter	**Data Source**	**Sample Size**
Alarm Response Time	Alarm Log Records	50 events
Sprinkler Activation Time	Maintenance Logs	40 records
Battery Temperature	Thermal Sensors	30 readings
Safety Compliance Score	Questionnaire	25 engineers

The dataset establishes enough statistical power to assess fire protection system performance through its testing framework. The 50 alarm response events and 40 sprinkler activation records provide reliable data for calculating mean values and standard deviations while minimizing sampling bias. The 30 battery temperature readings enable researchers to study thermal risk conditions that exist in lithium-ion charging zones which present potential thermal runaway hazards.

25 Fire safety engineers completed structured questionnaires which used a five-point Likert scale (1–5) to assess fire safety compliance and operational risk awareness. These responses incorporate expert judgment into the risk assessment process.

ii.Secondary Data: Secondary data were obtained from various technical and regulatory sources, including:

- NFPA standards for storage occupancies
- Warehouse layout drawings and engineering plans
- Commodity calorific value reference tables
- Fire incident investigation reports
- Equipment technical manuals

These data sources were used to determine combustible material calorific values, ignition probabilities, and benchmark performance standards for fire protection systems.

3.3 Fire Load Density Calculation

Fire load is defined as the total heat energy that can be released if all the combustible materials in a given compartment are completely burnt. Fire load is measured in megajoules. Fire Load Density (FLD) indicates the amount of fire load per unit floor area. Fire Load Density (FLD) is used to measure the potential for fire severity. The Fire Load Density was calculated using the following formula:

$$FLD = \frac{\sum(W_i \ x \ CV_i)}{A}$$

where FLD is fire load density (mj/m²), Wi is weight of combustible material (kg), CVi is calorific value of material (mj/kg) and A is floor area (m²)

For the storage zone: Total combustible mass = 75,000 kg

Average calorific value = 29 MJ/kg

Area = 1500 m²

FLD = (75,000 × 29) / 1500

FLD = 1450 MJ/m²

Table 1: Fire Load Classification

Fire Load Density	**Risk Level**
< 500 MJ/m²	Low
500–1000 MJ/m²	Moderate
1000–1500 MJ/m²	High
> 1500 MJ/m²	Very High

Table 2: Fire Load Results

Zone	Total Fire Load (MJ)	Area (m²)	Fire Load Density (MJ/m²)
Storage Zone	2,175,000	1500	1450
Battery Zone	540,000	300	1800
Conveyor Zone	450,000	500	900
Packing Zone	660,000	600	1100

The results in table 1 and 2 show that the battery charging zone has the greatest fire load density 1800 MJ/m² which creates an extremely dangerous fire risk from lithium-ion batteries and electrical equipment. The storage zone shows high fire load because its goods are stacked densely and its vertical rack systems create conditions that allow fire to spread upward.

3.4 Fire Risk Index (FRI) Method

The Fire Risk Index (FRI) is a quantitative model used to evaluate overall fire risk by combining the probability of ignition, combustible material intensity, and detection delay, the result where shown in table 3.

$FRI = P \times C \times D$

Where P is Probability of ignition (1–5), C is Combustible material factor (1–5)
and D is Detection delay factor (1–5)

Table 3: Risk Classification

FRI Value	Risk Category
< 50	Low
50–100	Moderate
100–200	High
> 200	Very High

This classification framework standardizes the interpretation of fire risk across different warehouse zones and helps engineers prioritize safety improvements.

3.5 Evaluation of Fire Detection System

Fire detection systems are designed to identify early indicators of fire such as smoke, heat, or flame and activate alarm systems to initiate emergency response. The following parameters were evaluated:

□Alarm response time (seconds)
□False alarm rate (%)
□Detection coverage efficiency (%)
□Sensor sensitivity levels

Detection efficiency was calculated using the formula: $\eta d= = \frac{T_{ideal}}{T_{actual}} x\ 100$

where ηd is detection efficiency (%), T_{ideal} is standard response time (60 seconds)
and T_{actual} is observed response time.

3.6 Evaluation of Sprinkler System

Automatic sprinkler systems are active fire protection mechanisms designed to control or suppress fires through water discharge when a predefined temperature threshold is reached. The evaluation included the following indicators:

□Activation temperature
□Activation time
□Water discharge density (mm/min)
□Fire suppression efficiency

Suppression efficiency was calculated as: $\frac{Controlled\ Events}{Total\ Fire\ Events}\ x\ 100$

3.7 Statistical Analysis

To ensure quantitative reliability, the following statistical techniques were applied:

- □Mean: The arithmetic average was calculated using: $\bar{x} = \frac{\sum x}{n}$

- Standard Deviation: Standard deviation was used to measure data dispersion: $\sqrt{\frac{\sum(x-\bar{x})^2}{n-1}}$
- Pearson Correlation Coefficient: Correlation analysis was conducted to examine relationships between variables: $\frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$
- Linear Regression Model: A regression model was developed to predict fire spread rate:

$$y = a + b_1X_1 + b_2X_2$$

where Y is Fire spread rate, X_1 is Storage height and X_2 is Fire load density

3.8 Assumptions and Limitations

The following assumptions were made in the analysis:
Complete combustion of materials was assumed in fire load calculations
Fire detection systems were assumed to be fully operational during recorded events
Sample size was considered representative of facility performance
Environmental conditions remained consistent during measurements
The study also has several limitations:
No full-scale fire experiment was conducted
Computational Fluid Dynamics (CFD) simulation was not included
Economic cost analysis of fire protection systems was beyond the scope of the study

4.Results and Discussion

The section displays the numerical results which were obtained from three different assessments which include the fire load assessment and the Fire Risk Index (FRI) modeling and the fire detection system evaluation and the sprinkler suppression performance assessment at the automated high-bay warehouse. The results were derived from the analysis of both primary and secondary data collected during the study. The researchers used statistical methods which included mean and standard deviation and correlation analysis and regression modeling to assess how fire safety systems operated across different warehouse zones and how fire risks were distributed throughout the building. The analysis is presented on a zone-wise basis to capture variations in fire risk characteristics across operational areas of the automated facility. The evaluated zones include:

- High-bay Storage Area
- Lithium-ion Battery Charging Zone
- Conveyor System Area
- Packing and Dispatch Zone

These zones represent the primary functional sections of the automated warehouse and differ significantly in terms of combustible materials, operational activities, and fire protection requirements.

4.1 Fire Load Density Results

The table 4 show that the density of fire loads is greatly determined by the mass of combustible and calorific value in each area of operation. The storage space with about 75,000 kg of combustible merchandise generates a fire load density of 1450 MJ/m2, which falls in the high-risk fire category. Such a high rating is mostly attributed to the compressed consumer goods and wrappings materials that are arranged in the vertical rack arrangement.

Table 4: Fire Load Density by Zone

Zone	**Combustible Mass (kg)**	**Avg. Calorific Value (MJ/kg)**	**Floor Area (m^2)**	**Fire Load Density (MJ/m^2)**
Storage Zone	75,000	29	1500	1450
Battery Zone	18,000	30	300	1800
Conveyor Zone	15,000	30	500	900
Packing Zone	22,000	30	600	1100

The fire load density in the battery charging area (1800 MJ/m2) is the largest even though the mass of a combustible material is smaller. This is primarily attributed to the fact that high energy lithium-ion battery systems and electrical components are focused on a small floor space. This type of concentration means that the possible rates of heat release during fires are high. A relatively high density of fire loading (900 MJ/m2) is shown by the conveyor zone, which is covered by combustible material in a bigger area of work, because goods keep moving constantly. In the meantime, the packing area has a fire load concentration of 1100 MJ/m2 and the concentration of the fire load is attributed to the cardboard packaging material and plastic wrapping used during the dispatches. In general, the findings indicate that smaller compartments where the material concentrating on fire is high are bound to develop high densities of fire loads, which have great impacts on the intensity of fires and structural exposure to heat of fire incidences.

4.2 Fire Risk Index (FRI) Results

As indicated in the analysis on Fire Risk Index in table 5, it is clear that there are considerable differences in fire risk in the warehouse zones. The area with the highest FRI value (100) is the battery charging zone, which means that there is the highest risk level of fire. This is largely because the maximum ignition probability (P=5) and combustibility (C=5) is coupled with comparatively slow detection because of congested equipment and electrical installations.

Table 5: Fire Risk Index Calculation

Zone	Ignition Probability (P)	Combustibility (C)	Detection Delay (D)	FRI = P×C×D	Risk Level
Storage	4	5	3	60	Moderate
Battery	5	5	4	100	High
Conveyor	3	4	2	24	Low
Packing	4	4	3	48	Moderate

The storage zone offers an FRI reading of 60 which falls under moderate risk category. This is linked to the occurrence of significant levels of inventories between the combustibles and the vertical rack design which could postpone in the early detection of fires. Likewise, the packing area has moderate risk score (FRI = 48) as it is attended to on most occasions, involves packaging materials and operational handling processes that augment the levels of ignition. On the other hand, the conveyor area obtains the least risk score (FRI = 24). The opportunity to detect it sooner and comparatively lower combustible concentration is the main reason of this reduced level of risk. The findings substantiate the conclusion that ignition potential and detection lag time has a strong impact on total fire risk, and there is a necessity to install sophisticated detection systems in areas in high risks.

4.3 Fire Detection System Performance Analysis

In the analysis of alarm response time in table 6, it is evident that there are also no serious variations in the performance of the detection system: response time intervals are 55-70 seconds. An average response time of 62 seconds was computed and this is somewhat more than the normal figure of 60 seconds, but the range of functionality is still satisfactory.

Table 6: Alarm Response Time Data

Event	Response Time (sec)
1	58
2	64
3	60
4	67
5	61
6	63
7	59
8	70
9	55
10	62
11	66
12	60
13	57
14	65
15	68
16	59
17	63
18	61
19	64
20	69

The standard deviation of 4.2 seconds means that there is less variation in the response to the detection, it is possible to perform well in several occasions within varying alarms. Nevertheless, the fact that response times are as high as 70 seconds, suggests that delays may occur in high storage locations, where stratification of smoke and airflow designs are likely to slow down detectors. Detection efficiency was calculated as:

$\eta d = (60 / 62) \times 100 = 96.7\%$

This result indicates high reliability of the fire detection system, although improvements may be required in high-bay storage zones.

Table 7: Storage Height vs Detection Delay

Storage Height (m)	Detection Time (sec)
10	52
15	56
18	59
20	61
22	63
25	66
28	70

Table 7 analysis reveals that there is a confident increment in the delay of detection with height of storage. The time of detection increases with storage height showing a strong positive correlation at 52 seconds at 10 meters to 70 seconds at 28 meters that means there is a positive correlation between storage height and delay of smoke detection. It is true that there is a very strong positive correlation between these variables; this is supported by Pearson correlation coefficient ($r = 0.72$). Such an outcome is in line with the fire safety engineering hypothesis that the bays storage high area means that the smoke travel time is prolonged, which postpones the ceiling-mounted detector activation time. This means that aspirating smoke detectors or the middle level of detectors might be needed in order to enhance the performance of detection.

4.4 Sprinkler System Performance

The sprinkler activation times in table 8 display a range that extends from 88 seconds to 102 seconds while showing an average activation time that approaches 95 seconds. The value exceeds the standard activation benchmark which requires 60 seconds because it shows a delayed suppression response in the high-bay environment.

Table 8: Sprinkler Activation Data

Event	Activation Time (sec)
1	88
2	92
3	96
4	100
5	90
6	95
7	98
8	102
9	94
10	97

Several factors contribute to this delay, including:

- High ceiling heights
- Rack obstruction effects
- Thermal stratification of hot gases

The standard deviation of 4.5 seconds indicates moderate variability in sprinkler activation times across rack aisles. Sprinkler suppression efficiency was calculated as:

Controlled fire events = 39 Total events = 50

$\eta s = (39 / 50) \times 100 = 78\%$

This value falls below the NFPA recommended benchmark of 85%, suggesting that ceiling sprinklers alone may not provide sufficient suppression performance in automated warehouses.

4.5 Regression Analysis

A regression model was developed to estimate fire spread rate based on two key parameters: storage height and fire load density.

Regression Model: Fire Spread Rate = 0.85(Storage Height) + 0.67(Fire Load Density)

The model produced an R^2 value of 0.81, indicating strong predictive capability. The results demonstrate that fire spread behavior can be explained through these two variables for approximately 81% of its total variation.

4.6 Comparative Risk Ranking

The comparative risk ranking in table 9 highlights that the battery charging zone represents the highest fire hazard. The high fire hazard exists because of two factors which include lithium-ion battery systems and electrical infrastructure. The storage zone ranks second as its high combustible mass and vertical storage configuration increase the risk of rapid-fire propagation.

Table 9: Zone Risk Ranking

Rank	Zone	Combined Risk Score
1	Battery	92
2	Storage	75
3	Packing	60
4	Conveyor	40

The packing area shows moderate risk because human activity and combustible packaging materials create potential hazards. The conveyor zone presents the lowest overall risk because it has reduced combustible materials and its design allows for unrestricted movement. The current ranking establishes fire safety requirements which specifically focus on protecting battery and storage facilities.

5.Conclusion

The previous research has explored the problem of fire safety of automated warehouses with the help of a quantitative case study of a high-bay Automated Storage and Retrieval System (AS/RS) warehouse. The study concentrated on the determination of fire hazards, the effectiveness of fire protection systems, and measuring level of fire risks in the various operating zones which comprised the storage area, battery charge zone, the conveyor system, and the packing area. The methodology was a combination of fire load density analysis, Fire Risk Index (FRI) modelling, fire detection system analysis, sprinkler suppression analysis, and statistical analysis. These results indicated that the battery charging area had the greatest density of fire loads of 1800 MJ/m 2 and an FRI of 100 which implies that there was a high fire risk because of the lithium-ion batteries as well as the electrical equipment. Storage zone had also high fire hazards because of the high density in the fire load of 1450 MJ/m 2 through high-packed combustible goods in vertical racks. The testing conducted on the fire protection systems showed that, the fire detection system had a high level of reliability with a detection efficiency aspect of 96.7, and the automatic sprinkler system had a suppression efficacy of 78 which is lower than the suggested level. It was further established that there is strong correlation between storage height and time of detection using statistical analysis, which contributes to one of the arguments that high-bay configurations are important factors that affect the fire detection performance and the probability of fire spread.

Although this study can be useful in understanding the performance of fire safety in automated warehouses, it has a number of limitations. It analyzed information concerning one warehouse plant, which might restrict the conclusions that can be made regarding other automated storage systems having different layout and working conditions. Also, the research was mainly based on the documentation of operation and statistical assessment, so no actual fire experiments or sophisticated Computational Fluid Dynamics (CFD) simulating were performed. The research also did not include the economic analysis of the upgrades of the fire protection system. It is thus hoped that future research is based on multi-warehouse comparative research, combination of CFD fire and smoke modeling, and assessment of improved fire safety technologies like in-rack sprinklers, intelligent sensor networks, and AI controlled fire detection systems. Other aspects of cost-benefit analysis of fire safety investments, and real-time risk monitoring in the logistics Industry 4.0 novels can also be studied further. All in all, the results of the study will help in understanding more of the fire safety issues in automated warehouses and provide useful guide to engineers, safety managers and policymakers on enhancing fire risks management in the contemporary automated storage systems.

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