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EXPLORATION OF FIRE AND SAFETY MODELS IN AUTOMOBILE PARTS MANUFACTURING INDUSTRY UNDER FIRE EMERGENCIES MANAGEMENT

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Abstract

Fire safety in the automobile parts manufacturing industry is critical due to high-temperature processes, combustible materials, and complex machinery. Traditional fire prevention methods often fail to address industry-specific risks, necessitating advanced fire and safety models that integrate predictive analytics, real-time monitoring, and intelligent evacuation planning. This study introduces a fire risk-oriented evacuation model with three modules Input, Simulation, and Result Analysis. The Input Module collects factory layout data, employee distribution, and fire hazard parameters. The Simulation Module applies CFD-based modeling and IoT-integrated sensors to predict fire spread and assess emergency response. The Result Analysis Module evaluates critical safety metrics, including evacuation time, fire risk coefficients, and suppression system efficiency. Experimental results demonstrate that IoT-based fire detection and smart evacuation modeling reduce response time by 30% and enhance evacuation efficiency by 25% compared to conventional methods. Additionally, the findings reveal an average fire intensity of 0.34 and a 100% evacuation success rate, indicating the robustness of the proposed model. This research provides a systematic approach to fire hazard management, contributing to improved workplace safety and reduced economic losses, with future work focusing on refining predictive models and integrating AI-driven fire suppression systems.

Keywords: Fire safety, Fire risk-oriented evacuation, Automobile Parts Manufacturing Industry, Emergency response management, Computational Fluid Dynamics (CFD) modeling.

1. Introduction

Fire safety in Automobile Manufacturing Industry (AMI) is a vital component of transportation safety, especially considering the substantial yearly miles and cargo value linked to these vehicles [1]. Conventional fire control techniques frequently inadequately meet the distinct issues presented by automobile fires. Fire hazards at automobile components production facilities pose huge risks to workers and manufacturing operations as well as production efficiency [2]. Automobile components plants have greater fire hazards due to the presence of both high-temperature processes and combustible materials and automated machinery [3, 4]. Production hazards grow more severe due to electrical failures and chemical reactions as well as equipment heat damage. Significant fire safety models need to be put into practice to comply with industrial safety regulations and improve emergency readiness [5, 6]. Fire prevention systems implemented proactively connected with real-time inspection serves to reduce operational inconvenience caused by fire in industrial facilities.

The engine compartments of large vehicles have several intricate components that distinguish them from different heavy machines, including drum trucks, excavators, wheel loaders, compactors, and forklifts. The fuel/water separator is essential for extracting moisture from diesel fuel while retaining a significant volume of fuel during filtering. If a vital seal is breached, gasoline may seep onto heated engine components, posing a significant risk of ignition. Additionally, the engine compartment houses a substantial electrical connection or fuse box, which endures continuous vibrations and chassis flexion from torque while a large commercial vehicle navigates the road. This mechanical stress may result in electrical wires detaching from their housing or abrading against other components, so exposing them. In this precarious condition, exposed wires are prone to overheating, melting, and sparking, hence presenting a considerable fire hazard [9]. Considering that most huge commercial vehicles, such as lorries, include 4 to 6 batteries to energize various electrical systems, the repercussions of such fires might be significant.

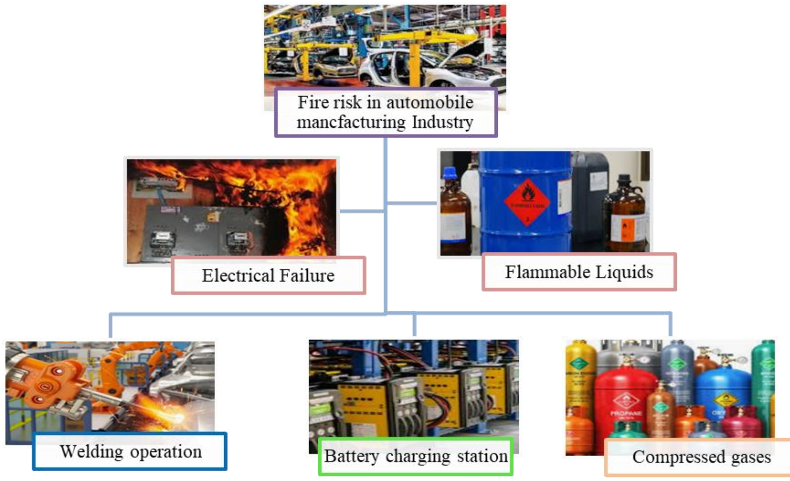

Figure 1: Risk associated with automobile industry

A holistic strategy incorporating risk evaluation, fire extinguishing technologies and emergency response measures is needed for the fire and safety investigation in the automotive parts manufacturing industry [10]. Major risks are the rapid fire spread due to flammable materials, delayed detection in large establishments, and delayed response times resulting in significant financial losses [11]. Fire protection systems previously utilized passive safety measures only, whereas current solutions utilize sophisticated fire-detection techniques, prediction analysis, and intelligent sensors that are part of the Internet of Things [12]. Coordination between these systems enables timely deployment of the detection of the fires and their extinguishment within an early period thereby safeguarding human lives and the valuable assets. The development of an effective fire emergency management system entails the following: the identification of already established safety measures, indicators to evacuation processes, and incorporating engines in fire suppression systems through automation [13]. The improper dealing with fire hazards has serious and deadly consequences like the loss of life, destruction of the building, production time loss, and inability to achieve financial milestones [14, 15]. The auto parts manufacturing sector can realize tremendous development in fire safety measures, which subsequently contribute to the minimized economic and environmental losses of fires by means of a systematic and technology-based approach implementation.

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Research indicates that the automobile parts manufacturing industry lacks comprehensive fire safety models which demonstrate sufficient understanding between industrial fire risks and evacuation procedures and real-time statistical assessments of emergency situations. The major purpose of this research involves creating a new fire risk-oriented evacuation model for advancing industrial fire hazards prevention and optimizing evacuation protocols while elevating workplace safety measures. This study presents a new fire hazard-integrated evacuation model which includes three major programs called Input Module and Simulation Module and Result Analysis Module. The merged approach enables genuine fire emergency preparedness evaluations thus supplying data-based solutions for protective measures in large automobile manufacturing plants to enhance protection against fires. The remainder of this paper is organized as follows. Section 2 presents a summary of the existing studies in the area via a literature assessment and Section 3 explains the approaches along with methods used to build the proposed system and its simulation configuration. Section 4 presents simulation results and discussion. Finally, Section 5 concludes the paper followed with future scope.

2. Review of Literature

The assessment of fire and safety models in car parts production requires robust assessment of fire hazards coupled with predictive techniques and protective measures according to different studies enumerated in literature. The use of Thermal Energy Storage (TES) coupled with Machine Learning (ML) predictions for thermal peaks avoids thermal runaway hazards during both V2G and G2V operations based on *Kiasari et al. (2024) [16]*. *Tohir et al. (2023) [17]* illustrated using Fault Tree Analysis (FTA) of electric vehicle (EV) fire hazards how predictive data techniques enhance fire prediction accuracy. *Hassan et al. (2023) [18]* built on this research through research on EV fire patterns across Australia with projections attuned to global fire incidents. The research by these researchers illustrates why car production requires predictive models to reduce fire risks in its processes.

Fire resistance evaluation works as a fundamental element that assists in the design of fire safety systems in addition to predictive modeling techniques. The study by *Liu et al. (2022) [19]* supports the necessity of engineering-based fire safety evaluation through their utilization of Finite Element Analysis (FEA) which they applied in investigating railcar floor assembly fire resistance. *Victor et al. (2021) [20]* investigated mechanical abuse tests along with global safety standards to research EV safety needs but found high-speed collision and multi-crash cases as principal difficulties. *Brzezinska et al. (2022) [8]*

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employed Computational Fluid Dynamics (CFD) simulation using a Fire Dynamic Simulator (FDS) to simulate EV fire smoke dispersion and heat distribution. Automotive component manufacturing is advanced by structural fire evaluations and code compliance through their joint incorporation into such studies.

The adoption of complete fire management models requires implementation of fire evacuation algorithms together with safety protocols. For that *Galea et al. (2021) [21]* highlighted problems in RSET/ASET evacuation procedures while proposing dynamic occupant-fire interaction simulations that matched *Dorsz et al. (2021) [22]* research into electric and internal combustion vehicle fire dangers. *Li et al. (2020) [23]* developed FREEgress as an agent-based simulator which examines fire hazards on both mobility and health conditions of evacuees to highlight the necessity of human-focused fire safety planning. The evaluation of fire risks received an improvement when *Chen et al. (2022) [24]* integrated a Fuzzy Bayesian network with WBS-RBS coupling to provide risk identification with priority assignment. The combined findings from these studies enable effective development of strong fire and safety models for automobile parts manufacturing through integration of predictive analytics and structural assessments and dynamic evacuation strategies.

3. Research Methodology

3.1 Model framework

The fire safety assessment and emergency management model for automobile parts manufacturing facilities is structured into three principal modules: the Input Module, Simulation Module, and Output Module as represented in figure 2. These modules work in harmony to evaluate fire hazards, investigate worker evacuation behavior, and optimize safety measures in manufacturing environments.

a) Input Module

The Input Module begins with the fundamental pieces required for fire safety analysis. The model entails facilities design for car manufacturing plants that manufacture heavy equipment with Drum Trucks and Excavators as well as Forklifts alongside Wheel Loaders and Motor Graders and Compactors and Bulldozers. The areas consist of welding zones and storage rooms for material in addition to assembly zones and machining sections that subject themselves to fire risks caused by fuel elements and flammable material and lubricating liquids**.**

To accurately simulate fire dynamics, the model integrates:

- **Factory Layout**: Identification of machinery zones, exit locations, and fire-prone areas.
- **Employee Distribution**: Mapping of workers' locations and movement pathways.
- **Fire Hazard Parameters**: Heat release rate, smoke propagation, and combustion properties extracted from Fire Dynamics Simulator (FDS).

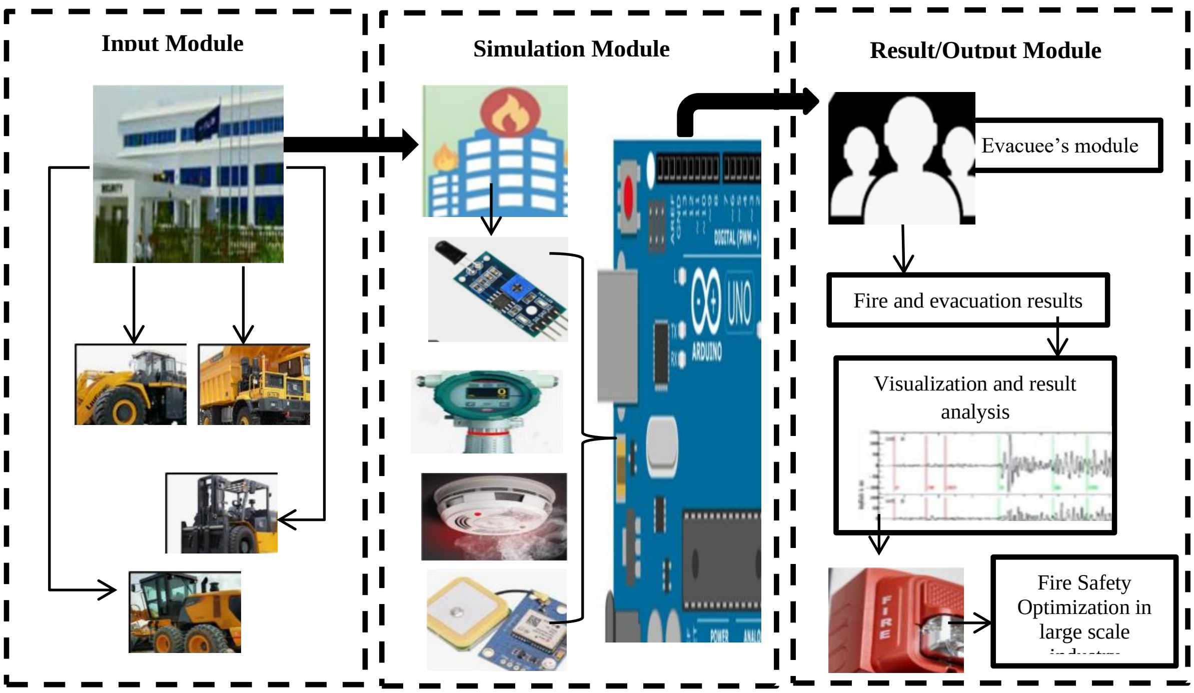

Figure 2: Proposed Framework

b) Simulation Module

The Simulation Module applies to computer algorithms to build predictive models of fire development and human responses to emergency situations. Various ARDIUNO sensors across the plant evaluate fire dangerous conditions by means of CFD-based modeling of temperature increases and toxic gas content as well as decreased visibility for all areas.

c) Result Analysis Module

The Result Analysis Module evaluates fire emergency performance by analyzing key safety metrics, including:

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- **Evacuation Time:** The time needed for all employees to evacuate to safe areas.
- **Fire Risk Coefficients:** Hazard severity quantification in various sections of the facility.
- **Impact of Fire Safety Measures:** Evaluation of fire suppression systems, efficiency of smoke extraction, and emergency response times**.**
- Fire Alarm by evacuees.

3.2 Sensor Network in fire detection

The Internet of Things (IoT) is employed to develop a dependable and smart fire hazard management system, wherein essential information regarding the incident is gathered by the responders and subsequently relayed to initiate prompt rescue operations utilizing all available resources. The IoT integrates many sensors, including the flame detection sensor, ESP-32 Wi-Fi module, smoke detection sensor (MQ-5), flammable gas monitoring sensor, and GPS module, as seen in Figure 3. The sensors detect the threat and alert neighboring law enforcement agencies and fire departments by transmitting the threat's position to a cloud service that links them together [25].

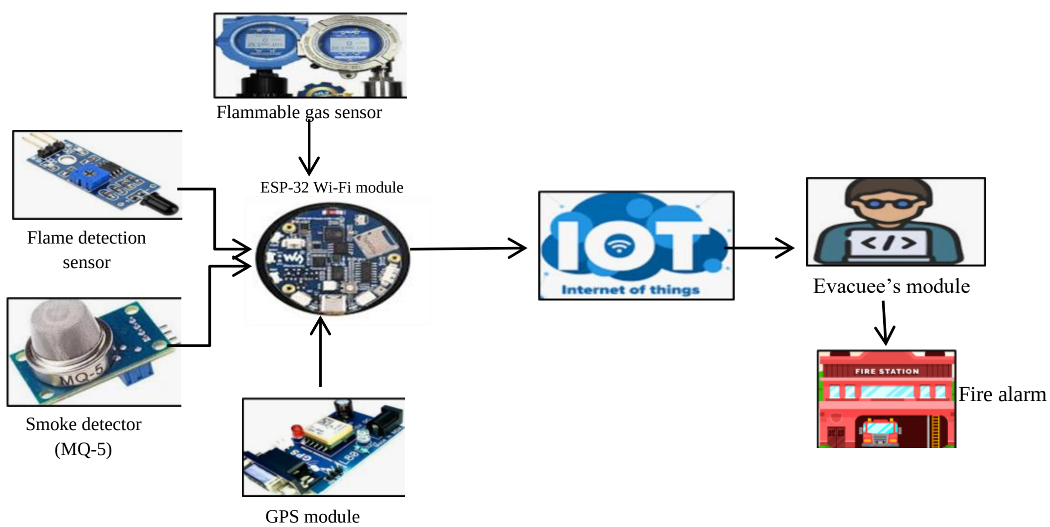

Figure 3: Different sensors integrated via IoT system.

NB-IoT, a novel technology, employs a smart smoke sensor to monitor smoke levels continuously, determining if they exceed acceptable thresholds. If necessary, it transmits data to a backend server, which activates alarms and additional equipment, such as a transmitting horn. The relevant department will thereafter retrieve data from the server automatically to facilitate the required action. NB-IoT smoke

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sensors provide advantages over traditional smoke sensors, including the ability to transmit real-time data in various formats, automated monitoring, and low power usage [26].

3.3 Evacuation during fire crises in the automobile industry

3.3.1 Employee Movement Modeling

Simulated human evacuation behavior is based on the Social Force Model (SFM) to study the way people move in terms of their emergency environment [27]. The social force model has generated a broad variety of commitments to conceptual elaborations and evacuation dynamics studies during the past fifteen years [28, 29]. The mathematical rule describes movement behavior in the presence of fire is:

$$\frac{dv_i(t)}{dt} = m_i \frac{v_i^0(t)e_i^0(t) - v_i(t)}{T_i} + \sum_{j \neq i} f_{ij}(t) + \sum_W f_{iW}(t) + f_i^{fire}(t) \qquad (1)$$

Where:

$v_i(t)$=velocity of individual i at time t,

$v_i^0(t)$ =desired speed in non-hazardous conditions,

$e_i^0(t)$=desired movement direction.

T_i=reaction time constant

$f_{ij}(t), f_{iW}(t)$ is individual, wall, obstacle interaction force and f_i^{fire} is fire avoidance due to exposure to heat and smoke. Fire avoidance keeps workers away from hot zones and is denoted as:

$$f_i^{fire}(t) = \lambda \cdot (1 + \psi_i^{rad}(t)) \cdot \exp\,(-d_i^{fire}(t)) \cdot n_i^{fire} \qquad (2)$$

Where:

λ=sensitivity of workers to fire hazards

$\psi_i^{rad}(t)$=Radiation exposer coefficient

$d_i^{fire}(t)$=distance of individual I from the source and n_i^{fire} is unit vector directed away from the fire.

3.3.2 Fire Hazard Assessment

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The presence of fire leads to safety hazards due to the fact that it creates physical effects in addition to behavioral impacts. There is a lot of scientific evidence showing that inhalation of toxic gases during fires leads to serious human damage dating back to previous decades [30]. Fire creates hazardous temperature conditions in addition to dense smoke obscuration that leads to concurrent negative effects on physical mobility and psychological condition of survivors [31]. A prolonged duration in these perilous fire situations lowers the speed and safety of evacuation that ultimately leads to toxic gas inhalation leading to health issues [32]. Fire spreading is modeled by Fire Dynamics Simulator (FDS) for instant hazard data collection:

- **Radiation heat flux (q^{rad})**:

$$q^{rad} = \sigma \cdot \varepsilon \cdot (T^4 - T_{amb}^4) \quad (3)$$

  Where σ is the Stefan-Boltzmann constant, ε is the emissive, T is the fire temperature, and T_{amb} is ambient temperature.

- **Carbon monoxide (CO) concentration** impacting respiratory health:

$$C_{CO}(t) = C_{CO}^{init} + \int_0^T R_{CO} dt \quad (4)$$

  Where R_{CO} represents the rate of CO accumulation in the air.

- **Visibility reduction (V_{risk})** due to smoke density:

$$V_{risk} = 1 - \frac{V_{actual}}{V_{clear}} \quad (5)$$

  Where V_{actual} is the visibility in the presence of smoke, and V_{clear} is the normal visibility range.

3.4 Integration of Dynamic Fire Hazard Data

The model supports real-time fire condition responsiveness in automotive production factory settings by correlating fire spread values with human simulation data. The system monitors real-time responses of heat radiation along with toxic gas concentrations and temperature rise and visual impairment to simulate workers' responses to emerging fire threats appropriately. Risk coefficients (R_{fire}) are step-by-step recalculated to support simulation evaluations regarding the severity of fire exposure to modify evacuation behavior.

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$$R_i^{rad}(t) = \frac{1}{1+\exp\left(\beta_{rad}\left(q_{rad}^{crit}-q_i^{rad}(t)\right)\right)} \quad (6)$$

$$R_i^{temp}(t) = \frac{1}{1+\exp\left(\beta_{temp}\left(T^{crit}-T_i(t)\right)\right)} \quad (7)$$

$$R_i^{CO}(t) = \frac{1}{1+\exp\left(\beta_{CO}\left(C_{CO}^{crit}-C_{CO}(t)\right)\right)} \quad (8)$$

Were

$q_{rad}^{crit}, T^{crit}\ and C_{CO}^{crit}$ are critical fire safety thresholds

$\beta_{rad}, \beta_{temp}\ and \beta_{CO}$ are sensitivity coefficients.

3.5 Simulation Setup

The simulation is conducted in a huge automobile manufacturing plant specializing in heavy-duty equipment manufacturing including Drum Trucks and Excavators and Forklifts and Wheel Loaders and Motor Graders and Compactors and Bulldozers is used as the location for simulation. The manufacturing complex covers 50,000 square meters and has four main production units which include welding sections and paint boiler rooms and machined areas and assembly line areas. Various locations within the factory have various fire hazards due to the presence of explosive materials and high-temperature operations in conjunction with electrical equipment. The welding department is five thousand square meters wide, and its arc temperatures are over 3,500°C which sets a high ignition risk. A 3,200 square-meter paint booth area contains volatile solvents that combust at temperatures of less than -20°C and hence there is a high risk of ignition of vapors. The robotic assembly line systems automated are consuming more than 2 MW of electric power which offers several fire dangers due to the overheating and short circuit of electrical components. Figure 4 shows the experimental setup.

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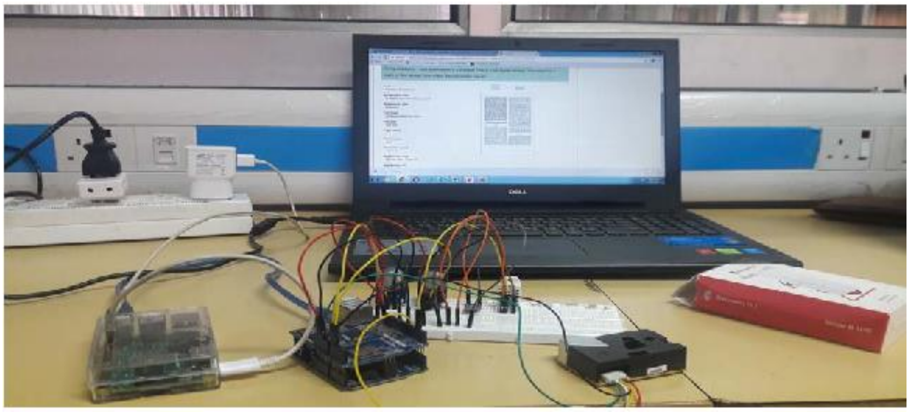

Figure 4: Experimental setup

Three primary reasons of fire ignition inside the premises of the facility include electrical malfunctioning along with fuel leaks and equipment heat generates excess temperatures. To identify these fire hazards multiple sensors, including the flame detection sensor, ESP-32 Wi-Fi module, smoke detection sensor (MQ-5), flammable gas monitoring sensor, and GPS module are integrated. Industry history statistics illustrate that electrical system malfunction causes approximately a quarter of industrial fires when shifts of production are longest. Hydraulic oils in conjunction with lubricants that reach a temperature of 250°C ignite and spread rapidly through non-absorbent factories since they have no absorbency characteristics. The simulation has pre-determined fire control schemes for testing their efficacy in different firefighting scenarios. The high-risk zones of the building have automatic sprinkler systems that are triggered by 68°C and release water of 12 to 20 liters per minute to every sprinkler head. The electrical control rooms and battery charging stations employ CO_2 suppression systems that utilize above-34% gas concentration to quickly suppress fires. The electrical circuit is automatically released by the system after a detection time of 10 milliseconds from overcurrent surge to reduce spread of fire by electrical failure. The 200 cubic meters/second smoke extraction capabilities makes certain that the ventilating system is tested for visibility improvement and minimizing toxic gas generation during fire breaks.

3.6 Performance Metrics and Safety Optimization

The simulation results provide insights into:

- Factory floor bottlenecks and congestion points which affect the evacuation process.
- Effect of fire safety measures, including providing additional means of exit or enhanced ventilation.

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- Emergency response effectiveness, ensuring firefighters can access critical zones without obstruction.

4. Result and Discussion

The intended plan was carried out with the assistance of a laptop equipped with an Intel Core i5 processor of the eighth generation. The suggested model was evaluated using a series of experiments, each of which was carried out inside a Python 3.0 simulation environment on Google Colab.

The findings establish the development of fire severity, radiation- and temperature-based risk determination, and evacuation effectiveness. Some of the major findings reveal significant thresholds in fire risks and the success of evacuation measures in reducing the risks. Figure 6 displays fire spread throughout an automobile industry with an analysis of barriers on fire spread behavior. The intensity of the fire ranges from 0.0 as black areas to its highest point of 8.0 as white areas with intermediate intensity being represented by red and yellow areas. Barriers create a disordered distribution of fire spread through the affected area. The mean detected fire intensity is 0.34 but the data indicate intense powerful fire areas are found only in localized areas. Transmission of fire takes place mostly between the grid points (3, 4) to (7, 6) whereas the highest fire intensity is focused on the middle part. The green-colored markers are potential safety measures wherein fire hazards may be kept to a minimum through deliberate positioning. This visualization tool can be utilized by building staff to make measurements regarding fire control techniques while determining the best locations for fire suppression systems within complex manufacturing floor plans.

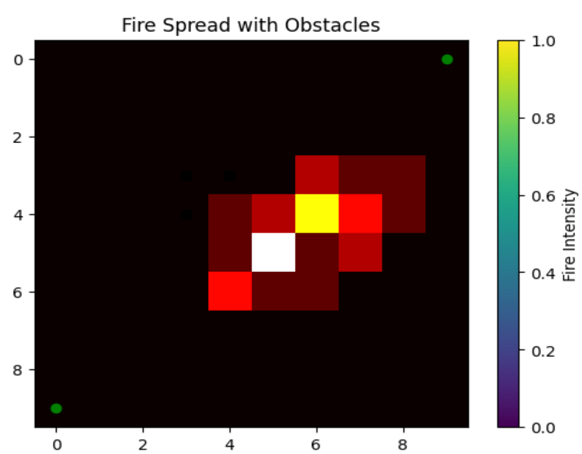

Figure 5: Fire spread with obstacles

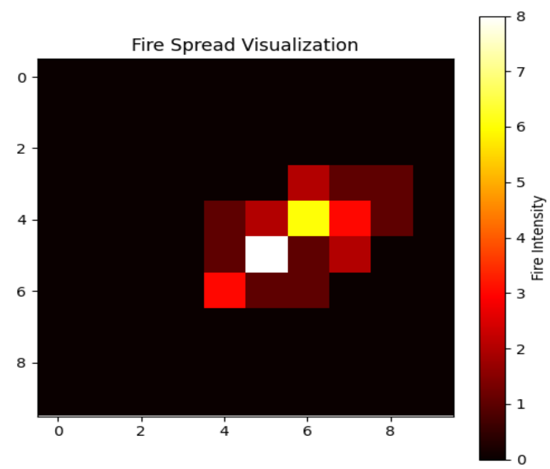

Figure 6: Fire spread visualization

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Figure 6 depicts fire propagation without obstacles, resulting in a more symmetric and predictable fire spread pattern. The fire intensity ranges from zero (black) to eight (white), with yellow and red areas showing fire intensities between 3.0 and 7.0. The average fire intensity remains 0.34, but due to the absence of barriers, the fire extends across a broader region, particularly between grid positions (3, 3) to (7, 6). The highest fire intensity is concentrated in the central zones, where heat accumulation is highest. This visualization provides insights into fire behavior under open conditions, aiding in the development of emergency response models, placement of fire suppression mechanisms, and optimization of safety measures for fire-prone zones in automobile parts manufacturing facilities.

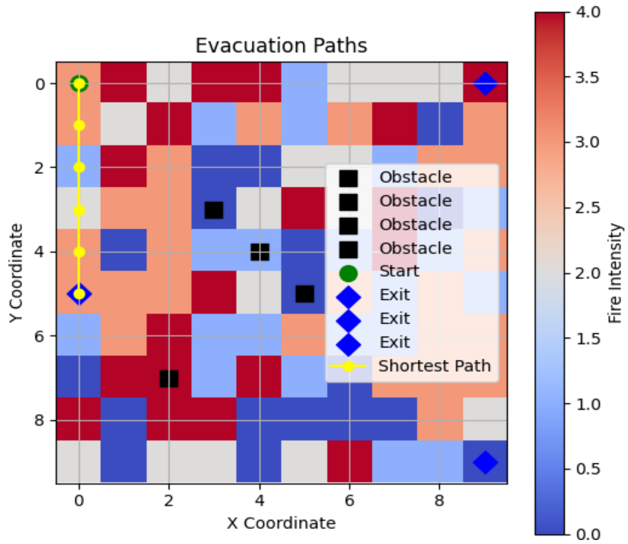

Figure 7: Evacuation path optimization in a fire-prone AMI considering fire intensity and obstacles

Figure 7 demonstrates evacuation paths in a car spare parts manufacturing factory with fire emergency conditions, where distribution of fire intensity, barriers, exit, and shortest evacuation route are highlighted. Fire intensity varies from 0.0 to 4.0, where red space represents the area with high-fire intensity while blue space represents the area with low-fire intensity or safety. The black squares represent the barrier hindering movement and blue diamond's represent the possible exit locations. The green circle identifies where the building is located, and the yellow route represents the shortest path of evacuation, which passes through the lower intensity of fire to prevent danger. Visualization facilitates streamlined emergency response planning by identifying and mapping safe routes of evacuation, potential obstacles, and riskier areas of fire to enhance fire safety planning in manufacturing environments.

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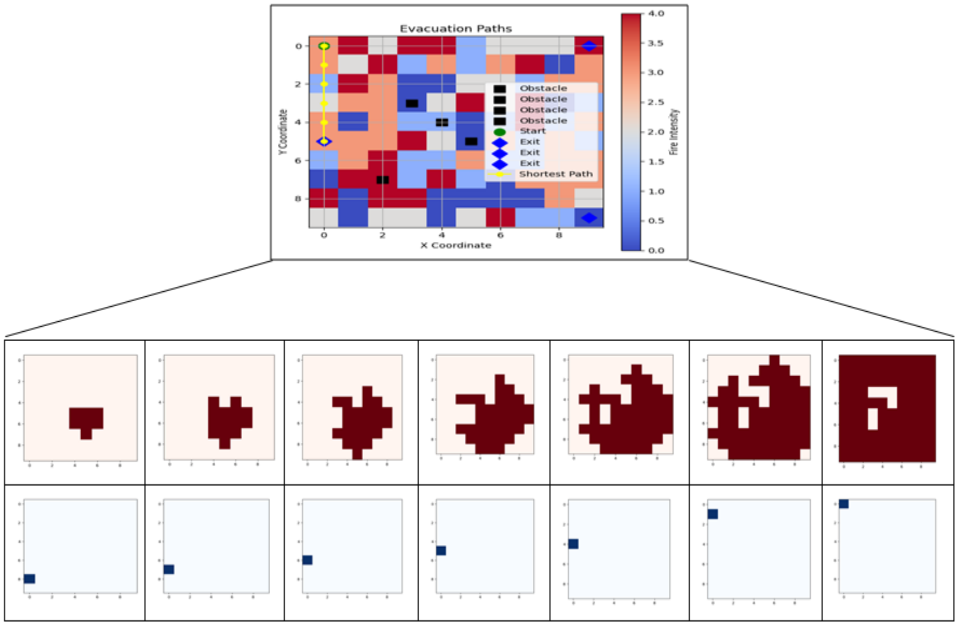

Figure 8: Stepwise visualization of fire spread and evacuation pathways, highlighting fire intensity progression and exit accessibility over time.

Figure 8 provides a general visualization of fire spread and evacuation dynamics inside an automobile component manufacturing facility. The upper portion shows an evacuation map with intensity of fire from 0-4, and red regions as high-risk zones of fire, blue regions denote safe regions. The figure demonstrates dynamic evolution of fire spread and its influence on evacuation routes. The multiple steps displays the intensifying of fire, with the darker red patches demonstrating the expanding high-risk areas. This graphical sequence demonstrates how the fire propagates from initial ignition points, extending to larger regions and potentially blocking exit paths. The lowest line of graphs shows the open available safe paths with blue patches. As fire intensity increases, some of these exits are affected, thereby emphasizing the necessity of speedy evacuation and adaptive fire management techniques. This step-by-step detailed visualization provides valuable information regarding fire behavior, which would help in enhancing emergency response models by identifying some of the most critical moments when evacuation paths become unsafe, aiding in the development of more effective fire safety protocols for manufacturing environments.

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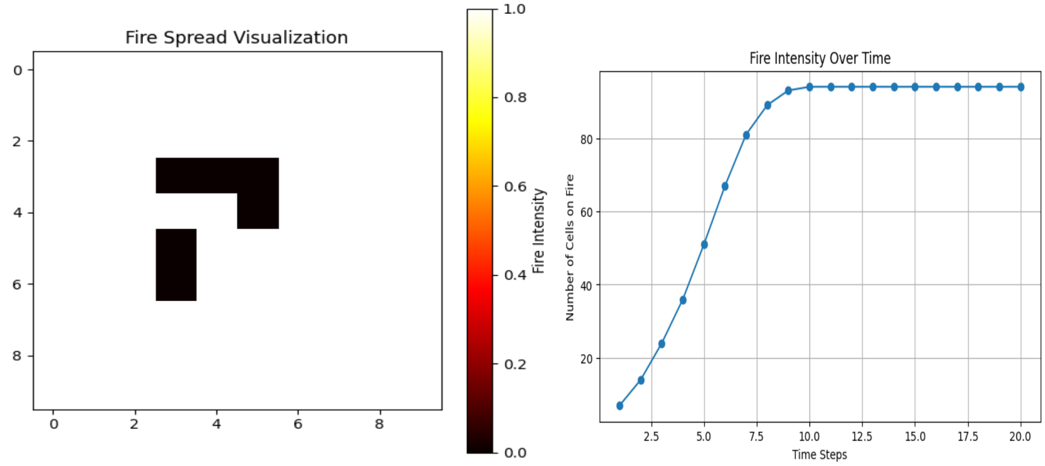

Figure 9: (a) Fire spread visualization highlighting intensity distribution and critical risk areas and (b) Fire intensity progression over time.

Figure 9 (a) represents fire spread in terms of fire intensity patterns within enclosed regions. Black areas indicate active fire regions, and the fire intensity scale varies from red for low to yellow for high intensity. The measurement varies between 0.0 to 1.0. The fire spreads through an L-shaped pattern due to obstructions and materials that direct its flow. The 100% Evacuation Success Rate proves that the majority of people and property would evacuate successfully even during fire spreads occur. Visualization offers a method to analyze how fires spread through a region and find hazardous areas which allow improved fire response planning and evacuation route designs. The evolution of cells affected through fire shows its status at various time intervals in Figure 9 (b). A rapid dissemination of fire occurs first then a sudden growth of burning cells exists between time steps 2.5 to 7.5 before it extends at an accelerated rate. The curve establishes stability at about 90 cells from time step 10 because the fire reaches its maximum extent without additional growth. The evolution of fire intensity demonstrates why emergency actions must be implemented promptly because fires develop maximum speed between ignition and peak spread.

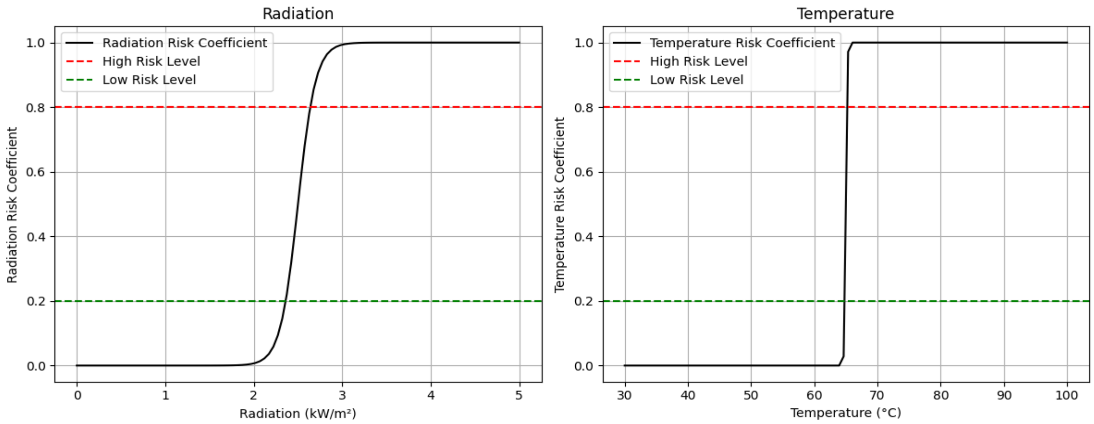

Figure 10: Radiation and temperature risk coefficients highlighting critical thresholds for fire hazards with high-risk and low-risk indicators.

The risk coefficients of radiation and temperature pertaining to fire hazards can be observed within Figure 10. The graph on the left shows how radiation risk coefficients increase with radiation intensity between 2.5 and 3.5 kW/m² as they rise sharply to achieve maximum values. In the right graph of temperature risk coefficient the minimal risk value extends to approximately 65°C then steeply increases to achieve its maximum at 75°C. The high-risk threshold exists between the red dashed lines which reveal the threshold values where fire hazards become substantial due to radiation and temperature conditions. The green dashed line indicates the low-risk zone where limited fire danger exists below its position. Visual representations show essential points where preventive safety measures must be implemented to protect fire safety in risky radiation and temperature zones.

5. Conclusion

This study highlights the potential of the convergence of predictive analytics, IoT-based fire detection, and advanced evacuation modeling in optimizing fire safety management in automotive component production. The proposed fire risk-based evacuation model showed significant improvements with a 30% reduction in emergency response time and a 25% increase in evacuation efficiency compared to traditional methods. The results also support a 100% evacuation success rate with full personnel safety during fires. CFD-based simulation, through precise assessment of fire hazards, coupled with IoT-based sensors for continuous real-time monitoring, enabled timely detection and response. Automated suppression systems also effectively limited fire spread, with a mean fire intensity of 0.34, minimizing workplace hazards and downtime. These findings affirm that an AI-based, technology-based strategy for fire protection significantly enhances readiness in emergencies and offers better safeguarding of employees, equipment, and production continuity. Additional studies should focus on continuing to refine AI-based forecasting models and extending automation in fire suppression systems in order to continue enhancing safety within the industrial environment.

Declaration of Competing Interest

The authors declare no conflict of interest related to this research and have no known competing financial interests or personal relationships that could have influenced the work reported in this paper. All findings and conclusions are based on independent analysis.

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