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Contributing to the Identification of Fire Hazard Zones in High-Bay Warehouses

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ABSTRACT

Given that the determination of fire hazard zones in high-bay warehouses has not been sufficiently researched, this paper aims to present a novel methodological approach to address this issue. Based on the COPRAS multi-criteria decision-making method, a new procedure has been developed for the precise identification of zones with potential fire risks. The advantage of the proposed method lies in its ability to quickly and easily determine all potential fire hazard zones. This procedure represents the first step in the planning and layout design of the warehouse. The effectiveness of the proposed method was validated through a relevant numerical example.

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1. Introduction

The term "fire" refers to a serious threat to both human safety and property, whether it involves residential buildings, storage facilities, or industrial sites. Managing the risk of fire outbreaks presents a significant challenge in both urban and rural environments (Alkış, 2021). Warehouses, as facilities where various activities related to the storage, transportation, and handling of goods take place, are prone to accidents that can lead to injuries, material damage, and endanger the work environment—particularly in the event of a fire.

While fires in warehouses represent a small percentage of total fires, they often have much more severe consequences in terms of heat release, the extent of the affected area, the degree of damage to the building, and the material losses involved. As integral parts of logistics, warehouses undergo frequent improvements during development to enhance performance, capacity, and efficiency. These changes result in larger and taller warehouses, the use of automated storage and retrieval systems (AS/RS), higher storage density, and the placement of storage units at greater heights (Dinaburg, 2012). However, these modifications also increase the risk of fire spread, make detection and localization more difficult, and contribute to higher smoke emissions and toxic substances, which significantly impact employee health and safety.

In recent years, fires in warehouses have caused both human casualties and substantial material losses. Many deaths in such fires are attributed to inhalation of toxic gases (CO, CO2), thick smoke, and a lack of oxygen (Fu, 2016). The August 2015 fire at a warehouse in the Port of Tianjin, China, which resulted in 173 fatalities and hundreds of injuries, highlighted the critical importance of fire safety in warehouses. The cause was improper storage of explosive materials (nitrocellulose) alongside 40 other flammable substances, such as refined naphthalene and ammonium nitrate (Martin, 2016).

Another devastating fire occurred in August 2020 in a warehouse in Beirut, Lebanon, causing 203 deaths, over 7,000 injuries, and leaving 300,000 people homeless. The fire was caused by improperly stored ammonium nitrate that had been left unattended for six years without proper fire safety measures (Tahmid, 2022).

These catastrophic incidents have sparked a significant amount of research focused on fire safety in warehouses. The primary goal of this research, and of this paper, is to address critical issues such as fire risk assessment, safe evacuation strategies, effective fire suppression, localization, and the reduction of fire hazards.

2. Literature review

The procedure developed in this paper consists of four main parts. The first part focuses on selecting the parameters used in fire risk assessment methods, which are necessary for determining the weighting coefficients required for identifying fire hazard zones using multi-criteria decision-making procedures (Basuri et al., 2026). The second part presents the COPRAS method, chosen for its relevance in obtaining the weighting coefficients necessary for further calculations, as demonstrated in (Valipour, 2017; Chanthakhot, 2021). The third part outlines the characteristics and advantages of the three-dimensional (3D) method for determining the parameters related to the contents in the warehouse, which are crucial for fire risk assessment and fire hazard zone identification. The fourth and final part introduces the 3D Center of Gravity (COG) method, which is used to determine potential fire risk zones within the warehouse based on location.

Selection of Parameters for Multi-Criteria Analysis - The core concept behind the developed method is to combine factors related to harmful substance emissions (due to frequent poisoning during fires) with factors related to the burning process of materials in a fire. Due to the limitations of the COPRAS method regarding the number of criteria that can be applied, seven key parameters were selected based on the available literature. These parameters serve as criteria in the multi-criteria analysis procedure and are divided into two groups: criteria related to human health impact and criteria related to the thermal properties of stored materials.

Determination of Simulation Parameters Using the COPRAS Method - The COPRAS method is widely applicable across various fields, including risk assessment in construction, selection of materials for solar panels, optimization of composite material processing, and the choice of robotization in production. The COPRAS method was used to determine the weighting coefficients, which serve as input parameters for fire risk assessment in high-bay warehouses, as the authors outlined in their previous work (Bošković, 2023). The COPRAS method includes six steps: from the creation and normalization of the decision matrix to determining and ranking the relative importance (weight) of each alternative.

3D Method for Determining Storage Parameters - To accurately determine parameters related to the location of transport units and the flexibility of the warehouse layout, a three-dimensional model of the warehouse with associated elements was developed. The structure of this procedure for determining warehouse parameters is illustrated in the Figure 1.

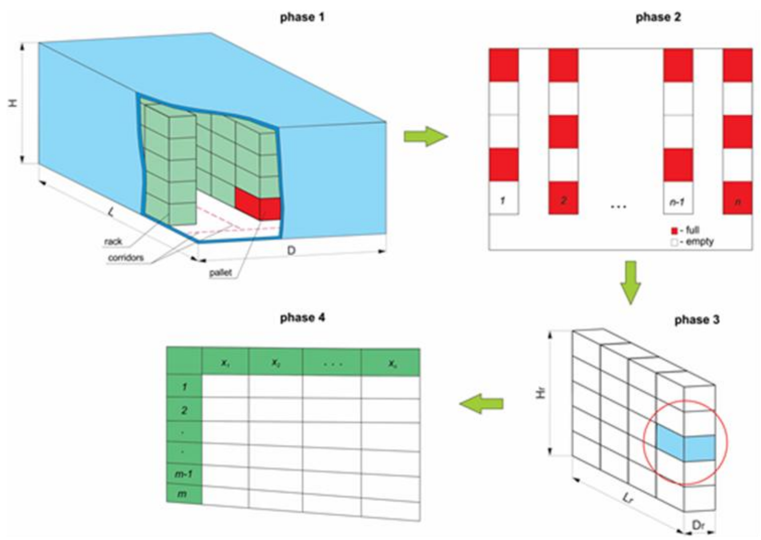

Figure 1. Schematic representation of the creation of a 3D warehouse model and the process of obtaining the relevant parameters.

The procedure for determining the coordinates of potential hazard zones - For simplified presentation and computation, transport units with fixed positions in the warehouse are modeled as material points. Evaluating their centers of gravity and corresponding weighting coefficients is essential for identifying potential fire risk zones. While the classical center of gravity (COG) method determines optimal locations in the two-dimensional X–Y coordinate system, an enhanced COG approach is applied here to assess potential fire risk zones and their coordinates.

3. Materials and Methods

In the numerical example presented in this section, the parameters of the high-bay warehouse related to its dimensions and layout, as shown in Figure 2, were adopted from the study presented in (Bošković, 2023). Based on the considerations discussed in the previous chapter, and in order to obtain the most accurate data required for further simulation, five types of solid materials - wood, cardboard, chipboard, PVC plastic, and rubber, were selected as alternatives in the multi-criteria decision-making process, which constitutes the subject of the subsequent calculations.

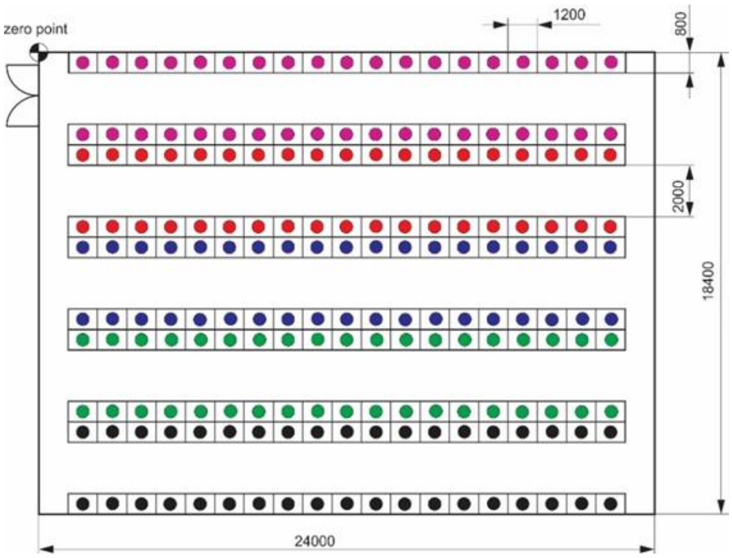

Figure 2. The layout of a high-bay warehouse with associated dimensions and materials (• wood, • cardboard, • chipboard, • PVC, and • rubber)

The list of materials and the numerical values of the seven selected parameters are presented in Table 1. The combustion-related material characteristics shown in this table serve as criteria in the multi-criteria decision-making process (Varada Rajulu, 2013).

Table 1. Input parameters in the procedure of determining the weighting coefficients required for the simulation

Material	CO [mg/kg]	CO2 [mg/kg]	Smoke density [kg/m3]	Ignition temperature [°C]	Thermal conductivity [W/mK]	Specific heat capacity [J/(kg K)]	Calorific value [MJ/kg]
Wood	6	1696	100	350	0.15	1360	14.4
Cardboard	0.1	1450	39.8	427	0.061	1400	13.5
Plywood	6	1774	400	150	0.13	2500	17
PVC	71	657	55.03	391	0.185	900	41
Rubber (tire)	600	1911	8000	315	1.85	1880	35

The first three parameters are considered useful, as they account for the emission of harmful gases affecting human health, whereas the remaining four parameters (criteria) are regarded as useless. By following all steps of the COPRAS method, the weights of each alternative wi and the corresponding ranking are obtained, as presented in Table 2. Similarly, the parameters for Case 2 can be determined by reversing the criteria classification, whereby the last four parameters are treated as useful and the first three as useless.

Table 2. Calculated weights of alternatives for Case 1 and Case 2

Case 1		*Case 2*	
wei	Rank	*wci*	Rank
0.14821	3	0.19179	4
0.13642	4	0.20419	3
0.15195	2	0.21666	2
0.11238	5	0.23213	1
0.45105	1	0.15523	5

The obtained results were compared using correlation analysis based on Spearman's rank correlation coefficient and the standard deviation of the alternative rank levels. The value of Spearman's rank correlation coefficient R indicates a strong correlation, with R=0.74, which lies within the range $0.7 \leq R$ (R=0.74).

Each material listed in Table 1 occupies two racks, resulting in a total of 10 racks in the warehouse and a maximum capacity of 1200 transport units. Since warehouses are rarely operated at full capacity, the effectiveness of the proposed method is evaluated by varying the layout of transport units within the racks. In this analysis, the warehouse is filled to a maximum of 70% capacity, with the constraint that each material accounts for an equal share, i.e., 20% of the total number of transport units.

4. Results and Discussion

Based on the parameters related to the locations of transport units, determined by implementing the procedure shown in Figure 2, along with the weighting coefficients obtained using the COPRAS method and input into the COG algorithm, the potential fire risk zones in the high-bay warehouse are identified.

Based on the obtained spatial coordinates and using a three-dimensional model of the high-bay warehouse, two spheres representing potential fire risk zones were generated (see Figure 3). These spheres delineate areas considered vulnerable to fire, encompassing both typical and random material distribution scenarios within the warehouse. The left sphere, with center coordinates $x = 8.7$ m, $y = 12$ m, $z = 4.8$ m and radius $r = 4$ m, and the right sphere, with center coordinates $x = 10.2$ m, $y = 12$ m, $z = 4.8$ m and radius $r = 4.1$ m, were generated based on the symmetrical arrangement of racks along all axes, the homogeneity of stored materials, and the overall warehouse occupancy.

The x-coordinate of each sphere reflects its longitudinal position along the warehouse length, which is sensitive to variations in material distribution along the racks. The y-coordinate indicates the position along the warehouse width, which remains constant due to the symmetrical layout of the racks. The z-coordinate represents the height of the potential risk zones and corresponds to the vertical stacking of materials within the racks, while the radius of each sphere defines the spatial extent of the area potentially affected by fire. Figure 3 illustrates how deviations along the x-axis occur as a result of different storage patterns, highlighting how material distribution can influence the location of risk zones.

The practical value of this method lies in its ability to provide a clear, three-dimensional visualization of fire risk areas with minimal input requirements. It allows warehouse planners to quickly assess the most vulnerable zones, optimize material placement to reduce potential hazards, and perform real-time simulations of various storage scenarios. The approach is resource-efficient, requires simple data acquisition, and can be readily integrated into existing warehouse management and safety planning systems, making it a versatile tool for both operational and safety decision-making.

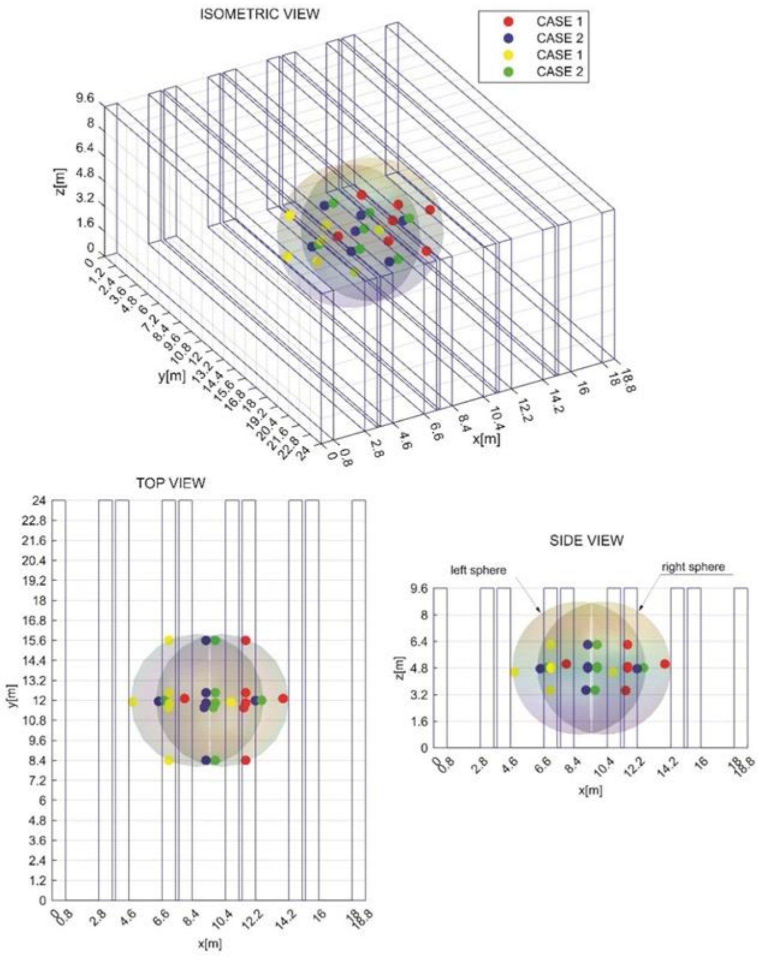

Figure 3. Graphical representation of fire risk zones in the warehouse, shown in isometric, top, and side views

5. Conclusions

The Critical Chain Method (CCM) is a relatively recent approach in project planning and management that has gained significant recognition and acceptance in practice. It builds on traditional project scheduling techniques by explicitly considering resource constraints and uncertainty in task durations. Due to its focus on buffer management and efficient use of critical resources, CCM has been successfully applied across a wide range of industries and business sectors worldwide, helping organizations improve schedule reliability, reduce project durations, and increase the likelihood of on-time project completion.

In project management, the CCM method can serve as a foundation for developing a comprehensive project plan, providing a structured approach to scheduling and resource allocation. During project execution, CCM functions as a vital tool for managing and mitigating risks within the project network. This is achieved through the systematic monitoring and control of Feeding Buffers (FB) and Project Buffers (PB), which absorb uncertainties and delays in both critical and non-critical tasks. By focusing on buffer management, CCM helps ensure that critical activities are completed on time, resources are optimally utilized, and potential project delays are identified early, allowing project managers to take corrective actions to maintain the planned schedule.

The effectiveness of the Critical Chain Method (CCM) is evident in its ability to shorten project durations and optimize resource utilization, which in turn improves cost control. Research results have demonstrated that using CCM for project planning can reduce the total project duration by approximately 25% compared to traditional CPM planning, highlighting its efficiency and practical benefits in managing complex projects.

Despite its many proven advantages over traditional methods, the CCM method is less widely adopted in the construction industry, primarily because its implementation requires substantial effort, changes to existing processes, and thorough training of personnel within a company's operations.

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