CONTRIBUTION TO DETERMINING FIRE RISK ZONES IN THE HIGH-BAY WAREHOUSES

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Abstract: Considering that the determination of fire hazard zones in warehouses is not sufficiently researched and studied, this paper aims to present a new methodological approach concerning the mentioned issue. Based on the COPRAS multi-criteria decision-making method, a new method was developed for the precise determination of potential zones where there is a risk of fire. The advantage of the described method is that it allows quick and easy determination of all orientation fire risk zones. The mentioned procedure represents the first step when planning the layout and arrangement in the warehouse itself. The effectiveness of the proposed method was confirmed through a suitable numerical example.

Keywords: *Warehouse; Fire risk zones; COPRAS Method*

INTRODUCTION

Fire represents a serious threat to the aspect of safety of people and property, regardless of whether it is about residential buildings, storage facilities, or industrial facilities, therefore managing the risk of fire outbreaks is a big challenge in urban and rural environments (Alkış et al., 2021). Warehouses, as objects in which some activities and work processes are performed regarding the storage, transportation, and manipulation of goods and materials, are places where various accidental situations can often occur, which can result in the injury of employees, the occurrence of material damage and the endangerment of the working environment, especially in cases of fire.

Warehouses, as an integral part of logistics, are often exposed to various improvements and corrections in the development phase, all with the aim of better performance, capacity, and efficiency of the warehouses themselves. The aforementioned improvements result in larger and higher warehouses, the use of automated systems for storage and retrieval of storage units

(AS/RS systems), increased storage density, and placement of storage units at higher heights (Dinaburg and Gottuk, 2012). The mentioned improvements have made the warehouses efficient, but at the same time, they have introduced potential dangers in terms of fire protection. In modern society, we are witnesses of fires that occur in warehouses in which there are often human victims and large material losses. It is known that most deaths in fires are the result of inhalation of toxic gases (CO, CO2,...), thick smoke, and insufficient amount of oxygen (Martin et al., 2016; D'Evelyn et al., 2022]. The fire that occurred in August 2015 in the warehouse of the port of Tianjin in North China, due to the large number of victims and caused material damage, pointed out the importance of the issue of fire protection in warehouses. In this event, 173 people died, and several hundred were injured (Fu et al, 2016). At least 49 people, including nine firefighters, were killed in a major fire in 2022 at a container warehouse near a port city in southeastern Bangladesh (Tahmid et al, 2022), and more than 100 people were injured in total. The cause of such a large fire was the explosion of a container that was full of chemicals.

Based on the large number of fires in warehouses, which by their scope and consequences can sometimes be considered catastrophic and which occurred around the world at the end of the last century and during this century, a large number of research related to this topic was initiated. The primary goal of these investigations consisted of answering questions related to risk assessment, safe evacuation from the warehouse, effective fire extinguishing and localization, as well as reducing the risk of the fire itself.

MATERIALS AND METHODS

The method developed in this paper consists of four parts. The first part refers to the selection of parameters used in fire risk assessment methods, needed to obtain the weighting coefficients necessary for determining fire hazard zones using multi-criteria decision-making procedures (Bošković et al., 2022; Chanthakhot et al., 2021). In the second part, the COPRAS method is presented, which was selected as relevant for obtaining the weighting coefficients necessary for further calculation, as in the paper (Valipour et al., 2017). The third part describes the characteristics and advantages of the three-dimensional method for determining the parameters related to the contents placed in the warehouse necessary for calculations, fire risk assessment, and determination of fire hazard zones. In the last, fourth part, the 3D COG method (Center of Gravity Method) is presented, which is used to determine locations within the warehouse that are considered potential risk zones in case of fire.

Selection of Parameters for Multicriteria Analysis

The basic concept in the development of the method was to combine factors related to the emission of harmful substances due to the frequency of poisoning in fires, as well as factors related to the process of burning materials in a fire. Due to the limitations of the COPRAS method related to the number of criteria that can be applied, 7 key parameters were selected based on the available literature. The mentioned parameters represent the criteria in the multi-criteria analysis procedure, which are divided into two groups: criteria related to the impact on human health and criteria related to the thermal characteristics of the stored materials.

Determination of Simulation Parameters Using the COPRAS Method

The COPRAS method has a very wide field of applications. It was used for risk assessment in the construction industry, for the selection of materials for solar panels, for the selection of mechanical processing of composite materials, for the selection of the type of robotization in production, etc. In this paper, the COPRAS method was used to determine the weighting coefficients, which also represent input parameters for risk assessment in the case of a high-bay warehouse, as the authors presented in their paper (Bošković et al., 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 determine the most precise parameters related to the locations of transport units, flexibility in terms of the configuration of the layout within the facility itself, and using the approach as in the literature, a procedure was developed for the formation of a three-dimensional model of the warehouse with associated elements. The proposed structure of the procedure for determining the parameters of the warehouse, as shown in Figure 1, includes three main phases for the calculation and determination of the necessary parameters related to the storage of materials inside the warehouse.

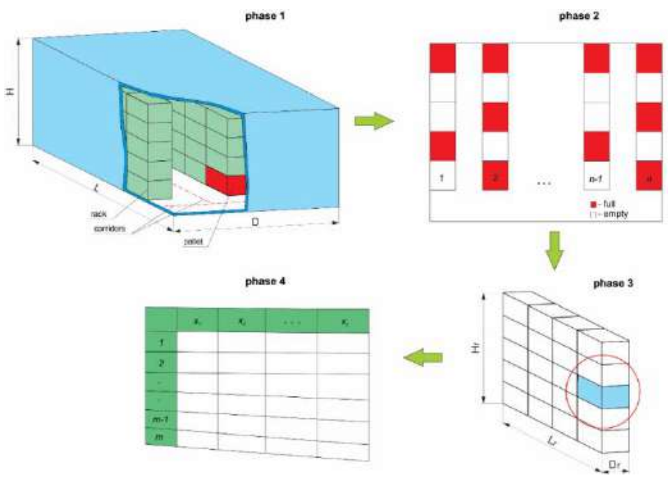

Figure 1. Schematic representation of the formation of a three-dimensional warehouse model and the procedure for obtaining the relevant parameters

The procedure for determining the coordinates of potential risk zones

To simplify the presentation and further calculation, transport units as bodies of appropriate dimensions and characteristics that occupy only a stationary position in the warehouse will be represented by a material point. In this way, the dimensions of the transport units can be considered infinitely small, assuming that each point of the volume has the same properties, ie. that the content of the transport unit is homogeneous.

The procedure for evaluating the center of gravity of transport units represented in the form of a material point and determining the weighting coefficients for materials placed in the warehouse are the main prerequisites for determining the potential fire risk zone. The classical approach to the method of determining the center of gravity (COG method), enables the determination of optimal locations in the two-dimensional coordinate system XoY. To assess potential fire risk zones and their coordinates, an improved version of the COG method will be used.

NUMERICAL EXAMPLE

In the numerical example shown in this section, the parameters of the high-bay warehouse related to dimensions and layout (see Figure 2) given in the paper (Bošković et al., 2023) were used. Based on the considerations given in the previous chapter, to obtain the most accurate data needed for further simulation, it was decided to select 5 types of solid materials (wood, cardboard, chipboard, PVC plastic, and rubber) as alternatives in the multi-criteria decision-making process, which will be the subject of further calculations.

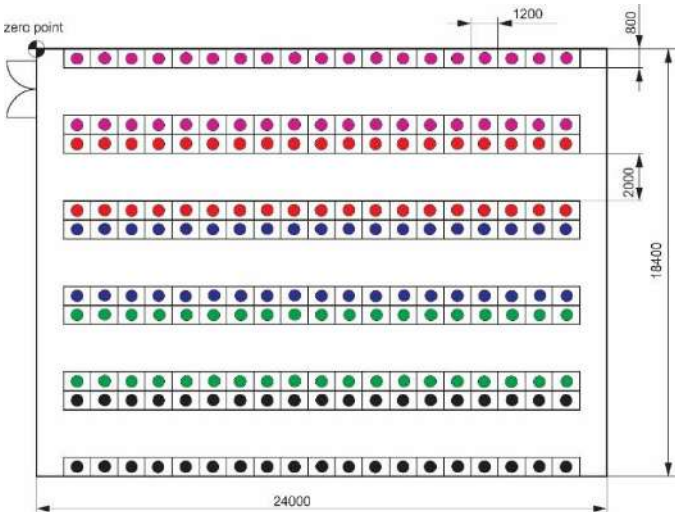

Figure 2. The layout of a high-bay warehouse with associated dimensions and materials (• wood, • cardboard, • chipboard, • PVC, and • rubber)

The list of materials and the numerical values of the seven selected parameters are given in Table 1. The listed characteristics of materials related to combustion shown in the mentioned table represent criteria in the multi-criteria decision-making process (Ch. Varada Rajulu et al., 2013; Ding, et al., 2020).

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

Material	CO [mg/g]	CO_2 [mg/g]	Smoke density [kg/m^3]	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 because they take into account the emission of harmful gases affecting human health, while the other four parameters (criteria) are declared useless. Following all the steps provided by the COPRAS method, weights for each of the alternatives Qi and the corresponding ranking are obtained as shown in Table 3. Identically, the parameters for case 2 can be determined when the parameters are replaced so that the last four parameters are considered useful, and the first three parameters are considered useless.

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

Case 1		Case 1	
w_{ei}	Rank	w_{ei}	Rank
0.14821	0.0566	0.14821	3
0.13642	0.0573	0.13642	4
0.15195	0.0598	0.15195	2
0.11238	0.0768	0.11238	5

0.45105	0.1495	0.45105	1

Each of the materials presented in Table 1 occupies two racks, so the total number of racks in the warehouse is 10, with maximum of 1200 transport units in the warehouse. It is rarely the case that the warehouse is filled to 100%, so testing the effectiveness of the proposed method is done by varying the layout of the transport units in the racks, the warehouse is filled to a maximum of 70% as in (Tahmid et al, 2022), with the rule that the percentage share of each of material should be equal, i.e. is 20% of the total number of transport units (168 units).

To confirm the functionality of the method and the comparative presentation of the results, the coordinates X, Y, Z, and the vector r were calculated for the following variants of warehouse filling:

- Variant 1: The first three racks on the left side of the warehouse are completely emptied and the filling of the warehouse with the remaining 840 transport units starts from rack number 4,

- Variant 2: The last three racks on the right side of the warehouse are completely emptied and the filling of the warehouse with the remaining 840 transport units starts from rack number 1,

- Variant 3: The content of each of the racks on the upper front side is reduced by 30%,

- Variant 4: The content of each of the racks on the lower front side is reduced by 30%,

- Variant 5: The content of each of the racks in the uppermost rows is reduced by 30%,

- Variant 6: The content of each of the racks is reduced by 30% in the initial lower rows,

- Variant 7: The content of each of the racks is reduced by 30% and the arrangement of transport units within the racks is done randomly.

RESULTS AND DISCUSSION

Based on the parameters related to the location of the transport units determined by implementing the procedure shown in Figure 12, the weighting coefficients obtained using the COPRAS method and entering the mentioned parameters into the COG algorithm, the locations of the potential fire risk zone in the high-bay warehouse are obtained.

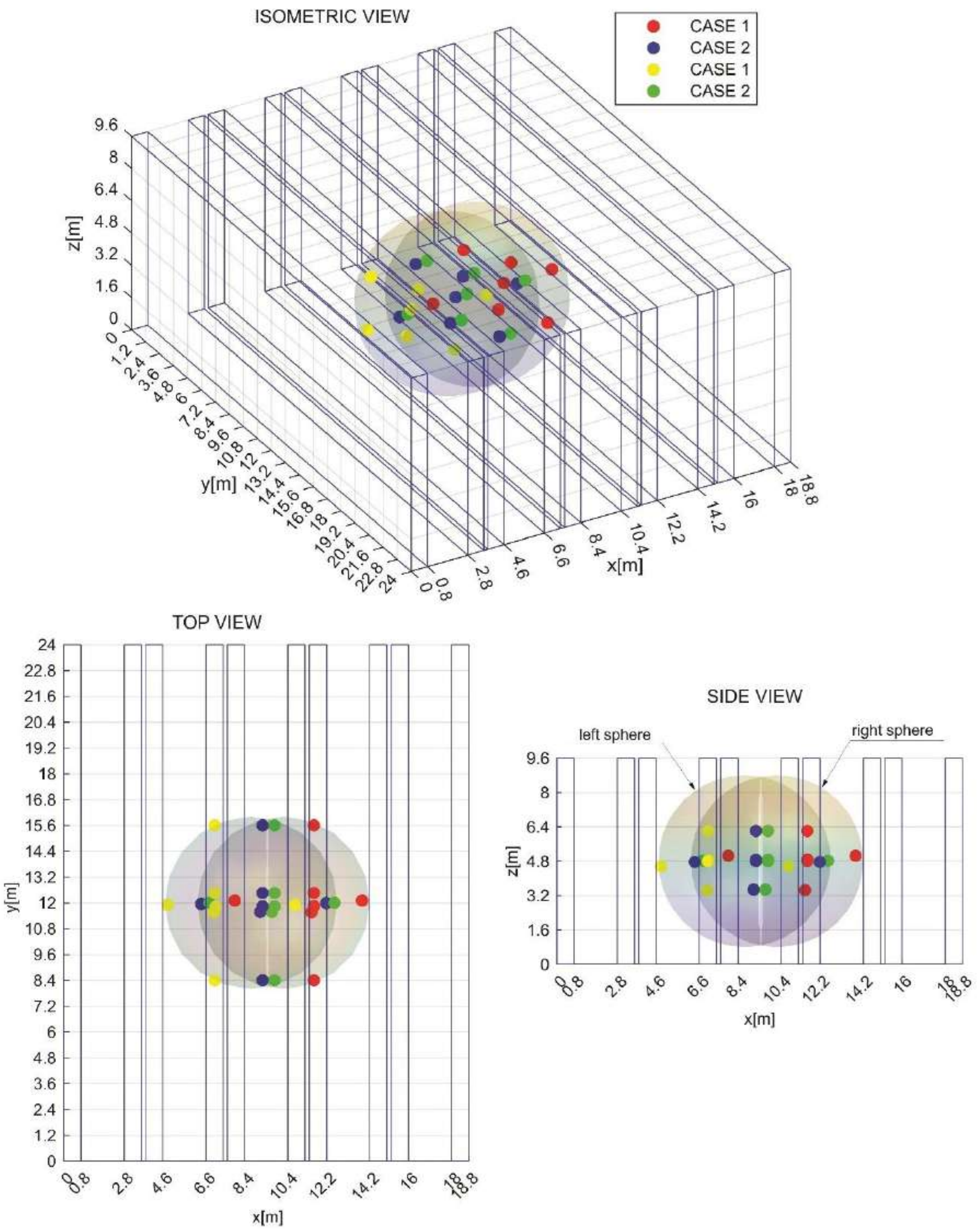

Figure 3. Graphic representation of the fire risk zones in warehouse with isometric view, top view, and side view

Based on the obtained coordinates of spatial points and using a three-dimensional model of a high-bay warehouse, two spheres that define potential fire risk zones, were generated (see

Figure 3). The mentioned spheres represent the space that is considered vulnerable in terms of fire and which includes normal and random variants of material distribution within the space of the observed high-bay warehouse. Considering the symmetrical arrangement inside the warehouse along all axes, the homogeneity of the stored material and the warehouse occupancy, the left sphere (coordinates of center x=8.7 m, y=12 m, z=4.8 m, and r=4 m) and the right sphere (coordinates of center x=10.2 m, y=12 m, z=4.8 m, and r=4.1 m) are generated. Figure 3 shows the deviation in the coordinates of the spheres along the x-axis, which is directly related to the change in the distribution of materials in the racks. Coordinates of spatial points are obtained for the warehouse cases of layout when the tire occupies the first two racks and when it occupies the first two racks, respectively.

About the existing fire risk assessment methods (e.g. Gustav method), in the proposed approach, the simulation results are obtained based on the weight coefficients related to the materials that are stored, the percentage share of storage units, and the parameters related to the dimensions of the warehouse. The practicality and usability of the proposed method are reflected in the simplicity and practicality of application with fewer necessary parameters and resources, simple data acquisition, and the possibility of a three-dimensional display of risk zones in real-time. The described method was not meant to be a replacement for the Gustav method. The Gustav method (Ju et al., 2023)is more complicated and can be more complex. This means that it takes some time to adapt it and use it by the warehouse designer, and it gives broader results. The method described in this paper can be utilized quicker and it provides general guidelines for the warehouse designer, but it does not provide results as detailed as Gustav's method.

CONCLUSIONS

A method for risk assessment and determination of potential fire hazard zones in high-bay warehouses is presented in this paper. Concerning existing methods related to risk assessment in warehouses, the proposed method is based on weight coefficients related to the type of material being stored, the percentage share of storage units, as well as parameters related to the structure and configuration of the warehouse. Weight coefficients related to the type of material represent input parameters in the process of simulation and determination of potential fire hazard zones. They are determined by a multi-criteria decision-making process using the COPRAS method.

Compared to other, mostly two-dimensional methods, this method enables simple data acquisition in the form of data tables and the generation of a three-dimensional model of the warehouse, which contains spatial points that define potential risk zones. By incorporating the mentioned spatial points within the 3D model of the high-bay warehouse, a sphere is obtained, whose radius represents the critical area of the risk of fire. The results obtained by the proposed method can be a good basis during the planning and design of the warehouse, the layout of the object, and also when designing the appropriate fire protection and evacuation systems in the warehouse.

ACKNOWLEDGEMENT

The authors wish to acknowledge the support of the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, through the Contracts for the scientific research financing in 2024, 451-03-65/2024-03/200108 and 451-03-65/2024-03/200156.

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