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METHODOLOGY OF DETERMINATION OF FIRE HAZARD ZONES IN THE HIGH-BAY WAREHOUSES

Research paper

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Abstract: Searching relevant literature sourcesit was found 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 enables quick and easy determination of all orientation zones of fire risk in a quick and simple way. The method requires fewer hardware resources compared to the existing ones and enables the display of the warehouse space in the form of a 3D model with calculated fire hazard 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 [1]. In comparison with other places of fire origin, fires in warehouses have a small share in the total number of fires. Still, in terms of heat release, the size of the area affected by the fire, the degree of damage to the building itself, and material damage, these fires have significant consequences compared to fires in other types of buildings.
Warehouses, as the main factors of logistics and distribution, are often exposed to various improvements and corrections in the development phase, for the sake 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 [2]. With the increase in the height and density of storage, the possibility of the spreading and growth of flames in the case of fire increases, thereby reducing the possibility of a quick detection and localization of the fire, as well as increasing emissions of smoke and harmful substances, which significantly affects the health and safety of employees 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 [3]. 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 [4]. 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 [5], and more than 100 people were injured in total. 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 end of the last century and during this century a large number of research related to this topic was initiated.

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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.

MATERIAL AND METHODS

The method presented 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 [6]. 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. 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 the 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 Multi-Criteria 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. To determine potential fire risk zones in warehouses based on data sources [7], 7 different parameters were selected: the concentration of CO [mg/g], the concentration of CO2 [mg/g], smoke density [kg/m3], ignition temperature [°C], thermal conductivity [W/mK], specific heat capacity [J/(kg K)], and calorific value [MJ/kg].

Determination of Simulation Parameters Using the COPRAS Method

The COPRAS method [8] has a very wide field of applications. It was used for risk assessment in the construction industry, in the selection of materials for solar panels, in the selection of mechanical processing of composite materials, in 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 the paper.

Three-Dimensional Method for Determining Storage Parameters

To determine the most precise parameters related to the locations of transport units and flexibility in terms of the configuration of the layout within the facility itself, 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 2, includes three main phases for the calculation and determination of the necessary parameters related to the storage of materials inside the warehouse.

The Procedure for Determining the Coordinates of Potential Hazard Zones

The classical approach to the method of determining the center of gravity (COG method) used in logistics enables the determination of optimal locations in the two-dimensional coordinate system *XoY*. To assess potential fire hazard zones and their coordinates, an improved version of the COG method will be used to determine the center of gravity in a three-dimensional coordinate system, which has found application in medicine, electrical engineering, mechanics, and other fields.

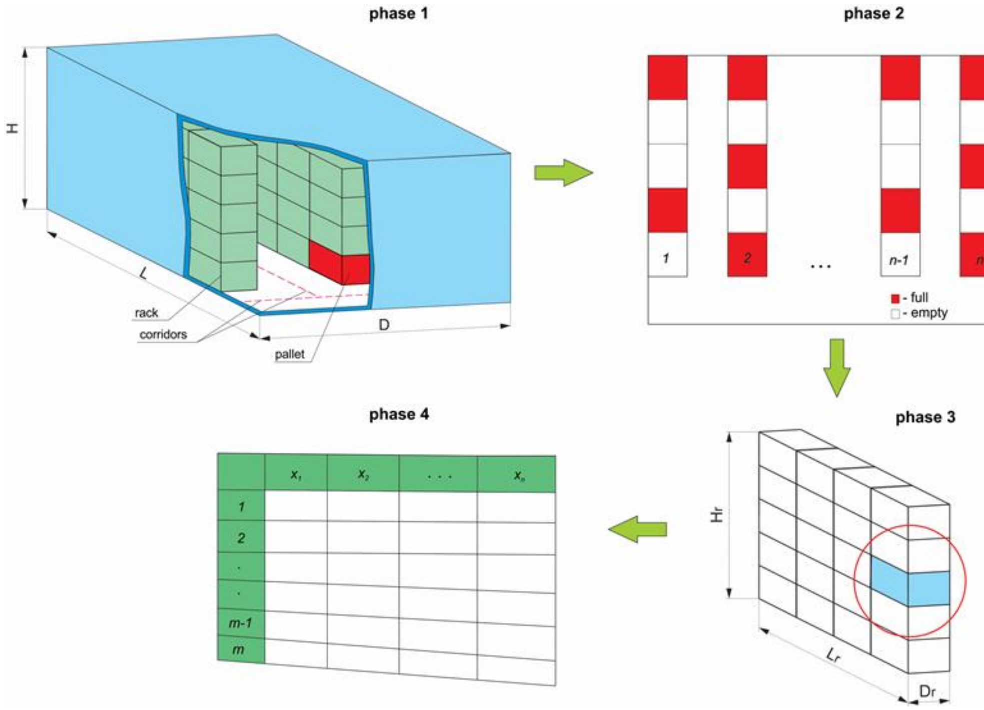

Fig. 1. *Schematic representation of the formation of a three-dimensional warehouse model and the procedure for obtaining the relevant parameters.*

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). Based on the considerations presented in the previous section, to obtain the most accurate data needed for further simulation, it was decided to select five types of solid materials (wood, cardboard, chipboard, PVC plastic, and rubber) as alternatives in the multi-criteria decision-making process.

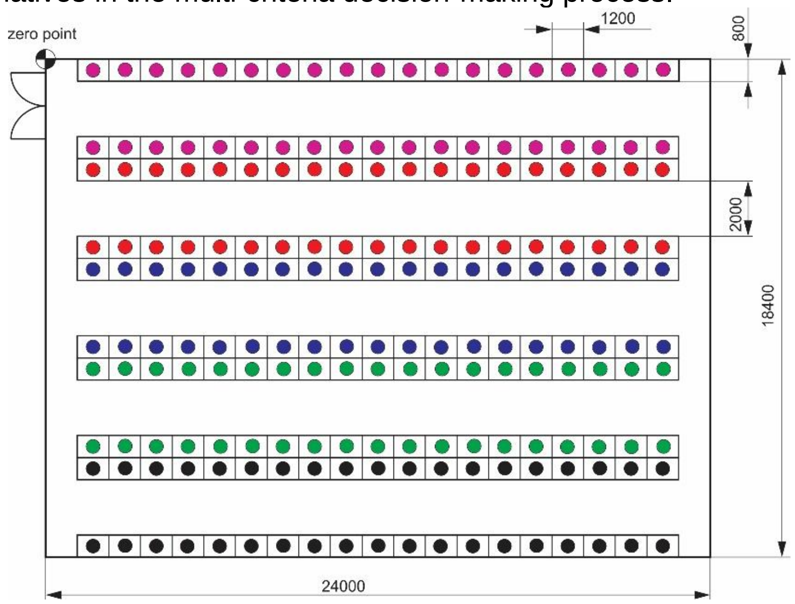

Fig. 2. Layout of a high-bay warehouse with associated dimensions and materials (• wood, • cardboard, • chipboard, • PVC, and • rubber).

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 and are taken from the literature.

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/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

Table 1 presents the criteria in the order shown in the previous Section. C1, C2, and C3 are considered useful because they take into account the emission of harmful gases that affect human health. In contrast, the other criteria, C4, C5, C6, and C7, which take combustion into account, are declared useless in the first case. Alternatives related to materials are marked with *Aj* (*j = 1, …,5*). After converting the qualitative attributes into quantitative ones, the decision matrix with assigned weighting coefficients is shown in Table 2.

Table 2. Decision matrix (CASE 1)

Criteria	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
Unit of measure	**[mg/g]**	**[mg/g]**	**[kg/m³]**	**[°C]**	**[W/mK]**	**[J/(kg K)]**	**[MJ/kg]**
Goal	**min**	**min**	**min**	**max**	**min**	**max**	**min**
	Beneficial			**Non-Beneficial**			
Weights	0.2	0.2	0.2	0.1	0.1	0.1	0.1
A1	6	1696	100	350	14.4	1360	0.15
A2	0.1	1450	3.8	427	13.5	1400	0.061
A3	6	1774	400	150	17	2500	0.13
A4	71	657	55.03	391	41	900	0.185
A5	600	1911	8000	315	35	1880	1.85

Identically, the parameters for case 2 can be determined when the decision matrix is replaced, so parameters C4, C5, C6, and C7 are considered useful, and the other criteria, C1, C2, and C3, are considered useless.

Table 3. Tubular representation of obtained weight coefficients w_{ei} and w_{ci}

Case 1			**Case 2**	
w_{ei}	**Rank**		w_{ci}	**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

RESULTS AND DISCUSSION

Each of the materials presented in Table 1 occupies two racks, so the total number of racks in the warehouse is 10; that is, there can be a maximum of 1200 transport units in the warehouse. In practice, it is rarely the case that the warehouse is filled to 100%, and so testing the effectiveness of the proposed method is carried by varying the layout of the transport units in the racks so that the total percentage of the warehouse is filled to a maximum of 70%, with the rule that the percentage share of each of material should be equal, i.e., 20% of the total number of transport units. In this way, each rack contains 168 transport 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 carried out randomly.

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

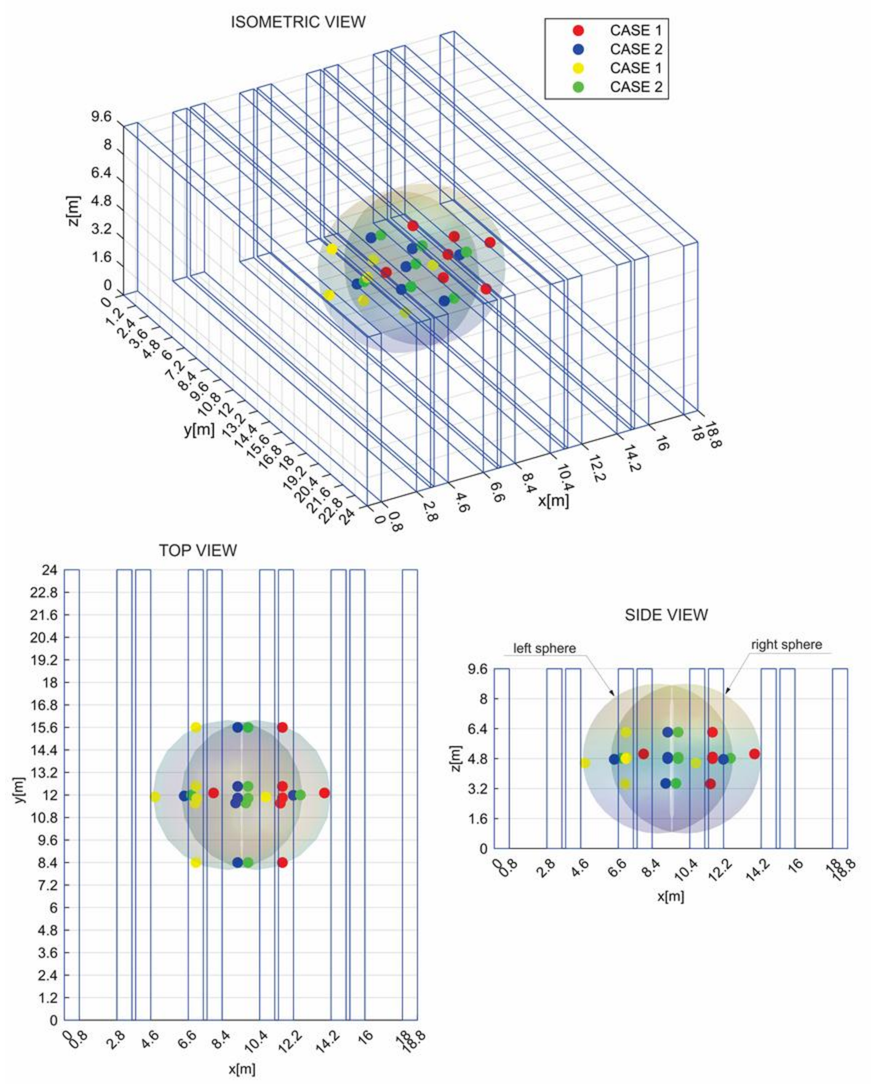

Fig. 3. Graphic representation of the fire risk zones in the warehouse with isometric view, top view, and side view.

CONCLUSION

A method for risk assessment and the 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 the 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 objects, and also when designing the appropriate fire protection and evacuation systems in the warehouse.

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