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Cost implications and sustainable design for warehouses considering fire safety regulations

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Abstract

This paper explores the impact of sustainable design practices on warehouse construction costs in the context of fire safety regulations. The inherent fire risk during the operation of industrial facilities is a critical consideration in their design. This study evaluates various cost and technological aspects of sustainable solutions within the "design and build" framework, focusing on fire protection systems across three different fire zone configurations. The modeling analysis examines how fire zones influence smoke dispersion, temperature variations at a specific location above the fire source, and visibility. Numerical results reveal variations in smoke distribution among the three configurations, though these differences do not significantly affect evacuation efficiency. The findings indicate that increasing the number of fire zones within the warehouse can mitigate the potential impact of a fire. This research underscores that fire protection and evacuation conditions significantly affect investment costs.

Keywords: Warehouse facilities; Construction costs; Sustainable technology; Fire safety requirements; Fire simulation

1. Introduction

The rapid growth of transportation infrastructure in Poland, including the expansion of highways and expressways, supports the rise of large-scale warehouse and production facility construction. Poland's central position between Western and Eastern Europe fosters the development of logistics networks and attracts international investors. Each year, numerous warehouses, production and storage facilities, and logistics and industrial buildings are erected throughout the country.

Polish legislation provides comprehensive guidelines for the design, construction, and utilization of building structures, including warehouses and halls. It specifies the responsibilities of property owners and managers for conducting regular inspections and technical evaluations. This regulatory framework is governed by several laws and regulations, including the Construction Law Act, the Minister of Infrastructure's regulations on technical building requirements and their siting, the Minister of Labour and Social Policy's general occupational health and safety regulations, the Minister of the Interior and Administration's rules on fire water supply and access roads, and the Minister of Interior and Administration's standards for building fire protection [1–5]. These regulations directly influence the technical, construction, and fire protection standards for buildings and determine the choice and type of fire protection systems and components used.

Fire safety regulations within the built environment are determined by EU Member States, but the rapid technological advancements and the growing demand for energy-efficient buildings necessitate the development of a cohesive European strategy for establishing standards in this area. In Europe, key organizations such as the Economic

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Commission for Europe, the Institute of Building Control, and the Consortium of European Building Control oversee regulations related to construction design and fire safety. Technological progress and evolving European regulations over recent decades have underscored the need for a unified European strategy to set standards [6].

The European Union has implemented various policy and regulatory frameworks for the construction industry, including a series of European Standards (EN) that encompass ten standards from EN 1990 to EN 1999 [7–16]. These standards, consisting of 59 parts, provide comprehensive guidelines for building and civil engineering design. They address foundational aspects of structural design, load actions on structures, and the design of various construction materials such as concrete, steel, composite steel-concrete, timber, masonry, and aluminum, along with geotechnical, seismic, and fire safety considerations [17].

Aligned with the EU's strategy for smart, sustainable, and inclusive growth (EU2020), standardization supports industrial policy in the era of globalization. The adoption of Eurocodes is recognized in the "Strategy for the Sustainable Competitiveness of the Construction Sector and its Enterprises"—COM (2012) 433—and is viewed as a mechanism to harmonize national and regional regulatory approaches. Consequently, the Eurocodes have been adopted across European countries, with ongoing efforts to extend their international use [17]. While an integrated standard system is now in place across Europe, the level of implementation into national legal systems varies. For instance, performance-based fire design is included in the national fire codes of the Czech Republic, UK, Finland, Hungary, and Italy. In Belgium, such design is permitted with ministerial approval, and France allows partial application for fire resistance and smoke propagation design. Notably, the UK has utilized performance-based fire design for the longest period [18,19].

Although designing warehouse halls is a significant engineering challenge, a review of existing literature reveals a lack of systematic approaches or guidelines for this type of construction [20–23]. Key considerations for selecting suitable sustainable construction technologies for warehouse halls include [22–28]:

- The purpose and design of the facility
- Material logistics and transportation
- Internal layout and system installations

Warehouse halls, which are designed for various activities requiring extensive covered space, come in different types, each with distinct features [29]. Generally, warehouse structures are categorized into steel, reinforced concrete, prefabricated, and hybrid types. Industrial warehouses, in particular, often have larger dimensions for columns and beams compared to other types of facilities. The size and configuration of entrances and gates can also influence the choice of structure [30,31]. Furthermore, due to their specialized use, industrial warehouses may be repurposed for functions beyond their original design [32].

The specific characteristics of industrial warehouses are influenced by their intended use, construction site, and other relevant factors, such as cross-sectional dimensions, support spacing, bracing types, reinforcement arrangements, roof openings, roof coverings, and roof slopes [24,33]. Additionally, factors like wind, snow, and seismic loads, as well as geotechnical conditions at the construction site, play a crucial role in the design and construction process [29].

Sustainability, green building certifications, and regulations increasingly affect the evaluation of high-performance buildings. The choice of technology often depends on the investor's budget, construction costs, and ongoing operational expenses [34–37]. The cost of constructing these warehouses is significant due to their large volume and the extensive installations required [38]. Occupational health and safety, along with fire protection, also impact the investment budget. Despite the growing emphasis on sustainability in recent years, it is crucial to consider safety and resilience, as these factors are interrelated and affect the overall design of the facility [39].

The use of advanced technology in fire simulation and evacuation processes plays a crucial role in planning emergency responses by addressing practical, economic, and safety considerations. Computer tools are essential for evaluating architectural designs, fire protection systems, and evacuation strategies to ensure safe and effective evacuation [40,41]. Fire simulation using computer models is a rapidly advancing field within fire safety engineering. As a result, the literature increasingly features studies on computer fire modeling. These studies often detail fire development and the associated risks, such as smoke propagation and temperature increases in the gaseous environment [42]. Additionally, computer simulations are employed to analyze the concentrations of volatile compounds like CO2 and CH4 generated during a fire [43].

The literature also covers the integration of fire and evacuation simulations, particularly for large-scale structures. Studies by Jasztal et al. and Wang et al. illustrate this approach [44,45]. In this article, the authors utilized two simulation tools: Pathfinder 2022 [46] for assessing evacuation from warehouse halls, and PyroSim 2022 [47] for analyzing fire dynamics and smoke dispersion within these facilities. The reliability of PyroSim software has been well-documented in various publications focusing on numerical simulations of fire scenarios in warehouses [48]. Many studies [49–56] have explored the intersection of fire development and combustion products with evacuation simulations, examining how these factors influence evacuation conditions and effectiveness.

This manuscript aims to evaluate the effectiveness of sustainable warehouse design in relation to fire regulations and costs. The research hypothesis is that fire safety regulations and fire safety engineering, including fire simulations, significantly impact the design and construction costs of warehouses.

2. Facility Characteristics

The facility under analysis comprises a single-story warehouse, integrated into a high-bay warehouse section, along with a two-story social and office complex. According to relevant regulations, the building is classified as medium-high (MH) due to its height of approximately 12.5 meters. The warehouse and technical sections are designated for temporary occupancy, while the office section is intended for permanent use.

Materials will be delivered to the facility via dock handling systems. Unloading will involve pallet trucks and forklifts within the warehouse. The structure will be a uniform cuboid block with protruding social and office areas (see Figure 1).

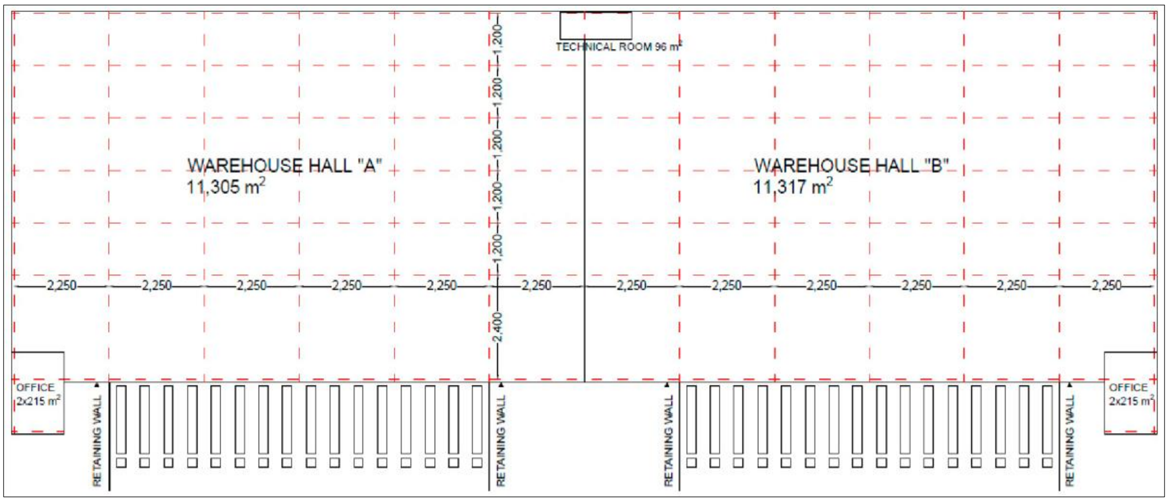

Figure 1 The concept of a warehouse building with social and office complexes

The warehouse itself will be a single-story building that includes a technical room housing a transformer station and both medium voltage (MV) and low voltage (LV) switchgear. The interior storage height will be 10 meters from the finished floor to the bottom of the trusses or purlins. The overall building height will be approximately 12.5 meters to the top of the parapet, with dock dimensions of 22.5 × 24 meters. The warehouse will be divided into two sections according to the design plan. The roof and façade will feature lightweight construction materials, with the roof designed to admit daylight (2%) through smoke vents or skylights. Structural elements, roof, and walls will be fire-resistant for a fire load density up to 4000 MJ/m^2.

To prevent mechanical damage to the façade, reinforced concrete walls will extend from -1.20 to +4.20 meters in height in the dock area and entrance gates from the ground level, while in other parts of the building, reinforced concrete foundations will be raised 30 cm above floor level. The building's external windows and doors will be made of aluminum. The delivery area will be equipped with 32 system dock gates (3 × 3.2 meters) and gates with access from the ground level (3.5 × 4.2 meters). Heating within the hall will be maintained at 15°C using radiators or gas heaters. Mechanical exhaust ventilation will provide airflow at a rate of 0.25 w/h (19.6 m^3/s), and rainwater will be managed through a vacuum roof system.

A sustainable building should be designed and constructed to meet specific fire protection standards. These standards include ensuring the load-bearing capacity of structural elements, controlling the spread of fire and smoke to facilitate effective evacuation, and preventing fire from affecting adjacent zones or structures. Proper classification and zoning of the building based on its category are crucial for determining the fire resistance requirements for various building components, the size of fire zones, and the length of fire escape routes. For instance, the social and office sections fall under the ZL III category, while the warehouse section is classified as PM [2].

2.1. Variants of Warehouse Hall Construction with Social and Office Annexes

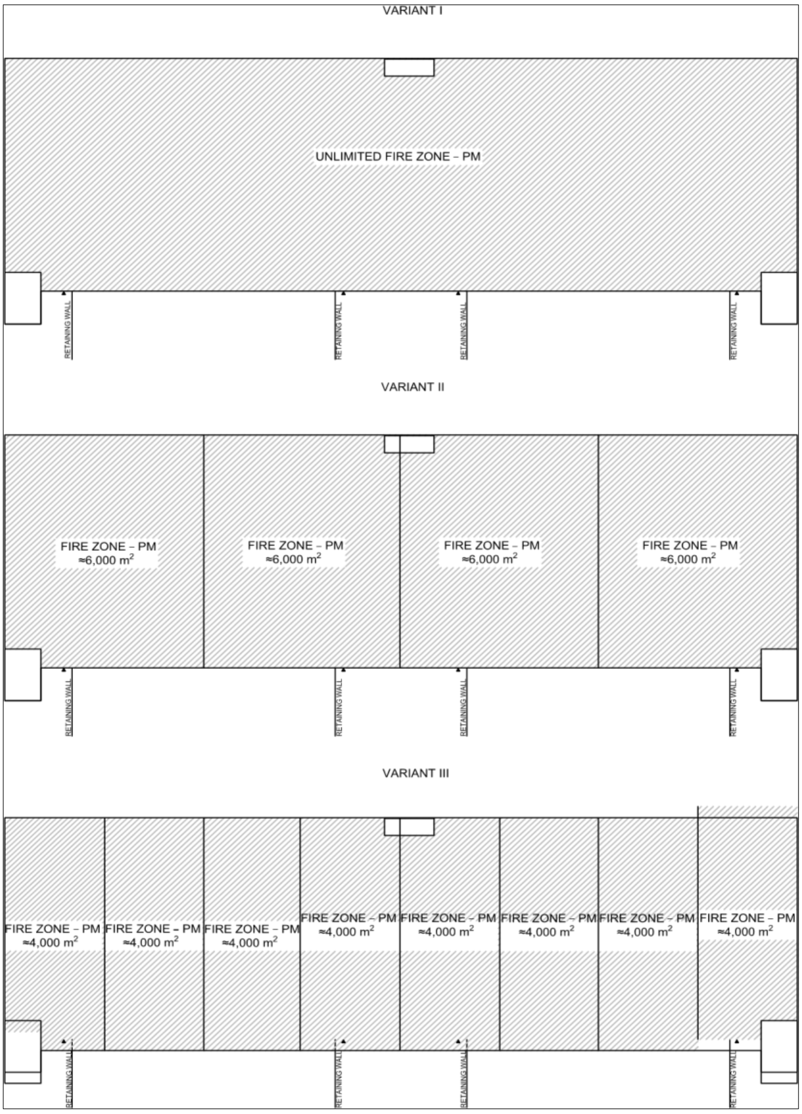

Figure 2 Division into fire zones for variants I, II, and III

The construction and cladding of the building will be influenced by its classification and the associated fire safety requirements. These requirements impose certain restrictions that may not always align with budget constraints or project timelines. Nevertheless, strategic design can mitigate the impact of fire safety features on the building's sustainability. Thus, the analysis of the warehouse building construction will be considered in three variants:

- Variant I: A hall with Class "E" fire resistance, incorporating building elements that are fire-resistant and equipped with permanent water-based extinguishing systems and automatic smoke extraction devices. In this scenario, the PM zone will be one continuous fire zone. The layout for Variant I is illustrated in Figure 2.
- Variant II: A warehouse hall with Class "E" fire resistance, featuring fire-resistant building elements and automatic smoke extraction systems. The PM zone will be divided into four fire zones, each with a maximum area of 6000 m^2. The layout for Variant II is depicted in Figure 2.
- Variant III: A warehouse hall with Class "B" fire resistance. The PM zone will be segmented into six fire zones, each with a maximum area of up to 4000 m^2. The layout for Variant III is shown in Figure 2.

For the social and office sections, the applicable regulations stipulate a Class "D" fire resistance standard.

2.1.1. Cost Estimation of Technological Variants of Hall Construction

In this study, the unit cost method was used to estimate the costs for different technological variants of hall construction. This method involves multiplying the quantity of each work item by its unit price, using Norma Pro Software ver.4.65 (Athenasoft, Poland).

- Variant I: Permanent Water Extinguishing Devices and Automatic Smoke Removal System

For Variant I, incorporating permanent water extinguishing devices and an automatic smoke removal system will enhance fire safety but also impact cost. This setup will change the fire resistance classification of the warehouse from "B" to "E". An advantage of this approach is the flexibility in warehouse arrangement, as it allows the entire warehouse to be one unrestricted fire zone.

2.2. System Design

- The sprinkler system will follow the NFPA 13 Standard for the Installation of Sprinkler Systems, known for its rigorous requirements but also its effectiveness in minimizing water waste and reducing the number of sprinklers needed.
- The hall will be divided into six sprinkler sections (ST1–ST6), with the largest section covering 3807 m^2.
- The system will use black steel pipes, with sections connected via grooved connections and threaded couplings. Pipelines will be spaced 2.75 to 3.1 meters apart, and sprinklers will be spaced 2.8 to 3.1 meters apart to meet NFPA 13 requirements.
- Required components include:
- Sprinklers: 2504 pcs of ESFR K240, 3.6 bar
- Water Pipes: Approximately 7600 running meters
- Power Collectors: Approximately 440 meters
- Control and Alarm Stations: Six units, with basic equipment including non-return and shut-off valves with electrical or mechanical position indicators.
- Additional Equipment: Electronic flow sensors for the control and alarm stations.

2.3. Water Supply Considerations

- Internal hydrants will be supplied from the sprinkler system manifolds, eliminating the need for a circumferential hydrant system.
- Ten internal hydrants will be installed, using two 20 + 20 m hoses each.
- The NFPA 13 standard specifies water requirements for 12 sprinklers, and additional water demand for internal and external hydrants must be considered.
- The water supply network will provide a working pressure of 0.4 MPa, with an external hydrant network demand of 50 L/s.

The cost of implementing this variant will reflect the complexity of the sprinkler system and the associated fire protection measures, but it offers comprehensive fire safety and flexibility in warehouse layout.

Fire Protection Systems and Equipment

Water Reserve and Pumping Station

- Water Reserve Tank: A tank with a capacity of 724 m^3 will be provided to support the fire protection systems.
- Fire Pumping Station: To ensure adequate water flow, a pumping station with two diesel pumps will be installed.
- Piping Specifications:
- Sprinkler System Pipes: DN80 mm
- Supply Manifolds: DN150 mm
- Valve Station: DN250 mm
- Supply Network: PP Ø315 mm, with a pressure loss of 1 m H_2O/100 m and a velocity of 2 m/s between the pumping station and the ST1 section.

2.4. External Firefighting Network

- Perimeter Hydrant Network: Made of polypropylene pipes with:

- Hydrants: 6 DN100 mm, spaced 150 m apart.
- Diameter: Ø250 mm, with a pressure loss of 0.8 m H_2O/100 m and a velocity of 1.5 m/s.
- Reserve Capacity: 25% of the total circuit capacity will be reserved to supply the sprinkler system.

2.5. Smoke Exhaust System

- Smoke Vents:
- Dimensions: 1.5 × 2.5 m
- Active Exhaust Area: 2.63 m^2
- Quantity: 86 units
- Roof Skylights:
- Quantity: 54 units
- Daylighting: Ensures 2% daylight illumination of the hall.
- Design Standards: The smoke exhaust system will comply with NFPA 204: Standard for Smoke and Heat Venting, requiring the active surface of smoke exhaust to be about 1% of the building area. This approach reduces the number of required smoke vents and contributes to cost savings in construction and roofing.

2.6. Additional Equipment

- Dock Gates: Equipped with UPS units to ensure they open in the event of a power failure.
- Fire Alarm System: The POLON 4900 (POLON-ALFA, Poland) will be used to automatically activate the smoke exhaust system.

This setup integrates advanced fire protection measures and equipment, ensuring both safety and operational efficiency while aiming for cost-effectiveness in construction and maintenance.

Cost Analysis of Technological Variants for Hall Construction

Table 1 Variant Calculations

Variant I of Hall Construction Calculated Item			Value [EUR]
Sprinkler system	448,072.33		
Installation of internal hydrants	3170.13		
Internal hydrants installation ring—834.40 lm			
Fire pumps 2			
Container pump house building	32,612.95		
Water storage tank with a capacity of 724 m^3	39,135.54		
Foundation for the tank	742.53		
Reinforcement of the foundation plate	1945.59		
B10 concrete foundation for the fire protection tank	1123.19		
Hydrant network Ø250 (without earthworks—865.26 m			
Hydrant network Ø315 (without earthworks)—460.21 m			
External hydrants—6 pcs	9632.60		
Fire alarm installation	16,185.41		
Smoke removal installation	17,468.85		
Daylight illumination with roof skylights 1.5			
Total	759,494.85	× EUR 69.92	

2.6.1. *Variant I: Comprehensive Fire Protection System*

- Total Cost: EUR 759,494.85
- Key Features:
- Sprinkler System: Comprehensive installation with a high labor intensity and a long delivery time for fire pumps (10-12 weeks).
- Flexibility: Allows for any arrangement of the warehouse, as the fire protection regulations are met with a single unrestricted fire zone.
- Multi-Building Capability: The fire tank and pumping station can support multiple warehouse facilities, with additional costs only for subsequent sprinkler installations.

2.6.2. Variant II: Enhanced Smoke Exhaust with Divided Fire Zones

- Fire Resistance Class: Building fire resistance class is reduced from "B" to "E" with automatic smoke exhaust devices.
- Fire Zones: Facility divided into multiple fire zones.
- Fire Alarm System:
- Extended with fire and smoke detection sensors.
- Calibrated using the POLON 4900 system, similar to Variant I.
- Smoke Exhaust System:
- No need for smoke curtains due to fire separation walls.
- Internal Hydrants:
- Piping: Ø48.3 mm steel pipes with pressure losses of 1.4 bar.
- Water Supply Network: Ø250 PE pipes with pressure losses of approx. 0.03 bar over 396.64 meters.
- Discharge Pressure: 0.2 MPa.
- Hydrophore Pumps: Provide a working pressure of 3.43 bar and flow of 10 L/s.
- External Hydrant Network:
- Piping: PE100 SDR13 Ø250 pipes, including a 25% reserve for internal hydrants.
- Fire Pumps: Two diesel fire pumps (primary and reserve) with a capacity of 50 L/s and a working pressure of 3.43 bar.
- Water Reserve:
- Capacity: Slightly larger tank required (min. 756 m^3) with dimensions of 12.12 m height and 9.17 m width.
- Proposed Tank: 768 m^3 capacity.

Approximate Cost for Variant II: Details of the cost for individual elements are provided in Table 2.

2.7. Summary

- Variant I offers high flexibility in hall arrangement and is suitable for logistics parks with multiple warehouses but has high labor and delivery time requirements.
- Variant II introduces a more complex fire zone division and requires adjustments in the external and internal firefighting infrastructure. This variant has a slightly larger water reserve requirement and increased costs for external firefighting capabilities.

Cost Analysis of Technological Variants for Hall Construction

2.7.1. Variant III: Basic Fire Protection with Class "B" Fire Resistance

- Total Cost: EUR 342,289.48
- Savings: EUR 344,254.25 compared to Variant I.
- Key Features:
- Fire Resistance Class: Building constructed to class "B" fire resistance.
- Fire Protection: Basic fire protection using internal and external hydrants.
- Fire Alarm System:
- Limited to manual activation through manual call points.
- Upon activation, the system triggers an audible alarm, shuts off the gas supply, and disables the ventilation system.
- Cost: Same as Variant I.
- Daylight Illumination:
- Replaces smoke vents with 138 roof skylights, which must have a roof fire resistance class of EI 30.
- Hydrant Installation: No differences compared to Variant II.
- Water Supply Tank & Pumping Station: Same specifications as Variant II.

2.8. Summary

- Variant III offers the most cost-effective and time-efficient solution. It provides essential fire protection with a class "B" fire resistance building, uses manual fire alarm activation, and achieves daylighting through additional skylights, but does not include advanced sprinkler or smoke exhaust systems.
- The significant cost savings and shorter execution time make this variant the most advantageous for budget-conscious and time-sensitive projects.

Variant Analysis of Fire Protection System Operation

2.9. Simulation Overview

- Simulation Software: PyroSim (2022)
- Fire Source: Rectangular fire simulator model with dimensions 1 × 1 × 0.5 m (width × length × height) located in a corner of the hall.
- Combustible Surface:
- Material: Oak wood
- Combustible Surface Temperature: 5000 °C
- Fire Load Curve Parameter (HRR): 500 kW/m^2
- Simulation Parameters:
- The simulation assumes flaming of the combustible surface begins at the start.
- Smoke dampers are controlled and are set to open at the tenth second of the simulation.

2.10. Key Considerations

- Purpose: To evaluate the effectiveness of the fire protection system under different variants by controlling the smoke dampers.
- Control of Smoke Dampers: The simulation will illustrate how opening the smoke dampers affects the fire dynamics and smoke management.

This analysis will help determine the efficiency of various fire protection strategies and how they impact smoke control and evacuation during a fire scenario.

2.11. Computational Grids

In the numerical simulations, three fire scenarios were analyzed to assess the performance of the fire protection system:

- Variant I: The entire hall is treated as one fire zone.
- Variant II: The hall is divided into four fire zones.
- Variant III: The hall is divided into six fire zones.

2.11.1. Parameters of Computational Grids

- Mesh Density:
- Variant I and II: Larger fire zones with coarser meshes.
- Variant III: Smaller fire zones with higher mesh density for more precise results.

2.11.2. Analysis

- Simulation Time: Uniformly set at 120 seconds for all variants.
- Results:
- Temperature Values: Reliable quantitative results for temperature at specific points within the computational domain.
- Isothermal Surface Distribution: Presented for two temperature values.
- Evacuation Model: Utilized the Pathfinder program to estimate the evacuation time for 100 people from the warehouse, with results showing a significant increase in available evacuation time (from 65 seconds to nearly twice that value).

2.11.3. Significance

- Mesh Density in Variant III: Allows for detailed analysis due to the smaller volume of fire zones, enhancing the accuracy of temperature and smoke distribution results.
- Evacuation Time: Provides insights into the effectiveness of fire protection strategies and their impact on evacuation efficiency.

The analysis helps in understanding the impact of fire zone division on temperature distribution and evacuation time, thereby informing decisions on the optimal fire protection system configuration.

2.12. Impact of Fire Zones on Smoke Spread

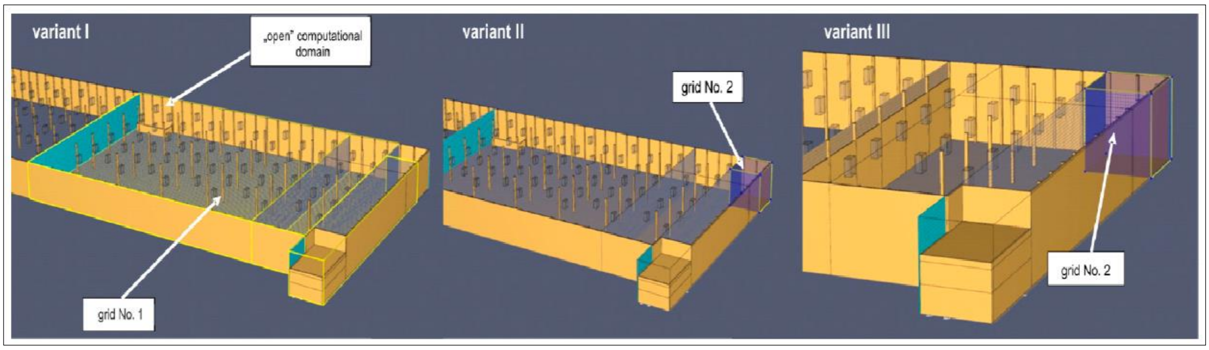

Figure 3 Demonstration of Fire and Smoke Zone

2.12.1. Variant II: Four Fire Zones

- Objective: Examine the effect of dividing the hall into four fire zones on smoke spread.
- Method:
- Partitioning: Enabled reduction in the number of computational grid elements.
- Grid Density: Local compaction of the grid near the fire source.
- Focus: Studied the spread of smoke in the extreme zone where the fire simulator was located.

2.12.2. Variant III: Six Fire Zones

- Objective: Assess the effect of dividing the hall into six fire zones on smoke spread.
- Method:
- Partitioning: Similar to Variant II, allowed for fewer finite elements.
- Grid Density:
- Near Fire Source: Increased mesh density with each element being a 10 cm cube, compared to 25 cm in previous variants.
- Advantages: Improved resolution allowed for detailed temperature measurements and visibility analysis.
- Additional Analysis:
- Temperature Changes: Monitored at a specific point above the fire source.
- Visibility: Assessed using an additional result plane to evaluate smoke obscuration.

2.12.3. Results Visualization

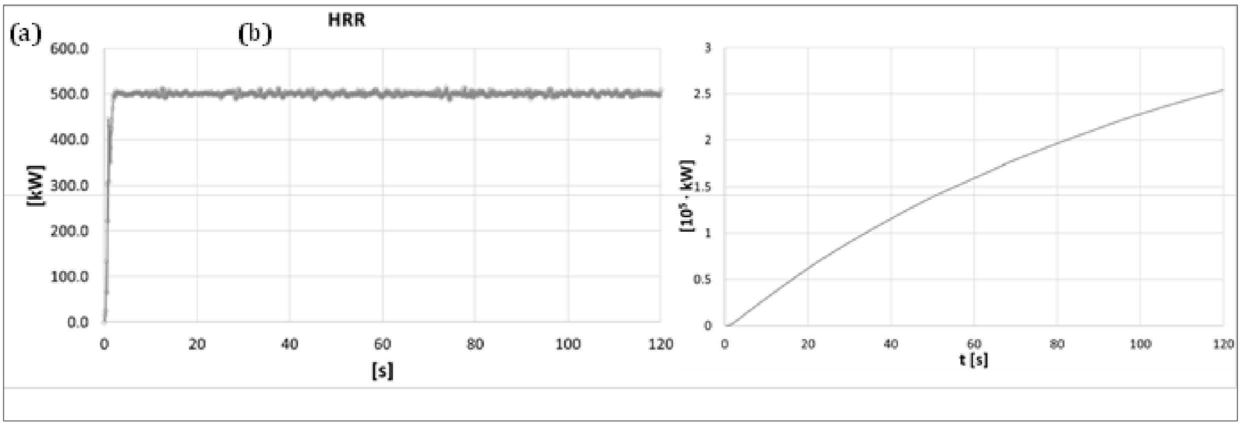

Figure 4 Result Visualization

- HRR Characteristic: The Heat Release Rate (HRR) value stabilized at 500 kW after the initial ignition period.
- Total Heat Flux: The total heat flux curve increased to approximately 200 kW within 120 seconds of simulation.

2.12.4. Summary

- Variant II: Provided insights into the smoke spread with moderate grid density.
- Variant III: Offered more detailed analysis with higher grid density, resulting in enhanced understanding of temperature variations and smoke visibility.

3. Discussion

3.1. Overview of Fire Protection Variants

The analysis evaluates three variants for implementing fire protection systems in building construction, considering their cost implications and adherence to fire regulations. Each variant presents different approaches to meeting fire protection requirements, impacting the overall building design, structure, and costs.

Cost Breakdown of Fire Protection Systems

- Variant I: EUR 759,494.85
- Features: Reduction of fire resistance class from "B" to "E". High flexibility in warehouse arrangement due to one unrestricted fire zone.
- Variant II: EUR 415,240.60
- Features: Reduction of fire resistance class from "B" to "E" with division into four fire zones. Provides a balance between cost and fire protection.
- Variant III: EUR 342,289.48
- Features: Maintains fire resistance class "B" with basic fire protection measures. Least expensive option.

3.1.1. Detailed Cost Comparisons

- Installation Costs:
- Internal Hydrants: EUR 3,170.13 (consistent across all variants)
- External Hydrants: EUR 9,632.60 (consistent across all variants)
- Container Pumping Station: EUR 32,612.95 (consistent across all variants)
- Foundation for Water Storage Tank: EUR 43,483.93 (consistent across all variants)
- Specific Costs:
- Internal Hydrant Installation Ring: EUR 20,862.72 (Variants II and III)
- Fire Pumps: EUR 36,961.34 (Variants II and III)
- Ø250 Hydrant Network: EUR 87,891.38 (Variants II and III)

3.1.2. Cost Savings Analysis

- Variant III: The most cost-effective, saving EUR 41,7205.37 compared to Variant I and EUR 72,951.12 compared to Variant II.
- Variant II: Savings of EUR 344,254.25 compared to Variant I.
- Flexibility and Practical Considerations
- Variant I: While the most expensive, it offers significant flexibility in warehouse arrangement due to its unrestricted fire zone, eliminating the need for additional fire separation partitions. This can be advantageous for large-scale or dynamically used facilities.
- Variant II: Offers a compromise between cost and fire protection, with a reduction in the number of fire zones compared to Variant III, which could be beneficial for balancing expense and operational efficiency.
- Variant III: Although the least expensive, it involves basic fire protection and may be less flexible in terms of warehouse configuration, potentially requiring additional measures to meet specific needs.

4. Conclusion

The choice of variant depends on the priorities of cost management, flexibility in warehouse design, and adherence to fire safety regulations. Variant I provides the greatest flexibility but at a higher cost, while Variant III is the most economical but with more basic fire protection. Variant II represents a middle ground, balancing cost with a moderate level of fire protection and flexibility.

4.1. Numerical Simulations and Results

4.1.1. Smoke Spread Analysis

Numerical simulations focused on the spread of smoke within the computational domain were conducted. The results indicated several key observations:

- Maximum Smoke Accumulation: Smoke accumulation was observed to be most pronounced in the ceiling zone. However, the thickness of the smoke layer decreases with an increasing number of fire zones. This is due to the physical constraints on smoke propagation along the hall's length.
- Visibility: The thickness of the ceiling smoke layer in Variant III, while significant, remains substantially less than the total height of the hall. Therefore, visibility during evacuation from 0 to 120 seconds is not critically impaired. Visibility results indicate that significant visibility reduction occurs only above the combustible surface and at select points in the hall's corners.
- Heat Impulse: The simulations confirmed that there is no risk of a heat impulse affecting the hall within the first 120 seconds of the fire event. The distribution of isosurfaces at 40°C and 60°C corroborates this observation.
- Total Heat Flux: The total heat flux in the computational domain ranged between 250 kW and 300 kW during the simulations.

4.1.2. Implications for Variant Selection

Selecting the most suitable variant for the investment requires a comprehensive evaluation of technological solutions and associated costs, including:

- Earthworks
- Construction Solutions
- Industry Installations

These factors, combined with the fire simulation results, will guide the decision on the most effective and safe design for the warehouse hall, including social facilities.

4.1.3. Next Steps

- Cost Analysis: Detailed analysis of the costs associated with earthworks, construction solutions, and industry installations.
- Escape Route Optimization: Determining the most optimal escape routes to enhance safety and reduce evacuation time, complementing the fire simulation results.

The upcoming analysis will integrate these aspects to ensure a well-rounded decision-making process for the warehouse hall design and its associated fire protection and safety measures.

4.2. Summary and Conclusions

The analysis of technological variants for constructing a warehouse hall with a social annex, considering fire regulations, reveals distinct differences in both costs and practical implications:# Cost Analysis

- Variant III: The most cost-effective solution is Variant III, which involves building in class "B" of fire resistance. This variant requires dividing the warehouse into six fire zones, each with a maximum area of 4000 m^2. While financially advantageous, this division may impose restrictions on the flexibility of space arrangement for logistics and storage, potentially affecting operational efficiency from an investor's perspective.
- Variant I: Although Variant I involves the highest initial costs due to comprehensive fire protection systems, it offers significant advantages in terms of flexibility. This option allows for a hall of any size and proves cost-effective as the area increases. The inclusion of a sprinkler system and smoke exhaust system is particularly beneficial as it directly enhances fire safety and effectiveness in extinguishing fires. The high effectiveness of sprinklers—extinguishing 8 out of 10 fires with a maximum of four sprinklers—makes this variant highly practical. Additionally, the use of sprinklers can lead to substantial savings on building insurance, with the cost of installation often recouped within four years due to lower insurance premiums.
- Variant II: Serves as a middle-ground solution. It provides more flexibility in warehouse space arrangement compared to Variant III (four PM zones of 6000 m^2 each) but incurs higher fire protection installation costs (over EUR 70,000 more than Variant I) due to the use of automatic smoke exhaust devices.

4.2.1. Practical Implications

- Variant I: Although it involves a higher upfront cost, it is the most flexible and effective in terms of fire safety. The integration of sprinklers and smoke exhaust systems significantly enhances the building's fire protection, making it a preferable choice for long-term benefits and operational efficiency.
- Variant II: Offers a balanced approach, providing more spatial flexibility than Variant III but at a higher cost than Variant I. This variant may be suitable for scenarios where intermediate solutions are preferable, considering both space flexibility and cost.

In conclusion, the choice of the variant should balance between initial costs, long-term benefits, and operational flexibility. Variant I, while the most expensive, offers the best fire safety and insurance benefits. Variant III is the most cost-effective but may limit spatial flexibility. Variant II provides a compromise between cost and flexibility, making it a viable option depending on specific project needs and constraints.

4.2.2. Use of PyroSim Computing Package: Conclusions and Findings

The use of the PyroSim computing package provided valuable insights into the fire safety and evacuation strategies for the warehouse hall design. The simulations conducted focused primarily on the effective spread of smoke, but the program's capabilities also enabled the monitoring of additional parameters such as temperature changes. The following conclusions were drawn from the analysis:

4.2.3. Key Findings

Impact on Time and Costs

- The design and effectiveness of fire protection and evacuation systems have a substantial impact on both the time required for investment and the overall cost.

Cost and Insurance Implications:

- Lowering the fire resistance class of the building, while incorporating automatic smoke exhaust and fixed water fire extinguishing systems, can significantly reduce insurance costs. However, it does not decrease the initial investment cost.

Economic Justification for Systems

- The installation of a sprinkler system and smoke exhaust system is economically justified for large-scale logistics parks or warehouse facilities exceeding 20,000 m^2.
- Cost Reduction with Fire Zone Division
- Dividing the warehouse into six fire zones, without automatic installations, can lead to substantial reductions in installation costs.

Smoke Accumulation Observations

- Numerical simulations confirmed that smoke accumulation is highest in the ceiling zone. The thickness of the ceiling smoke layer decreases as the number of fire zones increases, due to the physical limitation of smoke propagation along the hall’s length.

Visibility and Safety

- In the third calculation variant, the thickness of the ceiling smoke layer was significantly lower than the total height of the hall, which did not pose a risk to visibility during evacuation within the first 120 seconds.
- Visibility results showed a notable reduction from 0 to 12 meters only above the combustible surface and in specific corners of the hall. The risk of a heat impulse was effectively excluded up to 120 seconds after ignition.

Heat Flux Data

- The total heat flux at any given time within the computational domain was measured between 250 kW and 300 kW, providing crucial data for assessing fire dynamics.

These conclusions provide a comprehensive overview of the fire safety performance of different design variants, highlighting the importance of integrating effective fire protection measures and considering both economic and safety factors in the design of warehouse facilities.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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