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Method of the fire safety level assessment on the example of historic buildings

Metoda oceny poziomu bezpieczeństwa pożarowego na przykładzie budynków zabytkowych

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Abstract. The article presents an innovative semi-quantitative method of analysis and assessment of the level of safety in relation to the formulated objectives of the fire protection strategy in the context of historic buildings. This method is based on the Delphi method and the British standard PAS 911:2007. It involves a point assessment of the proposed twenty four components of the fire protection system in the tested facility based on precisely defined criteria and sub-criteria, as well as determining the fire safety level indicator based on the adopted fire protection strategies. The proposed method was verified on two real historic buildings. It was shown that additional fire protection measures should be introduced in the analyzed buildings. The analyzed cases confirm the effectiveness of the proposed method.

Keywords: fire protections; fire protection strategies; safety; historic building.

Streszczenie. W artykule zaprezentowano innowacyjną półilościową metodę analizy i oceny poziomu bezpieczeństwa pożarowego względem sformułowanych celów strategii ochrony przeciwpożarowej w kontekście budynków zabytkowych. Metoda ta bazuje na metodzie delfickiej i brytyjskim standardzie PAS 911:2007. Polega ona na ocenie punktowej zaproponowanych dwudziestu czterech składowych systemu zabezpieczeń przeciwpożarowych w badanym obiekcie na podstawie precyzyjnie zdefiniowanych kryteriów i podkryteriów, a także wyznaczeniu wskaźnika poziomu bezpieczeństwa w oparciu o przyjęte strategie przeciwpożarowe. Zaproponowana metoda została zweryfikowana na dwóch rzeczywistych budynkach zabytkowych. Wykazano, że w analizowanych obiektach budowlanych należy wprowadzić dodatkowe zabezpieczenia przeciwpożarowe. Analizowane przypadki potwierdzają skuteczność zaproponowanej metody.

Słowa kluczowe: zabezpieczenia przeciwpożarowe; strategie przeciwpożarowe; bezpieczeństwo; budynek zabytkowy.

The requirements for buildings and construction facilities regarding fire safety standards evolve with the advancement of modern technologies. These advancements range from building materials that enable the construction of high-rise buildings using wooden structures, to the development of active fire protection systems (e.g., fire suppression systems such as water mist [1] or foam mist), and the increasingly common use of photovoltaic panels, which can introduce fire hazards from previously unknown sources, thus not covered by existing regulations. According to the Latin legal principle „Lex retro non agit," meaning „the law is not retroactive," buildings or construction facilities completed in accordance with the regulations in force at the time of their acceptance are considered compliant until they undergo reconstruction, expansion, or a change in usage. An exception to this would be situations where failing to make any changes poses a threat to the health and life of the building's occupants or significantly hinders their evacuation (as indicated by Polish regulations). In other cases, compliance with current regulations is not required. Examples of spectacular fire-related disasters in the USA, often occurring in historic buildings over 100 years old, and sometimes even older (such as the Ghost Ship warehouse in Oakland, California (2016); the historic center of Manistee in Michigan (2018); and downtown Charleston in South Carolina (2020), demonstrate that mere compliance with fire protection regulations does not guarantee safety. In a situation where, for certain reasons, we want to assess the level of safety of a specific building or construction facility, we have several different methods at our disposal. In Poland, the most commonly used solutions are based on adapting technical and organizational concepts to ensure the expected level of safety in accordance with current legal regulations, functional objectives, or a combination of both methods [2]. Based on legal regulations, a prescriptive approach is usually supplemented by an engineering approach to designing advanced fire protection systems. Increasingly, formulated regulations

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do not impose specific solutions; the requirement is merely to meet a defined functional objective. This is the case, for example, with solutions used in fire ventilation or the protection of service openings in production and storage buildings. It is the engineer who decides on the selection of solutions and means of protection that will ensure smoke removal with the required efficiency or prevent the spread of fire between fire zones. In § 207.1 of the Regulation of the Minister of Infrastructure on the technical conditions to be met by buildings and their location (Journal of Laws 2022.0.1225) [3], the basic requirements for the building and related devices are outlined in a sufficiently general manner, opening the way for an engineering approach to designing fire protection systems [4]. The application of general regulations is particularly relevant in designing fire safety for historical and heritage buildings, which often do not meet the requirements of current regulations.

The article presents a comprehensive method for analyzing and evaluating the components of a fire protection system and the effectiveness of their performance, targeted towards the objectives of fire protection strategies in historic buildings. This methodology is based on the Delphi approach [5] and the British standard PAS 911:2007 [6]. As part of the proposed methodology, the evaluated protective measures were adjusted to better align with the Polish legal system. Additionally, the criteria and sub-criteria for the evaluation of protections were modified in relation to the primary and specific goals of the fire protection strategy. The advantage of the proposed solution lies in its simplicity, as it does not require advanced expert knowledge. This methodology clearly demonstrates the level of advancement of fire protection measures in a building. It also allows for a comparative analysis of buildings with similar purposes and levels of construction complexity. Based on this analysis, it is possible to estimate differences in the fire safety levels of buildings and establish a hierarchy for implementing subsequent investments to minimize the impact of fires, particularly when all these buildings are owned by a single entity or the projects are funded from a single budget. The proposed methodology was verified on two actual historic buildings.

Analytical Method

The proposed method for analyzing and evaluating individual components of fire protection systems and safety levels in historic buildings was based on the Delphi method and the guidelines provided in standard PAS 911:2007 [6, 7]. The overarching goal of the analysis (CN) was to calculate the fire safety index of the analyzed building. Four primary objectives were considered: human life and health protection (CW1), building protection (CW2), environmental protection (CW3), and continuity of functioning/productivity (CW4). Each of these objectives, based on [8], was divided into five detailed aspects (CSi): load-bearing capacity and statics of building structures (CS1), limitation of smoke and fire spread within the building's interior (CS2), the possibility of safe evacuation of building occupants or their rescue by alternative means (CS3), limitation of fire spread to adjacent fire zones, buildings, and surrounding areas (CS4), and ensuring the safety of rescue teams (CS5).

In the next stage, the expert team determined the weighting factors for the primary and detailed objectives of the strategy. The team comprised designers and fire protection experts, representatives of fire protection authorities, a conservator of monuments, insurers, and individuals responsible for fire safety during building operation. Initially, proposed values for the weighting factors of the primary objectives of the fire protection strategy relative to the overarching objective (WW_{CWi-CN}) and the weighting factors for the detailed objectives of the strategy relative to the primary fire protection objectives ($WW_{CSi-CWi}$) were established. The data are presented in Tables 1 and 2. The weighting factors for the detailed objectives of the strategy (WW_{CSi}) relative to the overarching goal (W_{CN}) were obtained by multiplying the weighting factors of the primary strategy objectives (WW_{CWi-CN}) by the strategy's weighting factors relative to these objectives ($WW_{CSi-CWi}$), as per Equation (1). The results are presented in Table 3.

Table 1. Proposed weighting factors for the main objectives of the fire protection strategy

Tabela 1. Zaproponowane współczynniki wagowe głównych celów strategii ochrony przeciwpożarowej

Primay objective of strategy (CG_i)	Weighting factors (WW_{CWi-CN})
Human life and health protection	0,60
Building protection	0,20
Environmental protection	0,05
Continuity of functioning/ /productivity	0,15

$$WW_{CSi-CN} = \sum^{n}_{CSi-CWi} WW_{CWi-CN} \cdot WW_{CSi-CWi} \quad (1)$$

According to the values presented in Table 1, the priority in managing fire safety for a historic building is to minimize risks to the life and health of its occupants. Experts assigned a weighting factor of 0.6 to this parameter, indicating its critical importance. In the considered case, environmental protection was evaluated by the experts as the least significant parameter, resulting in a low weighting factor of 0.05. The factors that most significantly impact the protection of human life and health are those ensuring the safe evacuation of people from the building. For the protection of the building, environmental protection, and continuity of functioning, the evacuation strategy has minimal influence. The load-bearing capacity and statics of building structures have the greatest impact on the protection of the building. Meanwhile, in terms of environmental care, the most significant factor is a strategy focused on limiting the spread of smoke and fire within the building and preventing the fire from spreading to adjacent fire zones, other buildings, and surrounding areas. The strategy for ensuring continuity of functioning in historic buildings, such as museums, archives, and other cultural properties, is a complex process that involves a series of actions aimed at maintaining the integrity of collections and their

Table 2. Proposed weighting factors for the detailed objectives of the fire protection strategy
Tabela 2. Zaproponowane współczynniki wagowe szczegółowych celów strategii ochrony przeciwpożarowej

Specific objective of strategy (CS_i)	Weighting factors			
	$WW_{CSi\text{-}CW1}$ human life and health protection	$WW_{CSi\text{-}CW2}$ building protection	$WW_{CSi\text{-}CW3}$ environ-mental protection	$WW_{CSi\text{-}CW4}$ continuity of functioning/ /productivity
Load-bearing capacity and statics of building structures	0,22	0,36	0,22	0,20
Limitation of smoke and fire spread within the building's interior	0,14	0,25	0,34	0,34
Possibility of safe evacuation of building occupants or their rescue by alternative means	0,32	0,05	0,04	0,05
Limitation of fire development to adjacent fire zones, buildings, and surrounding areas	0,14	0,24	0,36	0,31
Ensuring the safety of rescue teams	0,18	0,10	0,04	0,10

Table 3. The resulting weighting factors of the detailed objectives of the fire protection strategy in relation to the primary objective
Tabela 3. Otrzymane współczynniki wagowe szczegółowych celów strategii ochrony przeciwpożarowej względem celu nadrzędnego

Specific objective of strategy (CS_i)	Weighting factors ($WW_{CSi\text{-}CN}$)
Load-bearing capacity and statics of building structures	0,245
Limitation of smoke and fire spread within the building's interior	0,202
Possibility of safe evacuation of building occupants or their rescue by alternative means	0,212
Limitation of fire development to adjacent fire zones, buildings, and surrounding areas	0,197
Ensuring the safety of rescue teams	0,145

accessibility even in the event of a fire or other emergencies. In practice, this means not only maintaining the institution's operations but also continuing exhibitions, providing access to digital collections, or other measures to ensure resource availability for the community. The analyzed approach focuses on actions that have the most significant impact on limiting the spread of smoke and fire within the building.

In the next stage, in addition to the organizational and technical criteria of the protection systems, areas dependent on the quality of organization and human behavior during a fire were considered. As a result of the analyses, twenty-four components of the fire protection system were defined (Table 4), which were divided into four layers of protection: fire safety management, passive fire protection system, active fire protection system, and rescue team actions. Ensuring the fire safety of the building depends on the synergy of all these protection system elements in the analyzed building. The absence or failure of any of these components can lead to negative consequences, which may be exacerbated in the event of a fire. Based on knowledge, experience, and literature review [5, 9, 10], appropriate point values (WW_{PSZi}) were assigned to each element, ranging from 0 (no impact) to 5 (crucial importance). Not all elements could be assessed solely based on a single criterion. Some required the formulation of additional sub-criteria, whose combined evaluation influenced the main criterion's result. Table 5 presents the assigned point values for the safe evacuation organization system, Table 6 for the distance from neighboring buildings, and Table 7 for the fire detection system, considering the article's size limitation.

Next, the influence of individual elements of the protection system (SZ_i), on the previously defined specific strategy objectives was determined. The impact was assessed based on assigned point values ($WP_{SZi\text{-}Si}$), ranging from 0 (no impact) to 5 (crucial importance). If a particular strategy objective could be achieved without considering a specific protection system or if its impact on strategy implementation was minimal, correspondingly lower point values were assigned. The compilation of assigned values is presented in Table 4. The weighting factors of individual fire protection system elements, related to the achievement of the overarching objective of the fire protection strategy, were determined based on the product of the strategy's weighting factors ($WW_{CSi\text{-}CN}$) and the point values of individual protection system elements ($WP_{SZi\text{-}CSi}$). The obtained results were normalized according to Equation (2).

$$WW_{SZi+CN} = WP_{SZi\text{-}CN} / \sum\nolimits^{n}_{i=1} WP_{SZi\text{-}CN} \quad (2)$$

Analyzing Table 4, it was determined that the parameter exerting the greatest influence on the fire safety level indicator is the building's construction or finishing material. In more advanced safety level analyses, considerations could extend beyond just fire resistance to encompass other properties such as durability, thermal insulation, or ecological impact, in order to select the most optimal solution balancing safety and sustainable development in construction. In the subsequent stage of analysis, the fire safety level indicator of the building (IBP), was calculated using equation (3), by summing the products of the weighting coefficient of the twenty-four parameters ($WW_{SZi\text{-}CSi}$) and the point values of the implemented fire protection measures in the analyzed building (WP_{SZi}):

$$IBP = \sum\nolimits^{n}_{i=1} WW_{SZi\text{-}CN} \cdot WP_{SZi} \quad (3)$$

The fire safety level in a building concerning the protection of life and health of individuals, property,

Table 4. Weighting factors for elements of the fire protection system
Tabela 4. Otrzymane współczynniki wagowe elementów systemu zabezpieczeń przeciwpożarowych

Layers of protection	L.p.	Fire protection system components	Specific objective					Weighting factors ($WW_{SZi\text{-}CN}$)
			CS_1	CS_2	CS_3	CS_4	CS_5	
Fire safety management	SZ1.1.	compliance with regulations, norms, and safety standards	5	4	4	4	4	0,052
	SZ1.2.	training of employees and management staff	2	5	5	3	2	0,042
	SZ1.3.	documentation regarding fire safety	3	2	4	2	4	0,036
	SZ1.4.	servicing and inspections of all fire protection equipment	4	5	5	3	5	0,054
	SZ1.5.	building security service	2	5	4	4	3	0,044
	SZ1.6.	organization of safe evacuation	2	5	5	1	3	0,039
Passive fire protection system	SZ2.1.	evacuation doors, smoke containment doors throughout the building	2	5	5	2	4	0,043
	SZ2.2.	building structural and finishing elements (flammable, non-flammable, non-spreading-fire [NRO])	5	5	5	5	5	0,061
	SZ2.3.	fire protection for electrical installations	2	2	3	3	5	0,035
	SZ2.4.	distance from adjacent buildings	4	3	1	5	4	0,041
	SZ2.5.	evacuation routes	2	5	5	0	4	0,039
Active fire protection system	SZ3.1.	fire alarm system	2	5	5	4	4	0,048
	SZ3.2.	audible warning system	2	1	5	0	0	0,021
	SZ3.3.	lightning protection system	2	0	2	2	1	0,018
	SZ3.4.	alarm transmission devices to rescue services	2	3	3	5	3	0,039
	SZ3.5.	fire ventilation system (natural, mechanical), including smoke and heat extraction devices and anti-smoke devices	4	5	5	5	4	0,057
	SZ3.6.	internal hydrants	4	4	5	4	2	0,048
	SZ3.7.	fire power switch	0	1	1	0	5	0,014
	SZ3.8.	emergency shutdown of utility and industrial gas installations	3	1	4	4	5	0,040
	SZ3.9.	fire suppression system - fixed water-based fire extinguishing devices (sprinklers, spray nozzles, mist systems), gas systems (fire extinguishing gases, inert gases), powder, foam	4	5	5	5	5	0,058
	SZ3.10.	emergency lighting installation	0	0	5	0	2	0,017
Rescue operations (Volunteer Fire Department, State Fire Service, internal fire departments within institutions/ /facilities)	SZ4.1.	rescue team response time	5	3	5	5	5	0,056
	SZ4.2.	building access, access roads for rescue teams	5	3	2	5	5	0,049
	SZ.4.3.	external fire water supply	5	3	2	5	5	0,049

Table 5. Proposed criteria and sub-criteria of the system for organizing safe evacuation (SZ1.6.)
Tabela 5. Zaproponowane kryteria i podkryteria systemu organizacji bezpiecznej ewakuacji (SZ1.6.)

Criterion K1.6.1. Evacuation Coordinators	$WP_{K1.6.1.}$
Lack of designated, trained evacuation coordinators	1
Designated, trained evacuation coordinators	2
Criterion K1.6.2. Evacuation drills	$WP_{K1.6.2.}$
Irregularly conducted evacuation drills in the facility	1
Regularly, at least every two years	2
Regularly, at least once a year, with summary and conclusions	3

Scoring value of fire protection system SZ1.6: Organization of safe evacuation		Regularly opinion					
	$WP_{SZ1.6.}$	1	2	2	1	3	4
Evacuation coordinators	$WP_{K1.6.1.}$	1	1	1	2	2	2
Evacuation drills	$WP_{K1.6.2.}$	1	2	3	1	2	3

Table 6. Proposed criteria and sub-criteria of the distance from neighboring buildings (SZ2.4.)
Tabela 6. Zaproponowane kryterium oceny odległości od sąsiednich budynków (SZ2.4.)

Scoring value of fire protection system SZ2.4: Distance (O) from adjacent buildings	$WP_{SZ2.4.}$
O < 6 m	1
6 m ≤ O < 8 m	2
8 m ≤ O < 12 m	3
O ≥ 20 m	4

Table 7. Proposed criteria and sub-criteria of the fire detection system (SZ3.1)
Tabela 7. Zaproponowane kryteria i podkryteria systemu sygnalizacji pożarowej (SZ3.1)

Criterion K3.1.1. Location of fire alarm system in the facility	
Sub-criterion PK3.1.1.1. Deployment of detection system in the facility	$WP_{PK3.1.1.1}$
None	1
Detection system in zones	2
Detection system in the facility	3
Sub-criterion PK3.1.1.2. Effectiveness of fire alarm system along evacuation route	$WP_{PK3.1.1.2}$
No	1
Yes	2

Scoring value of sub-criterion PK3.1.1.	Assessment criteria						
	$WP_{PK3.1.1}$	1	2	2	2	3	4
Deployment of detection system in the facility	$WP_{PK3.1.1.1}$	1	1	2	3	2	3
Effectiveness of detection system along evacuation route	$WP_{PK3.1.1.2}$	1	2	1	1	2	2

Criterion K3.1.2. Reliability of the fire alarm system	
PK3.1.2.1. Selection of appropriate detectors for types of threats in the facility	$WP_{PK3.1.2.1}$
Improper selection	1
Single-sensor detectors	2
Multi-sensor detectors	3
PK3.1.2.2. Reliability of the fire alarm system	$WP_{PK3.1.2.2}$
CNBOP certification	1
Certification of the system, execution in accordance with the design	2
Certification of the system, execution in accordance with the design, certified installation company	3
PK3.1.2.3. Fire brigade notification system (alarm transmission devices)	$WP_{PK3.1.2.3}$
No automatic fire brigade notification system	1
Single-stage fire brigade notification system	2
Two-stage fire brigade notification system	3

Scoring value of the criterion	$WP_{K3.1.2}$	Assessment criteria																	
		1	1	2	1	2	2	2	2	3	2	3	3	2	2	3	2	3	4
PK3.1.2.1.	$WP_{PK3.1.2.1.}$	1	1	1	1	1	1	2	2	2	2	2	2	3	3	3	3	3	3
PK3.1.2.2.	$WP_{PK3.1.2.2}$	1	2	2	3	3	3	1	2	2	3	3	3	1	2	2	3	3	3
PK3.1.2.3.	$WP_{PK3.1.2.3}$	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3

Scoring value of fire protection system SZ3.1. Fire alarm system, assessment criteria	$WP_{SZ3.1.}$	Assessment criteria									
		1	2	3	3	3	4	4	4	5	5
Location of the fire alarm system within the facility	$WP_{K3.1.1.}$	1	2	2	2	3	3	3	4	4	4
Reliability of the fire alarm system within the facility	$WP_{K3.1.2.}$	1	1	2	3	1	2	3	1	2	3

environment, and continuity of operation in the event of a fire can achieve a value on a four-point scale, as depicted in Fig. 1.

Case Study Analysis

To verify the correctness of the assumptions adopted for assessing the fire safety level, two historical buildings were selected based on their purpose, the nature of stored data, and operational continuity conditions. These buildings were constructed in entirely different historical contexts and thus reflect distinct fire protection approaches. Both buildings serve as national archive repositories and meet the minimum legal requirements for historical buildings of this type. Building A, a solid brick barrack completed in 1903, features walls varying in thickness from 65 cm to 100 cm. The roof structure is separated from the interior spaces by a fire-resistant plasterboard ceiling. The building, rectangular in plan, is four stories high without underground levels, standing at a height of 14.2 meters, classified as medium-high (MH). It has two stairwells located on opposite sides, each providing two evacuation directions. The stairwells are enclosed and equipped with EI30 class doors. Corridors are divided into smoke zones using EIS30 doors. The building constitutes a single fire compartment with an internal area of 3850 m^2, adhering to permissible fire compartment size limits. The exterior lacks insulated cladding (only brick), thus eliminating the risk of external fire spread. It has a fire resistance class of B, indicating that structural elements meet minimum fire resistance requirements in terms of load-bearing capacity (R), integrity (E), and insulation (I) during a fire: main load-bearing structure R120, roof structure R30 m, floors REI 60 m, external walls EI 30 m, internal walls EI 30 m, roof covering RE 30. Building B, erected in 1956, is a three-story rotunda joined by a connector to an eight-story rectangular warehouse building, where each floor serves as a separate fire compartment. The rotunda structure is masonry with 50 cm thick walls, while the warehouse and the connector are reinforced concrete. The entire complex

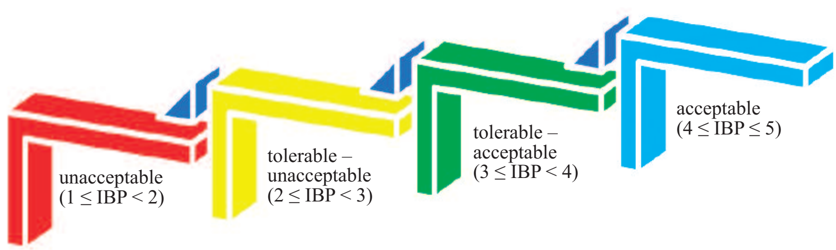

Fig. 1. Fire safety assessment scale based on the value of the fire safety index in historic buildings
Rys. 1. Skala oceny bezpieczeństwa pożarowego na podstawie wartości wskaźnika bezpieczeństwa pożarowego w budynkach zabytkowych

has a basement. Klein and Akerman floors are employed. Reinforced concrete stairwells are equipped with EI30 doors. The flat reinforced concrete roof is covered with roofing felt. Building B has a fire resistance class of C, indicating that structural elements meet minimum fire resistance requirements: main load-bearing structure R60, roof structure R15, floors REI 60, external walls EI 30, internal walls EI 15, roof covering RE 15.

Comparative analysis results of existing fire protection systems in Buildings A and B are depicted on a radar chart in Figure 2.

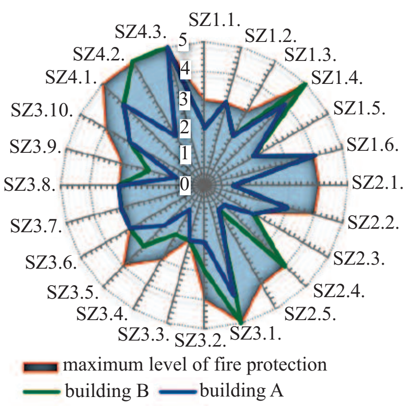

Fig. 2. Fire safety assessment grid for historic buildings
Rys. 2. Siatka oceny zabezpieczeń przeciwpożarowych budynków zabytkowych

There is a varied level of fire protection measures observed concerning: distance from neighboring buildings (SZ2.4), fire alarm system (SZ3.1), audible warning system (SZ3.2), alarm transmission devices (SZ3.4), fire suppression system (SZ3.9), and access for rescue teams (SZ4.2). For Building A, the calculated fire safety level index is IBP = 2.5, indicating that the building has been classified as not meeting (according to the adopted parameters) safe operational conditions. The analysis confirmed the feasibility of the adopted solutions; however, they still do not meet the desired safety level. The analysis results confirm the need for additional fire protection measures. Building A should be equipped with technical fire protection systems, such as a fire alarm system enabling automatic fire notification and transmission of a second-level alarm to the Fire Brigade, and critical areas of the building should have mist or gas extinguishing systems installed. The easiest and cheapest solution to achieve this would be improvement through organizational actions – in this case, ensuring regular servicing and inspections of existing fire protection systems. In contrast, for Building B, a fire safety level index value of IBP = 3.05 was obtained. This means that this building has been classified as meeting the minimum acceptable safety requirements.

Conclusion

Fire protection regulations, especially for historic buildings, do not provide clear guidelines for determining the adequacy of existing fire protection systems against prevailing risks or for establishing an accepted level of safety. A level deemed sufficient in one province may not meet specific safety requirements or standards in another, thereby potentially disallowing the building's use.

This article presents an innovative semi-quantitative methodology for analyzing and evaluating aspects of fire protection systems and the level of fire safety relative to formulated fire protection strategy goals. The developed methodology comprehensively integrates legal regulations concerning fire protection in Poland while also broadly implementing national and international best practices and standards. It enables a systematic and more objective analysis of fire protection system elements and safety levels. Consequently, it allows precise identification of areas requiring additional protection, facilitates effective measures to enhance safety, and minimizes the risk of fire occurrence.

A key advantage of this approach is its simplicity, speed, and minimal requirement for advanced expert knowledge. It empowers building owners or administrators to independently assess the actual state and choose solutions that are cost-effective, straightforward, and efficient in ensuring fire safety.

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