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A Methodology for Assessing Economic Implications of Fire Protection in Building Design

Metodologia oceny ekonomicznych implikacji ochrony przeciwpożarowej w procesie projektowania budynków

Abstract

The aim of the paper is to provide an insight on the topic of the economic implications of fire safety measures, i.e. the economic efficiency of fire protection. The presented work combines two elements – probabilistic fire modelling and a cost-benefit analysis. A worked example demonstrates the proposed methodology on three different occupancies – office, retail and industrial, and two levels of fire protection – sprinklered and unspriklered.

In the first step, the likely, or expected, outcome – fire damaged area – is established using the event tree analysis. Afterwards, fire loss is calculated and cost benefit analysis performed. Since there are a number of possible fire scenarios with varying extent of fire damage and degree of occurrence probability, two alternative approaches of fire loss are evaluated; fire loss based on the most likely outcome and fire loss based on all potential outcomes weighed by their occurrence probability. The latter approach appears to be more robust and realistic.

In the final step, the expected yearly fire loss and costs of fire protection are compared for the two scenarios. The presented results confirm the financial substantiation for sprinkler installation in the industrial and retail occupancy types. Nonetheless this study is aimed only at the economics of fire protection, i.e. property protection objectives and should be always used with a life safety analysis.

Keywords: economic efficiency, fire protection, cost-benefit analysis, probabilistic fire modelling, event tree analysis

Streszczenie

Celem artykułu jest przedstawienie analizy skutków ekonomicznych stosowanych środków zabezbieczeń przeciwpożarowych, czyli efektywności ekonomicznej ochrony przeciwpożarowej. W materiale połączono dwa elementy – probabilistyczne modelowania pożaru oraz analizę kosztów i korzyści. Opracowany przykład przedstawia zastosowanie proponowanej metody dla trzech różnych typów obiektów – biurowych, handlowych i przemysłowych oraz dwa poziomy ochrony przeciwpożarowej – z instalacją tryskaczową i bez niej. W pierwszym etapie, prawdopodobny lub oczekiwany wynikiem – obszar zniszczeń pożarowych – jest określany przy użyciu analizy drzewa zdarzeń. Następnie obliczane są straty pożarowe i przeprowadzona jest analiza kosztów i korzyści. Ponieważ istnieje szereg możliwych scenariuszy pożarowych o różnym zakresie strat pożarowych i prawdopodobieństwie wystąpienia, przeprowadzane są dwa alternatywne sposoby oceny strat pożarowych; straty pożaru w oparciu o wynik najbardziej prawdopodobny i straty na podstawie wszystkich możliwych wyników ważonych prawdopodobieństwem ich wystąpienia. To drugie rozwiązanie wydaje się być bardziej prawidłowe i realistyczne. W końcowym etapie, oczekiwane roczne straty pożarowe i koszty ochrony przeciwpożarowej są porównywane dla dwóch scenariuszy. Przedstawione wyniki potwierdzają uzasadnienie finansowe dla instalacji tryskaczowej w obiektach przemysłowych i handlowych. Należy podkreślić, że badanie to ma na celu jedynie ocenę ekonomiki ochrony przeciwpożarowej, czyli osiągnięcie celów ochrony mienia i powinno być ono zawsze stosowane łącznie z analizą bezpieczeństwa ludzi.

Słowa kluczowe: ekonomia ochrony przeciwpożarowej, analiza koszt-efekt, probabilistyczne modelowanie pożarów, analiza typu drzewo zdarzeń

1. Introduction

The inclusion of fire protection systems into building design is usually driven by two aspects – legal requirements and economic feasibility. Since legal requirements are mandatory they are not discussed in this paper. On the other hand, a particular fire protection system may and should be included in the building design if sufficient economic justification is provided. Economic justification is not a very straightforward task and depends on an array of parameters [1]. Fire engineered design standards, call [2], [3], however, for a holistic analysis, which is particularly important where multiple design alternatives are considered. The aim is always to provide the highest level of safety at a given level of cost.

Since it is usually not feasible to undertake a detailed deterministic analysis a more general probabilistic fire modelling is a good alternative to get a global view of the problem. The fire scenarios and outcomes – fire damaged area, are characterised by a value of probable occurrence, which may be also transformed into the occurrence interval of a given fire damage. The expected fire damage varies, of course, with the level of fire protection. Each fire protection system has the potential, direct or indirect, to reduce fire damage; sprinkler protection, increased compartmentation, etc.

To make the economic feasibility decision it is necessary to know the expected fire damage and associated loss for the individual fire protection alternatives and then compare them with the cost of such systems. A financial benefit in this case is the reduction of potential fire loss achieved by a particular fire protection system compared against "unprotected" or otherwise specified base scenario.

2. Proposed calculation methodology

For the analysis two calculation methods are employed; for risk estimation – the event tree analysis and for economic loss – cost per-area-damaged method.

2.1. Event tree analysis

The analysis is undertaken in the form of event trees. According to [1], event trees are most useful when there is little data on the frequency of outcomes of concern that are very infrequent, e.g. multiple fire deaths. A general form of an event tree is shown in Figure 1.

The frequency of each of the outcomes F_x is then expressed as:

$$F_x = F \cdot \Pi P_x \tag{1}$$

where F is the frequency of the initiating event – a fire starting in a given type of occupancy, and P_x represent the probabilities of nodal events occurring.

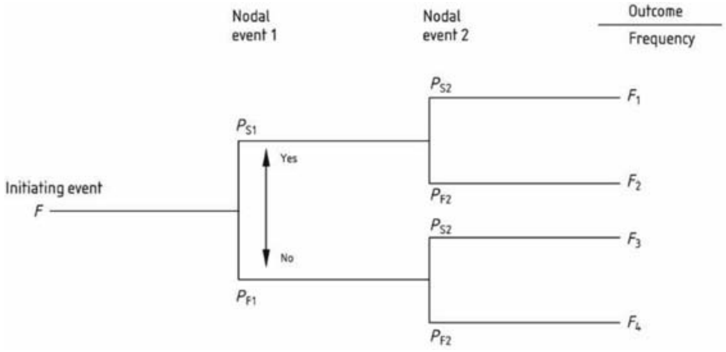


Figure 1. General form of an event tree

The problem with this type of analysis, however, is the limited availability of statistical data of required detail and structure [6], [7]. Whereas the data for deterministic fire models may be acquired via various methods of testing (e.g. [8], [9]) in relatively shorts periods of time, gathering the necessary statistical data is a long-term process. Engineering judgement and aproximation have therefore often to be used.

The primary probability – Initiating event (Fig. 1) – is the probability of a fire starting. This probability is closely tied with the occupancy type – purpose group – of a building. In general, the probability of a fire starting may be expressed as overall or area-dependent. The overal probabilities for selected occupancy types are listed in Tab. 1. Tab. 1 also lists the calculation conostants for equation (2), which can be used for the calculation of area-dependent probabilities [5].

$$F_i = a \cdot A_b^b \tag{2}$$

Where:

F_i – probability (frequency) of a fire starting [y^{-1}],

A_b – floor area of building [m^2],

a, b – probability (frequency) calculation constants for particular building type [–].

Table 1. Overall fire occurence probabilities and area-dependent probability calculation constants

Occupancy type	Overall probability of fire starting [year^{-1}]		Probability of fire starting calculation constants [5]	
	SK [6]	UK [5]	a	b
Education	$1,5 \times 10^{-3}$	$4,0 \times 10^{-2}$	0,0002	0,75
Hospitals	$3,0 \times 10^{-3}$	$3,0 \times 10^{-1}$	0,0007	0,75
Hotels	$1,9 \times 10^{-2}$	–	0,00008	1,0
Industrial	$8,1 \times 10^{-3}$	$4,4 \times 10^{-2}$	0,0017	0,53
Office	$4,1 \times 10^{-3}$	$6,2 \times 10^{-3}$	0,000059	0,9
Shops	$8,5 \times 10^{-3}$	–	0,000066	1,0
Warehouses	–	$1,3 \times 10^{-3}$	0,00067	0,5

2.2. Loss estimation – cost per area damaged by fire

In order to be able to estimate potential fire loss, the expected fire spread must be known. In addition to the area damaged by fire, fire loss is closely tied with value concentration; there is a vast difference between, say a 100 m^2, fire damaged area in an office and a warehouse.

To determine the expected fire loss, the destructive potential of fire is established at first, together with the probabilities of the individual outcome scenarios. The event tree analysis provides the probabilities and the extent of the scenarios is given by compartmentation and other fire protection measures present in the evaluated building.

In the final step, the financial loss is calculated as a product of the fire-damaged area and an arbitrary value density (cost) per unit of area [EUR/m^2] for the given type of building. The arbitrarity of value density is given by its nature, i.e. the stakeholder(s) has the option to place their own value on the building or its part and include even indirect costs.

3. Case study

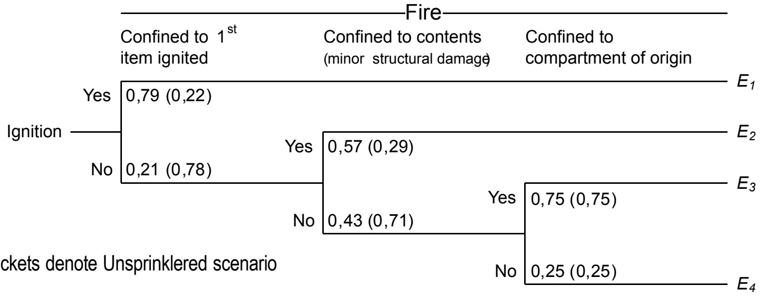
3.1. Description of buildings and probability of fire starting

The building in question consists of two compartments, each having a floor area of 1000 m^2; the total floor area of each building is 2000 m^2. Each compartment is further subdivided into at least two rooms. Three various occupancy types are assumed: office, shop and industrial. There are two levels of fire protection: sprinklered and unsprinklered.

Since the probabilities of a fire starting calculated using Eq. (2) are the most conservative from the available options, they were used in all subsequent calculations and are as follows: *Industrial* – 0,096; *Office* – 0,052; *Shop* – 0,132.

3.2. Event tree analysis formulation

Due to the lack of available statistical data for the Slovak republic, the probabilities from were used. The basic event trees for the sprinklered and non-sprinklered scenarios (values in brackets) with the probabilities for the individual nodal events are shown in Figure 2.



*values in brackets denote Unsprinklered scenario

Figure 2. Event trees for modelled fire scenarios

The probabilities of the final node – failure of a compartment boundary – are based on the reliability data for elements of fire protection from [5]. They represent the probability of that the compartment boundary will achieve at least 75% of the designated fire resistance.

Table 2. Extent of fire damage and outcome frequencies for defined fire scenarios

Fire scenario	Extent of damage	Outcome frequency FEi	
		Sprinklered	**Unsprinklered**
Confined to 1st item E_1	max. 5 m^2	0,790	0,22
Confined to contents E_2	50% of compartment 500 m^2	0,120	0,226
Confined to compartment of origin E_3	100% of compartment 1000 m^2	0,068	0,415
Spread beyond compartment of origin E_4	2 x compartment area 2000 m^2	0,023	0,139

3.3. Determining the probability, extent of fire damage and potential loss

Table 4 lists the probabilities and occurrence intervals for the individual fire scenarios, E_1 – E_4; the values were obtained using Equation (1). The most probable outcome for each fire protection level is in bold. It should be realized that the occurrence of a fire does not decrease for the individual fire scenarios E_x, but is rather divided among the possible outcomes.

It is also very important to take into account the expected lifespan of a building, in order to determine whether or not a fire scenario (event) is relevant to the building in question. Remoy [10] states that buildings in Europe and America have an expected lifespan of 50–70 years. This means that it is rather unlikely that a fire will grow beyond first item ignited – 5 m^2 for the sprinklered occupancies. On the other hand, with the exception of the office category, there is a possibility for even the most severe – fire spread beyond the compartment of origin – consequences and damaged area.

Table 3. Extent of fire damage estimation for the most probable fire scenario

Occupancy	**E1**		**E2**		**E3**		**E4**		**Sd**
	P	**O**	**P**	**O**	**P**	**O**	**P**	**O**	**[m^2·year-1]**
Sprinklered									
Industrial	$7,5\cdot10^{-2}$	13	$1,1\cdot10^{-2}$	87	$6,5\cdot10^{-3}$	155	$2,2\cdot10^{-3}$	464	0,39
Office	$4,4\cdot10^{-2}$	23	$6,6\cdot10^{-3}$	151	$3,7\cdot10^{-3}$	268	$1,2\cdot10^{-3}$	803	0,22
Shop	$1,0\cdot10^{-1}$	10	$1,6\cdot10^{-2}$	63	8,9·10-3	112	$3,0\cdot10^{-3}$	336	0,5
Unsprinklered									
Industrial	$2,1\cdot10^{-2}$	48	$2,2\cdot10^{-2}$	46	$4,0\cdot10^{-2}$	25	$1,3\cdot10^{-2}$	76	40,0
Office	$1,2\cdot10^{-2}$	82	$1,2\cdot10^{-2}$	80	$2,3\cdot10^{-2}$	44	$7,6\cdot10^{-3}$	131	22,7
Shop	$2,9\cdot10^{-2}$	34	$3,0\cdot10^{-2}$	33	$5,5\cdot10^{-2}$	18	$1,8\cdot10^{-2}$	55	55,6

P – probability [y^{-1}]; O – occurrence [y].

Taking the most likely outcomes into consideration, the yearly fire-damaged area S_d is based on 5 m^2 and 1000 m^2 for sprinklered and unsprinklered scenario, respectively, regardless of the occupancy type.

On the other hand, there is approximately two-fold difference in the occurrence intervals of the sprinklered and unsprinklered scenarios. This means that a direct comparison may produce somewhat skewed results. Therefore, as an alternative to the above values listed in Table 4, a different calculation method is implemented. Instead of selecting the most probable outcome and its occurrence interval as the representative value, a weighed mean is used to calculate the yearly expected fire damage, as per Equation (3).

$$S_d = \sum_{i=1}^{n} \frac{F_{Ei} \cdot S_{d,Ei}}{O_{Ei}} \tag{3}$$

Where:

S_d – expected fire damaged area per year for selected level of fire protection [$m^2 \cdot year^{-1}$],

F_{Ei} – outcome probability frequency for *i*-th outcome scenario E*i* (Table 2) [-],

$S_{d,Ei}$ – expected fire damaged area for *i*-th outcome scenario E*i* (Table 2) [m^2],

O_{Ei} – occurrence interval of *i*-th outcome scenario E*i* (Table 3) [year].

The above calculation method provides a more balanced approach, factoring in also the less likely (frequent) outcome scenarios. The results are listed in Table 4.

Table 4. Estimated extent of fire damage for weighed scenario occurence using Eq (3)

Occupancy	$\frac{F_{Ei} \cdot S_{d,Ei}}{O_{Ei}}$				**1.1.1. S_d**
	E1	**E2**	**E3**	**E4**	**[$m^2 \cdot year^{-1}$]**
Sprinklered					
Industrial	$3{,}04 \cdot 10^{-1}$	$6{,}90 \cdot 10^{-1}$	$4{,}39 \cdot 10^{-1}$	1.1.2. $9{,}91 \cdot 10^{-2}$	1.1.3. 1,53
Office	$1{,}72 \cdot 10^{-1}$	$3{,}97 \cdot 10^{-1}$	$2{,}54 \cdot 10^{-1}$	1.1.4. $5{,}73 \cdot 10^{-2}$	1.1.5. 0,88
Shop	$3{,}95 \cdot 10^{-1}$	$9{,}52 \cdot 10^{-1}$	$6{,}07 \cdot 10^{-1}$	1.1.6. $1{,}37 \cdot 10^{-1}$	1.1.7. 2,09
Unsprinklered					
Industrial	$2{,}29 \cdot 10^{-2}$	$2{,}46 \cdot 10^{+0}$	$1{,}66 \cdot 10^{+1}$	1.1.8. $3{,}66 \cdot 10^{+0}$	1.1.9. 22,7
Office	$1{,}34 \cdot 10^{-2}$	$1{,}41 \cdot 10^{+0}$	$9{,}43 \cdot 10^{+0}$	1.1.10. $2{,}12 \cdot 10^{+0}$	1.1.11. 13,0
Shop	$3{,}24 \cdot 10^{-2}$	$3{,}42 \cdot 10^{+0}$	$2{,}31 \cdot 10^{+1}$	1.1.12. $5{,}05 \cdot 10^{+0}$	1.1.13. 31,6

*Fabricated values – for demonstration only.

Table 5 provides a comparison of economic implications of the fire scenarios for the two calculation methods described above. It is also clear how sprinkler protection significantly decreases the potential loss. It is also clear from the data that the yearly fire loss estimates based on the most likely scenario exhibit far greater difference between the sprinklered and unsprinklered alternative.

This may be misleading when the probabilities of the individual outcome scenarios are similar and/or distributed evenly, i.e. no particular scenario has a probability significantly higher than the other scenarios.

There is approximately a 100-fold difference in the results for the unsprinklered and sprinklered alternatives when the calculations are made with the most likely outcome scenario. For comparison, the weighed-mean method, which accounts proportionally for each individual outcome scenario, yields approximately a 10-fold difference between the sprinklered and unsprinklered alternatives.

Table 5. Comparison of expected yearly fire loss

Occupancy	**Value density***	**Expected yearly fire damage based on scenario [m^{-2}·year^{-1}]**		**Expected yearly fire loss based on scenario [Ä·year^{-1}]**	
	[Ä·m^{-2}]	**most likely**	**weighed mean**	**most likely**	**weighed mean**
Sprinklered					
Industrial	300	0,39	1,53	117	459
Office	100	0,22	0,88	22	88
Shop	200	0,50	2,09	100	418
Unsprinklered					
Industrial	300	40,-	22,70	12 000	6810
Office	100	22,7	13,00	2270	1300
Shop	200	55,6	31,60	11 120	6320

*Fabricated values – for demonstration only.

Let the yearly costs of a sprinkler system installation be 3000 Ä; a fabricated value for demonstration purposes. This includes all costs, direct and indirect, e.g. system purchase installation, inspection and maintenance, rental space loss, etc.

From the economics standpoint, sprinkler protection is a financially feasible option for the industrial and retail occupancies. In the office type occupancy, the value density does not provide sufficient financial justification for a sprinkler system. This is also in resemblance to real-world sprinkler protection application; for non-highrise buildings office occupancies are not usually protected by a sprinkler system.

Conclusion

The question of financial implications of fire protection in building design remains a very important one. If no legal requirements exist and there is lack of financial substantiation, the stakeholder is very likely do decline an inclusion of a fire protection system in the building design. On the other hand if sufficient and convincing evidence is provided that a particular system brings financial benefits in the form of significant potential loss reduction, the fire protection system should be included even if no legal requirement exists.

This papers outlines and demonstrates a relatively simple method of fire protection economic efficiency assessments. The methodology is based on an event tree analysis which determines the occurrence probabilities of the individual outcome scenarios – expected area damaged by fire. These results are then transformed into expected fire damage per year. It was shown that in order to get more representative results it should be accounted proportionally for each of the individual outcome scenarios and not only for the most probable one.

The final part of the papers provides a relatively simple presentation of economic feasibility assessment of sprinkler protection. It was found that the protected value must be sufficiently high to justify for sprinkler installation where no legal requirement for sprinkler protection exists. The expected yearly loss in the unsprinklered industrial and retail occupancies is ten times higher than in the sprinklered counterparts. The reduction of expected yearly loss is therefore much greater for industrial and retail occupancies, even with yearly sprinkler system costs factored in.

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References

[1] Ramachandran G.: *The economics of fire protection*. London: E & FN Spon, 1998. ISBN 0419207805.

[2] BS 7974:2001. *Application of fire safety engineering principles to the design of buildings: code of practice*. London: BSI, 2001.

[3] ISO/TR 13387-1: 1999, Fire safety engineering – Part 1: *Application of fire performance concepts to design objectives.*

[4] DiNenno P.J. ed.: *SFPE handbook of fire protection engineering*. 4th ed. vyd. Quincy, Mass.?: Bethesda, Md: National Fire Protection Association?; Society of Fire Protection Engineers, 2008. ISBN 9780877658214.

[5] PD 7974-7: 2003. Part 7 *Probabilistic risk assessment*. London: BSI, 2003.

[6] Coneva I., Panáková J.: *Požiarovosť podľa kategorizácie stavebných objektov za obdobie 2008-2012* In: Bezpečnost, spolehlivost a rizika 2014 – Zborník konferencie, Liberec: Technická univerzita, 2014. - ISBN 978-80-7494-110-8.

[7] Coneva I., Panáková J.: *Požiare a ich následky na základe kategorizácie budov* In: Advances in fire and safety engineering 2014: recenzovaný zborník: Trnava: AlumniPress, 2014. - ISBN 978-80-8096-202-9.

[8] Xu Q., Zachar M., Majlingová A., Jin C., Jiang Y.: *Evaluation of plywood fire behaviour by ISO tests* in: European Journal of Environmental and Safety Sciences Vol. 1(1) (2013).

[9] Martinka J., Chrebet T., Balog K.: *An assessment of petrol fire risk by oxygen consumption calorimetry* in: Journal of Thermal Analysis and Calorimetry Vol. 115(3) (2014).

[10] Remoy H.T.: *Out of Office: A Study on the Cause of Office Vacancy and Transformation as a Means to Cope and Prevent*. Amsterdam: IOS Press, 2010.