SiF 2024 – The 13th International Conference on Structures in Fire
University of Coimbra, Portugal, 19 to 21 June 2024

APPLICATION OF COST-BENEFIT ANALYSIS METHODOLOGY FOR FIRE SAFETY MEASURES IN STRUCTURAL FIRE ENGINEERING

Andrea Lucherini[1], Shuna Ni[2], David Unobe[3], Thomas Gernay[4], Ranjit Kumar Chaudhary[5], Mengying Peng[6], Ruben Van Coile[7]

ABSTRACT

In fire safety engineering, cost-benefit analysis offers a systematic approach to determining whether the anticipated benefits of a fire safety measure justify its costs. Nonetheless, significant disparities persist in the methodologies employed for cost-benefit analysis, alongside a lack of quantitative data concerning the costs and economic impact of fire protection in buildings. In a recent research project, a reference methodology was suggested, based on the concept of Present Net Value (PNV) assessment and a combination of specialized construction database, fire statistics, and numerical modelling for estimation of the cost components. This study presents the application of this methodology to a specific case study related to structural fire engineering. The case study illustrates the implementation of the methodology to a nine-story office building, as well as data gathering, examination of fire statistics, and loss estimation, while it also demonstrates how the methodology aids decision-making when evaluating multiple design alternatives. The cost-benefit analysis considers various thicknesses of Sprayed Fire Resistive Material (SFRM) applied to the building steel gravity frames corresponding to 1-hour, 2-hour, and 3-hour of fire protection. For all cases, the estimated benefit of the investment in fire protection on the steel members exceeds the cost. For the specific case study, the use of a 3-hour fire rated thickness is found as providing the highest benefit, and the sensitivity analysis confirms the robustness of the investment recommendation.

Keywords: Fire safety; cost-benefit analysis; fire protection; fire statistics; structural fire engineering.

1 INTRODUCTION

Fires in buildings can lead to costly damages as well as loss of lives and injuries. Installed to protect buildings from fires and to limit the damage from such outbreaks, fire safety measures are common features in buildings. However, it is important to understand the benefits they bring to the building safety. An initial consideration is ensuring that the residual risk remains acceptable. While every design carries residual fire risk, it must be mitigated to a level deemed acceptable by decision-makers [1]. Determining this acceptability does not solely rely on understanding the costs and benefits of fire protection measures, but

[1] PhD, Senior Researcher, Slovenian National Building and Civil Engineering Institute (ZAG), Slovenia
e-mail: andrea.lucherini@zag.si, ORCID: https://orcid.org/0000-0001-8738-1018
[2] PhD, Assistant Professor, University of Maryland, College Park, USA
e-mail: shunani@umd.edu, ORCID: https://orcid.org/0000-0002-8795-176X
[3] PhD, Assistant Professor, Schreiner University, Kerrville, USA
e-mail: dunobe@schreiner.edu, ORCID: https://orcid.org/0000-0001-7145-5027
[4] PhD, Assistant Professor, Johns Hopkins University, Baltimore, USA
e-mail: tgernay@jhu.edu, ORCID: https://orcid.org/0000-0002-3511-9226
[5] PhD, Ghent University, Belgium
e-mail: ranjitkumar.chaudhary@ugent.be, ORCID: https://orcid.org/0000-0002-1104-5859
[6] MSc, PhD Student, Ghent University, Belgium
e-mail: mengying.peng@ugent.be, ORCID: https://orcid.org/0009-0000-8199-0939
[7] PhD, Professor, Ghent University, Belgium
e-mail: ruben.vancoile@ugent.be, ORCID: https://orcid.org/0000-0002-9715-6786

also on assessing the perception of exposure. This pertains to whether decision-makers can tolerate the likelihood of the risk materialising, particularly concerning low-probability-high-consequence events [1]. Once this tolerability criterion is satisfied, the discussion shifts to whether further risk reduction is necessary, and if additional safety systems can be incorporated into designs. However, these investments come at a cost, and as safety levels increase (e.g., through improved structural reliability), the marginal benefits decrease [1-2]. Therefore, a method is required to evaluate the cost-effectiveness of fire protection investments.

To understand their value, *Cost-Benefit Analysis (CBA)* detailing the costs and benefits of the systems provides a systematic method to assess whether the projected benefits from a fire safety measure outweigh its costs [2]. CBA measures the usefulness of the investment, typically quantified in monetary terms, though it could be assessed in other terms like environmental impact. On one side, the investment incurs a monetary cost, including maintenance. On the other side, a monetary value is assigned to the net benefit gained from the fire safety investment, usually in terms of avoided losses. After discounting appropriately, these costs are compared, aiding decision-makers in identifying the design that optimizes the building's lifetime utility.

It is crucial to consider the perspective of the decision-maker in this process. Code-makers and legislators have different goals compared to private owners. Code-makers assess whether increased fire safety measures for a class of buildings lead to an overall increase in societal welfare, considering an assumed tolerable residual fire risk in society. Private owners, however, focus on their return on investment if they invest beyond societal requirements. These differing viewpoints result in variations in how certain costs, for instance insurance expenses, are viewed [3-4].

Carrying out such an analysis requires methods for estimating both the cost of the fire safety measures and the losses caused by fires. Currently, different approaches are discussed in literature [2] and applied in the fire safety context [5-6]. Despite considerable interest, a clearly established methodology for conducting CBA in fire safety engineering is lacking [7]. It is unclear which approach should be favoured and why, how cost-effectiveness is evaluated, which costs are considered, and how the preferred design solution is defined. In addition, there is a lack of quantitative data on the costs and economic impact of fire safety measures in buildings, uncertainties surrounding fire frequency and severity, and complexities in quantifying the indirect consequences of fire events, which hinder objective decision-making [4].

In this context, the authors conducted a research project supported by the Fire Protection Research Foundation (research affiliate of NFPA). The aim of the research was to examine contemporary methods for estimating costs and losses resulting from fires, and to evaluate cost-benefit analyses. Subsequently, based on a critical literature review, a reference methodology for conducting Cost-Benefit Analyses (CBA) of fire protection measures in buildings was developed [4]. This paper outlines the application of this CBA methodology for a case study relevant for structural fire safety engineering. The case studies encompass the evaluation of the net benefit associated with passive fire protection on steel framing members in a multi-story office building.

2 METHODOLOGY FOR COST–BENEFIT ASSESSMENT

The proposed methodology for cost-benefit analysis of fire protection based on *Present Net Value (PNV)* evaluation combines specialized construction database, fire statistics, and numerical modelling [4, 8, 9, 10]. The methodology clarifies the minimum requirements for assessing cost-effectiveness, and highlights that only a PNV evaluation can be used to compare design alternatives. First, the fire protection cost estimation is performed, including selecting the building category from a list of updated building categories, computing the cost of the entire building and the cost of installation and maintenance of fire protection using construction databases, and computing multipliers, representative of buildings in the selected category. Then, the losses caused by fires are computed based on the definition of the fire hazard and its probability, followed by the estimation of both the direct (material and human) and indirect losses. The proposed methodology is illustrated in the flowchart in Figure 1.

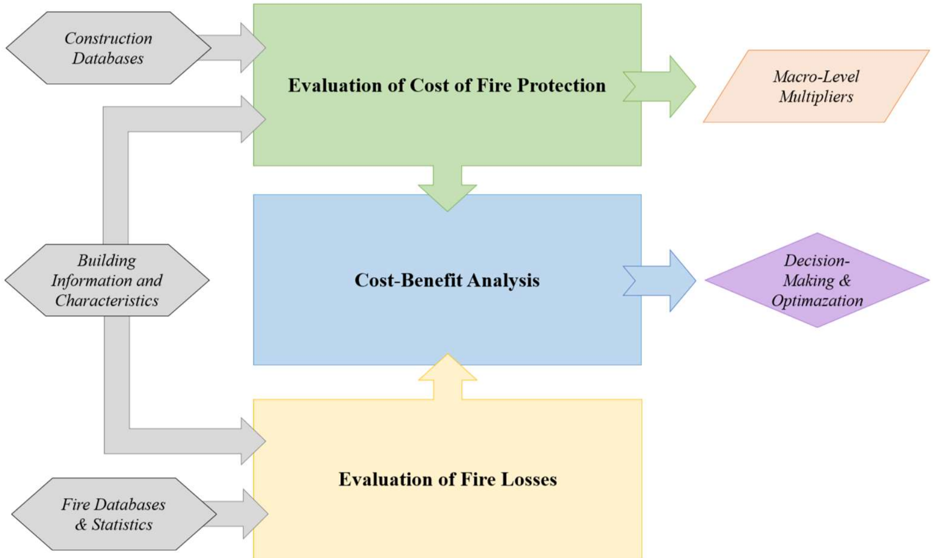

Figure 1. Flowchart of the methodology to assess the cost and benefit of fire protection in buildings.

When comparing different options in terms of fire protection measures, the objective is to determine the design with the highest lifetime utility [11]. The lifetime utility of an investment is conceptually represented by equation (1), where Z is the total (net) utility, B is the benefit derived from the safety feature's existence, corresponding with the avoidance of the (expected) fire damage in the reference state absent of the additional safety investment, C is the cost of construction or implementation (including maintenance); A is the obsolescence cost, and D is the direct and indirect costs in case of failure.

$$Z = B - C - A - D \tag{1}$$

Since the scope is focused on the costs and benefits of the safety measure (as opposed to evaluating these for the entire structure), the terms in equation (1) can be simplified in equation (2) and equation (3), where C_{dd} and C_{id} are the PNV for the direct and indirect losses, respectively (with the subscript o and p refer to the original configuration and the proposed configuration), C_I is the PNV of the investment costs, C_M is the PNV of the maintenance costs, and C_A is the PNV cost resulting from building obsolescence.

$$B - D = (C_{id} + C_{dd})_o - (C_{id} + C_{dd})_p \tag{2}$$

$$C + A = C_I + C_M + C_A \tag{3}$$

These terms also allow the evaluation of a *Cost-Benefit Ratio (CBR)*, $(C+A)/(B-D)$, or *Benefit-Cost Ratio (BCR)*, $(B-D)/(C+A)$. While such terms are frequently reported, they only allow for guiding decisions on a single design alternative. Such ratios do not allow comparing multiple alternatives, and thus the lifetime utility or PNV evaluation has been recommended by the authors [4].

Cost evaluation involves aggregating the total expenses for materials, labour, and equipment necessary for installing and maintaining the considered fire protection systems. These costs are appraised using the RSMeans database [12], which utilises data representative of the USA market. Loss evaluation encompasses both direct and indirect losses. Direct losses pertain to the "damage caused to a building, its contents and occupants during the course of a fire" [7], comprising both material (structural and non-structural elements, along with contents) and human losses (civilian and firefighter fatalities and injuries). Indirect losses are defined as the "costs associated with a fire after it is extinguished" [7]. Examples include expenses related to the unavailability or loss of critical infrastructure or items of unique value, environmental damage and pollution/waste, losses incurred due to business interruption, and cascading effects on suppliers or clients of an affected company [4]. As various scenarios lead to different losses, these losses are weighted based on their likelihood of occurrence.

Assessing fire-related losses is a complex task. In this regard, the methodology relies on a blend of statistical information and predictive modelling. Where reliable data are accessible, the efficacy of a fire protection system can be gauged by contrasting fire loss data from buildings with and without such systems (yet otherwise similar). However, such detailed data may not always be available. In instances where fire loss data lack the requisite granularity to distinguish between similar buildings equipped with different fire protection systems, predictive simulations are employed alongside statistical data.

The methodology is usually applied (also in this study) from a societal viewpoint regarding costs and benefits. Consequently, the aim is to evaluate which fire protection standards bring most benefits to society, which can inform evolution of codes and specifications. Cost elements involving the redistribution of funds within society (e.g., the impact of implementing safety measures on insurance premiums) can thus be disregarded. These studies begin with the current level of fire protection within society, enabling the use of fire statistics collected from real fires. Within the extended research project [4], a series of illustrative case studies have been presented to provide practical examples for the application of the presented cost-benefit methodology. The case studies rely on several assumptions and simplifications, and the input parameters are evaluated using statistics, existing data, numerical simulations, and/or expert judgment. The calculations are completed in JupyterLab [13] (Python) scripts, which are available through the project website.

3 CASE STUDY: PASSIVE FIRE PROTECTION ON STEEL FRAMING MEMBERS IN A MULTI-STORY OFFICE BUILDING

3.1 Case study description

The described illustrative case study applies the presented prototype methodology for the cost-benefit evaluation of the passive fire protection for steel moment-frame commercial professional services buildings (COM4 occupancy class - commercial building, professional/technical/business services [14]). The assessment is done considering a combination of statistical data and numerical simulations using the structural fire engineering software SAFIR [15]. These simulations supplement fire loss statistics to estimate the impact of different fire safety alternatives. This is needed due to the insufficient granularity of fire loss statistics in distinguishing between buildings with varying fire safety measures. These simulations help estimate the expected structural damage levels depending on the implemented fire safety measures, with subsequent loss calculations derived from these damage assessments.

The building prototype is a nine-story steel-concrete composite building with a floor plan area of 2,090 m^2 for a total floor area of 18,810 m^2. The building design is based on the FEMA/SAC project for the Boston area post-Northridge [16]. The steel members of the interior gravity frames of the building (beams and columns) are protected with Sprayed Fire Resistive Material (SFRM). The evaluation considers different thicknesses of SFRM corresponding to 1-hour, 2-hour, and 3-hour of protection from qualified UL assemblies.

3.2 Input parameters

Cost estimates, sourced from the RSMeans database [12], are detailed in Table 1, with additional information provided on macro-level cost multipliers for the SFRM application. The reconstruction cost is the combined cost of demolition, disposal and (renewed) construction. Notably, maintenance costs for the SFRM are not considered in this analysis.

As regards to the loss assessment, the fire risk parameters outlined in Table 2 are adopted. The assessment of fatality and injury risk is conducted utilizing the concepts of Value of Statistical Life (VSL) and Value of Statistical Injury (VSI) methodology [4]. Fire frequency is aligned with the reported fires, while non-reported fires are presumed to cause minimal losses. The analysis does not incorporate the potential impact of early fire suppression by occupants or emergency services, leading to an overestimation of the frequency of structurally significant fires. Consequently, from this standpoint, the case study presents an upper limit for evaluating the cost-effectiveness of investments in passive fire protection measures.

Table 1. Cost parameters.

Parameter	Value	Cost multiplier
Construction cost	1,674 USD/m^2	
Demolition cost	59.82 USD/m^2	
Disposal cost	0.145 USD/m^2	
Re-construction cost	1,734 USD/m^2	
Cost of SFRM – fire resistance rating 1 hour	13.7 USD/m^2	0.82%
Cost of SFRM – fire resistance rating 2 hour	23.8 USD/m^2	1.42%
Cost of SFRM – fire resistance rating 3 hour	41.0 USD/m^2	2.45%

The fatality and injury rates shown in Table 2 and used in the subsequent cost-benefit analysis are obtained from the published sources listed. These values are from recent data collected on both the civilian and firefighter casualties and injuries from fires across the United States. The property loss areas are obtained from Manes and Rush [17], which is based on 2014 USA fire statistics. In accordance with the Federal Emergency Management Agency (FEMA), the replacement cost for the contents of a commercial office building is valued at 100% of the construction cost of the property [21]. For office buildings, the indirect loss was estimated as 25% of the direct loss [22], and this indirect loss value is added to the total property loss to obtain the total monetary losses from a fire incident. A discount rate of 3% is adopted, based on [23]. Obsolescence is neglected (i.e., an obsolescence rate of 0% is adopted).

Table 2. Parameters for estimating the benefits of fire protection (i.e., fire risk parameters).

Parameter	Value	Reference
Fire frequency (reported fires)	0.00423 per year	[17]
Civilian fatality rate	0.89 per 1,000 reported fires	[18]
Civilian injury rate	1.4 per 100 reported fires	[18]
Firefighter fireground fatality rate	6.9 per 100,000 reported fires	[19]
Firefighter response fatality rate	6.3 per 100,000 reported fires	[19]
Firefighter fireground injury rate	1.62 per 100 reported fires	[20]
Firefighter response injury rate	0.37 per 100 reported fires	[20]
Average damage area – no structural failure	83.5 m^2	assumption (compartment)
Average damage area – structural failure	18,810 m^2	assumption (whole building)
Content loss (% of total construction costs)	100%	[21]
Indirect loss (% of direct costs)	25%	[22]
Effect of structural failure on casualties	1 firefighter fireground fatality 4 firefighter fireground injuries no effect on civilians	assumption

The event tree illustrated in Figure 2 is considered to evaluate the different scenarios associated with the three thickness of SFRM. For each design, the event tree defines two scenarios: (i) "no structural failure", and (ii) "structural failure". The probability of each scenario is evaluated from numerical simulations of the thermal-structural response. The outcomes for each scenario are evaluated based on the statistics and assumptions outlined in Table 2. Specifically, the average fire-related losses are highly dependent on the occurrence of significant structural failure in a frame member, as such failure could lead to breaches in compartmentation and extensive structural damage beyond the compartment of fire origin. It is assumed that if the structural frame withstands the fire without collapsing, losses remain confined to the compartment of fire origin, whereas if the frame collapses during the fire, the entire building is deemed lost. Additionally, it is reasonable to anticipate that structural failure could impact fatalities and injuries. Instances of fire-induced structural failures are fortunately rare, resulting in a lack of available data. In this analysis, it is assumed that building failure leads on average to one fatality and four injuries for firefighters on the fireground, while civilian casualties are presumed unaffected, assuming evacuation is completed prior to collapse. The probabilities associated with each branch of the event tree are derived from numerical simulations, as detailed in the subsequent section. Risk assessment for a design then incorporates both the consequences of each scenario and their associated probabilities within the framework of PNV evaluation.

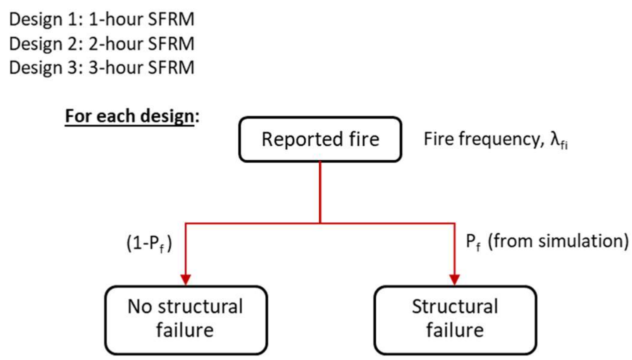

Figure 2. Event tree defining the scenarios for the cost-benefit analysis.

3.3 Numerical model for assessing fire losses for the design alternatives

The primary structure of the office building is modelled using the finite element software SAFIR [15]. The design and dimensions of the frame members, derived from the FEMA/SAC prototype developed for post-Northridge designs in the Boston area, are extensively detailed in a prior study [24] and shown in Figure 3. To ensure computational efficiency, a 2D frame model is utilized for probabilistic analyses.

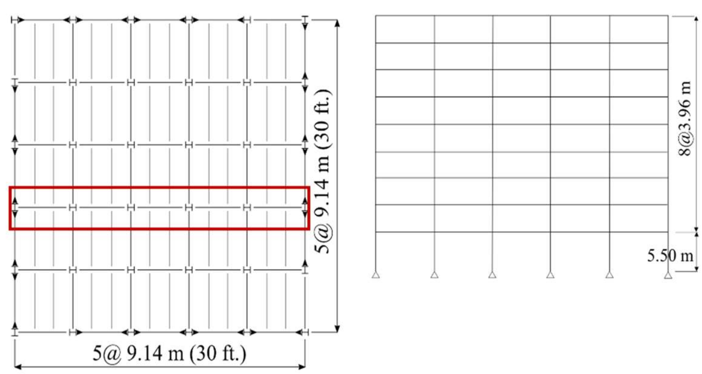

Figure 3. Analysed gravity frame for the multi-story office building.

The building is categorized as Type I B, necessitating a 2-hour ICC fire resistance rating for the primary structural frame members. The insulation materials chosen are X829 CAFCO BLAZE-SHIELD II for the columns and N823 UL CAFCO BLAZE-SHIELD II for the beams and girders. Additionally, thickness variations for achieving 1-hour and 3-hour fire resistance ratings are assessed, as the cost-benefit analysis explores different fire protection alternatives. The member sections and fire protection thicknesses are detailed in Table 3, ranging from 10 to 48 mm.

Table 3. SFRM insulation thickness for the various members of the gravity frames.

Member type	Storey	Size	1-hour [m]	2-hours [m]	3-hours [m]
COLUMNS	1	W14x145	0.011	0.022	0.033
	2	W14x145	0.011	0.022	0.033
	3	W12x120	0.011	0.022	0.033
	4	W12x120	0.011	0.022	0.033
	5	W14x90	0.015	0.030	0.044
	6	W14x90	0.015	0.030	0.044
	7	W12x65	0.016	0.032	0.048
	8	W12x65	0.016	0.032	0.048
	9	W8x48	0.016	0.032	0.048
BEAMS	1-8	W16x26	0.010	0.021	0.033
	9	W14x22	0.010	0.021	0.033

The distributed dead load on the floors amounts to 4.60 kN/m², with a typical live load for office occupancy at 2.40 kN/m². After reduction, the live load becomes 0.96 kN/m². These values are unfactored. According to the ASCE load combination for ambient temperature design, considering the reduced live load, a distributed load of 7.05 kN/m² is calculated. For fire situations, the ASCE load combination yields a distributed load of 5.99 kN/m². However, for a probabilistic cost-benefit evaluation, it is crucial to consider the expected value of loading rather than the code value. The expected loading value is determined based on a literature review conducted by Jovanović *et al.* [25]. The total load effect is described by $K_E(G + Q)$, where K_E is the model uncertainty with expected value of 1.0, G is the permanent load with expected value equal to the nominal value (i.e., 4.60 kN/m²), and Q is the imposed load with expected value equal to 0.2 times the nominal value (i.e., 0.48 kN/m^2). As a result, the beams are subjected to a uniformly distributed load of 5.08 kN/m² multiplied by the tributary width of 9.14 m, for a total of 46.4 kN/m.
To account for uncertainties, several parameters are treated as probabilistic [26], including the fuel load, the compartment opening factor, the thermal properties of the SFRM, and the yield strength of the steel at elevated temperatures. For the fuel load for office occupancy, two probability distributions are considered and compared: the one derived from a recent NFPA study (Generalized Extreme Value distribution, mean of 1,116 MJ/m² with a standard deviation of 604 MJ/m^2) [27] and the one prescribed in Eurocode 1 (Gumbel distribution, average 420 MJ/m^2 and 80% fractile 511 MJ/m^2) [28]. For the opening factor, the distribution is calculated according to the JCSS formula [29] (truncated lognormal distribution with mean 0.2 and standard deviation 0.2), where the maximum opening factor is calculated from Eurocode 1 [28] assuming that window glass is immediately broken when fire breaks out. The thermal properties of the boundaries of enclosure are: conductivity 0.48 W/mK, density 1440 kg/m^3, and specific heat 840 J/kgK. For the SFRM properties, the temperature-dependent conductivity, specific heat, and density are evaluated from a probabilistic model calibrated on a NIST study of three sprayed fire resistive materials.
The model adopts the probabilistic formulation outlined by Elhami Khorasani *et al.* [30] and is integrated into SAFIR under the name SFRM_PROBA for Sprayed Fire Resistive Material. Regarding the steel, which has a nominal yield strength of 345 MPa, the material model follows the stress-strain relationship in Eurocodes. However, the temperature reduction of yield strength conforms to a logistic EC3-based probabilistic model [30]. This material is incorporated into SAFIR as STEC3PROBA.
The structure undergoes initial loading at ambient temperature to determine the ultimate uniformly distributed load on the beams, which amounts to 82.8 kN/m. Consequently, the anticipated loading during a fire scenario is calculated as 46.4/82.8 = 56% of the ambient temperature capacity. Subsequently, the structural response is assessed under fire conditions. Single-compartment fire scenarios are simulated, given their higher frequency compared to multi-compartment fires. The structural analysis focuses on the gravity frame members of the nine-story building. For each design variation (e.g., differing thicknesses of fire

protection) and each fuel load distribution, 100 simulations are conducted. Fire curves are generated in accordance with the Eurocode parametric fire model [28]. The fire curves, derived from running 100 iterations with varying fuel loads and opening factors, are depicted in Figure 4. It is observed that the NFPA fuel load distribution leads to more severe fires compared to the Eurocode fuel load distribution, as expected due to the significantly higher values of fuel loads.

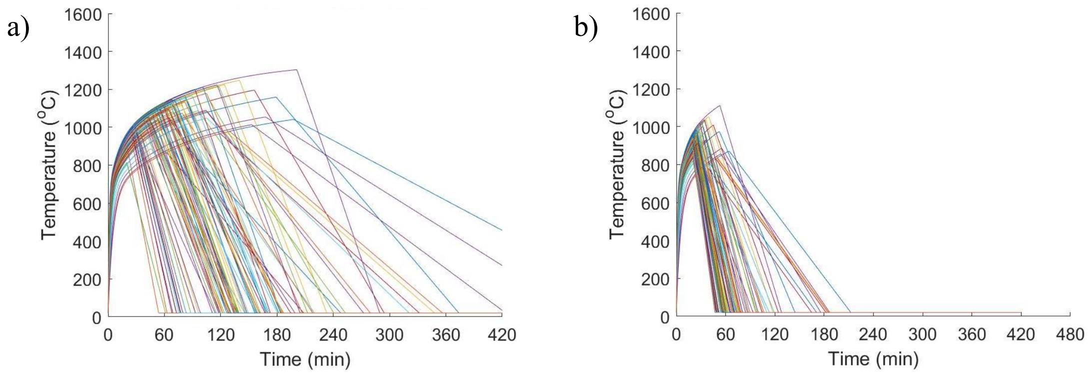

Figure 4. Gas temperature-time curves according to the Eurocode parametric fire curves methodology [28] considered in the simulations, based on two fuel load distributions for office occupancy: NFPA (a) and Eurocode (b) fuel load distributions.

4 RESULTS

4.1 Probabilistic structural analysis

Figure 5 illustrates the progression of vertical deflections in the fire-exposed beams for two specific scenarios. A notable divergence in response is evident between the instance resulting in failure (1-hour fire protection) and the one which does not fail (2-hour fire protection). Failure is identified when the simulation is unable to achieve equilibrium under the applied loading and fire exposure, assessing the structural response until full fuel burnout (simulations conducted for 7 hours). It is evident that the absence of numerical convergence correlates with a rapid escalation in deflections within the frame members, indicating a loss of stability, as depicted in Figure 5. Failures typically originate in the beams. It is noteworthy that, while composite floors are not included in the model, the prescriptive design practice in the US requires only a very limited amount of wire mesh reinforcement in the slab (about 60 mm^2/m) which does not allow development of alternative load paths and redistribution (such as membrane action) through the floors. This has been evidenced by recent full-scale experiments at the NIST.

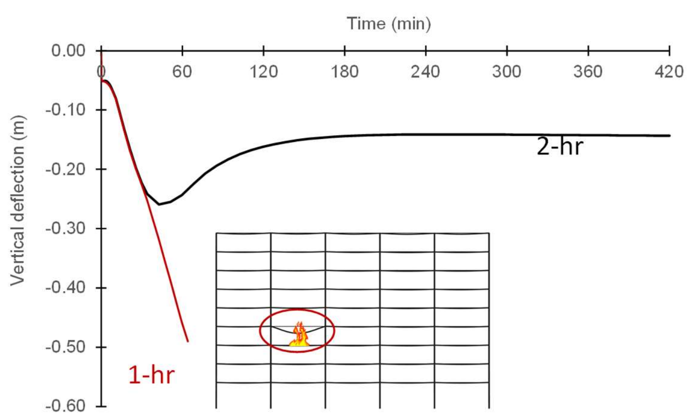

Figure 5. Evolution of the vertical deflections at mid-span of the beam in the fire compartment, for a case that fails (1-hr fire protection) and a case that survives the fire (2-hr fire protection).

The numerical results are presented in Table 4. The probability of failure is determined by dividing the number of failed simulations by the total 100 simulations conducted. As anticipated, the likelihood of failure diminishes with an increase in the thickness of SFRM. Moreover, the probability of failure is higher with the NFPA fuel load distribution compared to the Eurocode fuel load distribution, reflecting the greater fuel load values documented in the former study [27]. With the Eurocode distribution, the probability of failure for the prescribed 2-hour fire protection is calculated to be 15% in the event of an uncontrolled structurally significant fire, while 79% for the NFPA fuel load distribution. In the absence of any fire protection, the building is deemed to fail in all cases of structurally significant fires.

Table 4. Probability of failure for the steel frame structure with different fire protection levels.

Design fire rating	**Fuel load distribution model**	
	NFPA	**Eurocode**
SFRM prescriptive 1-hour	0.97	0.73
SFRM prescriptive 2-hour	0.79	0.15
SFRM prescriptive 3-hour	0.64	0.08

4.2 PNV evaluation

Table 5 outlines the PNVs across the various considered fire safety alternatives. Utilizing both models for fuel load distribution, each prescribed rating for SFRM yields a positive PNV, indicating that the benefits outweigh the costs. Consequently, under the studied conditions, these safety measures can be recommended as beneficial from an economic perspective. Particularly, both the NFPA and Eurocode fuel load density models advocate for a 3-hour fire resistance rating as the most optimal solution. This alignment is significant as it corresponds with the current prescriptive guidelines, which typically require either a 2-hour or 3-hour fire resistance rating for primary frame members. For generalization, it is advisable to conduct further modelling including other designs and explicit consideration of the potential redistribution of loads following the failure of a primary beam within a three-dimensional structural model, as this could alter failure rates and consequences.

It is important to note that the BCR is highest for the 2-hour fire resistance rating. Nonetheless, particularly when considering in the NFPA fuel load, there is an additional net benefit in opting for the 3-hour fire resistance rating. While the PNV evaluation accurately identifies the optimum solution, the BCR does not (as discussed in [4]). In essence, if the initial choice is to adopt the design with the highest BCR (2-hour rating), subsequent cost-benefit analysis regarding additional protection (upgrading to a 3-hour rating) would reveal a positive BCR for the transition (assuming equal costs and disregarding additional expenses associated with a phased approach). Whereas the PNV directly discerns the optimal outcome, a BCR approach will only converge to the same conclusion through iterations.

Table 5. Cost-benefit indicators.

Design fire rating	**NFPA fuel load**		**Eurocode fuel load**	
	PNV [USD]	**BCR**	**PNV [USD]**	**BCR**
SFRM prescriptive 1-hour	114,950	1.45	3,090,108	13.03
SFRM prescriptive 2-hour	2,156,338	5.82	10,090,093	23.58
SFRM prescriptive 3-hour	3,691,715	5.79	10,633,751	14.79

4.3 Sensitivity analysis

A parametric study is carried out to investigate the impact of the assumptions regarding the damaged area in instances where failure does not occur. While failure typically assumes total building damage, the scenario shifts when the building maintains stability, allowing for variations in the damaged area affected by significant deformations and fire-induced damages beyond the compartment of fire origin. As illustrated in Figure 6, the PNV is plotted as a function of the damaged areas, expressed as a percentage of the total floor area. It is evident that this variable significantly influences the PNV. The efficacy of fire protection is most pronounced when the assumed damaged area in the absence of failure is minimal. In such instances, successful fire protection, by preserving structural stability, mitigates repair costs. Conversely, presuming extensive damage across the floor area even without failure diminishes the benefit of fire protection, as repair costs persist despite structural stability. Nonetheless, the PNV remains positive until the damaged area approximates 90% of the total floor area. This underscores the cost-effectiveness of high-rated SFRM in this scenario. Even lacking precise data on fire-induced damaged areas, this sensitivity analysis indicates the robustness of the presented conclusion, irrespective of assumptions regarding the damaged area in the absence of failure.

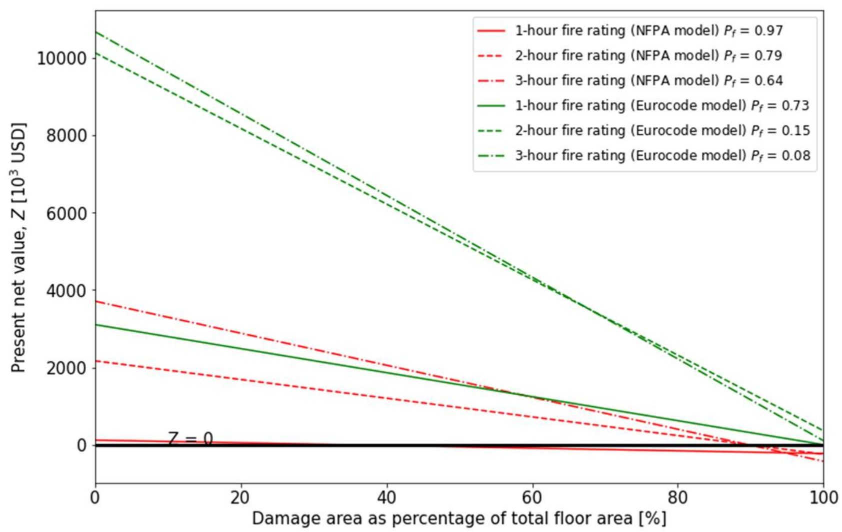

Figure 6. Cost-effectiveness of the passive fire protection for varying fire-induced damaged area.

5 CONCLUSIONS

Evaluating the costs and benefits of safety measures is a vital aspect of making well-informed decisions. Once a minimum threshold of tolerability is met (which is imperative), decision-makers can choose to prioritise an alternative design with either a greater or lesser investment in safety. A logical approach to inform this decision-making process involves conducting a Cost-Benefit Analysis (CBA) for each design option. In the field of fire safety engineering, CBA takes into consideration both the investment costs and the benefits derived from enhanced building performance during a fire, including reductions in injuries, casualties, direct losses, and indirect losses.

A methodology for conducting cost-benefit analysis of fire protection in buildings is presented and applied to an illustrative case study. The case study involves a nine-story office building, and the cost-benefit analysis is applied to assess passive fire protection alternatives, in particular different thicknesses of Sprayed Fire Resistive Material (SFRM) applied to the building steel gravity frames and corresponding to 1-hour, 2-hour, and 3-hour of fire protection. As expected, the probability of failure decreases with an increase in SFRM thickness, and the probability of failure is largely affected by the assumed fuel load distribution. Nevertheless, the PNV for the different fire resistance ratings always returns a positive value (i.e., benefit of the investment exceeds the cost), meaning that these fire safety measures can be recommended as beneficial from an economic perspective. In particular, the use of a 3-hour fire rated thickness of SFRM is found as providing the highest PNV. The sensitivity analysis on the assumption of the damaged area in the absence of structural failure shows that this parameter has a significant effect on the PNV. Nevertheless, it confirms the robustness of the investment recommendation because this conclusion holds almost regardless of the assumption for damage area in the absence of failure.

The presented results demonstrate the strength and relevance of the proposed methodology based on the concept of Present Net Value (PNV) and potential applications for structural fire engineering. The insights and suggestions presented in this research study underline how results obtained from the cost-benefit evaluations, adapted from the presented case study with project-specific inputs, can support decision making of various fire safety strategies for both private stakeholders (e.g. business/building owner, insurance companies) and society (e.g. policy makers).

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Fire Protection Research Foundation (FPRF) and the National Fire Protection Association (NFPA) for the funding through the project ‘‘Economic Impact of Fire: Cost and Impact of Fire Protection in Buildings’’. The authors thank Amanda Kimball, Birgitte Messerschmidt, and the members of the Project Technical Panel for their support. Dr Lucherini would also like to gratefully acknowledge the financial support for the FRISSBE project within the European Union's Horizon 2020 research and innovation programme (GA 952395).

REFERENCES

[1] Van Coile R., Hopkin D., Lange D., Jomaas G., Bisby L. (2019). The Need for Hierarchies of Acceptance Criteria for Probabilistic Risk Assessments in Fire Engineering. Fire Technology, 55:1111–46.
[2] Sunstein C.R. (2018). The cost-benefit revolution. MIT Press.
[3] Lundin J, Frantzich H. (2002). Cost-benefit and risk analysis-basis for decisions in the fire safety design process. Proceedings from the 4th International Conference on Performance-based codes and Fire Safety Design Methods, 370-381.
[4] Van Coile R., Lucherini A., Chaudhary R.K., Ni S., Unobe D., Gernay T. (2023). Economic impact of fire: cost and impact of fire protection in buildings”. National Fire Protection Association (NFPA).
[5] Butry D.T., Brown M.H., Fuller S.K. (2007). Benefit-cost Analysis of Residential Fire Sprinkler Systems. Gaithersburg, MD
[6] Hopkin D., Fu I., Van Coile R. (2020). Adequate fire safety for structural steel elements based upon life-time cost optimization. Fire Safety Journal, 103095.
[7] Ramachandran G. (2002). The economics of fire protection. Routledge, London, UK.
[8] Van Coile R., Lucherini A., Chaudhary R.K., Ni S., Unobe D., Gernay T. (2023). Cost-benefit analysis in fire safety engineering: State-of-the-art and reference methodology. Safety Science, 168, 106326.
[9] Unobe I. D., Lucherini A., Ni S., Gernay T., Chaudhary R., Van Coile R. (2024). State of the Art Methodologies for the Estimation of Fire Costs in Buildings to Support Cost–Benefit Analysis. Fire Technology.
[10] Gernay T., Ni S., Unobe D., Lucherini A., Chaudhary R.K., Van Coile R. (2023). Cost-benefit analysis of fire protection in buildings: application of a present net value approach”. Fire Technology, 59, 2023–2053.
[11] Van Coile R., Jomaas G., Bisby L. (2019). Defining ALARP for fire safety engineering design via the Life Quality Index. Fire Safety Journal, 107, 1-14.
[12] RSMeans. (2020). Building Construction Costs with RSMeans Data 2021. 79th ed. Rockland, MA: RSMeans Co.
[13] Kluyver T., Ragan-Kelley B., Pérez F., Granger B.E., Bussonnier M., Frederic J., *et al.* (2016). Jupyter Notebooks-a publishing format for reproducible computational workflows. IOS Press, Positioning and Power in Academic Publishing: Players, Agents and Agendas, 87-90.
[14] Federal Emergency Management Agency (2003). Multi-Hazard Loss Estimation Methodology: Earthquake Model, HAZUS-MH MR4.

[15] Franssen J.M., Gernay T. (2017). Modeling structures in fire with SAFIR: theoretical background and capabilities. Journal of Structural Fire Engineering, 8, 300–323.
[16] Federal Emergency Management Agency. SAC. (2000). FEMA 355C: State of the Art Report on System Performance of Steel Moment Frames Subject to Earthquake Ground Shaking. Washington D.C.
[17] Manes M., Rush D. (2019). A Critical Evaluation of BS PD 7974-7 Structural Fire Response Data Based on USA Fire Statistics. Fire Technology, 55, 1243–93.
[18] National Fire Protection Association (NFPA). (2022). Fires by occupancy or Property Type.
[19] Fahy RF, Petrillo JT. (2022). Firefighter Fatalities in the US in 2021. National Fire Protection Association (NFPA).
[20] Campbell R, Evarts B. (2021). United States Firefighter Injuries in 2020 Key Findings. National Fire Protection Association (NFPA).
[21] Federal Emergency Management Agency (FEMA). (2015) Earthquake loss estimation methodology, Hazus-MH 2.1: Advanced engineering building module (AEBM) - Technical and user's manual. Washington, DC.
[22] Ramachandran G., Hall J.R. (2002). SFPE Handbook of Fire Protection Engineering, Measuring Fire Consequences in Economic Terms, 79.
[23] Fischer K. (2014). Societal decision-making for optimal fire safety. Bericht IBK, 357.
[24] Gernay T., Elhami Khorasani N. (2020). Recommendations for performance-based fire design of composite steel buildings using computational analysis. Journal of Constructional Steel Research, 166, 105906.
[25] Jovanović B., Van Coile R., Hopkin D., Elhami Khorasani N., Lange D., Gernay T. (2021). Review of Current Practice in Probabilistic Structural Fire Engineering: Permanent and Live Load Modelling. Fire Technology.
[26] Gernay T., Elhami Khorasani E., Garlock M. (2019). Fire Fragility Functions for Steel Frame Buildings: Sensitivity Analysis and Reliability Framework. Fire Technology.
[27] Elhami Khorasani N., Salado Castillo J.G., Saula E., Josephs T., Nurlybekova G., Gernay T. (2020). Application of a Digitized Fuel Load Surveying Methodology to Office Buildings. Fire Technology.
[28] EN1991-1-2. (2002). Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire. European Standard.
[29] JCSS (2001). JCSS Probabilistic Model Code: Part 2: Load Models.
[30] Elhami Khorasani N., Gardoni P., Garlock M. (2015). Probabilistic Fire Analysis: Material Models and Evaluation of Steel Structural Members. Journal of Structural Engineering, 04015050, 1–15.