Safety Science 168 (2023) 106326

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Cost-benefit analysis in fire safety engineering: State-of-the-art and reference methodology

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ARTICLE INFO

Keywords:
Cost-benefit analysis
Fire safety
Investment
Maintenance
Loss
Statistics
Reliability

ABSTRACT

Cost-effectiveness is a key consideration within fire safety engineering. Currently, different approaches are being applied in literature. These approaches differ in how cost-effectiveness is evaluated, which costs are considered, and how the preferred design solution is defined. Recognizing this issue, the Fire Protection Research Foundation enrolled an international team of researchers, supported by a broad stakeholder panel, to develop a reference methodology. In this paper, this reference methodology for cost-benefit analysis in fire safety engineering is presented following an extensive literature review. The methodology clarifies the minimum requirements for assessing cost-effectiveness, and highlights that only a present net value evaluation can be used to compare design alternatives. Commonly used cost-benefit ratios should only be used when deciding on the effectiveness of a single package of fire safety measures. An illustrative case study demonstrates the application of the methodology and shows how designs based on cost-benefit ratios can be sub-optimal when evaluating multiple possible fire safety measures.

1. Introduction

Cost-Benefit Analysis (CBA) can be used to determine the cost-effectiveness of investments in fire protection. This is of interest to (i) code-makers and legislators when prescribing fire safety measures for a class of buildings, and (ii) private decision-makers when considering whether to invest in (additional) safety for a specific project. The focus on cost-effectiveness acknowledges that additional safety investments are always possible. With increasing safety level, however, the return on additional investments (i.e., the marginal benefit) diminishes. CBA then provides a structured approach to weigh the costs and benefits of fire protection investments.

The CBA of fire protection investments must be understood within the larger context of fire risk management. Even the most thorough fire safety strategy and most advanced fire safety measures cannot fully reduce the fire risk to zero, and thus every design entails residual fire risk. Concluding that the safety level of a (class of) building(s) is adequate then hinges on two considerations (Van Coile et al., 2019b): (i) the residual risk is bearable, and (ii) further safety investments are not cost-effective. Evaluating whether the residual risk is bearable does not require insight into the costs and benefits of fire protection measures. The key question is whether the decision-maker can accept the possibility of the risk materializing, notably for low-probability-high-consequence events. This is denoted as the tolerability of the risk and relates to the perception of the exposure. A design which constitutes a residual risk that is not tolerable cannot be accepted and requires intervention (Van Coile et al., 2019b). The concept of tolerability allows to explain why one may decide in favor of fire safety investments also where these are not cost-effective.

When deciding on the net benefit of (fire) safety investments, it is really the utility of the investment which is of interest (Sunstein, 2018). From a societal perspective, the question is whether the investment results in an increase of societal welfare. From a private perspective, worthy investments are those for which the benefit to the owner outweigh the cost. The best approach currently available for the evaluation of utility is through a valuation in monetary terms, see (Sunstein,

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https://doi.org/10.1016/j.ssci.2023.106326
Received 16 May 2023; Received in revised form 12 September 2023; Accepted 22 September 2023

2018). In the following, the maximization of utility is therefore directly equated with a monetary cost-benefit evaluation.

The fire safety literature on cost-benefit analysis is diverse, with (at first sight) a steady albeit limited interest since the 1980 s. There is, however, no clearly established methodology. While Ramachandran listed different approaches in (Ramachandran, 1998), it is not clear whether or why one approach should be preferred over another. There is also no clear guidance on values for key parameters, such as the discount rate and the valuation of risk to life. In the following, these issues are explored, starting with a review of cost-benefit approaches in Section 2. Subsequently, two key concepts for CBA are discussed in more detail: the perspective of the CBA, and the valuation of risk to life. Considering the results of these literature review sections, a reference methodology for cost-benefit analysis in fire safety engineering is derived (presented in Section 4), followed by an illustrative application in Section 5 and conclusions.

The scope of the literature review is limited to costs and benefits of fire protection measures in the built environment. Other fire safety investments, such as investments in the fire and rescue service (FRS), product safety requirements and public awareness are not elaborated. From a technical perspective, the above means that the CBA investigated here considers the perspective of (i) a private decision-maker deciding on investments beyond prescriptive requirements, or (ii) a societal decision-maker deciding whether to implement prescriptive requirements. In both situations, the funding available for the FRS is considered beyond the decision power of the decision-maker. In other words, the FRS is considered as an "environmental" condition and not part of the optimization. The literature review was conducted considering (i) references known to the authors of the current report from previous studies, (ii) a keyword search in academic repositories, (iii) secondary referencing from the studied sources. The search for additional sources was halted when observing that the later investigations did not add new insights relative to the earlier investigations.

The discussions in this paper are the outcome of the project "Economic Impact of Fire: Cost and Impact of Fire Protection in Buildings" which was carried out from October 2021 to July 2022 and supported by the NFPA Research Foundation. The full report is available as (Van Coile et al., 2022). Throughout the project, input and feedback was obtained through a dedicated stakeholder panel with representatives from industry, fire and rescue service and research institutes.

2. Approaches for cost-benefit evaluation

2.1. Points of consensus within the state-of-the-art

From the literature review, the following points of consensus were identified which form a common framework for cost-benefit analyses (Van Coile et al., 2022). Studies which violate these principles thus cannot be considered to constitute a CBA, see (Van Coile et al., 2022) for examples. First of all, costs and benefits should be considered at constant prices. This means that input data should be corrected for inflation effects where relevant, see e.g., (Ramachandran, 1998). Secondly, costs and benefits should be evaluated considering a common time-frame, i.e. at a common point in time or on a recurring (e.g., annualized) basis. This implies the discounting of future costs and benefits, considering a discrete discount rate i or continuous discount rate γ, see e.g., (Ramachandran, 1998; Juås and Mattsson, 1994). Thirdly, there is consensus regarding key cost components. The cost of a fire safety measure includes both the initial investment cost C_I and the maintenance cost C_M. The benefits of investments in fire safety constitute the reductions in direct and indirect damages, C_{dd} and C_{id}, in case of fire. These losses should be "weighted" by their likelihood (i.e., the expected value of the fire-induced losses should be considered). Finally, risk to life must be taken into account in the CBA, except where it is considered negligible. Different approaches for the valuation of risk to life exist.

2.2. Present net value (PNV)

The *Present Net Value (PNV)* approach considers the lifetime sum of the costs and benefits of the fire safety investment. Projects with a positive PNV are considered efficient, meaning that they constitute a net benefit; therefore, the investment is cost-effective. Amongst competing projects, the project with the highest PNV should be preferred. As highlighted by Ramachandran (1998), investments in fire safety are really aimed at reducing losses, and thus the PNV-preferred design can also be referred to as the design with the minimum total lifetime (or annualized) cost.

Most CBA studies in Fire Safety Science and Engineering (FSSE) apply PNV evaluations. Early and noteworthy descriptions of the approach can be found in (Ramachandran, 1998; Juås and Mattsson, 1994). Also, in 1982 Offensend and Martin (1982) provided a good discussion on the need for a comprehensive evaluation of costs and benefits. This paper is, however, not clear on the discounting (although it can be contextually assumed that discounting was indeed intended). Other applications include (in chronological order) (Beck, 1983; Lundin and Frantzich, 2002; Simonson et al., 2006; Butry et al., 2007; Butry, 2009; Poh and Weinert, 2009; Paltrinieri et al., 2012; Johansson et al., 2012; BRE Fire and Security, 2013; Jaldell, 2013; McNamee and Andersson, 2015; Zhang, 2016; De Sanctis and Fontana, 2016; Dexters, 2018; Wassmer and Fesler, 2018; Van Coile et al., 2019a). Lifetime cost optimization (LCO) was considered in (Butry et al., 2012; Van Coile et al., 2014; Ni et al., 2020; Hopkin et al., 2021).

Overall, the PNV studies present widely differing levels of detail and abstraction. Some studies, such as (Paltrinieri et al., 2012) and (De Sanctis and Fontana, 2016), consider only the reduction in expected fatalities as a benefit. On the other hand, Beck (1983) performed a PNV evaluation whereby the risk to life was neglected. This is found to be also the case in (Poh and Weinert, 2009) and (Zhang, 2016). Dexters (2018) also does not take into account risk to life, noting that the life risk is considered very low within the warehouse environment of the considered case study. In these cases, an underestimation of the total benefit of fire safety investment is likely (except where there reasonably are no neglected benefits, as in the exit width optimization by De Sanctis and Fontana (2016). Interestingly, (Butry et al., 2012) and (De Sanctis and Fontana, 2016) take into account the cost of lost floorspace associated with more/larger escape stairs. This highlights that the investment and maintenance cost of fire protection measures should be interpreted broadly. It is thus important to take into account all costs and benefits as part of the CBA. In this regard, it can be recommended to start with a general formulation of costs and benefits, and to carefully determine whether or not some terms can reasonably be neglected. Adopting a reduced formulation at the start (e.g., focusing on life safety or property protection only) should be avoided.

2.3. Cost-Benefit Ratio (CBR) or Benefit-Cost Ratio (BCR)

The *Cost-Benefit Ratio (CBR)* or *Benefit-Cost Ratio (BCR)* is another popular approach for CBA. It provides an intuitive view of the cost-effectiveness of fire safety investments, i.e., the proposals with a CBR ≤ 1 or BCR ≥ 1. There is, however, no clear approach to choosing among cost-effective alternatives. The most intuitive approach is to prefer the alternative with the highest BCR or lowest CBR. This approach is suggested by Ramachandran (1998) for example. Choosing the design alternative with the highest BCR can be understood as choosing the alternative with the highest return on investment, i.e., the highest dollar value saved per dollar invested. Within the realm of safety investments, focusing on the return on investment measure can, however, be misleading. It may result in a very cheap investment with limited risk-reducing effect to be preferred over a much more expensive investment which provides a much larger risk reduction. This is illustrated with a conceptual example in Table 1: note that the annualized risk reduction benefit for option A is limited (this includes life safety and

Table 1
A conceptual example comparing BCR and PNV.

Option	Benefit (risk reduction) [$/year]	Cost (annualized) [$/year]	BCR [-]	PNV (annualized) [$/year]
A	100	10	10	90
B	10,000	5,000	2	5,000

appropriate discounting), while the much more expensive option B results in a much more considerable annualized benefit.

The use of a CBR or BCR can be very useful in case of a binary choice, i.e., when the only question is whether or not to implement a certain safety feature. Then, it provides direct insight into the cost-effectiveness of the proposal. In such situations where there is no comparison between investment alternatives, the BCR/CBR and PNV evaluations result in the same conclusion of cost-effectiveness.

The CBR and BCR have been presented in different forms. Hasofer and Thomas (2008) presented a direct application of the LQI (Life Quality Index) net benefit criterion introduced in (Nathwani et al., 1997). This criterion is a BCR evaluation which incorporates a specific valuation approach for the risk to life. The inverse of the LQI evaluation has been denoted as a “J-value” (Judgement value) evaluation. This is thus a CBR assessment, with fire safety engineering examples presented in (Hopkin et al., 2018; Hopkin et al., 2019; Arnott et al., 2021; Krasuski et al., 2022; Alimzhanova et al., 2022). Other CBR evaluations include (Li and Spearpoint, 2004) and (Runefors et al., 2017). Most of these studies consider the cost-effectiveness of sprinkler installation. As this is (in those case studies) a binary question, the application of a CBR/BCR approach is reasonable and equivalent to a PNV evaluation.

A specific consideration is the tendency within CBR/BCR to consider only the life safety benefit and neglect the efficiency of fire safety investments in reducing property loss. This underestimates the total benefit of the investment and thus biases the evaluation towards not implementing the safety feature. In other words, all costs and benefits (including a reduction in risk to life) must necessarily be taken in a single evaluation in order for an unbiased assessment of the cost-effectiveness. However, when the property loss effect can reasonably be considered small relative to the life safety effect, as stated in (Runefors et al., 2017), the underestimation resulting from neglecting these property losses can reasonably be considered limited.

2.4. *Other approaches*

Studies which could not be classified under the two main approaches above relate to (i) conceptual studies which discuss CBA without providing details, (ii) studies which contain a more qualitative analysis which cannot be considered a true CBA because of violating the state-of-the-art principles listed in 2.1, and (iii) studies which present alternative approaches which so far have found limited resonance in literature (some of these alternatives are compatible with the PNV evaluation).

Examples of conceptual studies are (Meacham, 2004) and (Salter, 2013). Meacham distinguishes between Cost-Benefit Theory (i.e., CBA), Social Choice Theory and Decision Theory (i.e., Utility Theory), and specifies that the optimal level of risk is where the marginal cost of risk reduction equals the marginal reduction achieved in societal cost. This is in agreement with the PNV approach. Also, the CBA concepts in (Salter, 2013) appear compatible with PNV evaluations, but no details are provided.

The studies presented in (Thor and Sedin, 1980; Asaduzzaman, 2018; Neto and Ferreira, 2020; Vaidogas and Šakėnaitė, 2010; Vaidogas and Sakenaite, 2011) are categorized as qualitative. Although these studies do not comply with the state-of-the-art consensus listed above under 2.1, they can provide valuable qualitative input. Neto and Ferreira for example show how different fire protection packages for a historical city center, with large cost differences, influence a fire risk index. Cases (seemingly) without discounting, such as (Thor and Sedin, 1980) and (Asaduzzaman, 2018), however, have to be considered obsolete. The multi-objective work in (Vaidogas and Šakėnaitė, 2010; Vaidogas and Sakenaite, 2011) can include a full PNV (or BCR/CBR), but in the end combines this assessment with other measures in a subjective manner. This makes the final cost-benefit evaluation qualitative (Neto and Ferreira, 2020).

Alternative approaches include *break-even analysis*, and evaluations of *opportunity cost* and *return on investment*. A break-even analysis is especially relevant in situations where there is a large uncertainty (or disagreement) regarding specific input values for the PNV or CBR/BCR evaluation, see also (Sunstein, 2018). Within the break-even analysis, the value of the uncertain variable is determined for which cost-effectiveness is achieved. Paltrinieri et al. for example determine for which combinations of the VSL (Value of a Statistical Life, i.e., a monetary valuation of the risk to human life) and the cost of fire protection, the coating of tankers is cost-effective (Paltrinieri et al., 2012). Also, Butry et al. include break-even analysis in their study of evacuation provisions (Butry et al., 2012). An evaluation of opportunity cost was presented in (Ashe et al., 2012). Here, expenditures in fire safety are equated with “equivalent lives lost”, based on the consideration that public expenditures reduce the money available for private expenditures and thus result in a loss of life expectancy, notably for disadvantaged groups. This is a well-documented phenomenon (Sunstein, 2018). Ashe et al. conclude that the benefit of public expenditures on fire safety is unlikely to compensate for this negative effect. However, they considered only life safety in their evaluation and neglected property protection effects, and therefore the benefit of fire safety investments has likely been underestimated. Return on investment is mentioned in (Johnson et al., 2016). This report is noteworthy for its referencing of medical studies with controlled trials on the effectiveness of fire prevention measures.

2.5. *Summary of the literature review*

The literature review indicates that there are two main approaches for CBA: PNV and CBR/BCR. When the necessary discounting is applied, both approaches are equivalent when evaluating the cost effectiveness of a single fire safety package. The CBR/BCR approach has the advantage of its intuitive nature (the investment is deemed efficient when the risk reduction benefits exceed the costs), but the main disadvantage is that it does not allow for the direct comparison of alternatives. As the PNV approach does not have this disadvantage, the PNV evaluation is preferred. From the alternative CBA approaches found in literature, the break-even analysis provides a valuable additional tool, as it allows to clarify the impact of assumptions in the analysis (e.g., from which level of indirect costs the optimum fire safety package changes). In summary, the PNV approach is put forward as the main approach for CBA in FSSE. Considering the clear description of the approach in early references such as (Ramachandran, 1998) and (Juås and Mattsson, 1994), it is unfortunate that the approach has not found more widespread application and that large differences in assumptions (e.g., discount rates, risk to life) are still observed. For communication purposes, the PNV approach can be supplemented with CBR/BCR and break-even analysis. CBR/BCR ratios should, however, never be compared.

3. Building blocks of the cost-benefit evaluation

3.1. *Perspective of the CBA*

The distinction between societal and private decision-makers is crucial. The societal requirements for safety define a lower bound safety level for further private considerations (Van Coile et al., 2019a; Fischer, 2014). Thus, conceptually a societal cost-benefit evaluation provides a constraint to subsequent private assessments. Furthermore, the valuation of costs at a societal level and at a private level are generally different. For example, in a market economy a loss of revenue experienced by a company following a fire is likely to be balanced by an uptake in revenue for competitors (Ramachandran, 1998). This private loss may thus be largely diminished at a societal level. On the other hand, emission of pollutants in case of fire may be of limited concern to a private decision-maker, while at the same time being a real societal concern. Within a CBA, the costs and benefits should be evaluated from the perspective of the (idealized) decision-maker. This means that the engineer making a societal cost-benefit analysis cannot take into account personal preferences or the preferences of the client, and that the societal valuation of costs and benefits is thus done from the perspective of an “idealized” person who has no personal preference. We acknowledge that it may be practically impossible to eliminate all subjective considerations, but this is what the assessor should strive for when performing a societal cost-benefit analysis. Many studies do not highlight the perspective of the analysis. This is, however, crucial for a correct specification of costs and benefits, as already emphasized by Juås and Mattson (1994) and Ramachandran (1998). The societal discount rate is narrowly defined, whereas a private decision-maker has freedom in determining the opportunity cost of fire safety investments. Generally, private decision-makers can be considered free in their valuation of costs and benefits, and in their choice not to consider cost-effectiveness at all. A clear conclusion from the above is that CBA studies should be explicit and consistent in the perspective of the cost-benefit evaluation.

In Table 2, an overview is presented, classifying studies into the following categories: (i) societal evaluation, (ii) private evaluation, (iii) sequential (i.e., societal and private) evaluation, and (iv) other (i.e., evaluations whereby the consideration of costs appears to mix societal and private considerations, and studies which are general in nature and can apply to both societal or private perspectives). As many studies are not explicit on the perspective used, interpretations have been necessary as part of the classification exercise. We want to apologize to the authors of the respective studies for any possible misinterpretation on our part.

3.2. Valuation of risk to life

Evaluating the cost-effectiveness of fire safety investments implies that a consistent metric should be used for both sides in the comparison. Commonly, this is conveniently taken as money. This can be easily misunderstood as placing a value on life, which is at odds with the common view that human life has infinite value (Keeney, 1990). The real valuation required for the CBA is, however, not that of human life, but of upfront investments in risk reduction (Nathwani et al., 1997). In other words, how much can be spent on risk reducing measures. This is a fundamental distinction. Whereas one cannot “buy” human lives, decisions on buying risk reduction measures are frequently made, e.g., when buying cars. Thus, this valuation of risk to life has no direct application to decision making regarding identifiable persons (e.g., during rescue efforts), or with respect to compensation of victims. There are thus many arguments against transposing such approach to guide decisions with respect to, for example, lockdown measures in an ongoing pandemic (Ale et al., 2023). Misunderstandings regarding these points easily result in undue hesitation with respect to CBA in FSSE.

Different approaches for the valuation of risk to life have been proposed. Often the terminology “Value of a Statical Life” (VSL) is used (Sunstein, 2018), but since this terminology may reinforce the misunderstanding that life itself is valued, the term “Societal Capacity to Commit Resources” (SCCR) is preferred here. Common approaches for the valuation of the SCCR are Willingness To Pay (WTP) studies (Sunstein, 2018). A more objective basis is to derive the VSL from the Life Quality Index proposed in (Nathwani et al., 1997). The Life Quality Index valuation has been incorporated into the ISO2394:2015 standard and has been applied in (a limited number of) fire safety engineering studies, such as (De Sanctis and Fontana, 2016; Van Coile et al., 2019a; Hasofer and Thomas, 2008; Hopkin et al., 2018; Arnott et al., 2021; Krasuski et al., 2022) and (Fischer, 2014).

Table 2
Overview of literature.

Reference	Approach	Perspective	Note / Focus
Offensend and Martin (1982)	PNV	Societal	Key conceptual statements
Beck (1983)	PNV	Private	Life safety and monetary loss (separate)
Juås and Mattson (1994)	PNV	Societal	Very clear early reference
Ramachandran (1998)	All	Other	Key general reference
Lundin and Frantzich (2002)	PNV	Private	Different private perspectives
Simonson et al. (2006)	PNV	Societal	Fire retardants
Li and Spearpoint (2004)	BCR/CBR	Private	Sprinklers in parking building
Butry et al. (2007)	PNV	Other	Mixed perspectives
Hasofer and Thomas (2008)	BCR/CBR	Societal	Residential sprinklers
Butry (2009)	PNV	Other	Mixed perspectives
Poh and Weinert (2009)	PNV	Societal	School building
Butry et al. (2012)	PNV	Private	LCO egress in tall buildings
Paltrinieri et al. (2012)	PNV	Societal	Includes breakeven analysis
Johansson et al. (2012)	PNV	Societal	Arson protection schools
BRE Fire and Security (2013)	PNV	Societal	Residential sprinklers Wales
Jaldell (2013)	PNV	Societal	Sprinklers in elderly homes
Van Coile et al. (2014)	PNV	Societal	LCO concrete slab
McNamee and Andersson (2015)	PNV	Societal	Flame retardants
Zhang (2016)	PNV	Other	Concept paper
De Sanctis and Fontana (2016)	PNV	Societal	Egress width optimization
Runefors et al. (2017)	BCR/CBR	Societal	Differentiation ifo population
Hopkin et al. (2018)	BCR/CBR	Societal	Concept paper
Dexters (2018)	PNV	Private	Warehouse compartmentation
Wassmer and Fesler (2018)	PNV	Societal	Upholstered furniture
Van Coile et al. (2019)	PNV	Sequential	Concept paper
Hopkin et al. (2019)	BCR/CBR	Societal	Residential sprinklers
Ni et al. (2020)	PNV	Societal	LCO concrete column
Arnott et al. (2021)	BCR/CBR	Societal	Residential sprinklers
Hopkin et al. (2021)	PNV	Societal	LCO steel beam
Krasuski et al. (2022)	BCR/CBR	Societal	Detailed egress evaluation
Alimzhanova et al. (2022)	BCR/CBR	Societal	Sprinklers in parking building

The SCCR is intended to inform societal CBA. As always, private decision-makers are free in their valuation of costs and benefits, but societally cost-effective safety measures constitute the minimum fire safety package. This sequential approach is in effect the application of an ALARP concept, see (Van Coile et al., 2019a,b). Values of the SCCR are listed in ISO 2394:2015 (there referred to as “Societal Willingness To Pay”, or SWTP). For the purpose of the discussions here, it is sufficient to accept that the valuation of risk to life is both necessary and ethical, and that it should not be misunderstood as placing a value on a(n) (identifiable) person.

4. Reference methodology

Based on the literature review, the prototype methodology is elaborated step-wise: (i) the concept of discounting cash flows is summarily introduced; (ii) the cost components for the CBA are listed; (iii) these cost components are combined into the PNV evaluation. For completeness also the BCR/CBR formulations are listed. For further elaboration, reference is made to (Van Coile et al., 2023). Insurance effects have not been considered, but can be included in the methodology. For private actors, insurance can have a key influence on decision-making. For societal decision-making, however, insurance should not play a key role as it concerns the transfer of funds within society.

4.1. Discounting and discount rates

As indicated in 2.1, costs and benefits need to be evaluated at a common point in time and using constant value currency. The latter is not an issue when evaluating future costs, as it is sufficient not to take into account future inflation. When basing assessments on historical data, correcting cost data for inflation is however necessary. The discounting itself relates to economic growth and the time preference for money. The time-dependency of the value of money can be considered by compounding or discounting. When compounding, the value of a sum is assessed at a later point in time by considering interest. When discounting, the value of a sum is evaluated at an earlier point in time, following the same mechanism. The higher the discount rate, the lower the present value of future costs or benefits. To evaluate the present value (or present worth) of a fire safety investment, all future sums are discounted to the decision point (e.g., the present) and combined with the investment sum (Watts and Chapman, 2016).

The time-value of money is commonly introduced through annual interests. Mathematically, considering an annual interest rate i, the value P_N after N years of an initial sum P_0 is given by Eq. (1). This equation also allows the evaluation of the current value of a future sum. If a fire safety measure reduces fire losses by a value P_N, N years in the future, the current value P_0 is given by Eq. (2). Fires however do not follow an annualized schedule, and it is therefore more convenient to consider continuous discounting. When applying continuous discounting, the current value P_0 of a sum P_t incurred at time t is given by Eq. (3), with γ the continuous discount rate and t the time. Commonly, t is evaluated in years and thus γ has dimension year^{-1}. To calculate an equivalent continuous discount rate from an annualized discount rate, it is sufficient to state that the time–values for 1 year of discounting or interest are equal, i.e., Eq. (4). An annualized discount rate of 3% thus has a continuous equivalent of 0.0296/year.

$$P_N = P_0(1+i)^N \tag{1}$$

$$P_0 = \frac{P_N}{(1+i)^N} \tag{2}$$

$$P_0 = P_t exp(-\gamma t) \tag{3}$$

$$exp(-\gamma) = (1+i)^{-1} \xrightarrow{yields} \gamma = ln(1+i) \tag{4}$$

In principle, a private decision-maker is free to choose the wanted return on investment, and thus the discount rate applied in fire safety cost evaluations (Van Coile et al., 2019a). For a societal decision-maker, on the other hand, concerns of equity apply. A discount rate which is set very low will result in an increased preference for future life-saving relative to saving lives today, while a very high discount rate results in a focus on current-day life-saving operations and values future life-saving less. The societal (continuous) discount rate can be set equal to the long-term growth rate (Fischer, 2014). A value of 2% to 3% is commonly assumed. Higher discount rates reduce the benefit of fire protection as future losses are valued less. Higher discount rates also reduce the impact of maintenance costs, resulting in a cost-reduction for fire protection measures with lower upfront investment costs and higher maintenance costs (relative to other fire protection measures which rely on a higher upfront investment and lower maintenance costs).

4.2. Cost components

The PNV of the investment cost is labeled C_I. It is typically an upfront investment (recurring costs can be grouped under maintenance). When all costs are evaluated at the time of investment, this term does not need to be discounted. When all costs are evaluated on an annualized basis, the equivalent annualized investment cost c_I is determined from Eq. (5). For an infinite time horizon L, the annualized investment cost c_I simplifies to $C_I\gamma$. Some fire protection measures have a finite lifetime after which they need to be replaced. When the lifetime is large, and the discount rate high, an infinite lifetime can be used as a simplification.

$$C_I = \int_0^L c_I e^{-\gamma t} dt = \frac{c_I}{\gamma}\left(1-e^{-\gamma L}\right) \rightarrow c_I = \frac{C_I \gamma}{\left(1-e^{-\gamma L}\right)} \xrightarrow{L \longrightarrow \infty} c_I = C_I\gamma \tag{5}$$

Many fire protection systems require regular maintenance. The PNV of the maintenance cost is denoted as C_M and is obtained from the annual maintenance cost c_M through Eq. (6). For an infinite time horizon, the PNV of the maintenance cost is given by c_M/γ. Different fire protection systems may have different useful design lives.

$$C_M = \frac{c_M}{\gamma}\left(1-e^{-\gamma L}\right) \xrightarrow{L \longrightarrow \infty} C_M = \frac{c_M}{\gamma} \tag{6}$$

Obsolescence refers to the situation where the building is demolished and rebuilt, or where extensive renovation effectively results in the same situation with respect to the considered fire protection measures. In effect, this means that new fire protection investment costs are incurred at the time of obsolescence. Obsolescence can be modelled through an obsolescence rate ω with dimension year^{-1} (Fischer, 2014). Considering the above, the PNV from future fire protection investment costs resulting from building obsolescence, C_A, is given by Eq. (7). Comparing with the equations' structure above, the annualized obsolescence cost is given by $C_I\omega$.

$$C_A = \int_0^L C_I \omega e^{-\gamma t} dt = \frac{C_I\omega}{\gamma}\left(1-e^{-\gamma L}\right) \xrightarrow{L \longrightarrow \infty} C_A = \frac{C_I\omega}{\gamma} \tag{7}$$

Fire-induced direct losses are defined by Ramachandran (1998) as "*damage caused to a building, its contents and occupants during the course of a fire*". Direct losses are the fire-induced damages which are in a first-order relationship with the fire. These include loss of life in a fire and direct property damage. The direct losses incurred at the time of fire are denoted as D_d. Since fire occurrence is uncertain, the PNV of the direct losses, C_{dd}, takes into account the occurrence frequency of the fire λ_{fi}. The PNV for a finite and infinite time horizon L is then given by Eq. (8). The losses D_d incurred at the time of fire can be highly uncertain and depend on the success of the available fire protection measures. For CBA purposes, an average (i.e., expected) value is sufficient information. Note that the damage uncertainty is important for the tolerability check (Van Coile et al., 2019b).

$$C_{dd} = \int_0^L \lambda_{fi} D_d e^{-\gamma t} dt = \frac{\lambda_{fi} D_d}{\gamma}\left(1-e^{-\gamma L}\right) \xrightarrow{L \longrightarrow \infty} C_{dd} = \frac{\lambda_{fi} D_d}{\gamma} \tag{8}$$

Indirect losses are defined by Ramachandran (1998) as "*costs associated with a fire after it is extinguished*". These losses can be denoted as being in a second-order relationship with the fire event. Examples include the cost associated with the unavailability of critical infrastructure, environmental damage, the losses incurred due to business interruption, as well as cascading effects with suppliers or clients of an affected company. For further discussion on indirect costs, see (Van Coile et al., 2022). The indirect losses incurred at the time of fire are denoted as D_i. Similar to the equations for direct losses, the PNV for the indirect damages, C_{id}, is given by Eq. (9).

$$C_{id} = \int_0^L \lambda_{fi} D_i e^{-\gamma t} dt = \frac{\lambda_{fi} D_i}{\gamma}\left(1-e^{-\gamma L}\right) \xrightarrow{L \longrightarrow \infty} C_{id} = \frac{\lambda_{fi} D_i}{\gamma} \tag{9}$$

4.3. The cost-benefit evaluation: PNV and CBR/BCR

The lifetime utility or PNV of an investment is conceptually represented by Eq. (10), where Z is the total (net) utility, B is the benefit derived from the safety feature's existence, 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.

$$Z = B - C - A - D \tag{10}$$

As hinted at above, fire safety engineering cost-benefit evaluations are generally done with a specific focus on the costs and benefits of the safety measure, and not on those of the larger structure. In such situations, the building project is considered a given, and the benefit of the project (i.e., the usefulness of the building) does not need to be considered. Thus, in fire safety engineering applications, the benefit *B* derived from the safety feature's existence is considered to correspond with the avoidance of the (expected) fire damage in the reference state absent of the additional safety investment. This benefit is independent of the assessed investment scheme. The damage term *D* then relates solely to the (expected) residual damages in the proposed design configuration. The net benefit is *B* – *D*. Considering the cost components introduced above, this net benefit is given by Eq. (11), where the subscript "o" indicates the original configuration and the subscript "p" indicates the proposed configuration with the additional fire safety measures. For brevity, an infinite time horizon is considered. The fire safety expenditures concerning the investigated fire safety scheme relate to the investment *C* (including maintenance), and the obsolescence cost *A*. Considering the sections above, these cost components are given by Eq. (12).

$$B - D = (C_{id} + C_{dd})_o - (C_{id} + C_{dd})_p = \frac{\left(\lambda_{fi}(D_d + D_i)\right)_o}{\gamma} - \frac{\left(\lambda_{fi}(D_d + D_i)\right)_p}{\gamma} \tag{11}$$

$$C + A = C_I + C_M + C_A = C_I + \frac{c_M}{\gamma} + \frac{C_I \omega}{\gamma} \tag{12}$$

Determining the optimum investment corresponds to determining the design with the highest lifetime utility (highest PNV). In case of a discrete set of design alternatives, the design alternative with the maximum PNV is readily determined by evaluating Eq. (10) for each of the alternatives. In case of a continuous decision variable (e.g., insulation thickness for a steel beam), an optimization calculation must be performed (Van Coile et al., 2023). A BCR or CBR can be derived from Eq. (10), i.e., Eq. (13) and Eq. (14). A proposed safety scheme is then considered cost-effective if the CBR ≤ 1, or equivalently, if the BCR ≥ 1.

$$CBR = \frac{C + A}{B - D} = \frac{C_I + C_M + C_A}{(C_{id} + C_{dd})_o - (C_{id} + C_{dd})_p} \tag{13}$$

$$BCR = \frac{B - D}{C + A} = \frac{(C_{id} + C_{dd})_o - (C_{id} + C_{dd})_p}{C_I + C_M + C_A} \tag{14}$$

5. Illustrative application: Sprinkler and/or compartmentation fire protection for warehouse

5.1. Introduction and case description

This illustrative case study applies the prototype methodology for the cost-benefit evaluation of sprinkler protection and compartmentation in a low-rise, medium-size commercial warehouse (6000 m^2). The warehouse stores goods with a total fire load density below 400 MJ/m^2. The case study is developed for a remote location whereby FRS intervention before the fully developed fire phase is unlikely. A societal perspective is adopted (i.e., the goal is to assess whether societal fire protection requirements should apply). Further details are presented in (Van Coile et al., 2022). Calculation files are available through the project website. Further case studies are presented in (Gernay et al., 2023).

5.2. Case input

No clear methodology for the assessment of costs and fire-induced damages exists. This is a major challenge for the widespread application of cost-effectiveness calculations in fire safety engineering. Here, based on the analyses in (Van Coile et al., 2022), construction, demolition and disposal costs, as well as the costs for fire protection systems, are assessed through the RSMeans database (Gordian., 2022), summarized in Table 3. A discount rate of 3% is adopted, based on (Fischer, 2014). Obsolescence is neglected (i.e., an obsolescence rate of 0% is adopted), considering that warehouses can be of use indefinitely. A basic fire detection system is considered to be the standard fire protection in the building. The cost-effectiveness of two additional safety features is evaluated: adding sprinklers, and creating compartments. For the sprinklers, an annual maintenance cost of 5% has been adopted as in (Hopkin et al., 2019), which includes the replacement cost of parts to allow for an indefinite lifetime extension. Compartmentation is assumed to be operationally feasible with no hindrance to the warehouse operations. The compartmentation, made of concrete blocks with gypsum plaster coating on both sides with a 30-minute fire rating, considers the minimum length needed for dividing the warehouse into the listed number of compartments (all compartments are of equal size). For the considered warehouse specification (fire load below 400 MJ/m^2), compartmentation with a 30 min rating can reasonably be expected to contain the fire. Nevertheless, the effect of a compartmentation failure probability will be explored in the following. It is assumed that no maintenance cost applies to the compartmentation. Fire risk parameters obtained from statistics are listed in Table 4, with the associated references. Injuries are valued at 0.047•SCCR (Van Coile et al., 2022). Content is expressed as a multiplier of the building structure loss, i.e., a content loss factor of 1 indicates a content loss equal in value to the building structure loss. The indirect cost is expressed as a multiplier of the direct material loss, i.e., an indirect loss factor of 0.65 means that indirect losses amount to 65% of the sum of the building structure loss and content loss.

5.3. Fire risk evaluation for the design alternatives

Fig. 1 shows the event tree for the considered case. The event tree defines three scenarios: (i) "suppressed by sprinkler", (ii) "not suppressed by sprinklers, suppressed by fire and rescue service", and (iii) "not suppressed". For scenario III, full fatality and injury rates for civilians and firefighters are considered (i.e., as listed in Table 4), and the damage area is assessed as the total compartment area. Note that the compartmentation is "perfect" in the sense that no compartmentation failure probability has been considered. The evaluation thus gives an upper bound for the PNV as the consideration of a (small) failure probability for the compartmentation will result in an increase of the expected fire damages. For scenario II, full fatality and injury rates for civilians and firefighters are again considered but the average damage area is reduced (Table 4). For scenario I, civilian injuries are reduced by 57% (Butry, 2009), while the fatality rate is considered reduced to zero.

Table 3
Case study parameters.

Construction cost (Single story warehouse, 100 m × 60 m × 7 m; incl. detector cost)	1,075 USD/m^2
Demolition + disposal + (re-)construction	1,187 USD/m^2
Cost of sprinkler system installation per m^2	61.7 USD/m^2
Annual maintenance cost for sprinkler system (assumed to include replacement cost for lifetime extension)	5%
Total compartmentation wall length and cost	
- 2 compartments	60 m; 63,000 USD
- 3 compartments	120 m; 126,000 USD
- 4 compartments	160 m; 168,000 USD
- 6 compartments	220 m; 231,000 USD
- 8 compartments	280 m; 294,000 USD

Table 4
Benefit of fire protection (fire risk parameters).

Parameter	Value	Reference
Fire frequency (reported fires) [per year]	0.00156	(Manes and Rush, 2019)
Probability of successful suppression by sprinklers [-]	0.95	(Vassart et al., 2014)
Probability of successful suppression by the fire and rescue service [-]	0.10 (remote)	Assumption
Civilian fatality rate [per 10^3 fires]	1.5	(NFPA, 2022)
Civilian injury rate [per 10^2 fires]	1.3	(NFPA, 2022)
Firefighter fireground fatality rate [per 10^5 fires]	2.8	(Fahy and Petrillo, 2021)
Firefighter response fatality rate [per 10^5 fires]	2.5	(Fahy and Petrillo, 2021)
Firefighter fireground injury rate [per 10^2 fires]	1.62	(Campbell and Evarts, 2021)
Firefighter response injury rate [per 10^2 fires]	0.37	(Campbell and Evarts, 2021)
Average damage area with sprinkler suppression [m^2]	22.6	(Manes and Rush, 2019)
Average damage area without sprinkler suppression, but with successful fire brigade suppression [m^2]	41.3	(Manes and Rush, 2019)
Average damage area in situations without successful fire suppression	Full compartment	Assumption
Content loss factor	1.0	(FEMA, 2015)
Indirect loss factor	0.65	(Ramachandran and Hall, 2002)
SCCR [USD/fatality]	$5.7{\bullet}10^6$	ISO2394:2015

Firefighter fireground fatalities and injuries are effectively reduced to zero, while response fatalities and injuries are not affected. The average damage area is listed in Table 4.

5.4. PNV evaluation

The PNV for the design alternatives is listed in Table 5, together with the BCR. For the considered input parameters, the design with 6 compartments and no sprinkler protection is found to be the optimal solution. Several other solutions are also cost-effective (i.e., result in a net benefit), but the largest net benefit is obtained for the 6 compartments design. The solutions that are not cost-effective are those that add both sprinklers and more than 2 compartments; these result in “over-investment” in safety returning a negative PNV. Note that the PNV of the optimum design (6 compartments) is approximately 200,000 USD higher than the PNV of the design with highest BCR (2 compartments). In other words, opting for the design with the highest BCR results in a significant “loss” relative to the optimum design. While sprinkler protection is found cost-effective, it is not the optimum solution, as other solutions result in a higher PNV.

5.5. Parameter study

Because prompt FRS intervention reduces the consequences of a fire, there is a relationship between the probability of successful FRS intervention and the cost-effectiveness of implementing the fire safety measures (sprinklers, compartments) in the warehouse. This is exemplified by changing the assumption on the probability of successful FRS intervention from 0.10 (Table 4, “remote” location) to 0.95 (reflecting a well-connected location, or FRS on site). In this case, the additional fire protection investments may not be warranted except where indirect costs increase significantly, see Fig. 2. The conclusion that fire protection investments are not cost-effective for medium-sized warehouses which can rely on a high likelihood of successful FRS intervention is in agreement with other studies such as (Dexters, 2018). This can be expected since a different finding would indicate that current safety levels correspond with an underinvestment in fire safety.

The sensitivity analysis on the indirect cost, or value of the content, is important for warehouses as these buildings may be critical for owners when the content stored is needed to operate an economic activity, i.e., in case of components of a supply chain. A supplier losing its stock could lose a client because the client cannot afford to wait for the content to be replaced and identifies a new supplier. The indirect cost factor can thus vary widely. As the cost factors are multiplicative, the parameter study also gives a view of the impact of changing the content value. Fig. 2 shows the PNV for different compartments as a function of the indirect cost factor. Compartmentation becomes cost-efficient as the indirect cost factor increases, and the optimum number of compartments increases with the increase in indirect cost. Dividing the warehouse into 2 compartments becomes economically justified as soon as the indirect cost factor exceeds 240% of the direct cost. Table 6 lists the PNV and BCR for an indirect cost factor of 20 (i.e., 2000%). The economic optimum (highest PNV) then corresponds with 6 compartments. The highest BCR is however obtained for 2 compartments. As highlighted earlier, the BCR should not be used to compare cost-effective design alternatives.

Additional sensitivity studies show that (i) the SCCR valuation has no impact on the conclusion, and (ii) the sprinkler success rate has only a limited impact.

A possible point of concern is that the case study did not consider a

Table 5
Cost-benefit indicators for investigated fire protection options.

Design alternative	PNV [USD]	BCR
Alternative a: sprinkler system only	55,463	1.06
Alternative b: compartmentation only		
- 2 compartments	487,035	8.73
- 3 compartments	607,380	5.82
- 4 compartments	657,052	4.91
- 6 compartments	685,725	3.97
- 8 compartments	668,561	3.27
Alternative c: sprinkler system and compartmentation		
- 2 compartments	19,964	1.02
- 3 compartments	–33,868	0.97
- 4 compartments	−71,285	0.94
- 6 compartments	−129,701	0.89
- 8 compartments	−190,409	0.85

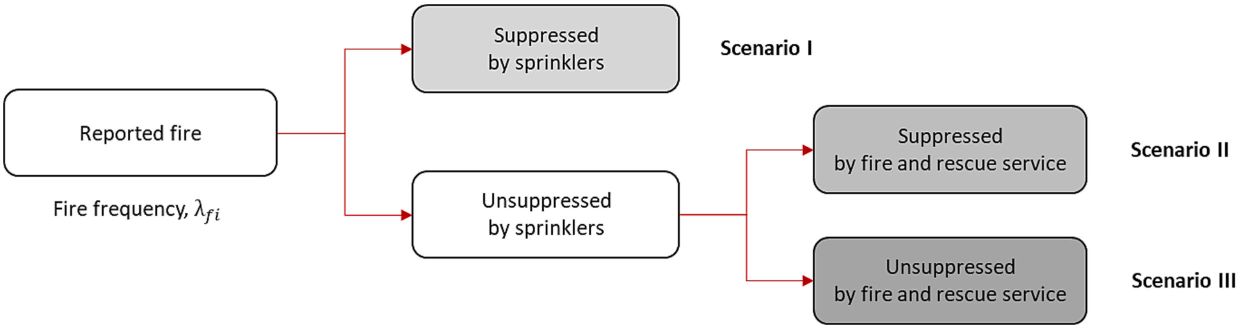

Fig. 1. Event tree defining scenarios.

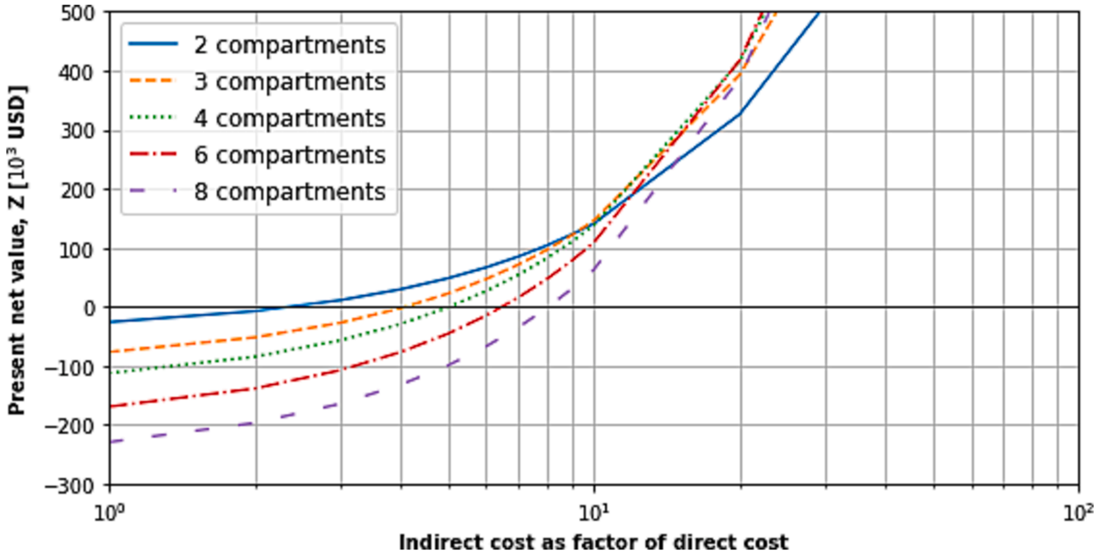

Fig. 2. Parameter study for Case 2 (probability of successful FRS intervention equal to 0.95).

Table 6
Cost-benefit indicators for Case 2, considering an indirect cost factor of 20 (2,000%).

Design alternative	PNV [USD]	BCR	Conclusion
Alternative b:			
compartmentation only	325,914	6.17	Investment cost-effective; optimum for 6 compartments
- 2 compartments	392,551	4.12	
- 3 compartments	415,370	3.47	
- 4 compartments	417,189	2.81	
- 6 compartments	386,599	2.31	
- 8 compartments			

failure probability for the compartmentation. This modelling assumption is based on the consideration that (i) the fire load for the considered warehouse is low; (ii) "failure" of compartmentation takes many forms, ranging from smoke leakage to fire spread to the adjacent compartments, and there is no data readily available to consider this as part of a simplified assessment. Within the wide spectrum of possible failures, many are considered to have only a small impact on the overall compartmentation performance. Advanced analysis to assess the likelihood and effect of compartmentation failure is not included in this illustrative application. For a view on how advanced modelling can be used to inform the methodology, reference is made to (Gernay et al., 2023). However, to fully address this point of concern, in Fig. 3 the result of an evaluation is presented where a compartmentation failure probability has been taken into account (all other parameters as in Table 4). Referring to the model of Fig. 1, when the fire is not suppressed (Scenario III), the damage area is the total compartment area with probability p_{comp} (i.e., the compartmentation reliability), and is the total warehouse floor area with probability (1-p_{comp}). From this visualization, it is clear that the conclusion on the preferred design solution is not sensitive to the compartmentation reliability. For compartmentation reliabilities above 70%, the conclusion remains unchanged. Only for low reliability values does the preferred design solution shift to a lower number of compartments. In this illustrative case study, the cost-effectiveness of the sprinklers only outperforms compartmentation for very high compartmentation failure probabilities (approximately 80%, i.e., $p_{comp} = 0.2$). The real reason why sprinkler systems have a lower cost-effectiveness than the compartmentation is the considered sprinkler

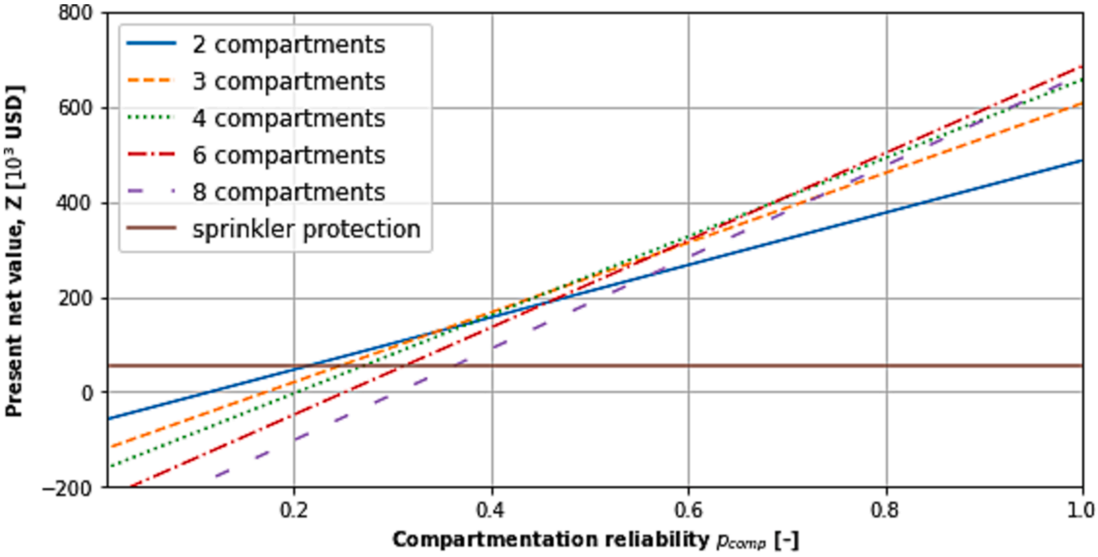

Fig. 3. Effect of compartmentation reliability, p_{comp}.

maintenance cost. The evaluation thus highlights that a better view on sprinkler maintenance costs is most relevant. With this example in mind, it is hoped that the cost-benefit methodology presented here will help objectify discussions on fire safety.

6. Conclusions

Based on a critical analysis of the literature, the recommended methodology for cost-benefit analysis is based on a Present Net Value (PNV) evaluation. The evaluation balances the costs of fire protection features with the anticipated averted losses over the building lifetime. Valuation of the reduction in risk to life is crucial for the full assessment of benefits of upfront investments in fire protection measures. This should not be misunderstood as a valuation of life itself. Users should be clear on the perspective of their analysis (societal vs private). A societal valuation requires the user to try to eliminate any biases in the valuation. Private valuations on the other hand take into account the private valuation of costs and benefits. The prototype methodology is elaborated in detail and applied to the assessment of fire protection measures in a warehouse. The case study demonstrates why the PNV evaluation is to be preferred over Cost-Benefit Ratios (CBR) or Benefit-Cost Ratios (BCR) in situations where multiple fire protection options are compared. To operationalize the cost-benefit methodology, a calculation approach for the assessment of costs and losses is recommended.

CRediT authorship contribution statement

Ruben Van Coile: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Andrea Lucherini:** Writing – review & editing, Visualization, Software, Investigation, Formal analysis. **Ranjit Kumar Chaudhary:** Visualization, Software, Investigation, Formal analysis. **Shuna Ni:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **David Unobe:** Formal analysis, Writing – review & editing. **Thomas Gernay:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: 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”.

Acknowledgements

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.

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