Cost–Benefit Analysis of Fire Protection in Buildings: Application of a Present Net Value Approach

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Abstract. In fire safety engineering, cost–benefit analysis provides a systematic method to assess whether the projected benefits from a fire safety measure outweigh its costs. However, there remains a wide discrepancy between methods used in the field for cost–benefit analysis, as well as a lack of quantitative data on the costs and economic impact of fire protection in buildings. In a recent research project, a reference methodology was proposed based on Present Net Value evaluation and on a combination of specialized construction database, fire statistics, and numerical modeling for estimation of the cost components. This paper presents the application of the methodology to four case studies. The case studies allow describing the methodology, the collection of data, fire statistics, and loss estimation, as well as illustrating how the methodology can support decision-making when multiple alternatives are compared. Under the assumptions adopted for the single-family house and the residential timber building case studies, it is found that for every 1\$ invested in sprinklers, \$1.06 is saved. This benefit–cost ratio increases with increasing valuation of indirect losses and statistical value of life. Sensitivity analyses are provided to explore the robustness of the investment recommendations. The results of evaluations, adapted from the presented case studies with project-specific inputs, can support decision making for policy makers, insurance companies, and individual building owners.

1. Introduction

This paper aims to study the cost-effectiveness of various fire safety investments in buildings using a methodology based on a present net value evaluation of the costs and benefits. In fire safety engineering, decisions must be made to adopt var-

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ious fire protection measures and ensure an adequate safety level. The first consideration is that the residual risk must be tolerable. As pointed out by Van Coile et al. [1], every design entails a residual fire risk but this residual risk must be brought down to a level that is acceptable to the decision-maker. Evaluating whether the residual risk is bearable does not require insight in the costs and benefits of fire protection measures; instead, it relates to the perception of the exposure, i.e., the question whether the decision-maker can accept the likelihood of the risk materializing, notably for low-probability-high-consequence events [1]. Once this condition is met, the question arises whether the risk should be reduced even further. For any design, additional safety investments can be made, such as the addition of an active fire protection system or more insulative material on the structure. However, these investments have a cost, and with increasing safety level (e.g., increase in structural reliability), the marginal benefit diminishes [1, 2]. A method is thus needed to assess the cost-effectiveness of investments in fire protection.

Cost–benefit analysis (CBA) provides a way to objectively weigh the costs of fire protection investments against the benefits incurred from their implementation in the design. A CBA assesses the utility of the investment [2], generally in monetary terms, but it could be performed in any other "currency" (e.g., environmental impact). On the one hand, a monetary cost is assigned to the investment, including maintenance. On the other hand, a monetary value is assigned to the (net) benefit derived from the implementation of the fire safety investment, generally in terms of avoided losses. These costs, after proper discounting, are compared and decision-makers are informed of the design that optimizes the lifetime utility of the building. In this process, the perspective of the decision-maker is important: code-makers and legislators have different objectives than private owners. The former assess whether enhanced fire safety provisions for a class of buildings (e.g., in building codes) result in an increase of societal welfare (starting from an assumed tolerable residual fire risk in society). The latter are concerned with their return on investment should they invest beyond societal (commonly: as implemented in prescriptive codes) requirements. These different perspectives lead to differences in how certain costs (e.g., insurance costs) are considered [3, 4].

The problem of determining the optimum safety investment, and the adoption of CBA approaches to solve this problem, have been extensively discussed in the literature [2], including for fire safety [5–8]. Despite this interest, there is no clearly established methodology for CBA in fire safety engineering. While Ramachandran [9] listed different approaches, it is not clear whether or why an approach should be preferred over another. Observed variations in key assumptions and parameter inputs, such as the perspective of the analysis, the discount rate, the consideration of certain costs rather than others, or the valuation of risk to life, make comparisons between published case studies difficult. Finally, evaluating the costs of fire protection measures and losses from fire events remains challenging due to limited data, uncertainties associated with fire occurrence and severity, and complexity of quantifying indirect consequences of disasters [4].

In this context, a research project was conducted by the authors with the support of the Fire Protection Research Foundation (the Research Affiliate of

NFPA). The research set out to review the state of the art on methods to estimate costs and losses from fires and to evaluate cost–benefit, then from a critical analysis of this state of the art, to provide a reference methodology for CBA of fire protection measures in buildings [4]. This paper describes the application of this CBA methodology to a series of case studies. The case studies include the assessment of the net benefit for: (1) sprinklers in a single-family house; (2) detection system and additional staircase in a multi-story government building; (3) passive fire protection on steel framing members in a multi-story office building; and (4) sprinklers and encapsulation in a multi-story residential mass timber building. The case studies were selected with inputs from the Fire Protection Research Foundation and the members of the project technical panel, to cover a range of building types and fire protection features. For each case study, the cost-effectiveness of the considered fire protection measure is analytically assessed by evaluating, within a present net value (PNV) framework, the cost of installation and maintenance, and the expected beneficial impact on direct and indirect losses in case of fire. The case studies are executed from the perspective of a code-maker and thus adopt a societal perspective on costs and benefits. Prior to the case studies, the CBA methodology (detailed in [4]) is briefly summarized hereafter.

2. Methodology for Cost–Benefit Assessment

The methodology for evaluating the total benefits and costs related to fire protection measures in buildings is based on the calculation of the cost of installation, maintenance, and the expected beneficial impact of building fire protection on losses in case of fire [4]. The methodology relies on the following key components: (1) the concept of discounting cash flows to evaluate costs and benefits at a common point in time and using constant value currency; (2) the incorporation of the relevant cost components, including risk reduction to human life and effect on indirect losses; (3) the combination of these cost components into the PNV evaluation. The flowchart of the methodology is shown in Figure 1.

When comparing different options in terms of fire protection measures, the objective is to determine the design with the highest lifetime utility [10]. The lifetime utility of an investment is conceptually represented by Eq. (1) [11], 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 Eq. (1) simplify into Eqs. (2) and (3). In Eq. (2), C_{dd} and C_{id} are the PNV for the direct and indirect losses, respectively, while the subscript o and p refer to the original configura-
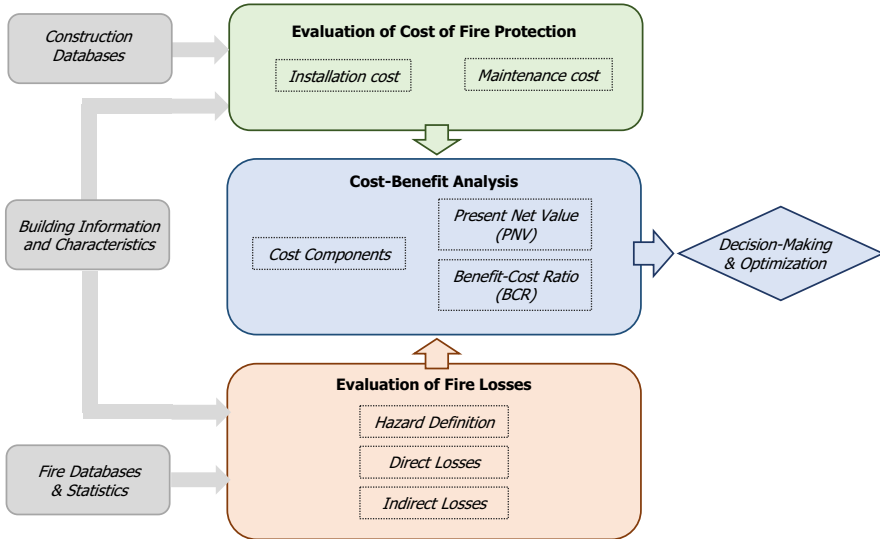
Figure 1. Flowchart of the methodology to assess the cost and benefit of fire protection in buildings.

tion and the proposed configuration with the additional fire safety measures, respectively. In Eq. (3), 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. Discounting is considered in all these terms. In the case studies, a discount rate of 3% is adopted, which is commonly assumed [12]. The reader is referred to [4] for more details:

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

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

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].

Evaluation of costs is performed through summation of the total cost of materials, labor and equipment, required for the installation and maintenance of the considered fire protection systems. These costs are assessed using the RSMeans database [13], considering data representative for the American market. The RSMeans provides several manuals including the facilities construction cost data manual and the residential costs manual which contain the cost of materials, labor and equipment necessary for installing fire protection systems in buildings. Evaluation of losses include direct and indirect losses. Direct losses refer to the "dam-

age caused to a building, its contents and occupants during the course of a fire'' [9], hence they have a material (structural and non-structural elements, plus content) and human component (fatalities and injuries of civilians and fire fighters). Indirect losses are defined as the ''costs associated with a fire after it is extinguished'' [9]. Examples include the cost associated with unavailability or loss of an infrastructure with a critical function or of unique value, the damage to the environment and pollution/waste, the losses incurred due to business interruption, as well as cascading effects with suppliers or clients of an affected company. As different scenarios result in different losses, the losses are weighted according to their likelihood of occurrence.

Estimating losses due to fire is complex. Here, the methodology draws on a combination of statistical data and predictive modeling. When high-quality data are available [14], the benefit from a fire protection system can be estimated by comparing fire loss data in buildings with and without said system (but otherwise similar). However, such data granularity does not always exist. When fire loss data are not sufficiently detailed to differentiate between similar buildings with varying fire protection systems, predictive simulations are used to complement the statistical data. In case studies 3 and 4, probabilistic thermomechanical simulations are used to assess the probability of the structure reaching different damage states for different amount of passive fire protection and, consequently, infer the direct and indirect losses in case of a structurally significant fire.

The case studies adopt a societal perspective on costs and benefits. As a result, cost components which constitute a transfer of money within society (e.g., effect of implementation of the safety measure on insurance premium) can be neglected. These studies start from the existing level of fire protection in society, which allows for the consideration of fire statistics. For the first two case studies (Sects. 3 and 4), the evaluation of losses (and averted losses owing to the fire protection measures) relies solely on statistics. For the other two case studies (Sects. 5 and 6), the evaluation of losses also leverages simulations of the fire performance of the structure. The calculations are completed in JupyterLab [15] (Python) scripts, which are available through the project website.

3. Case Study 1: Sprinklers in a Single-family House

3.1. Case Study Definition and Inputs

The first case study assesses the cost effectiveness of sprinklers in a single-family house. The building is a two-story wood light-frame house with a total floor area of 210 m^2. Fire detection is present as a minimum required safety feature. The net benefit of sprinkler protection is assessed.

The costs evaluated through the RSMeans database [13] are summarized in Table 1. The installation cost multiplier for sprinklers is 0.9% of the construction cost. An annual maintenance cost of 5% is considered for the sprinklers [16]. To evaluate the benefits from the sprinklers, fire risk parameters derived from available statistics are used. These parameters are summarized in Table 2. The risk to life is assessed through the value of a statistical life (VSL) at 5.7 million USD per

Table 1
Cost Parameters for the Single-Family House (Evaluated From [13])

Construction cost (incl. smoke detector cost)	1306 USD/m^2
Demolition + disposal + (re-)construction cost	1350 USD/m^2
Cost of smoke detectors	3.5 USD/m^2
Cost of sprinkler system installation	11.7 USD/m^2
Annual maintenance cost of sprinkler system (incl. replacement cost)	5%

Table 2
Benefit of Fire Protection (i.e., Fire Risk Parameters) for the Single-Family House

Parameter	Value	References
Fire frequency (reported fires)	0.00151 per year	[20]
Probability of fire suppression by sprinklers	0.95	[21]
Civilian fatality rate	7.4 per 1000 reported fires	[22]
Civilian injury rate	3 per 100 reported fires	[22]
Firefighter fireground fatality rate	2.4 per 100,000 reported fires	[23]
Firefighter response fatality rate	2.2 per 100,000 reported fires	[23]
Firefighter fireground injury rate	1.62 per 100 reported fires	[24]
Firefighter response injury rate	0.37 per 100 reported fires	[24]
Damage area without sprinkler suppression	35.7 m^2	[20]
Damage area with sprinkler suppression	4.9 m^2	[20]
Content loss (% of total construction costs)	50%	[25]
Indirect loss (% of direct costs)	50%	Assumption
Life risk reduction with sprinkler suppression	Civilian injuries: ↘57%	[19]
	Firefighter fireground injuries: ↘100%	Assumption
	Fatalities: ↘100%	Assumption

fatality [17]. Note that this value refers to the valuation of risk reduction, and should not be misunderstood as setting a monetary value on identifiable human lives. For injuries, the value of a statistical injury (VSI) is defined analogously, adopting an average moderate injury class ($0.047 \times$ VSL) [18].

The fire frequency relates to reported fires in residential buildings (USA data). Non-reported fires are considered to constitute limited losses (or more precisely: losses which are assumed independent of the sprinkler system). The adopted value in Table 2 is within the same order of magnitude as the values listed, for example, in PD 7974-7:2003 for dwellings and in [19].

As seen in Table 2, sprinklers when effective, reduce the average damage area from 35.7 to 4.9 m^2. These property loss areas are derived from 2014 USA fire statistics [20]. It should be noted that the population of fire incidents with sprinklers is relatively small and these values should be considered with a degree of uncertainty. Sprinklers also influence injuries and fatalities. When the fire is suppressed by sprinklers, civilian injuries are reduced by 57% [19], while the civilian

fatality rate is assumed to drop down to zero [19]. Similarly, firefighter fireground fatalities and injuries are considered reduced to zero. The firefighter response fatalities and injuries are however not affected. It is noted that the use of data from various sources, which is necessary to collect estimates of the different cost components, adds a certain degree of uncertainty as data reporting may not always be consistent between sources.

3.2. Results of the Cost–Benefit Analysis

The PNV calculation for the sprinklers in the single-family house shows that the presence of sprinklers reduces the fire-induced losses by $6912. Fire-induced losses amount to $8258 without sprinklers and $1346 with sprinklers. The amount of $6912 is an estimate of the PNV savings that result from avoided losses in damage areas and civilian and firefighter injuries and fatalities, accounting for the probability that a fire would occur and discounting. Figure 2 shows the breakdown of the cost components in the PNV evaluation. Note that the costs in Figure 2 account for the fire frequency and probabilities of losses. For example, the cost of fatalities without sprinklers is $2120, which accounts for a VSL of $5.7 M, a yearly fire frequency of 0.00151, a civilian fatality rate of 7.4 per thousand fire,
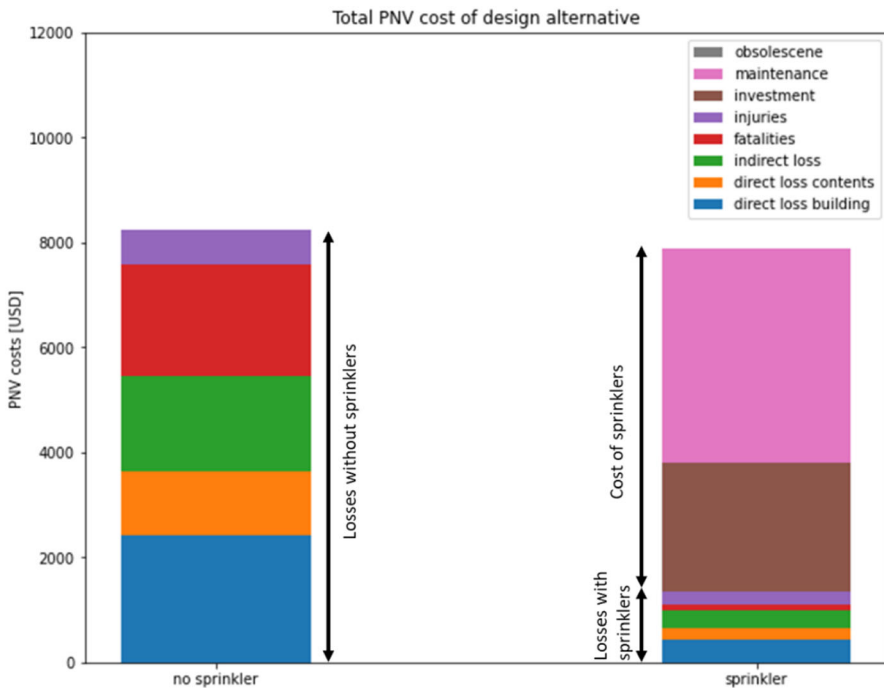

Figure 2. PNV breakdown for a case study of sprinkler installation in a single-family home. In this example, sprinklers are cost-effective because their lifetime cost ($6541) is lower than the averted losses ($8258 − $1346 = $6912).

and a firefighter fatality rate of 4.6 per hundred thousand fire. The benefit is small in terms of economic cost; reductions in direct property damage, indirect losses, and fatalities all contribute approximately equally. The total cost of having the sprinklers, including investment and maintenance over the life of the building, is $6541. The PNV is thus positive ($6912 − $6541 = $371) and the investment in sprinklers is recommended in this example. Since the PNV of the reduction in losses obtained from the sprinklers exceeds the PNV cost of the sprinklers, the sprinklers are cost-effective under the assumptions and parameter values listed in Table 2.

3.3. Sensitivity Study

Figure 3 shows a sensitivity analysis. The assumptions on VSL and on indirect loss markedly influence the PNV. In contrast, small changes in sprinkler reliability do not have a major impact on the cost-effectiveness. Indeed, changing the sprinkler reliability within a 0.92–0.98 range does not markedly affect the conclusions, when compared to the other considered parameters. Sprinklers are recommended when the PNV is positive. As can be seen, the higher the VSL, the more cost-efficient the sprinklers (because of their effect on life safety). On the opposite, when VSL and indirect losses are less valued, investments in fire safety features such as sprinklers cease to be efficient. The proposed methodology allows systematically quantifying these different cost components to support investment decisions based
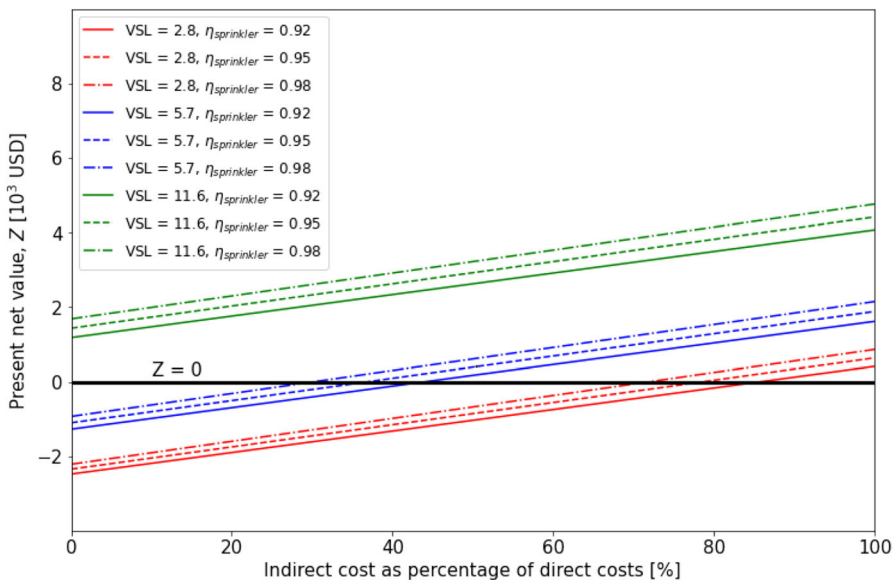

Figure 3. Sensitivity analysis for the sprinkler system in a house. Cost-effectiveness of the sprinklers depends on the Value of Statistical Life and indirect costs. Sprinklers are recommended when the PNV is positive.

on the specific inputs as illustrated herein. The case study is derived for a specific building type and should not be extrapolated to other occupancies. While the conclusion on cost-effectiveness depends on the chosen values for the inputs, this should not be misunderstood as indicating that any outcome can be obtained by appropriately choosing preferred input values. On the contrary, the PNV methodology makes clear in which conditions the fire safety investment is cost-effective, and thus helps stakeholders in objectifying discussions. Research is needed to better understand and quantify the indirect costs for improved evaluations of the cost-effectiveness of sprinkler systems.

4. Case Study 2: Detection System and Additional Staircase in a Multi-story Government Building

4.1. Case Study Definition and Inputs

This case study evaluates the cost-effectiveness of additional fire safety investments for a government office building. The building is a 6000 m² (6 floors of 1000 m²) mid-rise concrete frame office building, inspired by a previously published case study [26]. The baseline design is assumed to be representative of regular practice, including a basic fire detection system and one evacuation staircase. Three alternative designs are considered: (a) an advanced fire detection system; (b) an additional staircase; and (c) both an advanced fire detection system and an additional staircase.

The construction, demolition, and disposal costs evaluated from the RSMeans database [13] are listed in Table 3. The cost parameters for the fire protection systems are also provided in Table 3. The advanced fire detection system includes a fire alarm command center and voice alarm. Replacing the basic detection system with an advanced detection system incurs an excess cost of 15.8 USD/m². The cost of the additional staircase is evaluated based on the loss of usable floor area, at constant building footprint.

Considering the design alternatives, three scenarios may develop following occurrence of a fire. These are illustrated in the event tree of Figure 4. The event tree itself does not make a distinction between cases with/without an additional staircase. The additional staircase however, has an impact on the consequences for the scenarios, resulting in a reduction of the risk to life. Hence, for each of the

Table 3
Cost Parameters for the Government Building (Evaluated From [13])

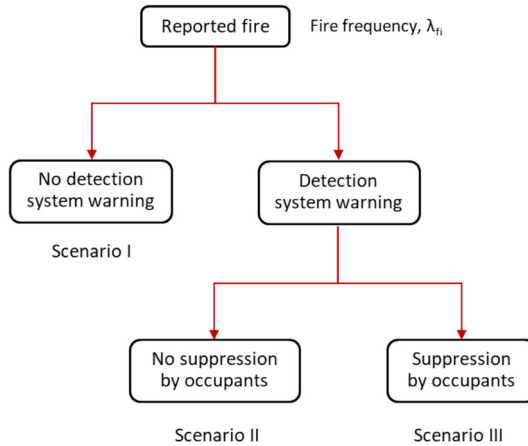|	
Construction cost	3903 USD/m²
Demolition + disposal + (re-)construction cost	4020 USD/m²
Cost of basic fire detectors	4.0 USD/m²
Cost of advanced fire detectors	19.8 USD/m²
Annual maintenance cost of detection system (incl. replacement cost)	5%
Cost of additional staircase: floor area usage	5.4 m²
Cost of additional staircase: annual rental cost	430 USD/m²

Figure 4. Event tree defining possible scenarios for a fire in the government building.

scenarios the consequences are assessed both with and without the additional staircase.

The losses associated with each design are evaluated using the fire risk parameters listed in Table 4. These parameters are derived from statistics and, where data are unavailable, assumptions. The average damage area in the baseline situation relates to non-sprinklered "mercantile and business" fires. Intuitively, this value may appear high, and an investigation into a further subdivision of the damage class is recommended for a detailed assessment. A lower value reduces the benefit of fire protection measures that contribute to property protection, i.e., in this case, the advanced fire detection system. Data for the effect of the additional staircase are lacking and therefore assumptions are made in terms of its effect on life risk reduction. The valuation of the fatality and injury risk is done through the VSL and VSI approach described earlier. Sensitivity analyses are warranted given the uncertainty on the assumptions.

Scenario I with no extra staircase represents the baseline, with no detection system warning. Consequences are estimated based on the statistics of Table 4, i.e., average damage area of 97.3 m^2 and no reduction in civilian and fire rescue service fatalities and injuries. With the additional staircase, evacuation is easier and thus the civilian risk to life is reduced by 30%; the residual risk to life is 0.7 times the baseline value. The additional staircase is considered to have no influence neither on property risk nor on fire and rescue service fatalities and injuries.

Scenario II is the case where the fire is detected through the advanced detection system, but the fire is not suppressed by the occupants. Owing to the earlier detection and consequent earlier onset of evacuation, the civilian risk to life is reduced by 40%. When an additional staircase is implemented on top of the advanced detection system, the risk reduction effects are considered multiplicative (which is reasonably an overestimation of the beneficial effect, thus resulting in a more generous assessment of the cost-efficiency of the implementation of both safety mea-

Table 4
Benefit of Fire Protection (i.e., Fire Risk Parameters) for the Government Building

Parameter	Value	References
Fire frequency (reported fires)	0.002 per year	[20]
Probability of successful detection and alarm	0.9	[27]
Probability of successful fire suppression by occupants	0.5	[28]
Civilian fatality rate	0.9 per 1000 reported fires	[22]
Civilian injury rate	1.4 per 100 reported fires	[22]
Firefighter fireground fatality rate	6.9 per 100,000 reported fires	[23]
Firefighter response fatality rate	6.3 per 100,000 reported fires	[23]
Firefighter fireground injury rate	1.62 per 100 reported fires	[24]
Firefighter response injury rate	0.37 per 100 reported fires	[24]
Average damage area—baseline situation	97.3 m^2	[20]
Average damage area—suppression by occupants	5.0 m^2	Assumption
Content loss (% of total construction costs)	100%	[25]
Indirect loss (% of direct costs)	25%	[29]
Life risk reduction—additional staircase	Civilian: ↘30%	Assumption
Life risk reduction—early detection and warning	Civilian: ↘40%	Assumption
Life risk reduction—occupant suppression	Civilian injuries: ↘50%	Assumption
	Civilian fatalities: ↘100%	

sures together). The material losses and the impacts on fire and rescue service injuries and fatalities are the same as in the baseline situation.

In Scenario III, the fire, detected early through the advanced detection system, is suppressed by the building occupants. The civilian fatality risk is considered effectively zero, while the civilian injury risk is reduced by 50%. The fire and rescue service risk relates only to the response risk. The fireground risk is considered to be effectively zero. The material damages are reduced through the lower average damage area as listed in Table 4.

The PNV is evaluated for each of the three designs. The PNV evaluation relies on the computation of the consequences for each scenario of the event tree, as discussed here above, and their associated probabilities, which are listed in Table 4.

4.2. Results of the Cost–benefit Analysis

The PNV of the three investigated designs for the additional fire safety measures in the government building are given in Table 5. Considering the input values discussed in Sect. 4.1, none of the design alternatives are considered cost-effective (negative PNV). The net benefit of the additional staircase is particularly low, resulting in a BCR of 3.4×10^{-4}. Given this low value, a decision-maker can conclude that the additional staircase is not cost-effective for the case at hand, and that this conclusion would not change with limited changes in inputs, for example resulting from detailed evacuation calculations. In other words, the early-stage investigation already provides a conclusive answer that allows ruling out the addi-

Table 5
Cost–Benefit Indicators for the Government Building

Design alternative	PNV (USD)	BCR	Conclusion
(a) Advanced fire detection system	− 264,500	0.10	Investment not recommended
(b) Additional staircase	− 515,820	< 0.01	Investment not recommended
(c) Advanced fire detection system and additional staircase	− 780,440	0.04	Investment not recommended

tional staircase. A further assessment is however, conducted with respect to the alternative design (a), to investigate sensitivity in some key input parameters.

4.3. Sensitivity Study

A sensitivity study is conducted to explore the limit conditions under which the advanced fire detection system becomes cost effective. Optimum performance assumptions are adopted whereby the detection system is considered 100% effective, resulting in 100% successful fire suppression by the occupants, and a complete reduction of the civilian life risk. The indirect loss is varied between 0 and 20 times the direct cost (i.e., indirect cost ranging from 0% to 2000% of the direct cost). Results are shown in Figure 5, indicating that even under the optimum reliability and loss reduction assumptions, the advanced detection system only becomes cost-effective in case of an indirect cost factor exceeding (approximately) 5.
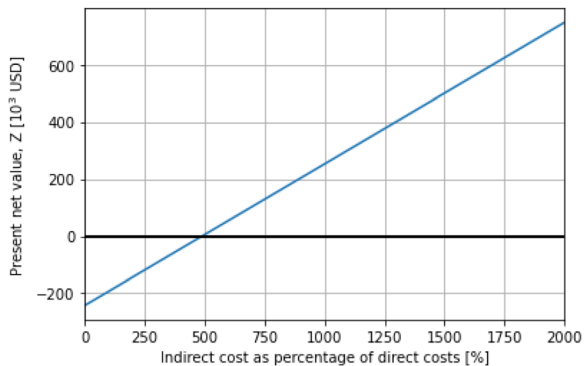

Figure 5.   Sensitivity analysis for the advanced fire detection system in a government building. The investment is recommended when the PNV is positive, which occurs only when indirect costs are expected to be large.

This case study thus suggests that the current baseline fire provisions for the considered government building, with a basic fire alarm and one staircase, are appropriate. The further investments that were studied as part of this case study do not generally appear to be worthwhile in terms of risk reduction, except possibly if indirect losses (e.g., due to business interruption) are highly valued.

5. Case Study 3: Passive Fire Protection on Steel Framing Members in a Multi-story Office Building

5.1. Case Study Definition and Inputs

This case study assesses the net benefit of passive fire protection for a steel moment-frame commercial professional services building. The prototype is a nine-story composite building with a floor plan area of 2090 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 [30]. The steel members of the interior gravity frames of the building (beams and columns) are protected with sprayed fire resistive material (SFRM). The evaluation compares designs with thicknesses of SFRM for 1-h, 2-h, and 3-h of protection from qualified UL assemblies.

The cost–benefit assessment is done considering a combination of statistical data and numerical simulations. The simulations are used to complement fire loss statistics in the evaluation of losses associated with the different designs. This is necessary because fire loss statistics are not sufficiently detailed to differentiate between similar buildings with varying amount of passive fire protection. Therefore, simulations are conducted using the finite element software SAFIR [31] to assess the expected damage level for the structure as a function of the amount of SFRM on the frame members. Losses are then derived from these structural damages.

The costs, evaluated from the RSMeans database [13], are given in Table 6. The cost multipliers for the SFRM are also given for information. No maintenance cost is considered for the SFRM.

The loss evaluation relies on the fire risk parameters listed in Table 7. The valuation of the fatality and injury risk is done through the VSL and VSI approach.

Table 6
Cost Parameters for the Office Building

Construction cost	1674 USD/m^2
Demolition + disposal + (re-)construction cost	1734 USD/m^2
Cost of SFRM—fire resistance rating 1 h	13.7 USD/m^2
Cost of SFRM—fire resistance rating 2 h	23.8 USD/m^2
Cost of SFRM—fire resistance rating 3 h	41.0 USD/m^2
Cost multiplier—fire resistance rating 1 h	0.82%
Cost multiplier—fire resistance rating 2 h	1.42%
Cost multiplier—fire resistance rating 3 h	2.45%

The fire frequency corresponds with reported fires. Non-reported fires are considered to constitute limited losses. No early suppression of reported fires by occupants or fire and rescue service is taken into account. This results in an overestimation of the frequency of structurally significant fires. Thus, from this perspective the case study provides an upper bound for the cost-effectiveness of passive fire protection investments.

The event tree of Figure 6 is considered to evaluate the different scenarios associated with the three thickness of SFRM. For each design, the event tree defines two scenarios: (1) "no structural failure", and (2) "structural failure".

The consequences for each scenario are assessed based on the statistics and assumptions listed in Table 7. Specifically, average fire losses depend heavily on the occurrence of major structural failure of a frame member as such failure would result in a breach of compartmentation and severe structural damage beyond the compartment of fire origin. Herein, it is assumed that, in cases where the structural frame withstands the fire through full burnout, losses remain contained in the compartment of fire origin, while in cases where the structural frame collapses during the fire, the entire building is considered lost. It can also reasonably be expected that structural failure would influence fatalities and injuries. Fortunately, cases of fire-induced structural failures are rare; but as a result data on these cases are lacking. Herein, it is assumed that the building failure results in one fatality and four injuries for firefighters on the fireground, while civilian casualties are not affected assuming they could evacuate. The probability associated

Table 7
Benefit of fire Protection (i.e., Fire Risk Parameters) for the Office Building

Parameter	Value	References
Fire frequency (reported fires)	0.00423 per year	[20]
Civilian fatality rate	0.89 per 1000 reported fires	[22]
Civilian injury rate	1.4 per 100 reported fires	[22]
Firefighter fireground fatality rate	6.9 per 100,000 reported fires	[23]
Firefighter response fatality rate	6.3 per 100,000 reported fires	[23]
Firefighter fireground injury rate	1.62 per 100 reported fires	[24]
Firefighter response injury rate	0.37 per 100 reported fires	[24]
Average damage area – no structural failure	83.5 m²	Assumption (compartment)
Average damage area – structural failure	18,810 m²	Assumption (whole building)
Content loss (% of total construction costs)	100%	[25]
Indirect loss (% of direct costs)	25%	[29]
Effect of structural failure on casualties	1 Firefighter fireground fatality 4 Firefighter fireground injuries No effect on civilians	Assumption

Design 1: 1-hour SFRM
Design 2: 2-hour SFRM
Design 3: 3-hour SFRM

For each design:

| Reported fire | Fire frequency, λ_{fi} |

$(1-P_f)$ P_f (from simulation)

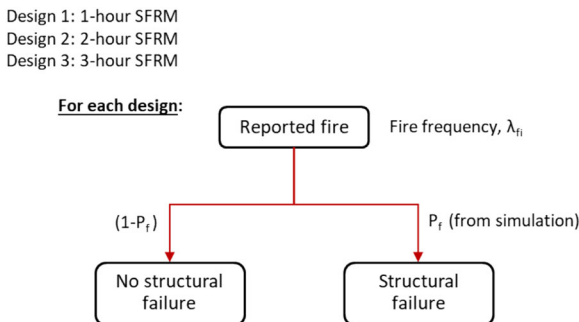No structural failure   Structural failure

Figure 6. Event tree defining the scenarios for the CBA of the SFRM thickness in the office building.

with each branch of the event tree is obtained from the numerical simulations (detailed in the next section). The risk associated with a design then considers the scenario consequences together with their probabilities, within the PNV evaluation.

5.2. Numerical Model for Assessing Fire Losses

The building primary structure is modeled in the finite element software SAFIR [31]. The design and dimensions of the frame members, based on the FEMA/SAC prototype for the post-Northridge design in Boston area, are detailed in a previous study [32] and shown in Figure 7. A 2D frame model is considered for computational efficiency, as probabilistic analyses are run.

The building is classified as Type I B. Therefore, the ICC fire resistance rating requirement for the primary structural frame members is 2-h. The insulation material is selected based on the X829 CAFCO BLAZE-SHIELD II for the columns and N823 UL CAFCO BLAZE SHIELD II for the beams and girders. Thickness for 1-h and 3-h fire resistance rating are also evaluated as the cost–benefit analysis considers the different fire protection designs. The member sections and thickness of fire protection are listed in Table 8.
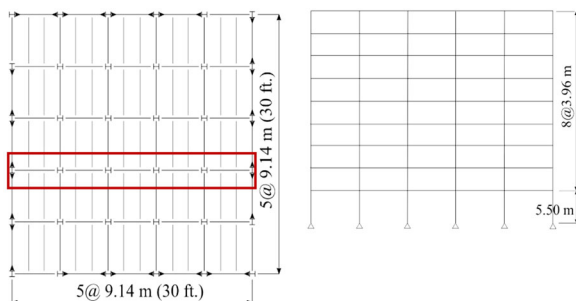
5@ 9.14 m (30 ft.)

5@ 9.14 m (30 ft.)

8@3.96 m

5.50 m

Figure 7. Gravity frame analyzed as part of the multi-story office building.

The distributed dead load on the floors is 4.60 kN/m^2. The typical live load for office occupancy is 2.40 kN/m^2 (50 psf). The reduced live load is 0.96 kN/m^2. These values are unfactored. For ambient temperature design, the ASCE load combination leads to a distributed load of 7.05 kN/m^2 (considering reduced live load). For fire situation, the ASCE load combination leads to a distributed load of 5.99 kN/m^2. However, for a probabilistic cost–benefit evaluation, the expected value of the loading should be considered rather than the code value. The expected value of loading is evaluated based on the literature review by Jovanović et al. [33]. 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/m^2), 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 $(1.0 \times 4.60 + 0.2 \times 2.40) = 5.08$ kN/m^2 multiplied by the tributary width of 9.14 m, i.e., 46.4 kN/m.

To capture the effects of uncertainties, the following parameters are taken as probabilistic [34]: the fuel load, the opening factor in the compartment, the thermal properties of the SFRM, and the elevated temperature yield strength of the steel. For the fuel load, two probability distributions are considered and compared. The first one is adopted from a recent NFPA study [35]. The conducted survey measured a mean of 1116 MJ/m^2 with a standard deviation of 604 MJ/m^2 for movable content in office compartments. The distribution is fitted by a Generalized Extreme Value distribution, with parameters k of -0.01995, σ of 483 MJ/m^2, and μ of 847 MJ/m^2. The second distribution is adopted from the Eurocode EN1991-1-2:2002 for office occupancy [36]. It is a Gumbel distribution with average 420 MJ/m^2 and 80% fractile 511 MJ/m^2. For the opening factor, the distribution is calculated according to: $O = O_{max}(1 - \zeta)$ [37], where O_{max} is the opening

Table 8
Gravity Frames: Member Sections and SFRM Insulation Thickness

Story	Size	1-h insulation thickness (m)	2-h insulation thickness (m)	3-h insulation thickness (m)
Columns				
1	W14 × 145	0.011	0.022	0.033
2	W14 × 145	0.011	0.022	0.033
3	W12 × 120	0.011	0.022	0.033
4	W12 × 120	0.011	0.022	0.033
5	W14 × 90	0.015	0.030	0.044
6	W14 × 90	0.015	0.030	0.044
7	W12 × 65	0.016	0.032	0.048
8	W12 × 65	0.016	0.032	0.048
9	W8 × 48	0.016	0.032	0.048
Beams				
1–8	W16 × 26	0.010	0.021	0.033
9	W14 × 22	0.010	0.021	0.033

factor calculated from Eurocode EN1991-1-2:2002 [36] for the maximum possible value assuming that window glass is immediately broken when fire breaks out. The JCSS formula introduces uncertainty on the fact that windows and doors allow ventilation, with ζ a random variable that follows a truncated lognormal distribution with mean 0.2 and standard deviation 0.2. 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 is based on the probabilistic formulation taken from Elhami Khorasani et al. [38] and is implemented in SAFIR as SFRM_PROBA. For the steel which has a nominal yield strength of 345 MPa, the material model has the same expression of stress–strain relationship as steel of Eurocodes but the reduction of yield strength with temperature follows a logistic EC3-based probabilistic model [38]. The material is implemented as STEC3PROBA.

The structure is first loaded at ambient temperature to determine the ultimate value of the uniformly distributed load on the beams. The ultimate load is 82.8 kN/m. Therefore, the expected loading in the fire situation is 46.4/82.8 = 56% of the ambient temperature capacity.

Then, the structural response is evaluated in case of fire. Only single-compartment fire scenarios are simulated, as these are much more frequent than multi-compartment fires. The structural model focuses on the gravity frame members and analyzes the nine-story structure. For each design (i.e., thickness of fire protection) and each fuel load distribution, 100 simulations are run. The fire curves are evaluated using the Eurocode parametric fire model [36]. The fire curves obtained by running 100 realizations with random fuel loads and opening factors are plotted in Figure 8. The NFPA fuel load distribution yields more severe fires than the Eurocode fuel load distribution, as expected given the much larger values of fuel loads.

Figure 9 plots the evolution of the vertical deflections in the fire-exposed beams for two of the realizations. A clear distinction in response can be observed between the case that fails (1 h fire protection) and the case that survives (2 h fire protection). Failure is deemed to occur when the simulation is unable to find equilibrium under the applied loading and fire exposure, where the fire response is evaluated until full burnout (analyses were run for a simulated duration of 7 h of the fire event). It is verified that the lack of numerical convergence corresponds with a rapid increase in deflections in the frame members, indicative of a loss of stability, as shown in Figure 9. Failure typically initiates in the beams.

The results are summarized in Table 9. The probability of failure is computed by dividing the number of simulations that failed over the 100 simulations realized. As expected, the probability of failure decreases with an increase in thickness of SFRM. The probability of failure is larger with the NFPA study fuel load distribution than with the Eurocode fuel load distribution, reflecting the larger fuel load values reported in the former study [35]. With the Eurocode distribution, the probability of failure for the prescriptive 2-h design is 0.15 in case of uncontrolled
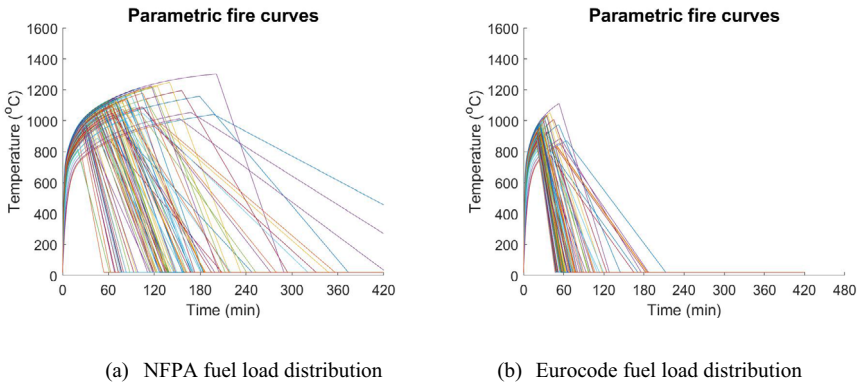
(a) NFPA fuel load distribution

(b) Eurocode fuel load distribution

Figure 8.   Gas temperature–time curves considered in the building simulations, based on two fuel load distributions for office occupancy.
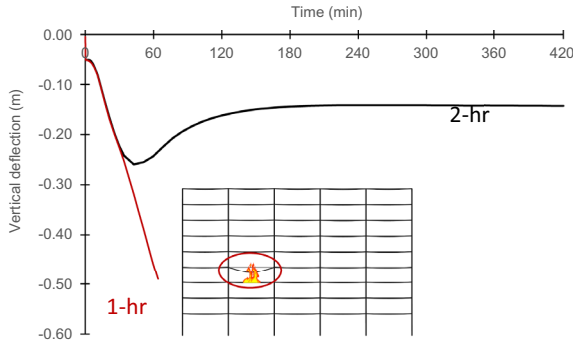

Figure 9.   Evolution of the vertical deflections at mid-span of the beam in the fire compartment, for a case that fails (1-h fire rating of the insulation) and a case that survives the fire (2-h rating).

Table 9
Probability of Failure (P_f) for the Steel Frame Structure Subjected to fire

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

These P_f are obtained by Monte Carlo simulation with 100 runs of a nonlinear finite element model in SAFIR

structurally significant fire. Without any fire protection, the building is considered to fail for all structurally significant fires.

5.3. Results of the Cost–benefit Analysis

The PNV for the different fire resistance ratings are given in Table 10. Using both fuel load distribution models, the PNV for each prescriptive SFRM rating returns a positive value (i.e., benefit of the investment exceeds the cost). As such, under the simulated conditions, these safety measures can be recommended as beneficial from an economic perspective. Both the NFPA fuel load density model and the Eurocode fuel load density model point to the 3-h fire resistance rating as the optimal solution. This is noteworthy in that it correlates with current prescriptive guidance which typically require 2 h or 3 h of fire resistance rating on primary frame members. However, more detailed modeling is recommended to investigate the possibility of load redistribution following failure of one of the primary beams, in a three-dimensional model of the structure, which may change the failure rates and consequences.

Note also that the BCR is highest for 2-h fire resistance rating. However, especially when considering the NFPA fuel load, there is additional net benefit to be obtained by opting for the 3-h fire resistance rating. This is correctly identified by the PNV evaluation, but not by the BCR (as discussed in [4]). In other words, if the choice was made to opt for the design with the highest BCR (2-h rating), and a cost–benefit evaluation was performed afterwards to regarding additional protection (upgrading to 3-h rating), then this second cost–benefit evaluation would indicate a positive BCR for increasing to 3-h rating (all costs being equal and disregarding additional costs due to working in a phased approach). While the PNV directly determines the optimum outcome, a BCR approach will only converge to the same result after iterations, see [39] for a discussion on the path-dependency of a societal net benefit criterion.

5.4. Sensitivity Study

A parameter study shows the effect on the PNV of the assumption on the damaged area in the absence of failure. While the damage area in case of failure is assumed to be the whole building, the damage area can be varied when the building remains stable, as large deformations and smoke could still affect parts of the

Table 10
Cost–Benefit Indicators for the Office Building

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

building outside the fire compartment. In Figure 10, the PNV is shown as a function of the damaged areas expressed as a percentage of the total floor area. As can be seen, this input has a significant effect on the PNV. The beneficial effect of the fire protection is largest when the damage area in the absence of failure is smallest. Indeed, in that case, when the fire protection succeeds in maintaining stability of the structure, repairs costs are limited. In contrast, assuming that even in the absence of failure a large part of the floor area is damaged results in a reduced benefit from the fire protection, because even when the structure maintains stability, repairs costs are still incurred in a large part of the building. Still, the PNV remains positive up to a damage area of about 90% of the total floor area. This shows that the SFRM with high rating is cost efficient in this example, and even with the unavailability of data on the exact damage area due to a fire outbreak, this sensitivity analysis shows that this conclusion holds almost regardless of the assumption for damage area in the absence of failure.

6. Case Study 4: Sprinklers and Encapsulation in a Multistory Residential Mass Timber Building

6.1. Case Study Definition and Inputs

This case studies investigates the cost-effectiveness of sprinklers and passive fire protection for mass timber multi-family dwellings. The building prototype is a ten-story mass-timber building with a floor plan area of 910 m^2 with design based on the NHERI TallWood-Home NSF project [40]. The analysis evaluates the cost–benefit of adding sprinklers, and using either no gypsum encapsulation, encapsulation with one layer of gypsum, or two layers of gypsum on the glulam members of the interior gravity frames.
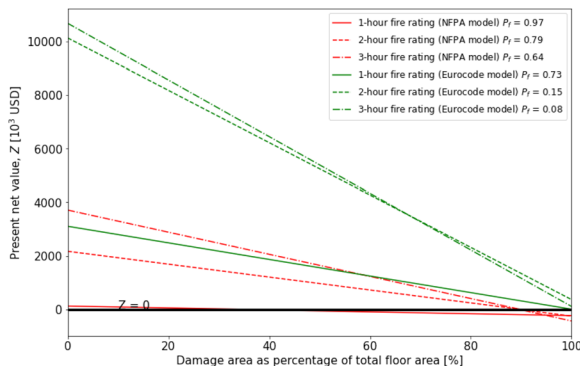

Figure 10. Sensitivity analysis for the passive fire protection on structural steel frames in an office building. The cost-effectiveness of the investment (positive when PNV is positive) is confirmed across a wide range of values for the assumption on fire-induced damage area.

The cost data are given in Table 11. The construction cost estimate is based on square foot cost data for the T3 mass timber building in Minneapolis in the US. The construction cost of T3 was 1512 USD/m^2 (based on a total cost of $30.9 million and a total floor area of 20,439 m^2). This cost is adjusted for inflation from the 2016 completion year value to the 2022 value, using the average annual inflation rate between both years (3.15%) and the time (6 years), leading to a cost of 1798 USD/m^2. The costs of the gypsum passive fire protection and the fire sprinkler system are evaluated using the RSMeans database [13]. Annual maintenance costs have been assumed as 5% for the sprinkler system [16] and zero for the gypsum protection.

The loss evaluation is conducted using the fire risk parameters listed in Table 12. The fire frequency relates to reported fires, under the assumption that all reported fires are structurally significant, with non-reported fires considered to constitute only limited losses. As discussed in the previous case studies, average fire losses are dependent on early fire suppression (by sprinklers) and on structural failure. The valuation of the fatality and injury risk is similarly done through the VSL and VSI approach.

Figure 11 shows the event tree illustrating, for each design, three possible outcomes: (1) fire is suppressed by the sprinklers, (2) fire is not suppressed, but structure withstand the fire with no structural failure, and (3) fire is not suppressed and leads to structural failure. If sprinklers are present, the probability of fire suppression is assumed as 0.95. If no sprinklers are used in the design, or if sprinklers are inefficient (0.05 probability), the structure may either resist the fire or fail; the probability associated with each branch is obtained from numerical simulations, as detailed in Sect. 6.2.

The consequences for each scenario are assessed based on the data in Table 12. For the scenario "suppressed by sprinkler", the average damage area is 4.92 m^2, while compared with the reference statistics civilian injuries are reduced by 57%, civilian fatalities are reduced to zero, firefighter fireground fatalities and injuries are reduced to zero, and firefighter response fatalities and injuries are unaffected. For the scenario with no suppression and no structural failure, the average damage area is taken as the area of the compartment (23.8 m^2), while injuries and casualties are as listed in Table 12. For the scenario with structural failure, conse-

Table 11
Cost Parameters for the Residential Timber Building

Construction cost	1798 USD/m^2
Demolition + disposal + (re-)construction cost	1854 USD/m^2
Cost of sprinkler system installation	48.9 USD/m^2
Annual maintenance cost of sprinkler system (incl. replacement cost)	5%
Cost of gypsum encapsulation—1 layer (per m^2 of building floor area)	52.7 USD/m^2
Cost of gypsum encapsulation—2 layers (per m^2 of building floor area)	90.5 USD/m^2
Cost of gypsum encapsulation—1 layer (total)	47,896 USD
Cost of gypsum encapsulation—2 layers (total)	82,298 USD

Table 12
Benefit of Fire Protection (i.e., Fire Risk Parameters) for the Residential Timber Building

| Parameter	Value	References
Fire frequency (reported fires)	0.00151 per year	[20]
Probability of fire suppression by sprinklers	0.95	[21]
Civilian fatality rate	7.4 per 1000 reported fires	[22]
Civilian injury rate	3 per 100 reported fires	[22]
Firefighter fireground fatality rate	2.4 per 100,000 reported fires	[23]
Firefighter response fatality rate	2.2 per 100,000 reported fires	[23]
Firefighter fireground injury rate	1.62 per 100 reported fires	[24]
Firefighter response injury rate	0.37 per 100 reported fires	[24]
Average damage area—sprinkler suppression	4.9 m^2	[20]
Average damage area—no sprinkler suppression, no structural failure	23.8 m^2	Assumption (compartment)
Average damage area—no sprinkler suppression, structural failure	910 m^2	Assumption (whole building)
Content loss (% of total construction costs)	50%	[25]
Indirect loss (% of direct costs)	50%	Assumption
Effect of structural failure on casualties	1 Firefighter fireground fatality 4 Firefighter fireground injuries No effect on civilians	Assumption
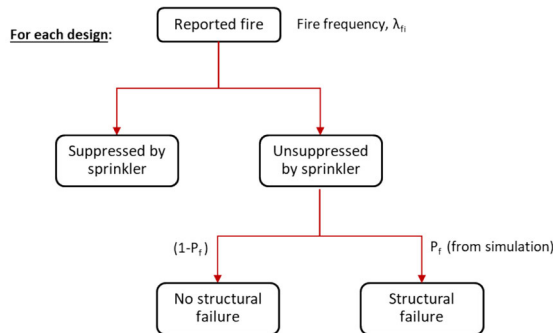
Figure 11. Event tree defining the scenarios for the CBA in the residential timber building.

quences can reasonably be expected to be much more severe, but no detailed statistics are available on fire losses specifically for cases of major structural failure of the primary load-bearing system. Here, it is assumed that the entire building is lost and would need to be reconstructed. Building failure is also assumed to lead to one fatality and four injuries for firefighters on the fireground, similar to case study 3. Civilian casualties are not affected. Other assumptions could easily be incorporated in variations of the case study.

6.2. Numerical Model for Assessing Fire Losses

A finite element model of the building is constructed in SAFIR [31]. The structure is ten-story, with a height of 4 m for the first floor and 3.4 m each for the other floors. Each floor has a total area of 90.95 m^2. The building is a Type IV-B with ICC fire resistance rating requirement for the primary structural frame members of 2-h. In the designs that use encapsulation, the material is type X 5/8″ gypsum boards for all the frame members. The member sections are given in Table 13. The stress class for glulam is 24F-1.8E (V4) [41]. The reference design strengths (allowable strength) were transferred to mean strengths of the materials [42–45]. The mean strengths are used in the numerical analysis, considering volume effect [44].

The distributed dead load on the floors is 5.27 kN/m^2 (110 psf) and the live load is 3.11 kN/m2 (65 psf). These values are unfactored. For ambient temperature design, the ASCE load combination leads to a distributed load of 11.3 kN/m^2. For fire situation, the load combination [33] leads to a uniformly distributed load of 5.89 kN/m^2, which multiplied by the tributary width of 3.5 m yields a load of 20.6 kN/m on the beams.

The fuel load and the opening factor in the compartment are assumed as probabilistic. For the fuel load, the Gumbel distribution with average 780 MJ/m^2 and 80% fractile 948 MJ/m^2 is adopted from Eurocode. No contribution from the timber structure to the fuel load is considered. For the opening factor, the distribution is calculated according to the formula provided by the JCSS as discussed in Sect. 5.2. Only single-compartment fire scenarios are simulated. The fire scenario that is modeled is an uncontrolled fire in a compartment of the second story. 50 fire curves are generated using the Eurocode parametric fire model, as shown in Figure 12, and applied to each of the three designs (i.e., no encapsulation, one layer of gypsum boards, or two layers). The thermal properties of the

Table 13
Section Dimensions for the Gravity Frame Members

Member	Size, mm × mm (in. × in.)
Column (Floors 1–2)	311 × 381 (12.25 × 15.0)
Column (Floors 3–6)	311 × 343 (12.25 × 13.5)
Column (Floors 7–10)	311 × 305 (12.25 × 12.0)
Beam	311 × 343 (12.25 × 13.5)

glulam follow the models in EN 1995-1-2 [46], with a density of 490 kg/m^3 and water content of 12%. The thermal properties of the gypsum boards follow the models in [47], with a density of 800 kg/m^3 and water content of 40 kg/m^3. The heat transfer coefficient is 35 W/(m^{2}K) for fire-exposed sides and 4 W/(m^{2}K) for unexposed sides and the emissivity is 0.8.

Failure is deemed to occur when the simulation is unable to find equilibrium under the applied loading and fire exposure, where the fire response is evaluated until full burnout. Failure typically occurs in a fire-exposed column. The probability of failure is obtained by dividing the number of simulations that failed over the 50 simulations realized. With the unprotected timber frame members, the probability of failure is 24%. This probability of failure decreases to 2% when one layer of 1/2″ type X gypsum boards is used for encapsulation of the timber members. No failure was obtained when two layers were used, i.e., the probability of failure was evaluated at 0% in this case.

6.3. Results of the Cost–benefit Analysis

The PNV for the different designs of the glulam frame structure are given in Table 14. The PNV consider the total investment cost (i.e., including maintenance and obsolescence) and benefits, based on the inputs and assumption of Sect. 6.1. Positive values of the PNV represent situations where the benefit exceed the costs, hence the investment would be recommended based on this cost–benefit analysis. Here, the use of sprinklers, encapsulation with one layer of gypsum, and encapsulation with two layers of gypsum all result in positive PNV, meaning that these fire protection strategies are cost effective under these assumptions. The encapsulation with one layer of gypsum, which reduces the probability of failure from 24% to 2% in case of structurally significant fires, provides the best return on investment. Coupling sprinklers and encapsulation, however, does not appear as cost efficient in this case study.

Table 14 also provides the PNV values computed under the assumption that structural failure does not lead to any additional firefighter casualty compared to
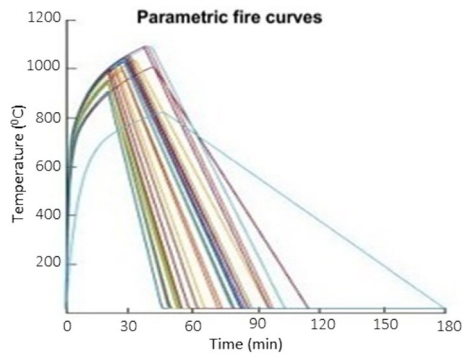

Figure 12. Gas temperature–time curves considered in the residential timber building simulations.

Table 14
Cost–Benefit Indicators for the Residential Timber Building

Design alternative	Additional casualties in case of collapse		No additional casualties in case of collapse	
	PNV (USD)	BCR	PNV (USD)	BCR
Sprinkler system	7185	1.06	− 69,940	0.41
Encapsulation with 1 layer of gypsum board	67,426	2.41	− 6992	0.85
Encapsulation with 2 layers of of gypsum board	43,512	1.53	− 37,672	0.54
Sprinkler system + 1 layer of gypsum board	− 34,944	0.79	− 115,790	0.30
Sprinkler system + 2 layers of gypsum board	-68,818	0.66	− 150,002	0.25

the case with no structural failure. Under that assumption, the occurrence of failure affects material losses only through an increased damage area. This alternative scenario leads to negative PNV for the considered fire protection strategies. In other words, for this multi-story building the benefit of fire safety investment becomes apparent when considering the life safety impact.

Figure 13 shows a breakdown of the costs associated with selected fire protection designs. This breakdown is provided for the baseline case which includes additional firefighter casualties in case of collapse. The total cost for designs with sprinklers and with one layer encapsulation is lower than that with no fire safety protection. This comes from the significant reduction in losses, particularly fatalities, when adopting fire protection measures. These gain in loss reductions outweigh the costs associated with installation and maintenance of the systems, leading to a net positive PNV. Therefore, in this specific case study based on the
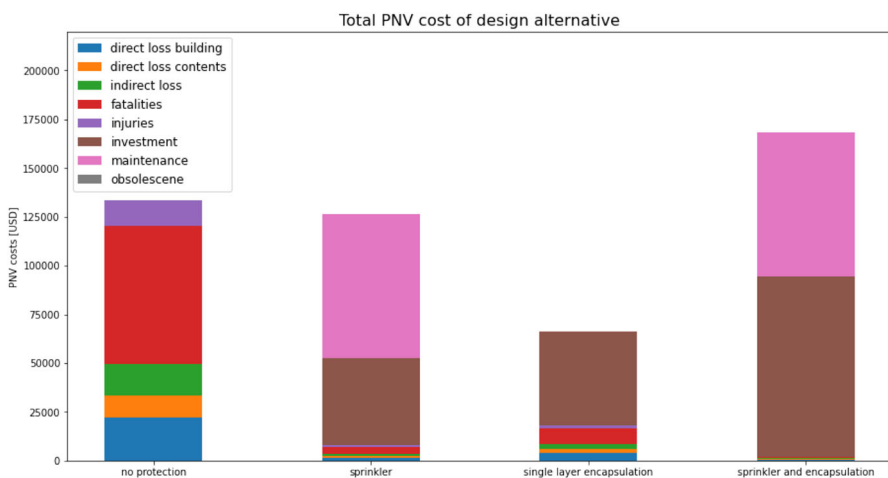

Figure 13. **PNV breakdown for the different fire protection systems in a multi-family residential timber building.**

provided assumptions, either the use of sprinklers or encapsulation can be recommended, with encapsulation providing the highest lifetime utility. It is important to note here that the outcomes of Table 14 are dependent on the assumptions of the specific case study. They should not be extrapolated as holding for a broad class of buildings.

6.4. Sensitivity Study

Figure 14 shows the effect of the indirect cost factor on the PNV. As the indirect costs incurred from a fire increase, the value of the fire protection measures (sprinklers, encapsulation) increases. However, the ranking between these alternatives is unchanged, all other factors being constant. Among the studied alternatives, the configuration with encapsulation using one layer of gypsum remains the design alternative returning the highest PNV. Sprinklers are also cost effective as long as indirect costs exceed about 20% of direct costs, which is expected for a multi-story building. Combining sprinklers and encapsulation does not seem economically justified in this specific case study.

7. Conclusions

The ability to assess the costs and benefits of safety measures is an important component of informed decision-making. Providing a threshold of tolerability is met (which is a must), a decision-maker has the option of favoring an alternative design with a higher or lower investment in safety. A rational method to support this decision is through a cost–benefit analysis (CBA) of each design alternatives. In fire safety engineering, CBA accounts for the investment costs and for the benefits, which derive from the improved performance of the building in case of fire in terms of reduction of injuries, casualties, direct losses, and indirect losses.

A methodology for conducting cost–benefit analysis of fire protection in buildings was presented in this paper and applied to four case studies. The case studies
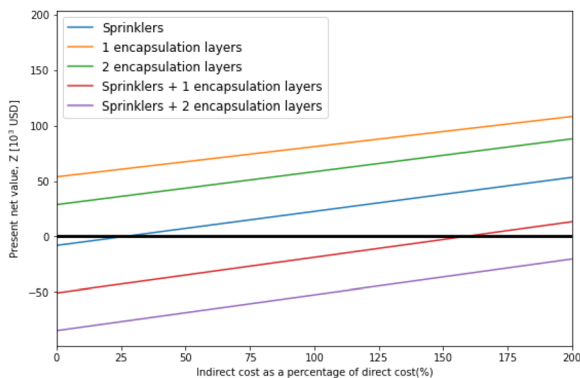

Figure 14. Sensitivity analysis for the residential multi-story timber building.

assess the cost-effectiveness in different buildings of selected fire protection investments beyond current code requirements. These case studies are not meant to assess the intrinsic value of a specific investment or to be extrapolated to an entire class of building; rather they serve to illustrate the methodology on specific examples, with inputs and assumptions particular to a given situation.

In the single-family house, the installation of a sprinkler system is found cost efficient when the Value of a Statistical Life is taken as $11.6 M (value used by the U.S. Department of Transportation), or when the VSL is taken at a lower value in line with ISO 2394:2015 and the indirect costs exceed about 40% of the direct costs. Cost-effectiveness of the safety investment is naturally related to assumptions on fire-induced losses, with the PNV of the investment increasing with an increase in expected losses in the baseline design. These findings suggest that, in countries where VSL is high and indirect losses (e.g., environmental costs, re-housing costs) are highly valued, sprinklers have become or will soon become worthwhile from a societal perspective in a broader range of individual houses.

Case studies on a government building, a nine-story office building, and a ten-story residential timber building, allowed comparing the PNV of multiple alternative designs. These case studies showed that the PNV approach is powerful to identify the design with the highest lifetime utility when many choices are considered, i.e., beyond a yes/no question. Advanced fire detection system, additional staircase, thickness of sprayed fire-resistive material on steel framing, sprinklers, and timber encapsulation with gypsum were design options explored in these case studies. Conclusions on the cost-effectiveness varied between the cases. For example, for the government building, no additional safety investment beyond the baseline code-mandated provisions was found as providing a net benefit. For the office building, the use of a 3-h fire rated thickness of SFRM was found as providing the highest PNV. For the multi-story residential timber building, both sprinklers and encapsulation were found as cost effective separately, while the combination of both measures was not.

Importantly, sensitivity analyses showed within what range of input values the investment recommendations hold. These sensitivity analyses are crucial to evaluate the robustness of the cost–benefit evaluations, especially considering the significant uncertainty on key inputs. In future, it is hoped that data will become ever better and more exhaustive, narrowing the uncertainty on such assessments. For now, though, it is recommended to consider sensitivity analyses as a fundamental component of the provided methodology, and to prefer evaluations that explore a range of input values over a single data point. Often, the conclusion on the preferred design alternative is found to be not sensitive to said uncertain inputs, meaning that the conclusion is clear even though there may be considerable debate on the correct value for some of the inputs. Overall the application of such cost–benefit analyses aims at supporting stakeholders in objectifying discussions both on input parameters and on fire safety investments, for a rational and efficient use of resources in service of a fire safe built environment.

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Declarations

Conflict of Interest The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: under a license agreement between Gesval S.A. and the Johns Hopkins University, Dr. Gernay and the University are entitled to royalty distributions related to the technology SAFIR described in the study discussed in this publication. This arrangement has been reviewed and approved by the Johns Hopkins University in accordance with its conflict of interest policies. Dr. Gernay serves as an associate editor for Fire Technology. Dr. Van Coile serves as an editorial board member for Fire Technology.

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