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Economic Impact of Fire: Cost and Impact of Fire Protection in Buildings

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Foreword

The National Fire Protection Association's (NFPA's) vision includes the elimination of economic loss from fire and related hazards. An important component in realizing that loss is its measurement – what are the various dimensions of the economic impact of fire? How can this be measured so that the cost of fire prevention and other interventions can be weighed against their benefits?

The economic impact of fire needs to be considered in macro scale, the national impact of fire, and in micro scale, the cost of fire protection and its potential return of investment. NFPA has traditionally been the recognized source of information on the national economic impact of fire through our study on the cost of structure fire. This study has however identified several gaps in the data available on cost of fire and hence further research is needed to provide a more comprehensive study.

With a continued focus on bringing the cost of construction down and with fire protection measures being a significant portion of the construction cost of new buildings it is necessary to provide updated models for calculating the fire protection part of building construction expenditure.

To justify the investment in fire protection the question is often asked about the return on investment. Whereas the total cost of fire shows the total loss and expenditure due to fire the impact of fire protection specifically is not identified. To better understand the impact of installing fire protection in buildings the cost of this needs to be considered in relation to the potential property loss in case of fire. However, there is no method that has been applied to calculate this at present. Therefore, the Fire Protection Research Foundation initiated this study to recommend an updated calculation model for the fire protection part of building construction expenditure as used in the Total Cost of Fire study that is more holistic and includes the impact of protection on property loss. In addition, a micro-scale methodology was developed and applied to five case studies.

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About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

Keywords: **economic impact, fire protection, macro level, micro level**

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Economic Impact of Fire

Cost and Impact of Fire Protection in Buildings

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Summary

This report has been prepared for the NFPA Research Foundation. It presents the outcomes of the project entitled "Economic Impact of Fire: Cost and Impact of Fire Protection in Buildings" which was carried out from October 2021 to July 2022 in response to a Request for Proposal from the Foundation. The report has been prepared by Dr Ruben Van Coile, Dr Andrea Lucherini, and Mr Ranjit Chaudary at Ghent University, Dr Shuna Ni and Dr David Unobe at Utah State University, and Dr Thomas Gernay at Johns Hopkins University.

The objective of the work is to establish and apply a methodology for evaluating the total benefits and costs related to fire protection features in buildings. An important component to reducing economic loss from fire is the ability to measure this loss. The work focuses on identifying the various dimensions of the economic impact of fire. It also seeks to measure these dimensions so that the cost of fire prevention and other interventions can be weighed against their benefits.

Specifically, the project addresses four tasks which are summarized in this report: (i) literature review on methods to measure costs and losses from fires, and methods for cost-benefit evaluation from fire protection features in buildings, (ii) critical analysis of the identified methods including the data needs, advantages and limitations, (iii) recommendation of a holistic calculation method for evaluating the total benefits and costs related to fire protection features in buildings, and (iv) presentation of five case studies.

Based on the 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 from the presence of these features. The evaluation of costs includes cost of installation and on-going maintenance. The evaluation of averted losses is based on the expected beneficial impact of building fire protection on property loss, human loss, and indirect loss in case of fire. Estimation of fire losses may rely either on statistics or on a combination of statistics and predictive (structural fire) modeling.

The methodology provides a systematic framework to investigate the issue of cost effectiveness of investments in fire protection features. It can be applied to a class of buildings (e.g., single family residential buildings in a certain area) to support rational policy and decision making. In this case, the costs and fire loss evaluations are averaged for a representative building prototype. Alternatively, the methodology can be applied to a specific building and investment decision. This could be the case, for example, to analyze fire protection investments in a particular manufacturing location where specific occupancy-related hazards and processes require specific evaluation. The costs and fire loss in the methodology are then evaluated for this particular case.

The five case studies cover a range of building types and fire protection features. They are used for demonstration purpose and their outcomes should not be generalized to draw conclusions on effectiveness of particular fire protection measures for broad classes of buildings. Importantly, sensitivity analyses are provided to illustrate the effects of varying input data on the present net value. The sensitivity studies show the importance of input data in evaluating the cost-benefit analysis of fire protection measures. Through these sensitivity analyses, the methodology allows evaluating the robustness of the cost-benefit evaluations. The code, which is made available through the Foundation, allows users to input their own data in order to run calculations for their specific applications. The results of such evaluations can support decision making for policy makers, insurance companies, and individual building owners.

1 Introduction

1.1 Objectives

This project aims to establish and apply a prototype methodology for evaluating the total benefits and costs related to fire protection features in buildings. The methodology is based on calculation of the cost of installation, on-going maintenance, and the expected beneficial impact of building fire protection on property loss in case of fire. The calculation draws on a combination of probabilistic/reliability theory, data analysis, and advanced numerical modeling to predict the fire induced damage and property loss in buildings protected with different features. The methodology is applied to calculate the total benefits and costs for five case studies of fire protection features in buildings.

With respect to the cost of fire protection, a distinction is made between the cost evaluation at macro level (i.e., for a class of buildings), and at micro level (i.e., for a specific building). This is discussed further below.

1.2 Method

Methodologies for calculating the cost of a fire protection system for a building, the property loss evaluation, and the cost-benefit assessment are reviewed. The available methodologies are then analyzed in depth in terms of data needs and data availability, benefits and limitation, and applicability. According to those criteria, prototype methodologies are recommended at micro-level. Within the larger project, the prototype methodologies are applied to five case studies.

1.3 Scope and limitations

When deciding on the net benefit of (fire) safety investments, it is really the utility of the investment which is of interest (Sunstein, 2019). From a societal perspective, the question is whether the investment results in an increase of societal welfare. A similar statement can be made regarding private decisions. The best approach we currently have for the evaluation of utility is through a valuation in monetary terms (Sunstein, 2019). In this report, the maximization of utility is therefore directly equated with a monetary cost-benefit evaluation. For a more in-depth justification of using monetary cost-benefit evaluations for decisions on safety investments, the reader is referred to (Sunstein, 2019).

This report focusses on 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. The methodology is nevertheless applicable to such questions as well. From a technical perspective, the above means that this report considers the perspective of (i) a private decision maker deciding on investments beyond prescriptive requirements, or (ii) a societal decision maker deciding on prescriptive requirements to be put in a code (see discussion in Section 2.2). 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 is not part of the optimization. For a studies on the economic impact of FRS intervention, reference is made to (Evans, 2014) and (Delorme and Waterhouse, 2021). Other decision-maker perspectives are possible (see also Section 7 Identified gaps and areas for future research).

The case studies presented at the end of the report are intended as demonstration cases for the methodology. They are not intended as a comprehensive assessment of the costs and benefits of different fire safety investments. Considering the prior research of the project team, the case studies relate to fire inside buildings. No case studies on external fires, fires within the wildland-urban-interface, or fires in industrial facilities were elaborated. In principle, the methodology is general and also applicable to such cases given adjusted evaluation of costs and benefits.

The case studies are intended to be general and do not take relate to a specific jurisdiction. Considering trade-offs allowed within prescriptive guidance of some codes, private decision makers may find that there are costs and benefits associated with such trade-offs. For example, a private decision maker may put considerable value on being allowed a larger total floorspace when sprinklers are installed. Similarly, some jurisdictions may allow to reduce the fire rating of compartments in case of active suppression systems. Such costs and benefits accrue to the private decision maker but are not elaborated further here because (i) they are jurisdiction specific; and (ii) private decision makers are free in the valuation of costs and benefits (as well as in the choice of the discount rate).

1.4 Concepts and structure of the report

This intermediate report presents the findings of the literature review and analysis, together with the current prototype methodologies. The aim of the report is to solicit feedback from the project panel. This will inform further iterations on the concepts presented in this report, and is invaluable for the elaboration of the case studies in the next phase of the project. The above also implies that this report is intended to be superseded by a final report at a later date.

As part of the project execution, it became clear that the project sub-topics (cost of fire protection, property loss estimation, and cost-benefit analysis) are closely linked. This intermediate report therefore starts with the discussions on the cost-benefit analysis. This sets the scene for the cost of fire protection and the property loss evaluations, and also allows to more fluently introduce valuation concepts (notably, discounting).

Figure 1 provides a reference point for the detailed discussions in the next sections. To reduce/manage the *Economic Impact of Fire*, cost-benefit analysis (CBA) can be a most valuable tool. The CBA is informed by the evaluation of the losses in case of fire (including property loss). The extent of the loss is informed by the fire protection present, and the costs of said fire protection. For a given building, the fire protection cost can be evaluated (see Section 3). This is a micro level evaluation. When the micro level evaluation is done for a building which can be considered representative for its building category (or alternative, if the evaluation is done for a large number of cases within the category), the micro level evaluation of the fire protection costs informs the macro level evaluation. All of the above is informed by the building costs and building characteristics.

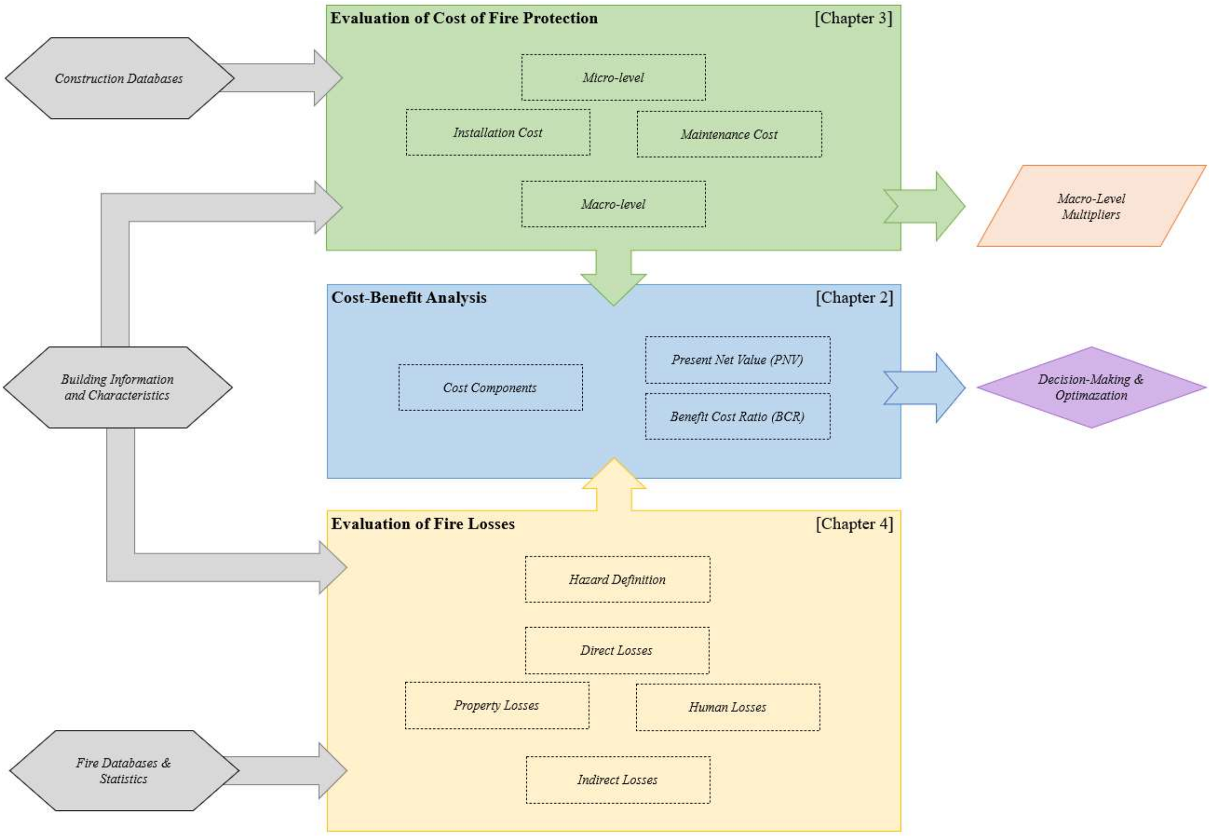


Figure 1 - Components within the assessment of the Economic Impact of Fire.

2 Cost-Benefit Analysis of Fire Protection in Buildings

2.1 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 or not to invest in (additional) safety for a specific project.

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., 2019): (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 in the costs and benefits of fire protection measures. The key question is whether the decision-maker can live with the likelihood 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., 2019). The concept of tolerability allows to explain why one may decide in favor of fire safety investments also where these are not cost-effective. Often, however, tolerability is not determinative for the final design (requirement), but cost-effectiveness is.

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.

It is important to distinguish between societal and private decision-makers. The societal requirements for safety define a lower bound safety level for further private considerations (Fischer, 2014), (Van Coile et al., 2019b). Consequently, 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.

In the following, the results are presented of a literature review of CBA in fire safety science and engineering (FSSE). Subsequently, a prototype methodology is recommended.

2.2 Literature review of CBA in FSSE

2.2.1 Introduction

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 (i.e., references listed within studied sources, and citations of these studied sources). The sources were investigated with a focus on (a) the CBA approach followed, and (b) the perspective (e.g., societal, private) of the analysis. The search for additional sources was halted at approximately 40 sources, observing that the later investigations fit the classification derived from the earlier investigations.

In the following, an overview is given of the identified CBA approaches, as well as the perspective of the evaluation. As one take-away from the literature review, it was concluded that the overview provided in (Ramachandran, 1998) is still very relevant.

2.2.2 CBA approach

2.2.2.1 *General considerations*

There is consensus in the literature regarding the following points. Together these constitute a common framework for the state-of-the-art. Studies which violate these principles cannot be considered to constitute a CBA.

- Costs and benefits should be considered at constant prices, i.e., input data should be corrected for inflation effects where relevant.
- 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.
- The cost of the fire safety measure constitutes 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).
- 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 are considered.

2.2.2.2 *Present Net Value (PNV)*

The 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. Amongst competing projects, the project with the highest PNV should be preferred. As highlighted by Ramachandran (1998), investments in fire safety are really investments 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 FSSE apply PNV evaluations. Early and noteworthy descriptions of the approach can be found in (Juås and Mattson, 1994) and (Ramachandran, 1998). Also the 1982 paper by Offensend and Martin (1982) provides good discussion on the need for a comprehensive evaluation of costs and benefits. This paper is however not clear on the applied discounting (although it can be contextually assumed that discounting was indeed intended). Other applications include (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), (De Sanctis and Fontana, 2016), (Zhang, 2016), (Dexters, 2018), (Wassmer and Fesler, 2018) and (Van Coile et al., 2019b). Lifetime cost optimization (LCO) was considered in (Butry et al., 2012), (Van Coile et al., 2014) and (Ni, 2020). As noted above this minimization of lifetime cost is equivalent to the evaluation of the present net value of the safety investment.

Overall, the PNV studies present widely differing levels of detail and abstraction. Some studies, such as (Paltrinieri et al., 2012) and (De Santis 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 regards, 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. Adopted a reduced formulation at the start (e.g., focusing on life safety or property protection only) should be avoided.

2.2.2.3 *Cost Benefit Ratio (CBR) or Benefit Cost Ratio (BCR)*

The CBR or BCR provides an intuitive view on 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 choose among cost-effective alternatives. The most intuitive approach is to prefer the alternative with the highest BCR (lowest CBR). This approach is for example suggested in (Ramachandran, 1998). Choosing for the design alternative with the highest BCR can be understood as choosing for 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 a 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 considerable risk reduction. This is illustrated conceptually in Table 1. With respect to the conceptual example of Table 1, note that the annualized risk reduction benefit for option A is limited (this includes life safety and appropriate discounting), while the much more expensive option B results in a much more considerable annualized benefit.

Table 1 – 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

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 implement a certain safety feature. The CBR/BCR then provides direct insight in the cost-effectiveness of the proposal. In such situations where there is no comparison between investment options, 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) and (Krasuski et al., 2021). Other CBR evaluations include (Li and Spearpoint, 2006) 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. However, when the property loss effect can reasonably be considered small relative to the life safety effect, as stated by Runefors et al. (2017), the underestimation can reasonably be considered small.

2.2.2.4 *Other*

Studies which could not be classified under 2.2.2.2 or 2.2.2.3 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 2.2.2.1, (iii) and studies which present alternative approaches which so far have found limited resonance in literature (some of these alternative approaches are compatible with the PNV evaluation). Examples are summarily discussed in the following.

(i) *<u>Conceptual studies</u>*

Meacham (2004) distinguishes between CBA (*Cost-Benefit Theory*), *Social Choice Theory* and utility theory (*Decision Theory*). Meacham specifies that *the optimal level of risk is that at which the incremental or marginal cost of risk reduction equals the marginal reduction achieved in societal cost*. This is in agreement with the PNV approach. Also Salter et al. (2013) discuss CBA concepts which appear compatible with PNV evaluations, but no details are provided.

(ii) *<u>Qualitative studies</u>*

Examples of a qualitative CBA are (Thor and Sedin, 1980), (Asaduzzaman, 2018) and (Neto and Ferreira, 2020). Although these studies do not comply with the state-of-the-art listed in 2.2.2.1, they can provide valuable qualitative input. Neto and Ferreira (2020) for example show how different fire protection packages for a historical city center, with large cost differences, influence a fire risk index. Cases which (appear) not to apply discounting, such as (Thor and Sedin, 1980) and (Asaduzzaman, 2018), however, have to be considered obsolete.

The studies by Vaidogas and Sakenaite (2010, 2011) are also categorized here under the qualitative approaches. The multi-objective work by Vaidogas and Sakenaite 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.

The fire and rescue service economic benefit evaluation by Delorme and Waterhouse (2021) compares trends in fire protection investment with trends in, e.g., property value, employment, fire-induced injuries and deaths. The comparison suggests a correlation between the investment and the societal benefits.

For completeness, a study (Taylor et al., 2019) was also found which lists the ratio of money spent to lives lost (i.e., not lives saved). It is unclear how this measure can inform decisions on fire safety.

(iii) *Alternative approaches*

As part of their PNV evaluation, Paltrinieri et al. (2012) also performed a break-even analysis. Such type of 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. (2012) 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. Also Butry et al. (2012) include break-even analysis in their study of evacuation provisions.

An interesting alternative approach was presented by Ashe et al. (2012), providing an evaluation of the opportunity costs of investments in fire safety. 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; for a discussion see (Sunstein, 2018). Ashe et al. conclude that the benefit of public expenditures on fire safety are unlikely to compensate for this negative effect. They however considered only life safety in their evaluation, and neglected property protection effects. The benefit of fire safety investments has therefore likely been underestimated in this publication.

Furthermore, the report by Johnson et al. (2016) refers to PNV, CBR and other measures (return on investment). This report is noteworthy for its referencing of a medical studies with controlled trials on the effectiveness of fire prevention measures.

As a final CBA measure to be listed here, Ramachandran (1998) mentions the 'payback period'. This measure can be evaluated consistently with the PNV, but non-consistent approaches exist. Ramachandran in this regards notes that "*the PP method can be of use but only as a supplementary analysis (not on its own)*".

2.2.3 CBA perspective

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). Within a CBA, the costs and benefits should be evaluated from the perspective of the (idealized) decision-maker. The emission of pollutants in case of fire may, for example, may be of limited concern to a private decision-maker, while at the same time being a real societal concern. The societal discount rate is narrowly defined, whereas a private decision-maker has freedom in determining the opportunity cost of fire safety investments. In the following, 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 perspective). There are also conceptual studies which remain general in their discussions and do not provide detail on the perspective of the evaluation; these studies are not included in the list below. As many studies are not explicit on the perspective used, interpretations have been necessary as part of the classification exercise. These interpretations have been thus to classify the studies within the first three categories where possible.

A clear conclusion from the above is that CBA studies should be explicit and consistent in the perspective of the cost-benefit evaluation. Each of the first three approaches listed below is considered correct when applied in the appropriate situation. Problems only arise when the perspective of the valuation is mixed (i.e., when societal and private elements are used concurrently, without clear justification).

(i) *Societal evaluation*

The early study by Thor and Sedin (1980) specifies a societal goal whereby fire protection and fire damage costs are to be minimized on a national level. Also Juås and Mattson (1994) are concerned with societal CBA. The literature review indicates that societal CBA has been the focus of most studies, e.g., (Offensend and Martin, 1982), (Simonson et al., 2006), (Ashe et al., 2012), (Paltrinieri et al., 2012), (Jaldell, 2013), (Johnson et al., 2016), (De Sanctis and Fotana, 2016), (Runefors et al., 2017), (Hopkin et al., 2018), (Taylor et al., 2019), (Hopkin et al., 2019), (Krasuski et al., 2021), (Arnott et al., 2021), and (Hopkin et al., 2021) all adopt a societal perspective. In effect, this means that the CBA should be understood as input for setting requirements in regulatory documents, or as an evaluation of the ALARP requirement (Van Coile et al., 2019b). In some cases, there is no private decision maker possible, e.g., in cases where the state is also the building owner, or where the investment relates to fire and rescue service funding.

The 2013 BRE study on sprinkler protection in residential homes in Wales is explicitly targeted at Regulatory Impact Assessment (BRE Fire and Security, 2013). Also McNamee and Andersson (2015) and (Wassmer and Fesler, 2018) refer to the relevance of the societal CBA for regulatory decisions.

A societal valuation is assumed to apply to (Hasofor and Thomas, 2008), (Poh and Weinert, 2009) and (Johansson et al., 2012) considering the topic of the respective case studies and the context of the papers. Also the qualitative study on fire risk indexing by (Neto and Ferreira, 2020) has a societal perspective, considering its stated goal of informing the authorities on the effectiveness of mitigation strategies.

(ii) *Private evaluation*

The analysis by Beck (1983) optimizes for property protection will constraining the results to reach a life safety risk level no worse than the life safety risk level implicit in building regulations. As such, Beck's analysis is a private optimization. Similarly, Butry et al. (2012) minimize the lifecycle cost of evacuation measures without consideration of the effect on risk to life. The design alternatives compared are all compliant with the International Building Code and as such are deemed-to-satisfy with respect to life safety.

Also the investigation of sprinkler installation in parking buildings by Li and Spearpoint (2006) adopts the perspective of the building's owner.

In the study by Lundin and Frantzich (2002) different private perspectives (building owner and building contractor) are compared. This provides an additional take on the relevance of clearly specifying the perspective of the evaluation.

(iii) *Sequential (societal and private) evaluation*

The societal safety requirement is considered as a lower bound for private considerations (Fischer, 2014) and (Van Coile et al., 2019). Such sequential analysis has been applied to a number of conceptual case studies in (Van Coile et al., 2019b).

(iv) <u>*Other*</u>

The studies (Butry et al., 2007) and (Butry, 2009) refer to a home-owner's perspective, but apply societal valuations for the risk to life. While home-owners can evaluate risk to life in accordance with societal considerations (i.e., the societal capacity to commit resources to avoid a statistical fatality), the very personal nature of fire safety in one's own house makes such an assumption precarious.

Because of the use of general cost parameters, the cost optimization studies by Van Coile et al. (2014) and Ni et al. (2020) could be considered to apply to both societal and private decision makers. Also Dexters' evaluation of compartmentation cost-effectiveness, and the general CBA description in (Zhang, 2016), can be considered to apply to both societal and private decision makers.

2.3 Prototype methodology for CBA

2.3.1 Introduction

The literature review indicates that there are two main approaches for CBA: PNV and CBR/BCR. When the necessary discounting is applied (see 2.2.2.1), both approaches are compatible. 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 (Juås and Mattson, 1994) and (Ramachandran, 1998), it is unfortunate that the approach has not found more widespread application and that large differences in assumptions (e.g., discount rates, consideration of risk to life) are observed. For communication purposes, the PNV approach can be supplemented with CBR/BCR and break-even analysis. CBR/BCR ratios should however not be compared.

In the following, the prototype methodology is elaborated step-wise based on (Van Coile et al., 2022): (i) first the concept of discounting cash flows is summarily introduced; (ii) secondly 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; (iv) finally, a short discussion is presented on the topic of valuation of risk to life, as misunderstandings with respect to its interpretation easily result in undue hesitation with respect to CBA in FSSE. For further elaboration, reference is made to (Van Coile et al., 2022). 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.

2.3.2 Discounting and discount rates

As highlighted in 2.2.2.1, the state-of-the-art is clear on the need to evaluate costs and benefits at a common point in time, and using constant value currency. The latter point is generally 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 basic mechanism. 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. For more elaborate discussions on discounting, see (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 equals:

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

Eq. (1) 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:

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

Fires however don't 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}.

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

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).

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

An annualized discount rate of 3% thus has a continuous equivalent of 0.0296/year.

The higher the discount rate, the lower the present value of future costs or benefits. The discount rate can have a major effect on cost-effectiveness considerations for fire safety investments.

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, 2019b). 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. Taking into account Fischer (2014) and ISO 2394:2015, the societal discount rate can be set equal to the long-term growth rate per capita. A continuous discount rate of 2-3% is commonly assumed. Fischer (2014) adopted a 3% continuous discount rate.

In this report, a constant continuous discount rate is adopted. More complex formulations with time-dependent (i.e., non-constant) discount rates can be obtained when considering the discount rate γ to be time-dependent in the integrations listed below in 2.3.3.

2.3.3 Cost components

Investment cost

The PNV investment cost C_I 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 Eq. (6). 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.

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

$$c_I = C_I \gamma \tag{6}$$

Maintenance cost

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. (7). For an infinite time horizon, the PNV of the maintenance cost is given by (8). Different fire protection systems may have different useful design lives. This is covered in Section 3.

$$C_M = \frac{c_M}{\gamma}(1 - e^{-\gamma L}) \tag{7}$$

$$C_M = \frac{c_M}{\gamma} \tag{8}$$

Obsolescence cost

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 1/year (Fischer, 2014). Considering the above, the PNV from future fire protection investment costs resulting from building obsolescence, C_A, is given by Eq. (9). For an infinite time horizon this cost simplifies to (10). Comparing the structure of these equations with the equations above, the annualized obsolescence cost is given by $C_I\omega$.

$$C_A = \int_0^L C_I \omega e^{-\gamma t} dt = \frac{C_I \omega}{\gamma}(1 - e^{-\gamma L}) \tag{9}$$

$$C_A = \frac{C_I \omega}{\gamma} \tag{10}$$

Fire-induced direct losses

Ramachandran (1998) defines direct losses 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 are then given by:

$$C_{dd} = \int_0^L \lambda_{fi} D_d e^{-\gamma t} dt = \frac{\lambda_{fi} D_d}{\gamma}(1 - e^{-\gamma L}) \tag{11}$$

$$C_{dd} = \frac{\lambda_{fi} D_d}{\gamma} \tag{12}$$

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.

Fire-induced indirect losses

Ramachandran (1998) defines indirect losses 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 unavailability of critical infrastructure, the losses incurred due to business interruption, as well as cascading effects with suppliers or clients of an affected company. This cost component is discussed further in 4.2.5 as part of the literature review on loss estimation.

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 Eqs. (13) and (14) for a finite and infinite time horizon respectively.

$$C_{id} = \int_0^L \lambda_{fi} D_i e^{-\gamma t} dt = \frac{\lambda_{fi} D_i}{\gamma}(1 - e^{-\gamma L}) \tag{13}$$

$$C_{id} = \frac{\lambda_{fi} D_i}{\gamma} \tag{14}$$

2.3.4 PNV and BCR

In fire 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. The CBA relates to the usefulness of the fire safety investment. Thus, in fire 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) damages in the proposed design configuration. The net benefit is $B – D$.

Considering the cost components introduced above, the benefit and damage terms are given by Eqs. (15) and (16), where the subscript 'o' indicates the original configuration and the subscript 'p' indicates the proposed configuration with the additional fire safety measures. For brevity, the latter equalities relate to an infinite time horizon. The approach for a finite time horizon is the same, taking into account the Eq. (5) above.

$$B = (C_{id} + C_{dd})_o = \frac{\left(\lambda_{fi}(D_d + D_i)\right)_o}{\gamma} \tag{15}$$

$$D = (C_{id} + C_{dd})_p = \frac{\left(\lambda_{fi}(D_d + D_i)\right)_p}{\gamma} \tag{16}$$

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:

$$C = C_I + C_M = C_I + \frac{c_M}{\gamma} \tag{17}$$

$$A = C_A = \frac{C_I \omega}{\gamma} \tag{18}$$

PNV

The lifetime utility of an investment is conceptually represented by Equation (19), 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.

$$Z = B - C - A - D \tag{19}$$

Determining the optimum investment corresponds to determining the design with the highest lifetime utility. In case of a discrete set of design alternatives, the design alternative with the maximum lifetime utility is readily determined by evaluating Eq. (19) for each of the alternatives. This is less straightforward in case of a continuous decision variable (e.g., insulation thickness for a steel beam). In situations with a continuous decision variable, the optimum can be determined by evaluating the value of the decision variable for which the marginal change in utility is zero. This is equivalent to stating that the derivative of (19) should be zero; a standard approach for determining the extrema of a continuous function). Introducing *p* as the single continuous optimization parameter, the optimum is thus defined by Eq. (20). Here, the total lifetime cost of a design *Y*, is introduced for brevity in notation. Note that the design with the maximum present net value thus corresponds with the design having the lowest total lifetime cost. Hence, in practical terms the lifetime utility evaluation of fire safety investments is equivalent to a lifetime cost optimization (LCO).

As the benefit term is independent of *p*, it does not influence Eq. (20). The reference safety level incorporated in the benefit term is nevertheless important, since only designs with a positive lifetime expected utility *Z*(*p*) are feasible (i.e., only investments that constitute net benefits can reasonably be required or implemented). It is thus necessary to also evaluate the net lifetime utility through (19) once the optimum value of *p*, i.e., p_{opt}, has been determined.

$$\frac{dZ(p)}{dp} = -\frac{d}{dp}[C(p) + A(p) + D(p)] = -\frac{dY(p)}{dp} = 0 \tag{20}$$

BCR/CBR

A BCR or CBR can be derived from (19), i.e., (21) and (22). A proposed safety scheme is then considered cost-effective if the CBR ≤ 1, or equivalently, if the BCR ≥ 1.

$$CBR = \frac{C + A}{B - D} = \frac{C_I + C_M + C_A}{(C_{id} + C_{dd})_o - (C_{id} + C_{dd})_p} \tag{21}$$

$$BCR = \frac{B - D}{C + A} = \frac{(C_{id} + C_{dd})_o - (C_{id} + C_{dd})_p}{C_I + C_M + C_A} \tag{22}$$

2.3.5 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 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.

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, sometimes the term 'Societal Capacity to Commit Resources' (SCCR) is preferred. In the following, the terminology VSL is used for compatibility with previous NFPA reports, notably (NFPA, 2017). Common approaches for the valuation of the VSL are Willingness To Pay (WTP) studies (Sunstein, 2018). A more objective basis is to derive the VSL from the Life Quality Index proposed by 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 (Hasofer and Thomas, 2008), (Fischer, 2014), (De Sanctis and Fontana, 2016), (Hopkin et al., 2018, 2019), (Van Coile et al., 2019b), (Arnott et al., 2021), (Krasuski et al., 2021).

The VSL 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., 2019, 2019b). Values of the VSL are listed in ISO 2394:2015 (there referred to as 'Societal Willingness To Pay', or SWTP). For the purpose of this report, 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.

2.3.6 Perspective and goal of the CBA

The literature review highlights the importance of clearly distinguishing between societal and private perspectives (see 2.2.3). Related to this, it is crucial to be clear on the goal of the assessment. If the goal is a project-specific evaluation, then the costs and benefits can be determined taking into account the specifics of the building. If the goal is to determine fire protection strategies which are on average (clearly) cost-effective for a class of buildings, then building specific data is not relevant. When the costs and benefits within the category are largely comparable, such averaged evaluations will provide a very efficient approach to specifying fire protection (specifically, these solutions are then recommend for implementation in standards and guidance documents). When there is a large variation of costs and benefits within the category, however, the specification of broad brush guidance will result in clear over- and underinvestment depending on the case. Possibly, a finer granularity in building category can address such issues (see also 7.7).

3 Evaluation of Cost of Fire Protection

3.1 Introduction

The cost of fire protection in buildings is commonly estimated at two levels; the macro level and the micro level. The macro level describes the costs at a national or sub-national level, involving all buildings at the defined level and their fire protection costs, while the micro level entails the computation of the cost of fire protection systems in individual buildings. The cost of fire protection at the macro level is usually computed from data on the total construction cost of buildings through multipliers developed to represent the fraction of the overall building costs that can be attributed to fire protection systems. These multipliers are computed to represent broad categories of buildings classified based on building occupancies. As it is near impossible to compute the fire protection costs for each building within the area defined for the macro level, these multipliers are used alongside construction data to estimate an overall cost of fire protection installed in buildings.

Studies on the *Total Cost of Fire in the United States* (Hall, 1993, 2014; NFPA, 2017) have relied on multipliers to estimate the national expenditure on fire protection systems in building construction. These multipliers developed in earlier studies (Apostolow et al., 1978; Meade, 1991) for estimating the cost of fire protection at the macro level, have been in use for a long time and are due for updating considering the changes in technologies, costs, as well as code requirements for buildings' fire protection measures. In addition, the multipliers were developed for only a few building categories, making it necessary to group dissimilar buildings into the same category in order to compute their macro level cost of fire protection. However, these buildings have different fire safety requirements, and thus disparate costs of fire protection. This makes it necessary to update the building categories and corresponding multipliers to ensure that these multipliers are up to date and reasonably represent the cost of fire protection systems in each category. This chapter thus aims to present an updated methodology for computing the macro level cost of fire protection.

As part of the CBA evaluation described in Section 2 above, it is necessary to compute the cost of fire protection at the micro level, i.e., the cost of fire protection systems in individual buildings. The cost of fire protection at this level involves identifying the fire protection schemes used in the buildings and then computing the cost of installing and maintaining these systems. As elaborated further, the micro level cost evaluation is a key input for updating the macro level multipliers. The micro level cost of fire protection takes into account the cost of labor and products. This cost is considered independent of the perspective of the stakeholder. Individual stakeholders may consider additional subjective micro level costs (or cost reductions) as part of their cost-benefit evaluation. These subjective costs may for example relate to the aesthetics of a solution. As the consideration of such costs depends on the private decision-maker, they are not further considered here.

In the following section, a literature review for the cost of fire protection is presented, focusing first on the micro level evaluation and then on the macro level evaluation. Taking into account this literature review, prototype methodologies are then presented for both.

3.2 Literature Review

In this section, methods for calculating the cost of fire protection at both micro and macro levels are investigated, and their advantages and shortcomings identified and discussed. Data sources for computing the cost of fire protection at the different levels are also identified, including data sources for calculating the installation and maintenance cost of the fire protection systems, for calculating the construction cost of individual buildings, and data on national expenditure on building constructions. Necessary data which are currently unavailable are also identified.

3.2.1 Micro Level

Studies on the cost of fire protection at the micro level have consisted primarily of calculating the cost of installation of these systems by summing the cost of materials, labor and equipment needed to install the systems. The different types of fire protection measures are usually categorized into passive and active fire protection systems.

Passive fire protection systems include means of egress, fire separation elements (walls, doors and slabs) and structural fire protection. In some instances, the passive fire protection systems are installed specifically for fire protection and serve no other purpose. In such scenarios, the cost of fire protection of the systems is computed as the cost of construction/installation of these systems by first identifying the necessary materials, labor and equipment needed. Then, by utilizing available cost data, the total cost of construction/installation is computed (Chapman et al., 2010; Quarles & Pohl, 2018; Ramachandran, 2002). As an alternative to computing the cost of installation, some studies computed the cost of the fire protection system as a function of another important variable. For example, Esposito (2004) computed the cost of fire resistant elements (walls, doors and slabs) as a function of their fire resistance rating (FRR) (Esposito, 2004). As regards structural fire protection, some studies propose computing the cost of alternative structural members without the added fire protection. The difference between the cost of the fire protected system and the alternate is then used as the cost of fire protection for these specific systems (Napier, 2013).

Active fire protection systems refer to fire protection measures that are activated upon the outbreak of a fire such as fire sprinklers, ventilation systems, automatic detectors, fire extinguishers and emergency lighting systems. Similar to the passive fire protection measures, studies into these systems have focused on obtaining the cost of materials, labor and equipment (Aldrich & Arena, 2013; Brown, 2005; Butry et al., 2007; California Utilities Statewide Codes and Standards Team (CSUCS), 2011; Duncan et al., 2000; Ghosh, 2009; Johansson et al., 2012; NFPA, 2013; Newport Partners, 2014, Palmer et al., 2000; Russell et al. 2007; Zega 2018).

Most reviewed studies focused on computing the initial cost of fire protection measures and do not consider the recurrent cost of maintenance. A few studies do include the cost of maintenance of these systems (Duncan et al., 2000; Ramachandran, 2002; Schaenman et al., 1995). However, these usually compute the cost of maintenance as a somewhat arbitrary percentage of the initial capital costs.

Lufkin and Pepitone (Lufkin & Pepitone, 2010) in an annual publication detail the cost of maintenance for the different components of fire protection measures. Going forward, it is necessary to comprehensively incorporate these maintenance costs in the total costs of the measures for an accurate description of the expenditure necessary for these features. On a related note, it is important to acknowledge that not all costs of fire protection can be readily related to the direct costs of installation and maintenance. For example, Ramachandran (2002) and De Sanctis and Fontana (2016) computed the cost of fire stairs as a function of revenue lost due to their presence, assuming that the systems are taking up space that could alternatively be used for revenue generation.

Data used in these studies on computing the micro level cost of fire protection can be obtained from a number of cost reference manuals. These include the RSMeans datasets, particularly the Facilities Construction Cost Data manual (Gordian, 2021a) and the Residential Costs manual (Gordian, 2021c), both of which contain the cost of materials, labor and equipment necessary for installing fire protection systems in buildings. The Rawlinson's Australian handbook of construction (Rawlinson's Group, 2006), which contains information on cost of construction in Australia was also used in determining the cost of fire protection systems in Australia. To include the cost of maintenance into these costs, some maintenance costs reference manuals including the RSMeans data manual Facilities Maintenance and Repair Costs manual (Gordian, 2021b) as well as Whitestone Building Maintenance and Repair Cost Reference (Lufkin & Pepitone, 2010) can be used.

3.2.2 Macro Level

To determine the cost of fire protection in buildings at a macro level, different studies have carried out research and determined that these costs can be computed in two ways: as a fraction of the total cost of construction within the defined national or sub national space using cost multipliers, and by using sales data on fire protection systems.

3.2.2.1 *Method for Macro Level Estimation of Fire Protection Cost based on Multipliers*

This method involves calculating the fraction of the overall cost of construction of buildings that can be attributed to the cost of fire protection. To evaluate the macro level cost of fire protection, the cost of fire protection measures at the micro or individual building level is collected for buildings representative of a category. This fraction becomes a multiplier to be used in computing the macro level cost of fire protection systems. Several studies have used this method in developing multipliers for the cost of fire protection. These studies have generally collected the micro level data either by computing the costs for prototypical buildings, by relying on expert judgements on these costs, or by a survey of costs of construction projects.

Studies on the *Total Cost of Fire in the United States* (Hall, 1993, 2014; NFPA, 2017), base their analyses of the cost of fire protection at the macro level on multipliers for different categories of buildings as well as on the annual building construction costs for each corresponding category in the U.S. from U.S. Census Bureau (Value of Construction Put in Place Survey (VIP)) (U.S. Census Bureau, 2021). The multipliers were then used to calculate the fraction of the total national construction expenditure that went into fire protection for each category and the summation of all categories will be the total national fire safety cost for building construction. Prior to 2003, the *Total Cost of Fire in the United States* studies used the four categories in grouping buildings. However, for 2003 and beyond, these studies used just three categories to group buildings namely private residential, private non-residential and public buildings. The fourth category (other private buildings) was discontinued as the buildings listed under this category could viably be grouped into private residential or private non-residential categories (Hall 2014).

The multipliers used in these studies were developed in previous work (Apostolow et al. 1978, Meade 1991). In the study by Apostolow et al. (1978), buildings were divided into four categories namely private residential, private non-residential, public and other private buildings. Industry professionals estimated the cost of fire protection systems in prototype buildings as well as the cost of construction of prototype buildings. The ratio of both costs was then computed as the multiplier for each category that a particular prototype building represents. The multipliers developed for each category in this study were 2.5% for residential, 9% for private non-residential buildings, 3% for public buildings and 3% for other private building types. To update the multipliers, Meade (1991) interviewed some industrial professionals to collected cost data of several newly constructed manufacturing plants and warehouses to determine the cost of fire protection in each. This study led to the adjustment of the percentage of construction costs attributable to fire protection systems in private non-residential buildings from 9 % to 12%, and the costs of fire protection in public buildings from 3% to 4%.

This method used in the *Total Cost of Fire in the United States* studies, has some disadvantages. The multipliers have been in use for several decades and have not been updated since the study by Meade in 1991. Thus, they may no longer accurately represent the fraction of the building costs taken by fire protection systems. In addition, multipliers were only developed for a few building categories (private residential, private non-residential, and public buildings). These categories cover a broad array of building types with different fire protection requirements. As such, using a single multiplier for each category estimated from prototype buildings may not accurately portray the cost of the systems and how these costs are spread across the different building types. There is also no stated justification for the buildings selected for use as prototypes nor an explanation of how they were deemed representative of all buildings in a category.

Schaenman et al (1995) in a study to characterize the total cost of fire in Canada, attempted to correct some of the shortcomings in the previously developed multipliers. This study identified sub-categories within the defined categories and set out to determine multipliers for them. To compute the multipliers, the study utilized data on the cost of fire protection in different prototype buildings collected by Hanscomb Consultants for the National Research Council (Hanscomb Consultants Inc, 1993), which computed the fire protection costs for a high-rise apartment building and a high-rise office building. These buildings were constructed using different materials (concrete for the apartment building and steel for the office building). The computed costs of fire protection systems in these buildings allowed some expert inferences to be made with regards to multipliers for certain categories of buildings. These include a reduced percentage (2%) for fire costs of single-family dwellings, a separate multiplier (13.2%) for high rise apartment buildings, a multiplier for low rise apartment buildings (8%) inferred as a midpoint cost between the high-rise buildings' multiplier and that of single-family homes, as well as multipliers for commercial buildings (6%), institutions (4.5%) and other types of buildings (3%). The principal source of national construction data used in this study is an annual publication on construction expenditure in Canada published by Statistics Canada (2021).

This reclassification of buildings and development of multipliers for sub-categories of buildings helped reduce the limitations of the previously developed multipliers. The multipliers for the sub-categories can justifiably be said to represent the categories as most buildings within each sub-category have similar fire protection requirements. Although this study did go some way to addressing the issues associated with developing multipliers for different building categories that adequately represent the categories, it still fell short in a few areas. One of the shortcomings is only identifying sub-categories for the residential building category and not for others. Also, the study does not justify the assumptions made in developing multipliers for categories such as low-rise apartment buildings, institutions and other building categories where no prototype buildings were used. The multipliers for these categories were inferred based on previous studies (Apostolow et al., 1978; Meade, 1991) and expert judgement. In addition, the study did not justify how the prototype buildings used could be said to represent all the buildings in the corresponding categories.

In a similar study to define the cost of fire protection in Australia, Ashe et al (2009) computed multipliers for different categories of buildings. However, rather than directly use prototype buildings to compute these multipliers, the authors of this study relied on the Rawlinson's Australian Construction Handbook, an annually published handbook on construction costs (Rawlinson's Group, 2006) which lays out a range of percentages of overall construction costs dedicated to fire protection systems. These cost percentages are collected from construction costs of typical buildings in metropolitan areas around the country. Although the handbook offers fire protection costs for several categories, the study elected to recategorize these buildings into three larger classes; residential, private non-residential and public buildings. To obtain a single multiplier for each category, the authors used the midpoint of each range as a representative multiplier for the corresponding category. Furthermore, to compensate for fire protection measures not included in the costs computed by the handbook, the study adds 1% to the percentage in each category. This led to the development of multipliers of 2% for residential buildings, 5% for private nonresidential buildings and 5% for public buildings, as representing the percentage of building costs that go to fire protection systems. The primary source of data on the national expenditure on building constructions used in this study is the Australian Bureau of Statistics' annual publication on construction expenditure (Australian Bureau of Statistics (ABS), n.d.). The method used by Ashe et al. allows for easy updating of the multipliers and there is an assurance of the continued relevance of the data as the handbook is updated annually. However, the limited number of categories used mean that the multipliers are expected to cover different types of buildings with widely varying fire protection requirements. Table 2 summarizes the cost multipliers developed for the different building categories discussed in the studies listed.

Table 2 - Summary of Cost Multipliers for Computing the Cost of Fire Protection Systems.

Study	Location of Study	Building categories	Multipliers
Apostolow, et al (1978).	United States	Residential buildings	2.50%
		Private non-residential buildings	9%
		Public buildings	3%
		Other private buildings	3%
Meade, W. P. (1991).	United States	Residential buildings	2.50%
		Private non-residential buildings	12%
		Public buildings	4%

		Other private buildings	3%
Schaenman et al (1995).	Canada	Residential buildings	
		Single homes	2%
		Semi detached	2%
		High rise apartments	13.20%
		Low rise apartments	8%
		Mobile homes	2%
		Non-residential buildings	
		Industrial buildings	6%
		Commercial buildings	6%
		Institutional buildings	4.50%
		Other buildings	3%
Ashe et al (2009).	Australia	Residential buildings	2%
		Private non-residential buildings	5%
		Public buildings	5%

Table 3 - Advantages and Disadvantages of Methods based on Multipliers.

Advantages	Disadvantages
• For those multipliers that are based on the estimation of individual buildings, data for calculating those multipliers are also readily available and usually regularly updated. • The national expenditure on building constructions required by those methods, are readily available and regularly updated. • The process used for computing the macro cost of fire protection is straightforward once the multipliers have been established.	• Limited number of categories are used, and thus the single multiplier for each category may not adequately cover the cost of fire protection systems for different building types. • The multipliers have been used for a long time and may be out of date. • The studies which directly use prototype buildings do not adequately justify how the prototypes used in developing the multipliers were selected. It is unclear if the prototype buildings accurately represent the buildings in each category.

3.2.2.2 *Method for Macro Level Estimation of Fire Protection Cost based on Sales Data*

An alternate method proposed by Schaenman et al (1995) for computing the cost of fire protection measures at the macro level is by collating data from manufacturers and installers of fire protection systems on their sales for the year. This data can then be used to estimate the total expenditure on fire protection systems at the macro level. Although this method could in theory provide an accurate picture of the annual fire protection costs at the macro level as the data would capture new construction, renovations/retrofitting as well as repairs, it may be difficult to obtain such data due to the large number and geographical spread of manufacturers of the components of fire protection systems. In addition, while accurate for active fire protection systems, this method may not capture the costs of passive fire protection materials, such as concrete, which may already be an intrinsic part of the building construction.

3.3 Prototype Methodology for Evaluation of the Cost of Fire Protection

In line with previous studies, we propose a methodology for computing the cost of fire protection systems at the macro and at the micro levels. The evaluation at the macro level requires knowledge of the costs at the micro level to compute cost multipliers for selected building categories. The methodology at the micro level enables calculating the installation and maintenance cost of the fire protection measures for CBA on case studies. A description of the proposed methodology is described in this section.

3.3.1 Cost of Fire Protection in Buildings: Methodology for Micro Level

The methodology proposed to evaluate the cost of fire protection in buildings at the micro level is illustrated in Figure 2. This methodology applies to a single building. Fire protection measures are first identified. Then, the costs of the fire protection systems are evaluated. This evaluation includes both the initial costs and the lifetime maintenance costs for the fire protection systems. Discounted values are computed for both the installation costs and the maintenance costs to ensure that both costs are computed at a common reference time point. The total discounted cost of fire protection at the micro level is computed as a sum of the total discounted installation cost and the total discounted cost of maintenance.

The calculation procedure of initial installation cost for fire protection system can be used to determine the multipliers for the macro level methodology in 3.3.2 while the calculation procedure of the total fire protection cost (including initial installation and maintenance) can help identify the cost component in the cost-benefit analysis of fire protection in Chapter 2.

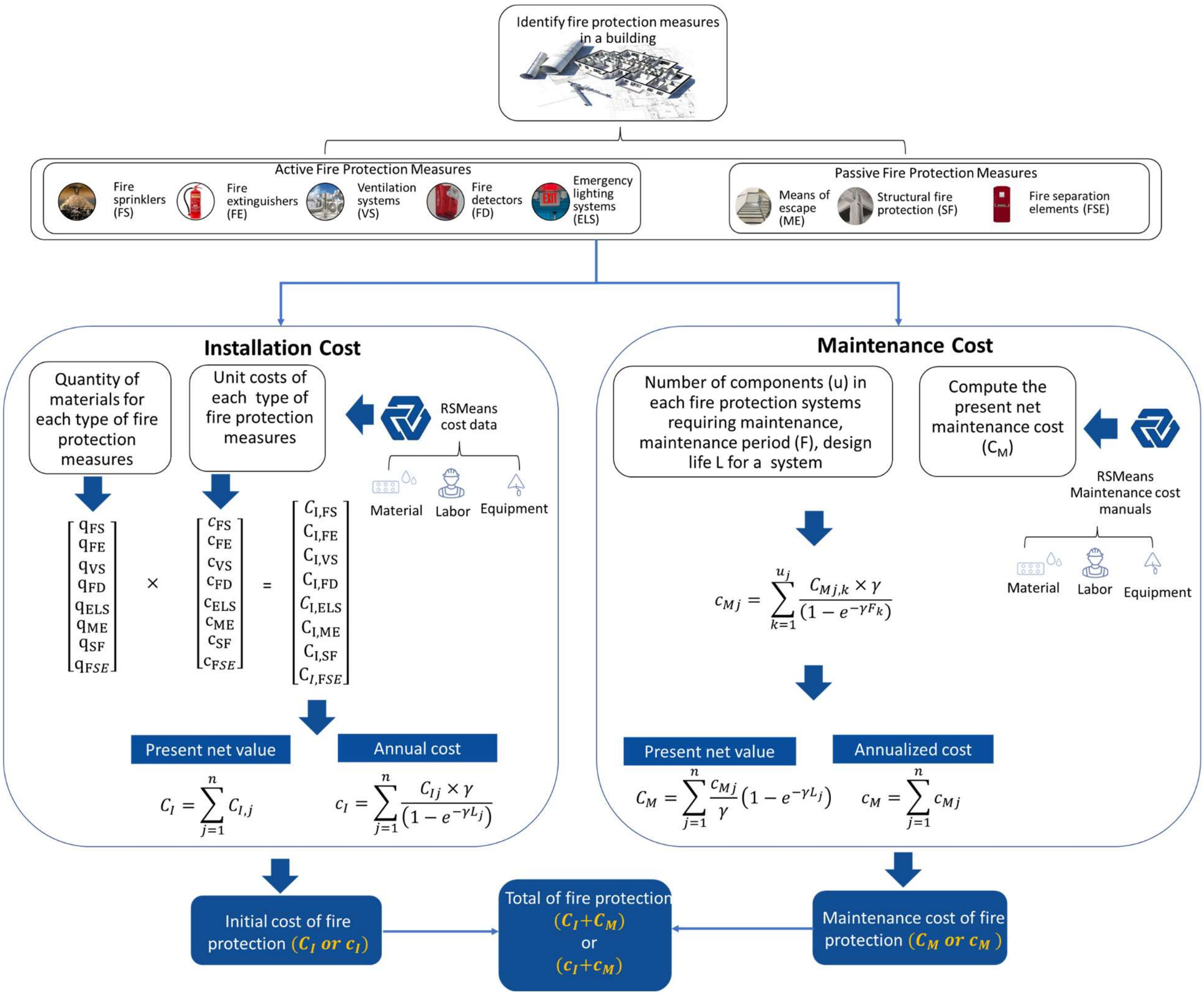


Figure 2 - Methodology for Computing the Cost of Fire Protection at the Micro Level.

3.3.1.1 *Initial installation cost*

The initial cost of installing fire protection systems in buildings encompasses the cost of materials and components of the systems in question as well as the cost of labor and equipment needed for the installation. These costs vary among the different fire protection systems in use and are generally determined by estimating unit costs and multiplying the unit costs by quantities required.

A procedure for the estimation of this initial cost is as detailed below.

1. Identify the fire protection measures to be used in the building. This could be a combination of some passive fire protection features (means of egress, fire doors and walls, and structural fire protection), and active fire protection features (fire sprinklers, fire extinguishers, ventilation systems, automatic fire detectors and emergency lighting systems).
2. Next, the components (e.g. fire sprinkler heads) and materials (e.g. sprayed fire-resistant materials) needed for the fire protection systems, as well as the quantities needed are determined.
3. The cost of the identified materials, as well as the corresponding cost of labor and equipment needed for installation can then be computed using regularly updated data from RSMeans including Square Foot Costs manual (Gordian, 2021e), Facilities Construction Cost Data manual (Gordian, 2021a), Residential Costs manual (Gordian, 2021c) and Building Construction Costs manual (Gordian, 2020). This is then taken as the initial cost of installation of a fire protection system. For passive fire protection systems which are a part of the building system, e.g., a fire resistance wall which is also a structural wall, the cost of fire protection can be the difference in the costs of these systems and the cost of alternative materials which are not fire resistant.
4. The total initial installation cost of the fire protection systems can be obtained as the sum of installation costs of the different fire protection systems in a building:

$$C_I = \sum_{j=1}^{n} C_{I,j} \tag{23}$$

   where C_I is the total installation cost of fire protection in a building, n is the number of fire protection systems in the building, and $C_{I,j}$ is the initial cost of installing fire protection system j.

5. Alternatively, as presented previously in Section 2.3.3, an annual continuous discounted cost of fire protection can be computed to determine the annual cost of these features in the building. The following equation is used to compute the annual continuous discounted installation costs.

$$c_I = \sum_{j=1}^{n} \frac{C_{I,j} \times \gamma}{\left(1 - e^{-\gamma L_j}\right)} \tag{24}$$

   where c_I is the annual continuous discounted installation cost of fire protection in a building, $C_{I,j}$ is the initial cost of installing fire protection system , γ is the continuous discount rate, L_j is the design life of fire protection system j, and n is the number of fire protection systems in the building.

The data on the installation cost of active fire protection systems can be collected from the RSMeans datasets, such as the Square Foot Costs manual (Gordian, 2021e), Facilities Construction Costs Data manual (Gordian, 2021a), and the Residential Costs manual (Gordian, 2021c). For instance, the data on the cost of sprayed fire resistant materials be found in both Facilities Construction Costs Data manual (Gordian, 2021a) and Building Construction Costs manual. All these data can also be found in the RSMeans' online database (Gordian, 2021d).

3.3.1.2 *Maintenance cost*

The maintenance costs for a fire protection measure is usually an aggregation of the maintenance costs for different components that make up the system. For example, a fire sprinkler system is made up of several components including the sprinkler heads and backflow preventer, which have different maintenance requirements and costs. The maintenance period for these components may also differ. It is thus necessary to annualize the cost of maintenance of the different components, ensuring they all have a common time frame of reference and then use these annual costs to estimate an annual maintenance cost for the entire system. The present net value or total cost of maintenance of the system over its design life can then be determined. The process used in obtaining the maintenance costs is described below.

1. Identify the components of a fire protection system that will require maintenance over the design life of the system.
2. The maintenance period of the components and their corresponding costs can then be obtained from maintenance cost resources such as RSMeans Facilities Maintenance and Repair Costs manual (Gordian, 2021b) as well as the Whitestone Building Maintenance and Repair Cost Reference (Lufkin & Pepitone, 2010). The RSMeans data can also be found in an easy to search online database (Gordian, 2021d).
3. The annual maintenance cost for a fire protection system is then computed as:

$$c_{Mj} = \sum_{k=1}^{u_j} \frac{C_{Mj,k} \times \gamma}{(1 - e^{-\gamma L_k})} \tag{25}$$

   where c_{Mj} is the annual cost of maintenance for a fire protection system *j*, u_j is the number of components of the fire protection system j that require maintenance, $C_{Mj,k}$ is the present maintenance cost of component *k* of the fire protection system *j*, γ is the discount rate and L_k is the maintenance period of component *k*.

4. The total annual cost of maintenance of these features in the building, can then be computed as:

$$c_M = \sum_{j=1}^{n} c_{Mj} \tag{26}$$

   where c_M is the continuous discounted cost of maintenance for all fire protection measures for the building, *n* is the number of fire protection systems present in the building, and c_{Mj} is the annual maintenance cost of fire protection system *j*.

5. Alternatively, as discussed in section 2.3.3, the present net value (PNV) cost can be used to determine the cost of the maintenance of the fire protection system at a common reference time point as shown in Eq. (27), and the total discounted cost of the maintenance of fire protection systems for the entire building can then be computed as shown in Eq. (28).

$$C_{Mj} = \frac{c_{Mj}}{\gamma}\left(1 - e^{-\gamma L_j}\right) \quad (27)$$

$$C_M = \sum_{j=1}^{n} C_{Mj} \quad (28)$$

Where C_{Mj} is the discounted PNV cost of maintenance for a single fire protection system *j*, c_{mj} is the computed annual cost of maintenance for the fire protection system *j*, *γ* is the continuous discount rate, L_j is the design life of the fire protection system *j*, C_M is the total discounted PNV cost of maintenance for fire protection for the building, and *n* is the number of fire protection systems in the building.

3.3.2 Cost of Fire Protection in Buildings: Methodology for Macro Level

The proposed methodology for evaluating the cost of fire protection in buildings at the macro level is shown in Figure 3. This methodology relies on the definition of building categories and cost multipliers. Models for computing cost multipliers are proposed that account for the different types of fire protection systems. In the following sections, we discuss the updated categorization of buildings in Section 3.3.2.1, the selection of prototype buildings in Section 3.3.2.2, the calculation of multipliers for each building category in Section 3.3.2.3, based on which, the calculation of the fire protection part of the building construction expenditure will be discussed in Section 3.3.2.4.

3.3.2.1 *Classification of building categories*

Ideally, for the categorization of buildings to compute multipliers, buildings in a single category should have very similar fractions of their overall costs going to fire protection. In other words, the buildings in each category should have similar cost multipliers that will not change significantly from each other. Also, the macro level cost expenditure for each category should be readily available. Those are the two criteria used in this study to develop the building categories for evaluation fire-protection expenditure in building constructions at the macro level.

The U.S. Census Bureau has delineated building types into categories to collect the annual building construction cost data in the U.S. (U.S. Census Bureau, 2021); the Federal Emergency Management Agency (FEMA) has its own building categorization used in determining the economic loss due to natural hazards (HAZUS & FEMA, 2003); and the National Fire Protection Association (NFPA) has its occupancy classification that drives the requirements for many different fire and fire safety features (NFPA, 2021). These categorizations have some similarities. Table 4 shows a mapping of both the FEMA categories and the NFPA categories into the U.S. Census Bureau categories. Two criteria, i.e., small variety of multipliers within each category and availability of construction cost data for each category, led to the selection of the U.S. Census Bureau's classification (U.S. Census Bureau, 2021) as the basis of categorization in this study. The U.S. Census bureau offers an annually updated publication on construction spending in each category. This is information not offered by either FEMA or NFPA in their categorizations of buildings. With nine identified building categories (residential, office, lodging, commercial, healthcare, educational, religious, manufacturing, and public safety) for which construction expenditure data are provided, multipliers for each category will better represent the buildings in the category than previous classifications.

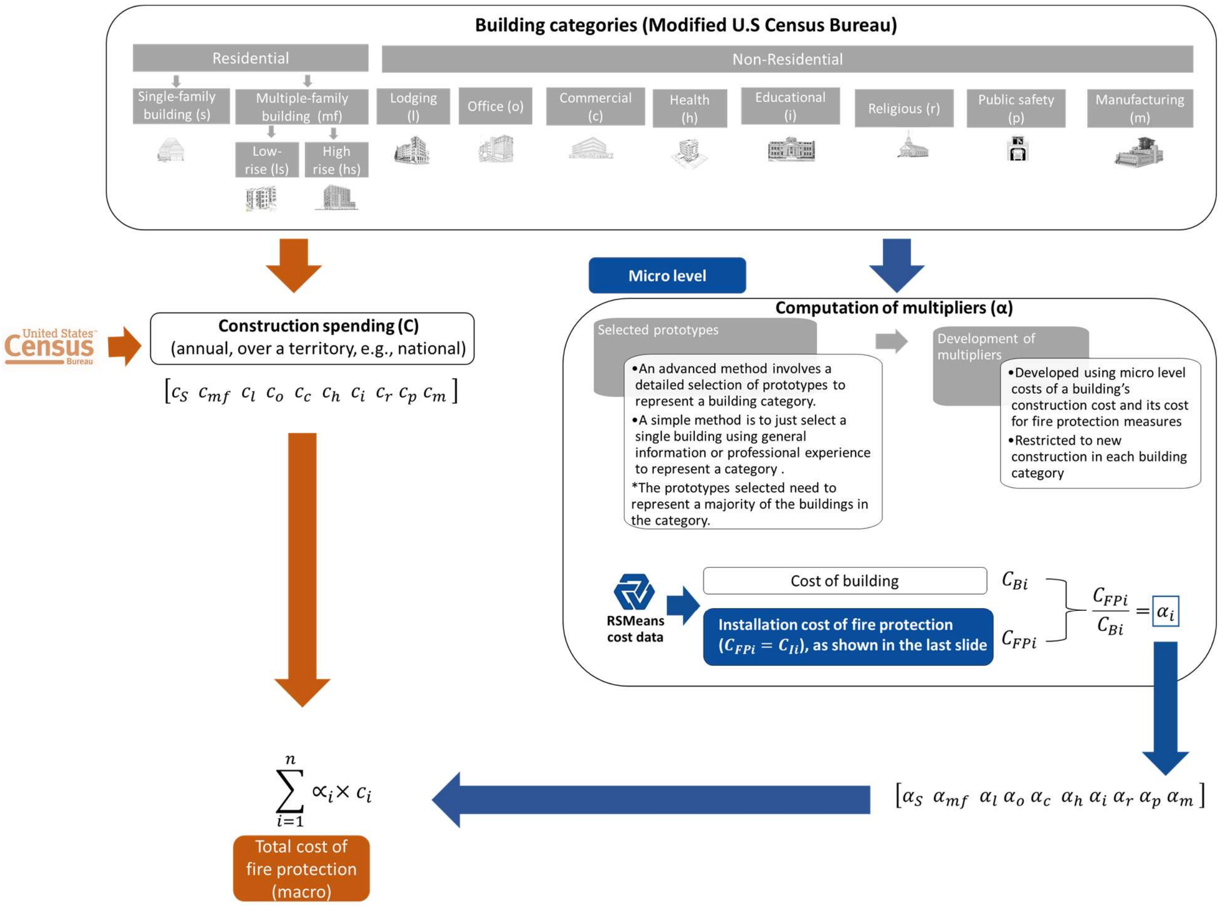


Figure 3 - Methodology for Computation of Fire Protection Cost at the Macro Level.

However, the U.S. Census Bureau categorization falls short in one critical aspect, by classifying all residential buildings into a single category. There are several types of residential buildings ranging from single family dwellings to low rise apartment buildings and high-rise apartment buildings, each requiring different fire protection schemes. Thus, the cost of fire protection within them will differ significantly as demonstrated by Schaenman et al (1995). It is therefore necessary to further subdivide the residential category into subcategories of single-family, low-rise apartments and high-rise apartments. No studies have investigated whether buildings in the non-residential categories have very similar multipliers and require dividing into sub-categories. Therefore, no further sub-categories will be proposed for those categories. Detailed studies into cost evaluations for buildings within these categories can be recommended for future work.

The final categories of buildings recommended by this study, Modified U.S. Census Bureau Categorization, is shown in Table 4. As can be seen, 11 categories are proposed. For comparison, studies reviewed in Table 2 commonly used 3 or 4 categories, except for Schaenman et al. who used 9.

3.3.2.2 *Selection of building prototypes*

To compute a multiplier which accurately represents the fraction of construction costs taken up by fire protection systems for buildings in a category, ideally several buildings are sampled from each category and their multipliers computed. An overall multiplier can then be calculated for the category. A possible method of determining the overall multiplier is using a probabilistic approach. In this approach, the multipliers for several prototype buildings in a category would be computed and the frequency distribution of the multipliers obtained. From the frequency distribution, the mean value of the multipliers can be selected as representative of the buildings in the category. If the multipliers differ greatly, it may be necessary to create sub categories and have a multiplier for each.

This method however may not be very practical. Alternatively, a few prototype buildings can nominally be selected to represent a category and an average multiplier computed for the category using these few buildings. As the number of buildings used to represent a category decreases, it becomes increasingly important to pay close attention to the selection of the buildings used as representative prototypes. At the extreme, only one building can be selected to represent each category but the buildings need to be carefully selected to adequately represent the average building in each category.

In this study, we will demonstrate the micro level cost evaluation for a limited number of prototype buildings. As such these case study buildings represent one or a very limited number of micro level evaluations for a prototype building for a given category. This data can be considered as a first evaluation for the macro level multiplier. In general, however, it is highly recommended to repeat the micro level evaluation for a number of buildings per category, as detailed above, or to justify that a selected prototype building for calculating the multiplier can represent the average building in each category.

Table 4 - Categorization of buildings proposed for the cost of fire protection evaluation at the macro level, and correspondence with FEMA and NFPA classifications.

Prototype methodology (Modified U.S Census bureau)			**FEMA**	**NFPA**
Residential	Single-family		• Single family dwelling • Mobile home	• One and two family dwellings • Apartment
	Multiple family	Low-rise High-rise	• Multi family dwelling • Institutional dormitory • Nursing home	• Apartments
Non residential	Lodging		• Temporary dwelling	• Residential board and care • Lodging or rooming house • Hotels and dormitory
	Office		• Banks • General Services	
	Commercial		• Retail Trade • Wholesale Trade • Personal and Repair Services • Professional/Technical/ Business services • Parking • Entertainment/ recreation/Theatres • Agriculture	• Assembly • Mercantile • Business • Storage
	Health-care		• Hospital • Medical office/ clinic	• Ambulatory health care • Health care
	Educational		• Colleges/ Universities • Schools/ Libraries	• Educational • Day care
	Religious		• Church/ Membership organization	
	Public safety		• Emergency response	• Detention and Correctional
	Manufacturing		• Heavy industry • Light industry • Food/ drugs/ chemicals • Metals/ mining/ processing • High technology • Construction • Agriculture	• Industrial

3.3.2.3 *Calculation of multipliers*

Total construction cost is a fundamental parameter within this study. After selecting justifiable prototype buildings, the total construction cost is adopted to estimate the multipliers for the cost of fire protection at macro-level. In the available literature, the total construction is commonly estimated based on construction statistics and databases. Mean costs per unit area (e.g., per square meter or square foot) are listed for different building occupancies and other characteristics (e.g., structural system type) and they approximate the cost of both structural, non-structural components, design fees etc. The building content and equipment is typically not included. These costs are usually offered in the form of databases and handbooks. For example, the American RSMeans data manuals including the Square Foot Costs data manual (Gordian, 2021e); those data are also available on their online database (Gordian, 2021d). Other similar data sources are also availabe in United States, e.g., National Building Cost Manual. Data sources for other countries include the British Building Cost Information Service (BCIS) data (RICS, 2022), SCI documents (Hicks, 2004; Lange et al., 2014) and those data sources mentioned in Section 3.2. Nowadays, commercial software are also available to estimate prices within the construction industry, for instance Xactimate developed by Xactware to support decision-making in the insurance market (Xactware, 2022). RSMean data are also available online (RSMeans Data Online (Gordian, 2021d)), which provides a quickest way to find reliable cost data on construction materials, equipment and labor. The RSMeans Data Online can also help a user to build complete estimates according to a building's information. Another approach to estimate the total construction is based on the Real Market Value (RMV) of a building (Standohar-Alfano et al., 2018; Weibe and Cox, 2014).

Similarly, the cost of installing fire protection systems as part of the initial construction can be roughly estimated by the fire protection cost per square foot (also available in the RSMeans' Square Foot Costs manual and online database) multiplied by the floor area. A more accurate method is to identify the quantity of materials and corresponding labor and equipment needed to install those fire protection measures and then collect the cost data per unit quantity. These data are available in RSMean datasets, e.g., Facilities Construction Costs Data manual (Gordian, 2021a) and the Residential Costs Data manual (Gordian, 2021c). The ratio of these two costs (fire protection costs and building construction costs) can then be used as the cost multiplier of fire protection in the building category as:

$$\frac{C_{FPi}}{C_{Bi}} = \alpha_i \tag{29}$$

where C_{FPi} is the cost of fire protection for a prototype in category *i*, C_{Bi} is the cost of construction of the prototype building, and α_i is the cost multiplier for fire protection for category *i*. The detailed calculation of C_{fpi} refers to the methodology for calculating the installation costs of individual buildings' fire protection measures, as discussed in Section 3.3.1.2.

It is worth mentioning that total construction cost is different from total replacement cost and total reconstruction cost. The latter two parameters are the key inputs for the estimations of the losses due to fire. Here, replacement cost is defined as the cost to construct or replace an entire building with equal quality and construction. A replacement cost does not include site improvements, demolition, debris removal, fees, and other costs associated with the construction process. The estimation of replacement cost is based on the assumption that current building material, design or layout will be available and used. A reconstruction cost is the cost to replicate the building at current construction prices and using the like kind and quality materials, construction standards, design, layout, and quality. Additional expenses related to the fees for repair and restoration contractors, the construction process itself, the location of the property, demolition costs, and debris removal are included in a reconstruction cost. Due to those factors, the reconstruction of a building is usually higher than its new construction cost. The cost estimation for a reconstruction or a replacement is similar to that for a new construction. For the replacement cost, the mean costs per unit area should not covers those activities that are not in its scope, e.g., design fees and site improvement. For the reconstruction cost of a building, as mentioned above, some additional cost needs to be considered, compared to the new construction cost, e.g., the demolishment cost. The demolishment cost can be estimated according to the quantity of materials that needs to be demolished. Unit costs for demolishing and debris removal are also available in RSMeasn datasets, e.g., RSMeans Concrete & Masonry Costs for concrete and masonry buildings.

3.3.2.4 *Fire protection part of the building construction expenditure*

The annual construction spending on buildings in each category is collected from the U.S. Census Bureau data. This data includes information on both new construction as well as extensive repairs and retrofitting of existing buildings, hence multipliers should be developed for both these processes. However, the data on national construction expenditure does not delineate between expenditure on new construction and expenditure on retrofitting. This makes it difficult to determine the percentage of the total cost of construction covered by each. Also, retrofitting of buildings involves different levels of complexity, meaning that the costs could differ significantly from one project to the next, increasing the difficulty in computing a multiplier that will encompass all retrofitting projects. Consequently, this study computes multipliers as a fraction of the cost of new construction and does not include cost of retrofitting. More studies need to be done in the future to evaluate multipliers for retrofitted construction.

The cost multiplier developed for each category is multiplied by the construction spending in that category to obtain the fraction of the construction spending that goes into fire protection schemes. The total cost of fire protection across all building categories can then be computed by summing up the costs obtained for each category, as:

$$C_{fp} = \sum_{i=1}^{m} \alpha_i \times C_i \qquad (30)$$

where C_{fp} is the macro level annual expenditure on fire protection, α_i is the cost multiplier for building category i, m is the number of building categories, and C_i is the annual construction expenditure on buildings in category i.

4 Evaluation of Fire Losses

4.1 Introduction

The estimation of the losses associated with the consequences of extreme conditions caused by natural hazards, like earthquakes and windstorms, represents a key aspect for making decisions about the robustness and safety of human infrastructure, both at private level and societal level. In particular, quantifying the effects of these events enables consideration about the costs and benefits of investing in different measures to reduce their likelihood of occurrence and/or consequences.

The current study focuses on fires in buildings, rare events that may occur in any construction, more or less frequently depending on the building occupancy and the implemented fire safety measures. Depending on the size and nature of the fire that may occur in a building, it can trigger a variety of effects, from minor damages to catastrophic consequences. In particular, fire can directly endanger human life and properties, as well cause indirect or consequential losses at financial, social and environmental level.

The current chapter analyses various methodologies for loss estimation available in the literature. Approaches related to other natural hazards (e.g., earthquakes, windstorms, tornadoes, tsunamis) are also touched upon and compared. In general, in each methodology, it is possible to distinguish three domains. The *"hazard domain"* typically defines the hazard characteristics, usually in terms of frequency of occurrence and intensity measure. The *"damage domain"* investigates the relationship between the defined hazard and the level of damage or consequences caused by the hazard. Finally, the *"loss or cost domain"* aims at translating the damage and consequences into a quantification of loss: this is commonly done on a monetary level because it is the common ground in which different consequences and losses can be easily associated with a cost.

Depending on the hazard, analysis goal and available information, the losses can be estimated with different level of complexity. For instance, a *"modelling-based approach"* is typically more suitable for comprehensive analyses, in which the effects of the hazard are quantified in detail. However, it requires a high level of information, and it can be time- and resource-consuming. On the other hand, a *"statistical approach"* can highly simplify the analysis by estimating some relevant parameters based on available statistics and databases. However, the outcomes may be quite general, as statistical analyses are highly dependent on the available data, which can be limited or inaccurate for fire hazards. In general, different approaches and methodologies with various levels of complexity can be adopted for loss estimation. The choice primarily depends on the question the analysis is trying to answer, but it is also influenced by the quality of the available information specific to the examined scenario.

In the following, the major outcomes obtained from an extended literature review on loss estimation in buildings due to fire are presented. Subsequently, a prototype methodology is recommended.

4.2 Literature Review

4.2.1 Introduction

An extended literature review was carried out focusing on general strategies and approaches for the estimation of losses in buildings due to natural hazards, especially for fire events. From the definition of the hazard, all the major causes of direct and indirect losses due to fire were investigated and discussed. Special focus was placed on the available statistical models and data sources available in the literature.

The literature review was conducted considering: (i) references known to the authors of the current report from previous studies, (ii) references recommended by the research project advisory committee, (iii) a keyword search in academic repositories, (iv) secondary referencing (i.e., references listed within studied sources, and citations of these studied sources).

The ignition and spread of a fire in a building can cause a wide range of damage depending on many different aspects, both from the fire side (e.g., size and duration) and the building side (e.g., fuel characteristics, ventilation conditions, and fire safety measures). As indicated in Section 2.3.3, fire losses are commonly subdivided in direct losses and indirect losses. The direct losses relate to damage/harm to the property and its content, the building occupants, and the fire service operations. These are all the losses that can be caused during the course of a fire. On the other hand, after the fire extinguishment, the fire can also affect the property business, the society, the environment, and a variety of other stakeholders that can be indirectly impacted by the fire consequences. These are the indirect or consequential losses.

The losses caused by a fire event are inherently "uncertain" and difficult to estimate in any a-priori-analysis. Furthermore, the cost associated to a fire need to take into account the likelihood (probability) of a fire occurrence as well as the "probable damage" due to fire. The probable damage is affected by a large number of parameters and series of assumptions. In particular, the probable reduction in fire damage related to a specific fire safety measure is challenging to quantify.

The main purpose of the literature review, and subsequent prototype methodology, is to estimate the effect of various fire protection measures on the consequences caused by the fire. Therefore, the output obtained from the loss estimation analysis should be sensitive to different fire protection measures to achieve significant insights in the cost-benefit analysis. For example, methods to evaluate direct and indirect losses due to fire should allow to incorporate a dependency on active or passive fire protection measures.

The presented literature review investigates different approaches and methodologies to estimate both direct and indirect losses cause by a fire event. In particular, the analysis focuses on understanding how different fire safety measures implemented within a building are likely to affect the extent of the damage in a fire scenario. Quantitative rather than qualitative fire loss models are central to the analysis (Lin et al., 2009). This represents a significant challenge for statistical approaches, mainly because of the lack of comprehensive data which explicitly enable to assess the influence of fire protection measures on the fire consequences.

4.2.2 Hazard definition

The first step for the estimation of losses caused by any hazard typically concerns the definition of the hazard itself. Certainly, the definition of the hazard depends on the characteristics of the specific hazard, but hazards are generally defined in terms of a frequency of occurrence (probability or return period) and an intensity measure. This is the case for fires, central to this study, as well as other natural hazards like windstorms and earthquakes (Ahmad et al., 2014; Chandler et al., 2001), tsunamis (Weibe and Cox, 2014), and tornadoes (Standohar-Alfano et al., 2018). For instance, the research study by Lange et al. offers an example of loss estimation for fire events in the context of the PEER framework. The PEER framework was originally developed to assess the performance of building systems and consequential damages due to earthquakes (Lange et al., 2014; PEER, 2022). In their analysis, the first stage involves the "hazard domain" and a range of fire events is defined in terms of a probability of occurrence and an intensity measure. In this paragraph, these two aspects are analyzed independently and referred as “fire frequency” and “fire severity”.

4.2.2.1 *Fire frequency*

In the available literature, numerous sources offer an estimate for the frequency of occurrence of a fire scenario in buildings, typically associated with the building occupancy and other relevant characteristics. However, it is important first to clarify what the term “fire” means, as fires in buildings can be generally divided into two categories. *“Fire ignitions”* refer to any fire that can be triggered in a building, no matter the size of it, while *“structurally-significant fires”* relate to any fire that may achieve flashover and challenge the structural integrity and stability of the load-bearing system. For example, it is important to highlight that, in its definition, structurally-significant fires already include the failure of various fire protection measures aimed at controlling or extinguishing the fire before reaching flashover.

Various sources can be referred to quantify the probability of fire occurrence. This frequency can be estimated starting from fire statistics collected and reported by the fire services or other authorities. Numerous databases gathered at regional (e.g., in Germany) or national level (e.g., UK Incident Reporting System and Australian Incident Reporting System) usually report much information related to a fire incident, like the building occupancy type, fire ignition cause and location. A comprehensive investigation on various European fire statistics has been performed within the EU FireStat project (EU FireStat, 2021). However, the most used and well-established fire recording systems and fire statistics are from England/UK and the USA (Manes et al., 2021), such as the American National Fire Incident Reporting System (NFIRS) (NFIRS 2022), the English statistics collected by Home Office (Home Office, 2022) or the British Fire Protection Association (FPA) Large Loss Database (BRE Global, 2013; FPA, 2022). These fire statistics are usually published every year and different authorities can periodically summarize and compare them in technical reports: for instance, the NFPA's reports in the United States (NFPA, 2022; NFPA, 2017). This data is used to inform policy makers to improve fire safety according to the most likely cause of fire and the most likely place where a building occupant may suffer an injury or fatality. However, these databases only contain data on relevant fires attended by public fire departments, typically where a fatality occurred, or the fires caused extensive damage. Therefore, using these data excludes small or extinguished fires and consequently they cannot be considered as fully reliable source to estimate the probability of fire ignition (Ramachandran, 1998; Salter, 2013). On the contrary, the fire statistics are a valuable source of data to estimate structurally-significant fires because, in these cases, the fire service is commonly notified. Greene and Andres (2012) used surveys to assess the ratio of unreported to reported fires. In this report, the reported fires are used as this data is more readily available.

In general, for any assessment involving fire statistics, it is very important to keep in mind the number of fires on which the data is based. Often, certain analyses related to fire have great deal of confidence due to the very large number of fires, while in some cases there are relatively few fires and caution must be exercised in drawing conclusions from the limited database (Thomas, 2002).

In different studies, the fire statistics have been used to characterize various analytical or more complex models to estimate the fire frequency in a specific building. For example, a power law based on the total area of the building and the building occupancy was first developed by Rutstein and Cooke (1979) and recently improved by Manes *et al.* using different updated fire statistics (Manes and Rush, 2021; Manes and Rush, 2019; Manes and Rush, 2017). In general, in these models, the probability of fire occurrence is expressed as a function of the building occupancy and size (total area or volume) (Fischer, 2014;

Ramachandran, 1998). Given the different nature of fire hazards and regulations around the world, the fire frequency is typically highly dependent on examined geographical area or country. For instance, Fisher employed data from three Swiss insurance sources to estimate the fire probability as a function of the building floor area and volume (Fischer, 2014): this information is inherently specific to Switzerland, and it should be applied to other geographical areas with care.

As regards to structurally-significant fires, nominal probabilities of fire occurrence can be also found in national and international standards, like in Eurocode 1 (EN1991-1-2:2002; Vassart et al., 2014). For example, these values were used by Ni and Gernay for the probabilistic estimation of the fire-related damage to concrete structures (Ni and Gernay, 2021), while Lange et al. estimated the frequency of structurally significant fires according to the natural fire safety concept, considering the probabilistic influence of fire fighters' intervention, detection and alarm systems and automatic suppression systems (Lange et al., 2014).

This last concept is very important within the current research study because the effects of certain fire protection measures on the fire-induced losses can be only estimated by understanding how different systems affect the probability of occurrence of a fire ignition or a structurally-significant fire. For example, in the Eurocode, this is solved by defining different conditional probabilities of a structurally-significant fire depending on the installed fire protection measures (e.g., automatic sprinklers systems, automatic alarm system, time to fire service intervention) (EN1991-1-2:2002; Vassart et al., 2014). Reduction factors or conditional probabilities for different fire protection measures can be found in several studies, depending on their focus (e.g., automatic sprinklers systems (BRE Global, 2013; Cebr, 2014; Ramachandran, 1998).

4.2.2.2 *Fire severity*

While the frequency of occurrence of a fire plays a key role for any probabilistic analysis aimed at loss estimation, the definition of the fire scenario, referred here as fire severity, is normally a necessary step for any "modelling-based approach". In this case, the definition of the fire exposure is fundamental to estimate the damage to property and people and, subsequently, the overall fire losses.

The definition of the fire severity highly depends on which type of damage or loss is the objective of the analysis, and the fire scenario is defined accordingly. Indeed, a fire can be defined in terms of time-histories of temperature, heat flux, heat release rate, or other. For instance, in a life safety analysis in which the fire growth phase is key, a typical pre-flashover αt^2 fire (heat release rate curve) can be the suitable option to investigate the fire dynamics and smoke movement and ensure safe evacuation of the building occupants (Drysdale, 2011). On the contrary, a post-flashover fire (or structurally-significant fire) is a more relevant scenario in analyses focused on ensuring structural integrity and stability during and after a fire, as well as safe operation of the fire and rescue service. In these cases, various approaches or models can be adopted to specify fire curves, generally defined in terms of a time-history of adiabatic surface temperature at fire-exposed structural elements. For post-flashover fires, the most used approaches are the standard temperature-time fire curve, typically for regulatory purposes, and the Eurocode parametric fire curves to reproduce natural fire exposures for performance-based design (EN1991-1-2:2002).

In addition to the fire exposure definition, the mentioned models can be also detailed at probabilistic level. Examples are offered by Lange et al. and Ni and Gernay (Lange et al., 2014; Ni and Gernay, 2021): in their studies, the main input parameters of the Eurocode parametric fire curves (i.e., fire load density, fire growth rate, compartment opening factor and thermal inertia of the enclosure boundaries) were defined with specific probability distributions. This enabled a probabilistic definition of the fire exposure, hence a probabilistic estimation of the fire-induced damages and losses.

4.2.3 Estimation of direct losses – property

After the definition of the hazard, the following step of typical methodologies concerns the estimation of the losses. A common intermediate phase is to first estimate the damage due to fire based on the defined hazard characteristics, and then translate it into a cost, for example monetary cost. This is the common procedure for modelling-based approaches, in which the performance of the building exposed to fire and with different fire protection measures is carefully investigated, and the induced damage estimated accordingly. This phase can be potentially skipped or highly simplified in statistical approaches, in which fire statistics are employed to estimate a probable damage or a probable cost directly.

In general, for the estimation of the direct property losses due to a certain hazard, it is important to consider all its components, within and outside the immediately affected fire compartment(s). Buildings are composed of both structural and non-structural systems, and they can contain sophisticated equipment and more or less valuable content. While the damage to the structural system is the most important measure of building damage, affecting catastrophic loss of function and possible casualties, the structural system itself typically represents only about 25% of the building's worth (FEMA, 2015). In fact, for certain building occupancies, the damage to non-structural systems and contents tends to dominate economic loss.

4.2.3.1 *Statistical approaches*

Most of the fire statistics previously mentioned for the estimation of fire frequency can be also employed to approximate fire-induced damages or losses in buildings. Fire statistics are usually collected by the ranking fire officer or loss adjusters at fire incidents and, along with general information about the fire (e.g., building occupancy type, fire ignition cause, location…), they often estimate the fire damage in terms of the area damaged by burning and/or the total area damaged by fire, smoke, water, and firefighting operations. This value can be used to quantify the fire loss as the product between the fire-damaged area and the construction cost per unit area (specified according to the building characteristics) (Manes and Rush, 2019; Manes and Rush, 2017). The average fire-damaged area can be estimated from various fire statistics and databases, like the American National Fire Incident Reporting System (NFIRS) (NFIRS, 2022) and the British Fire Protection Association (FPA) Large Loss Database (FPA, 2022), as previously explained for the fire frequency. On the other hand, construction cost databases, handbooks or software can be employed to estimate the average construction cost per area. An interesting application is the 2013 BRE study, which defined "high" and "low" estimates of the damage per square meter depending on the nature of damage (fire & smoke damage, fire damage, and smoke damage) (BRE Global, 2013). On the contrary, the damage due to firefighting operations is usually not explicitly considered.

Analyses related to the building damage can be also disregarded if fire statistics can directly offer cost estimates for fire incidents. For instance, the American NFIRS database provided by the U.S. Fire Administration reports loss estimates made by fire response personnel: "Fire loss is an estimation of the total loss to the structure and contents in terms of replacement in like kind and quantity. This estimation of fire loss includes contents damaged by fire, smoke, water and overhaul. It does not include indirect loss, such as business interruption" (Ahrens and Evarts, 2021; NFIRS, 2022). Using this information, a probable fire-induced cost can be estimated, and examples of these applications are available in the literature. For instance, Thomas used the American NFIRS statistics to analyze the effectiveness of different fire safety components and systems in terms of efficacy and reliability (Thomas, 2002), while the Centre for Economics and Business Research (Cebr) employed the British FPA statistics to examine the financial and economic impact in England and Wales of fires in warehouse buildings without automatic fire sprinkler systems (Cebr, 2014).

These fire statistics can be also processed to generalize analyses, for example by plotting the fire loss against the damaged area. Trend lines can be estimated based on various databases to assess an average cost of fire given an average damage area, for example using power relationships (Ramachandran, 1998). Constants usually vary depending on the building occupancy and fire risk category, and these expressions can be possibly yearly or quarterly updated according to the latest fire statistics and financials trends (e.g., inflation) (Salter, 2013).

However, as regards to any calculation and conclusion drawn from fire statistics, it is important to highlight two key aspects. First, by nature, this data is highly subjective and hard to verify because the data is based on the loss adjustor's experience and judgement. Second, as for the case of fire frequencies, these databases only contain data on relevant fires attended by public fire departments with serious injuries and/or fatalities, or extensive damage. Therefore, these data exclude small fires or fires extinguished by local authorities, sprinklers, and portable fire extinguisher. The use of said data to inform generalized fire loss models could lead to an overestimation of costs as all fires within the dataset will be the larger, more expensive fires (Ramachandran, 1998; Salter, 2013).

Furthermore, other types of data sources can be used to estimate fire-related losses. For example, building fire losses can be assessed from the insured value (Ramachandran, 1998), like Fischer who employed three different sources of Swiss fire insurance data (1995-2009) (Fischer, 2014), or from the Real Market Value (RMV) of the building determined from the U.S. Census (Standohar-Alfano et al., 2018; US Census Bureau, 2011; Weibe and Cox, 2014). Nevertheless, Salter has underlined how using data sources of various natures (insurance-focus vs. fire-service-based) can result in significantly different estimates, particularly for certain building occupancies (Salter, 2013).

However, with regards to the objectives of this study, it is usually challenging to associate the effect of different fire protection measures with the damage and the loss due to fire using fully statistical approaches. In the available fire statistics, this level of detail is rarely present. Therefore, the effect of different fire protection systems must be explicitly included, for example by suggesting reduction factors for the probability of fire occurrence and fire severity. As a consequence, there is a recent push for collecting fire statistics of higher quality, with additional and more structured information (Manes et al., 2021).

4.2.3.2 *Modelling-based approaches*

Contrarily to the statistical approaches, modelling-based approaches mainly rely on detailed models and simulations to analyze the building performance exposed to fire and quantify the damages and losses resulting from a specific hazard. The choice of the model directly depends on which damage or loss is the goal of the performed analysis. In fire safety engineering, the most common applications concern computational fluid-dynamics software - e.g., Fire Dynamics Simulator (FDS) (NIST, 2022) - aimed at investigating the fire and smoke dynamics in buildings equipped with different fire protection measures, and finite-element models aimed at examining the behavior of building load-bearing structures exposed to various fire scenarios (Lange et al., 2014; Gernay et al., 2016; Ni and Gernay, 2021). Similar applications related to other natural hazards can be found in the literature, such as Weibe and Cox who, in the case of tsunamis, estimated the physical damage to buildings based on numerical simulations (Weibe and Cox, 2014).

Structural and non-structural elements

The common outcome obtained from numerical models and simulations is a quantification of the building damage depending on defined hazard scenarios, with or without probabilistic distribution. The damages are usually not described in a continuous scale, but categorized into a number of damage classes or levels of damage, which provides an understanding of the building's physical condition (Chandler et al., 2001; FEMA, 2015; Lange et al., 2014; Ni and Gernay, 2021). A well-established damage classification in earthquake engineering is the one defined according to the FEMA/NIBS methodology and adopted by Hazus, which associates the direct economic loss due to components' failure with an expected percentage of the replacement value. The various damage states ("slight", "moderate", "extensive", or "complete" damage) are described in detail for each structural building types, both for structural and non-structural elements (FEMA, 2015). The International Federation for Structural Concrete (*fib*) and the Concrete Society offer another ranking for categorizing fire-related damages of concrete structures into 4 or 5 groups, from "superficial" to "severe" (fib, 2008; Concrete Society, 2008). Otherwise, Lange et al. defined cost consequence functions and repair time consequence functions associated with 3 damage measures (DMs) based on the post-fire residual deflections: no damage or repair needed (DM0), damaged element and repair needed (DM1), and collapsed element and replacement needed (DM2) (Lange et al., 2014). Finally, in the case of windstorms and earthquakes, Chandler et al. suggested 7 levels of Damage Index Criteria and provides a brief description of damages caused by the specific hazard: from level D0.0 for an undamaged element to level D3.0 for a complete element collapse (Chandler et al., 2001).

After the damage assessment, the replacement or repair cost of structural and non-structural elements is usually estimated according to the damage classes or the levels of damages previously defined, depending on the building occupancy (Chandler et al., 2001; Lange et al., 2014; Ni and Gernay, 2021). For example, Chandler et al. evaluated the damage cost as a percentage of the replacement value (namely Repair Cost Ratios - RCRs) and its standard deviation associated with Damage Index Criteria: the mean RCRs vary between 2% (undamaged) and 95% (complete collapse) according to the 7 levels of Damage Index Criteria (Chandler et al., 2001). Similarly, Hazus default values of direct economic loss for structural and non-structural systems are based on loss ratios corresponding to each state of damage. On average, "slight", "moderate", "extensive", or "complete" damage correspond to a loss of 2%, 10%, 50%, or 100% of the building's replacement cost, respectively (FEMA, 2015). However, Hazus also offers more detailed structural and non-structural repair cost ratios for different building occupancies based on statistics (FEMA, 2003). The concept of "building vulnerability/damageability" index introduced by Chandler et al. is another interesting addition, since it estimates the hazard-specific vulnerability to damage of a certain building based on some critical characteristics, such as building age, height, and occupancy (Chandler et al., 2001).

Specifically to structural components, Ni and Gernay proposed a framework for probabilistic fire loss estimation in concrete building structures (Ni and Gernay, 2021). The loss of structural elements due to fire was assessed based on loss functions and structural damage states, estimated using advanced finite-element structural models (e.g. SAFIR (Franssen and Gernay, 2017)). In case of building collapse, the financial loss was the cost of demolishing and reconstructing the building. For the non-collapsed case, the loss was estimated differently between the zone directly exposed to the fire (repair cost of damaged structural elements plus expected replacement cost of all the non-structural components and the content in the fire-exposed region) and the zone not exposed to the fire (repair cost of deformed structural and non-structural elements). The repair costs of structural elements were estimated according to different repair actions based on damage states, adopting the RSMeans construction costs database (FEMA, 2018; RSMeans 2019).

Regarding non-structural aspect, a common assumption is to consider that, in the case of fully-developed fire, all the non-structural components within the fire compartment would require complete replacement due to the damage caused by smoke and heat, regardless of the repairability of the structure (Lange et al., 2014). The replacement cost can be estimated as a fraction of the total construction cost depending on different variables, such as building occupancy or structural system type. For instance, Ni and Gernay (Ni and Gernay, 2021) assumed that, for an office building, the 38% of the total building cost comes from structural components and 62% from non-structural components, in accordance with (FEMA, 2015). In this case, these values were used to estimate the replacement cost of non-structural elements in each fire compartment, considering a homogeneous distribution of structural and non-structural components throughout the building. Otherwise, in the 90s, Kanda and Shah proposed a general theoretical model for failure cost evaluation in buildings, which normalizes all the losses due to structural failure (damage to structure, contents, non-structural components, equipment, function loss, injuries, fatalities, and psychological damage) by the initial construction cost (Kanda and Shah, 1997). In particular, they estimated that the damage cost due to structural failure is generally in the ranges 25-40% and 10-50% of the initial construction cost for structural and non-structural components, respectively (depending on the building occupation type).

In the case of pre-flashover fire, it is very challenging to estimate the partial damage to non-structural components and a statistical approach is usually preferred (i.e., probable fire-damaged area). A similar concept applies for the damage outside the compartment of fire origin.

<u>Content and equipment</u>
Apart from the structural and non-structural building components, a fire event can seriously damage the content and equipment within and outside the compartment of fire origin. Fischer states that "the insured loss to contents is often smaller than the building fire loss […], however in some fire events the contents loss may be much higher than the building fire loss" (Fischer, 2014). Consequently, the extent of the loss related to content and equipment typically depends on the building content and occupancy: it could be negligible or significant compared to the building construction cost. In manufacturing and commercial facilities, the inventory losses can vary considerably according to the business type.

Within the earthquake engineering practice, Hazus offers tables to estimate the content replacement cost as a fraction of the total construction cost depending on building occupancy: values from 50% (mainly residential) up to 150% (mainly industrial) (FEMA, 2003).

In their simplified theoretical model for failure cost evaluation in buildings, Kanda and Shah estimated the damage to contents due to structural failure as a normalized value of the initial construction cost for seven different occupation types: values for content and equipment vary from 30% for apartment houses, 100% for hospitals and up to 1000% for nuclear power plants (Kanda and Shah, 1997).

In applications related to fire hazards, in the case of a fully-developed fire, a common assumption is to consider that the content and equipment within the fire compartment would require complete replacement due to the damage caused by smoke and heat and the fire service operations, regardless of the repairability of the structure (Lange et al., 2014). Nowadays, technological and electronical equipment correspond to the highest value, and it is very likely to be also damaged by water and fire extinguishment procedures. Estimating the partial damage to content and equipment due to a pre-flashover fire within a compartment represents a challenging exercise. The same concept is valid for the estimation of the damage outside the compartment of fire origin, for example due to smoke, which is usually considered negligible and disregarded in any loss estimation calculation (Ni and Gernay, 2021).

4.2.4 Estimation of direct losses – human

So far, the loss estimation analysis has focused on the damage to material properties, but a fire in a building can also compromise the safety of the occupants and fire fighters. In a few studies, the fire-related casualties and injuries have been the focus of cost estimation analyses, such as the Canadian study by Delorme and Waterhouse where the efficiency of fire prevention was estimated as decreasing fatalities, reducing injury severity, and evacuating civilians and firefighters (Delorme and Waterhouse, 2021).

To estimate the monetary loss of human fatalities, the concept of Value of Statistical Life (VSL) is usually introduced (see also 2.3.5). This concept has been widely studied and adopted in welfare economics and in transportation risk analysis. VSL attempts to quantify the monetary value of increased safety and, in particular, the value of reducing the risk of mortality, hence preventing a statistical death (Andersson and Treich, 2011; Delorme and Waterhouse, 2021; Ramachandran and Hall, 2002; NFPA, 2017). In a recent NFPA study (2017), Zhang et al. estimated VSL as 9.6 million USD and a formula to calculate VSL from previous years has been also suggested by the U.S. Department of Transportation (U.S. Department of Transportation 2017, NFPA 2017). According to the latest report, VSL estimate is equal to 11.6 million USD using a base year of 2020 (U.S. Department of Transportation, 2021). This estimate is generally applicable for cases in the United States, but it has been shown that many parameters influence the value of human life, such as the time of the study, the population being studied and the methodological framework. For instance, in their 2021 Canadian study, Delorme and Waterhouse used a statistical value of a human life equal to 4.4 million CAN, but they also reported that VSL estimate can vary between 6.6 and 12.8 million CAN, according to different literature references (Delorme and Waterhouse, 2021). Other approaches and strategy to deal with the cost of human life are available in the literature, for example the holistic method proposed by Jonkman et al. (2010), but they are not investigated within the scope of this research study.

Similarly to VSL, also the concept of Value of a Statistical Injury (VSI) is introduced. In this case, this value attempts to quantify the value of preventing injuries. Equally to repair cost ratios, VSI is estimated as a fraction of VSL and grouped according to six Maximum Abbreviated Injury Scale (MAIS). These injury levels aim at defining coefficients that can be applied to VSL to assign each injury class a value corresponding to a fraction of a fatality: “minor”, “moderate”, “serious”, “severe”, “critical”, and “unsurvivable” (U.S. Department of Transportation, 2017; NFPA, 2017). In the 2017 NFPA study, the corresponding fraction values of VSL were defined as 0.003, 0.047, 0.105, 0.266, 0.593, and 1.000. On the contrary, in the study by Delorme and Waterhouse, only “serious” and “light” injuries were calculated and associated to 15% and 2% of VSL, respectively (Delorme and Waterhouse, 2021). It is important to highlight that the cost of an injury may also overcome the cost of human life, for example because of extensive medical costs or general loss of life quality. Taking into account feedback received by the project panel, it has become clear that the valuation of injuries is a topic which can be investigated further. For example, Thompson and

Wales (2015) report that people with minor injuries state that they would not change their behavior, suggesting that the impact of minor injuries is considered by the injured to be very small.

Once the Value of Statistical Life (VSL) and Value of a Statistical Injury (VSI) have been defined, the analysis moves towards estimating the rate of fatalities and injuries that can be expected in a specific fire event. Generally, the number of fatalities and injuries are separated and treated differently between civilians and fire service (Thomas, 2002). These numbers are expected to be influenced by the different fire safety strategies and implemented fire protection measures, but this process could be quite challenging.

As for the fire frequency and property losses, the rate of fatalities and injuries of civilians and fire fighters can be estimated using fire statistics and databases. For example, NFPA yearly compiles and publishes technical reports where these numbers are collected and discussed (NFPA, 2022). As for the case of property losses, these reports are sometimes combined to investigate overall periodical trends.

According to the latest statistics (period 2015-2019), the majority of the fires (77%) and reported civilian deaths (96%) and injuries (90%) are related to residential fires (NFPA, 2022). Specifically to the civilian injuries, 55% of those were reported as “minor”, 30% “moderate”, 9% “severe”, and 6% “life-threatening” (Ahrens, 2021). This implies that the median fire injury type is “minor”. However, this assumption could result in a significant underestimation of total injury costs, as more severe injury types would get underrepresented. As in (NFPA, 2017), a “moderate” MAIS level is usually chosen as a preferable option for the definition of a median injury type. In addition, an overestimation of the median injury type can also take into account the large number of minor fire-related injuries that are rarely reported in fire statistics, see e.g. (Ghassempour et al., 2021) for the underreporting of injuries.

On the contrary, fatalities and injuries in the fire service are usually reported with higher accuracy, since they concern health and safety in workplace. In addition, these numbers are usually divided into different categories based on the type of duty during which the fatality or injury happened: “fireground”, “responding to or returning from alarms”, “training”, “non-fire emergencies”, or “other on-duty”. According to the latest NFPA statistics (2020), most of the firefighter fatalities and injuries occur in fireground (32%) and the absolute trends are fortunately decreasing (in the United States, 62 deaths in 2020 against about 150-160 in the 1970s) (Campbell and Evarts, 2020; Fahy and Petrillo, 2021). One way to quantify the firefighters’ risk is to determine the number of fatalities and injuries per fire. The latest statistics (period 2015-2019) report numbers in the range 1.3-2.4 injuries per 100 fires and 2.4-2.7 deaths per 100,000 building fires (Campbell and Evarts, 2020; Fahy and Petrillo, 2021). These numbers are average values, and they certainly depend on many aspects. For instance, the fire departments that protect communities with larger populations have typically higher risk of firefighter injury (Campbell and Evarts 2020). Also, since residential fires are the most common, many more fatalities and injuries occur in these circumstances. However, fires in some non-residential structures, such as storage and mercantile properties, are as hazardous, if not more so, to firefighters. Surprisingly, the highest death rates in 2015-2019 were recorded in stores and offices (Fahy and Petrillo, 2021).

Nevertheless, it is important to highlight that these numbers collected by fire statistics refer to all the fire incidents, while this study focuses on fires in buildings. For example, in 2020, only 50% of fireground deaths were related to building fires, while the other 50% were related to wildland fires.

Apart from the VSL and VSI approach, other simplified methods can be also found in the literature to estimate the loss due to human consequences. For instance, in their theoretical model, Kanda and Shah estimate the cost of injuries and fatalities due to structural failure as a normalized value of the initial construction cost for different occupation types (Kanda and Shah, 1997). These values were found to vary within a wide range, from about 10-20% for residential and commercial buildings up to 100-2000 times the initial building costs for nuclear power plants catastrophes.

4.2.5 Estimation of indirect losses

Many different types of losses and associated costs can be the consequence of a fire event after its extinguishment (Thomas and Butry, 2011). Indirect losses or consequential losses are a constitutive part of the economic and societal impact caused by fires, but they are arguably the most difficult cost component to estimate (NFPA, 2017). The lack of research in this area is usually associated with the lack of usable data and well-developed techniques (Moller, 2001; Ramachandran, 1998). However, in the case of available data or performed analyses, the wide variation of values and parameters related to indirect loss estimation commonly makes the outcomes very uncertain and its relevance has been said to be often unclear (FEMA, 2003). Certain researchers have indicated that indirect losses are typically small for most fires, except a few exceptional cases (Ramachandran and Hall, 2002). On the contrary, an Australian case study highlighted that indirect losses are not negligible at all and the majority of the costs of fire (up to 96%) cannot be associated with a direct loss (Ashe et al., 2009).

In addition, the nature of indirect losses caused by a fire and their extent highly depends on the building occupancy and activity. For instance, large fires occurring in industrial and commercial properties can particularly cause consequential losses arising from loss of production, of profits, of employment, and of exports. Thus, they can destroy a significant percentage of the economic wealth of a private activity, a society, or even a country. In these cases, the need for appropriate fire safety strategies and fire prevention measures reaches its maximum level of importance because of the high risks of consequential losses (Ramachandran, 1998).

4.2.5.1 *Types of indirect losses*

Based on performed literature review, it was found that many different types of consequential losses can be indirectly caused by a fire, and they are listed and generally described in the following.

The first type concerns <u>business interruption or downtime</u>, indicating the time that a facility is not capable of conducting business or having its functionality. This can be caused by an extensive or limited damage, which leads to a period of repair, replacement, recovery, or service interruption. The downtime is a fundamental aspect for infrastructures (e.g., hospitals and fire stations) and utilities (e.g., water and electricity suppliers) with key functions. If a facility lost its functionality, it is also important to investigate the effects on adjacent infrastructures and buildings (FEMA, 2015).

A fire incident can also trigger other <u>indirect financial losses</u> at different levels. For a property owner, following a significant direct damage to the building, a fire can also highly reduce its property value. A firm can be affected by the loss of production, trade (profits), employment, market share, business growth, reputation and potentially bankruptcy. From a societal point of view, if the fire compromises businesses and therefore employment, additional costs to the society can arise from unemployment benefit payments and loss of income tax revenue (BRE Global, 2013; Cebr, 2014; FEMA, 2003; Ramachandran, 1998).

Fires can represent a serious hazard for the natural environment as well. <u>Environmental damage</u> can be caused by gaseous emissions and contamination of soil and aquatic environments, but also from the generation of new carbon emissions during the replacement and rebuild phase following a fire incident, treatment and recovery of pollutants (e.g., foams and powders), use and contamination of water to control the fire, and generation of waste (BRE Global, 2013; NFPA, 2016; McNamee et al., 2020).

Fire incidents with inappropriate fire safety measures can irremediably damage buildings of irreplaceable value, for instance heritage buildings or constructions of elevated cultural significance. Any damage to a building component or content can be inestimable due to its uniqueness.

Significant damage to buildings can also lead to a need for evacuation and relocation of building occupants and associated costs for individuals or society. For instance, the loss of function or habitability of buildings that contain housing units can result in the need for temporary alternative housing and displacement of people (FEMA, 2003). This problem can similarly arise in commercial facilities (e.g., offices).

The destruction caused by a fire has also mental effects on individuals, generating psychological damage. The collapse of homes and business facilities can destroy personal goods with sentimental value, as well as cause suffering from fatal or non-fatal injuries in families or individuals.

4.2.5.2 *Methods*

As highlighted earlier, in the literature there is not a comprehensive data source for indirect losses, particularly for fire-induced losses. Different studies have attempted to make estimates of different types of indirect losses, but no well-established method has been proposed so far.

One example is the NFPA study by NFPA, who carried out a general analysis on the total cost of fire in the United States (NFPA, 2017). They adopted an economic forecasting tool to evaluate the indirect economic impact of fires. The study underlined how the model works well for commercial facilities, but it is not applicable for residential fires. In addition, it highlighted the need for statistically strong data samples with respect to each business affected by fire.

Looking at seismic engineering, Hazus have developed an extensive methodology to evaluate the damages and losses due to a natural hazard considering all its aspects: the direct physical damages to buildings or lifelines (e.g., transportation system, utility systems), the induced damages (e.g., inundations, post-earthquake fires, hazardous material release), the social losses (e.g., casualties, household displacements), and the economic losses (e.g., loss of income, loss of function, inventory losses) (FEMA, 2003). In particular, the loss of function is associated with the overall structural damage state and quantified in terms of the time (days) necessary for building cleanup, repair and recovery.

Lange et al. applied the PEER framework developed for earthquake engineering and other extreme loading cases (e.g., wind, blast, hurricane) to carry out a decision-making analysis on structural fire engineering based on loss variables of interest, such as downtime or cost to repair (Lange et al., 2014; PEER, 2022). To calculate these quantities, they followed an approach similar to Hazus, in which they estimated the repair time and repair cost (normalized against the initial build time and cost) according to the calculated damage states obtained following a modelling-based approach.

Instead of focusing on business interruption, a recent NFPA project (McNamee et al., 2020) focused on evaluating the cost of the environmental impact of fires. For instance, this was done by following the ISO 14008 standard. This standard was developed to assist various entities with studies or reviews associated with monetary valuation of environmental impacts (ISO 14008:2019). Other studies suggested how any environmental damage can be converted into a monetary loss by defining a unit cost per ton of emitted

CO_2 (Cebr 2014). An assessment tool was developed as part of an earlier NFPA project (NFPA, 2016), in support of FRS decision-making. As the goal of this report is the development of a methodology for cost-benefit assessment and for the evaluation of macro level multipliers, environmental damage is in this report further lumped under indirect losses and not evaluated separately.

Finally, general research studies have been carried out to understand and quantify the indirect losses due to fire in different sectors (Hicks, 1979; Ramachandran and Hall, 2002). The latter were based on the assumption that small fires typically generate small indirect losses, while large fires produce larger indirect losses. Consequently, the indirect loss was measured as a fraction of the direct loss. In Ramachandran and Hall's study based on 109 fires from 1989, NFPA estimated that the indirect losses due to fire in the private sector (principally business interruption costs) were 65% for manufacturing and industrial properties, 25% for public assembly, educational, institutional, retail, and office properties; 10% for residential, storage, and special structure properties; 0% percent for vehicle and outdoor fires. The results cast doubts on the use of a constant value for the ratio between direct and indirect losses. However, the authors highlighted that "these percentages may appear low to anyone whose sense of indirect loss is based primarily on a few well-publicized incidents where indirect losses were much larger than direct damages. From a statistical standpoint, however, such incidents are more than offset by the far more numerous incidents where indirect loss is either small or nonexistent" (Ramachandran and Hall, 2002).

Finally, in their theoretical model, Kanda and Shah also assessed the cost of function loss due to structural failure as a normalized value of the initial construction cost for different occupation types: values vary from 10% for residential buildings, 200% for nuclear power plants and up to 1000% for hospitals and fire stations (Kanda and Shah, 1997). In this research, an attempt was also made for the psychological consequences of fires, estimated as low as 10-20% of the initial construction cost for most buildings, but 100% for private houses.

4.2.5.3 *Discussion*

In general, the literature review has highlighted the need for comprehensive methodologies and data sources related to the assessment of indirect losses due to fire. In particular, it was found how the nature of the analysis can fundamentally change depending on the situation characteristics and analysis objectives.

Specifically for this research project, it is very challenging to explicitly quantify the effect of various fire protection measures on indirect losses. To achieve the purpose of this analysis, the "indirect loss" should depend on different fire safety strategies. Only in this way the impact on costs and losses can be observed for different fire protection measures. However, if a certain fire protection measure is expected to reduce the direct losses, this will certainly reduce the indirect losses as well, regardless of how they are estimated.

Finally, it is important to underline that the indirect or consequential losses can be assessed at two main levels: private (e.g., individual, family, firm) and societal (e.g., national economy), see 2.2.3. Based on the defined level, indirect losses can be more or less relevant depending on the analysis perspective (Ramachandran, 1998). In fact, indirect losses are perceived differently if they concern an individual company or the entire society: different costs associated with fires do not fall equally on all parties (Ramachandran and Hall, 2002). For societal decision-making, it is relevant to consider indirect losses only if they affect society as a whole. Major consequences are usually expected for specific types of buildings, whenever the functioning of society is questioned due to an adverse event, such as fires in key infrastructures like nuclear power plants or facilities that provide essential needs (e.g., water). For typical building fires, this becomes only relevant if a large number of buildings is affected, like in wildfires. On the contrary, the burnout of a company's warehouse and the loss of inventory and production capacity, which may result in bankruptcy, primarily impact private decision-making (Fischer, 2014). However, at the national level, the loss may be compensated by competitors, which may increase their production capacity and sustain the national economy. In general, double-counting of indirect losses should be avoided because some costs relevant to one member of society may be offset by benefits accruing to others. Overall, if all indirect losses and gains due to fires occurring in a country or geographical area are added together, their net contribution at the national level is likely to be small (Ramachandran, 1998).

4.3 Prototype Methodology for the Evaluation of Fire Losses

Based on the presented extended literature review on approaches and methodologies for estimation of fire losses, a prototype methodology is proposed for the evaluation of fire losses. A flowchart illustrating the prototype methodology and the main steps to estimate the losses caused by a fire event in buildings are shown in Figure 4. In the following, the different steps are generally described and in the next phase of the project the methodology is applied in detail to a set of case studies.

4.3.1 Input variables and information

To carry out the analysis of fire-induced losses, some parameters and information related to the building and its characteristics are needed as input. The building occupancy class and the structural system (FEMA, 2003) can be chosen throughout the options described in Section 3. This information is fundamental to identify the main building characteristics and, in particular, to estimate the unit construction and replacement costs, which can be evaluated according to different databases (e.g., (RSMeans, 2022)), as explained in Section 3.

Any information related to the implemented fire safety strategy and fire protection measures are also of key importance, especially if the overall analysis aims at understanding the benefits and losses of installing or removing a certain fire protection measure.

In addition, if a modelling-based approach is foreseen, all the building characteristics and detailed information should be collected to exhaustively formulate the model used to estimate the damage or loss occurred in the building exposed to specific fire scenarios.

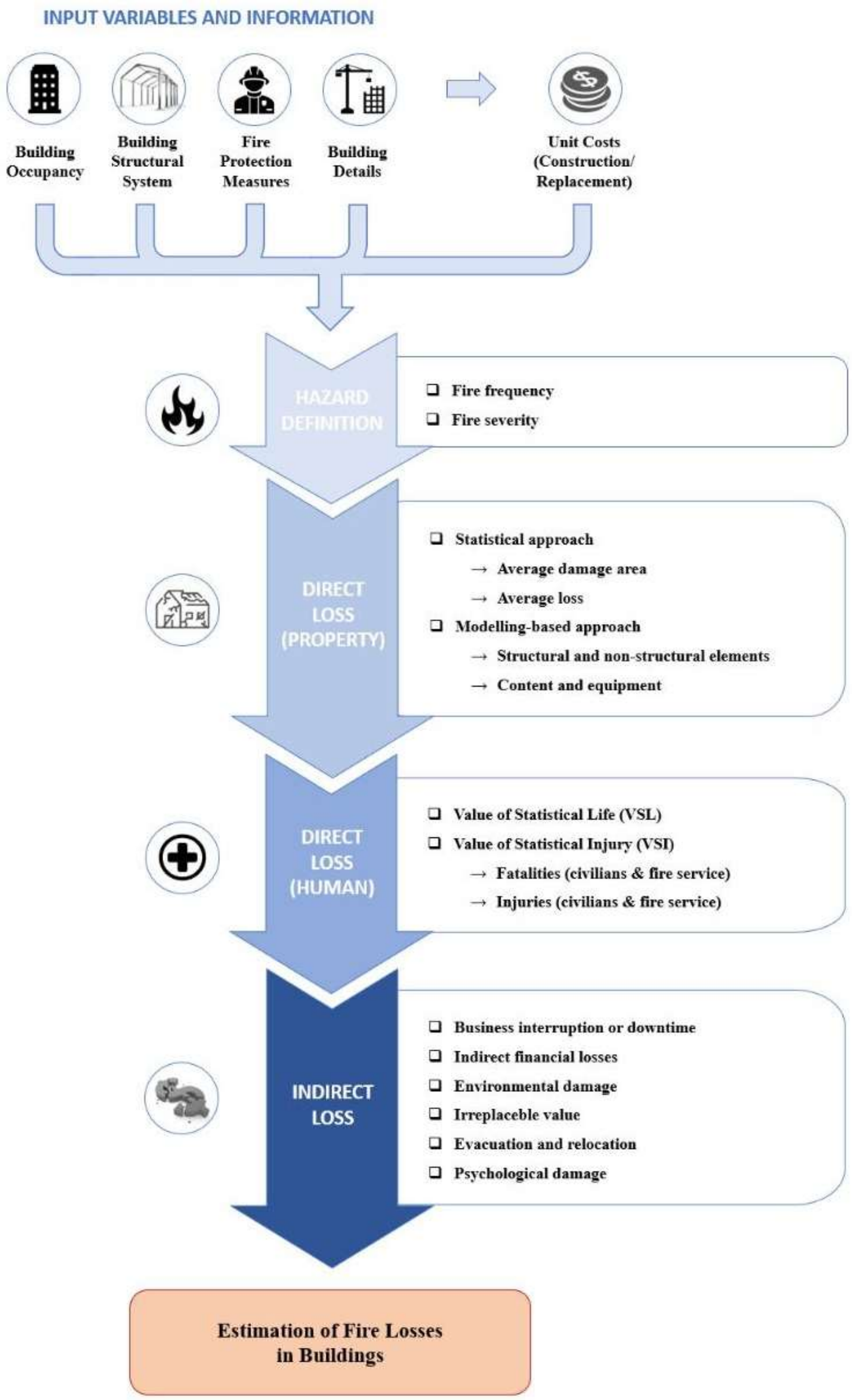


Figure 4. Flowchart illustrating the prototype methodology for estimation of fire losses in buildings.

4.3.2 Hazard definition

Once the building characteristics and unit costs are collected, the next phase concerns the definition of the fire hazard. As highlighted in the literature review, a fire event is usually defined in terms of a frequency/probability of occurrence (fire frequency) and an intensity measure (fire severity).

Depending on the building characteristics, primarily its occupancy, the probability of occurrence of "fire ignitions" and "structurally-significant fires" can be estimated using different sets of fire statistics (e.g., American National Fire Incident Reporting System (NFIRS) (NFIRS, 2022) or the British Fire Protection Association (FPA) Large Loss Database (FPA, 2022)). For fire ignitions, empirical or more complex models can also be adopted, for instance power relationships based on the building occupancy and size (Fischer, 2014; Manes and Rush, 2019; Ramachandran, 1998), while the probability of structurally-significant fires can be approximated using structural codes, for instance Eurocode (EN1991-1-2:2002; Vassart et al., 2014).

It is central to underline that, if a statistical approach is chosen, conditional probabilities of fire occurrence for various design options, such as different fire protection measures, have to be estimated. This can be done using a range of data sources and fire statistics, and it represents a key, but challenging, step for the estimation of fire losses.

For modelling-based approaches, the definition of the fire scenario (fire severity) is normally a necessary step. Depending on the focus of the analysis, pre-flashover (e.g., αt^2) or post-flashover fires (e.g. parametric fire curves) can be defined in terms of time-history of temperature, heat flux, heat release rate, or other (Drysdale, 2011; EN1991-1-2:2002).

The definition of the fire frequency and fire severity can be done in a probabilistic or deterministic way, based on the available information and the depth of the analysis.

4.3.3 Estimation of direct losses – property

4.3.3.1 *Statistical approach*

Following a statistical approach, most of the fire statistics previously mentioned for the estimation of fire frequency can be also employed to approximate an average fire-damaged area. In this case, the property loss can be calculated as the product with the construction/replacement cost per unit area. Otherwise, some fire statistics (e.g., American National Fire Incident Reporting System (NFIRS) (NFIRS, 2022)) can be used to approximate an average total loss caused by a fire incident directly for a building with a specific occupancy and fire risk category. In a fully-statistical approach, the real challenge is again to associate the effect of different fire protection measures with the damage and the loss due to fire.

4.3.3.2 *Modelling-based approach*

Modelling-based approaches mainly rely on detailed models and simulations to analyze the building performance and quantify the damages and losses resulting from the defined fire hazard. The model choice (e.g., structural finite-element model or computational fluid-dynamics) primarily depends on the analysis objectives.

Using the built model, the damage to structural elements can be estimated. Building damages are usually categorized into several damage classes or levels of damage. For example, the well-established damage classification in earthquake engineering adopted by Hazus can be selected to associate damages to building components to four damage states: "slight", "moderate", "extensive", and "complete" (FEMA, 2015). A detailed description of the damage states for each structural building types, both for structural and non-structural elements, is also reported in the cited document. After the damage classification, the replacement or repair cost of structural elements can be estimated according to the damage states previously defined, depending on the building occupancy. For instance, following the same methodology, Hazus defines default values of direct economic loss based on loss ratios corresponding to each state of damage: a loss of 2%, 10%, 50%, or 100% of the building's replacement cost, respectively, for the aforementioned damage states (FEMA, 2015). Replacement and repair costs of structural elements can also be obtained more in detail according to a detailed evaluation of different repair actions and adopting construction costs databases. Otherwise, in case of complete damage of the structural system, the replacement cost can be estimated using Table 5, in which it is approximated as a fraction of the total construction cost depending on different variables, such as building occupancy or structural system type. For instance, for an office building, the 38% of the total building cost is associated with structural components and 62% with non-structural components.

Table 5 – Replacement cost of structural and non-structural elements cost estimated as a fraction of the total construction cost depending on building occupancy (FEMA, 2015, Table 7.3).

Common Combinations of Occupancy and Building Type (Occupancy Group)	Fraction of Total Building Cost		
	Structural System	Nonstructural Systems (Percent of Total Nonstructural Cost)	
		Drift-Sensitive	Accel.-Sensitive
Single-Family Residences – RES1/W1 (All Single-Family Residences)	0.25	0.49 (65%)	0.26 (35%)
Multi-Family Residences – RES3/W1 (All Non-Single-Family Residences)	0.18	0.41 (50%)	0.41 (50%)
Retail Commercial – COM1/S1M (All Commercial Buildings)	0.38	0.25 (40%)	0.37 (60%)
Light Industrial – IND2/PC1 (All Industrial Buildings)	0.27	0.11 (15%)	0.62 (85%)

Regarding non-structural components of the building, their damage and loss can be thoroughly estimated using the outcomes of the built model and according to the same approach defined for structural elements. Otherwise, similarly to the structure, the replacement cost of non-structural components can be estimated as a fraction of the total construction cost depending on various buildings variables. If no additional information is available, common assumptions are to consider the same structural and non-structural components in each fire compartment, structural and non-structural components fully damaged (require complete replacement) within a compartment affected by a post-flashover fire, and no damage outside the compartment of fire origin (if no bridge of compartmentation is verified).

Lastly, the content and equipment replacement cost can be estimated as a fraction of the total construction cost depending on building occupancy, as shown in Table 6. For instance, in residential buildings, the replacements cost is 50%, in technical and professional services (e.g., offices) is 100%, and in heavy and light industrial facilities is 150%. Similarly to structural and non-structural components, in absence of more detailed information, common assumptions are to consider homogenously-distributed content over building volume, fully-damaged content within the fire compartment and no damage outside it (if no breach of compartmentation is observed).

Table 6 – Content replacement cost estimated as a fraction of the total construction cost depending on building occupancy (FEMA, 2003, Table 3.10).

No.	Label	Occupancy Class	Content Value (%)
	Residential		
1	RES1	Single family dwelling	50
2	RES2	Mobile home	50
3	RES3	Multi family dwelling	50
4	RES4	Temporary lodging	50
5	RES5	Institutional dormitory	50
6	RES6	Nursing home	50
	Commercial		
7	COM1	Retail trade	100
8	COM2	Wholesale trade	100
9	COM3	Personal and repair services	100
10	COM4	Professional/Technical/ Business Services	100
11	COM5	Banks	100
12	COM6	Hospital	150
13	COM7	Medical office/clinic	150
14	COM8	Entertainment & recreation	100
15	COM9	Theaters	100
16	COM10	Parking	50
	Industrial		
17	IND1	Heavy	150
18	IND2	Light	150
19	IND3	Food/drugs/chemical	150

4.3.4 Estimation of direct losses - human

The monetary loss of human fatalities and injuries can be estimated based the concept of Value of Statistical Life (VSL) and Value of a Statistical Injury (VSI), assessed as a fraction of VSL. According to the latest reports, in the United States the VSL estimate is equal to 11.6 million USD (U.S. Department of Transportation, 2021). On the other hand, VSI depends on the seriousness of injuries, usually grouped according to six Maximum Abbreviated Injury Scale (MAIS): “minor”, “moderate”, “serious”, “severe”, “critical”, and “unsurvivable” (U.S. Department of Transportation, 2017). These injury levels have been associated with fraction values of VSL: 0.003, 0.047, 0.105, 0.266, 0.593, and 1.000, respectively (NFPA, 2017). It is highlighted however that the definition of these fractions would benefit from in-depth research, noting that both the direct and indirect costs of fire related injuries may differ significantly from those in other areas.

Once VSL and VSI are defined, the analysis requires an estimation of rate of fatalities and injuries of civilians and fire fighters, usually separated and collected in a different manner. This can be done using yearly or periodical fire statistics and databases, such as the NFPA technical reports (NFPA, 2022). The number of fatalities and injuries can be expressed as a rate per year or a number of fatalities/injuries per a certain number (e.g., 100,000) of building fires (statistical approach). This can also be done using modelling-based approaches, for example using building fire evacuation models . As regards to injuries, a common way to estimate the direct losses is to define a median injury, approximated as the average injury based on the distribution of the injury levels.

In general, it is important to make sure that the numbers of fatalities and injuries refer to the specific category of fires and buildings that is the focus of the analysis. These numbers are expected to be influenced by the different fire safety strategies and implemented fire protection measures, but this quantification is typically quite challenging.

4.3.5 Estimation of indirect losses

As highlighted in the literature review, the estimation of indirect losses due to fire is highly challenging and uncertain due to the lack of comprehensive data and a well-established methodology. In addition, the characteristics of this loss analysis can be fundamentally different case by case.

The literature review has investigated the diverse natures of indirect losses caused by fires: business interruption or down time, indirect financial losses (property owner, firm, society), environmental damage, loss of buildings of extreme value, evacuation and relocation of building occupants, and psychological damage. A few studies and methodologies have been mentioned. It was found that different indirect losses can be relevant depending on the building occupancy and functionality, and the consequential losses can range from negligible up to extremely important.

In this methodology, it is deemed necessary to include indirect losses in the cost-benefit assessment, based on the literature review showing their possible significance. Neglecting indirect losses would lead to an underestimation of the impact of fires and hence an underestimation of the benefits of fire safety investments. Yet, given the uncertainty and lack of data on indirect losses, estimates must be made. It is recommended to use sensitivity analyses to test the robustness of the findings against different assumptions on indirect losses.

A really important aspect of the indirect losses estimation analysis is the perspective. Consequential losses can be assessed at private and societal level. At a national level, all the stakeholders affected by the fire should be considered, without double-counting indirect losses that may be offset by other members of the society.

5 Summary of Data Sources

The prototype methodologies presented above require data to inform the evaluations. To provide an overview of data availability and data gaps, data sources and data gaps listed in the Sections above are grouped below.

5.1 Available Data Sources

Category	Sub-category	Data Source
Cost of Fire Protection	Installation costs	These references contain the cost of materials, labor and equipment necessary for installing fire protection systems in buildings RSMeans datasets: - the Facilities Construction Costs manual (Gordian, 2021a) - the Residential Costs manual (Gordian, 2021c) - Square Foot Costs (Gordian, 2021e) - Building Construction Costs manual (Gordian, 2020) All these data can also be found in the RSMeans' online database (Gordian, 2021d). Australian construction costs: Rawlinson's Australian Construction Handbook [Group 2006]. This reference includes a range of percentages of overall construction costs dedicated to fire protection systems
	Maintenance costs	Reference for the maintenance period of the components and their corresponding costs. Whitestone Building Maintenance and Repair Cost Reference (Lufkin & Pepitone, 2010): an annual publication detailing the cost of maintenance for the different components of fire protection measures. RSMeans data manual Facilities Maintenance and Repair manual (Gordian, 2021b). This data can also be found in an easy to search online database (Gordian, 2021d).
Cost of building construction	Macro	U.S. Census Bureau's annual publication on cost of construction (U.S. Census Bureau, 2021) Australian data can be found in the Australian Bureau of Statistics' annual publication on construction expenditure (Australian Bureau of Statistics (ABS), n.d.) Canadian construction expenditure data published by Statistics Canada (Statistics Canada, 2021)

Fire loss	Fire frequencies	These databases only contain data on relevant fires attended by public fire departments, typically where a fatality occurred, or the fires caused extensive damage. Therefore, using these data excludes small or extinguished fires and consequently they cannot be considered as fully reliable source to estimate the probability of fire ignition. The EU FireStat project (EU FireStat, 2021) provides a comprehensive overview. The most used and well-established fire recording systems and fire statistics are from England/UK and the USA (Manes et al., 2021), such as the American National Fire Incident Reporting System (NFIRS) (NFIRS, 2022), the English statistics collected by Home Office (Home Office, 2022) or the British Fire Protection Association (FPA) Large Loss Database (BRE Global, 2013; FPA, 2022).
	Fire damaged area	The average fire-damaged area can be estimated from various fire statistics and databases, like the American National Fire Incident Reporting System (NFIRS) (NFIRS, 2022) and the British Fire Protection Association (FPA) Large Loss Database (FPA, 2022).
	Fire loss	The American NFIRS database provided by the U.S. Fire Administration reports loss estimates made by fire response personnel (Ahrens and Evarts, 2021; NFIRS, 2022).

5.2 Data Gap

Important data gaps exist with respect to the fire safety impact of fire protection measures. Specifically, the granularity of current statistics often does not allow to compare, on a statistical basis, the influence of different fire safety measures.

- A particular gap in available data for computing the cost of fire protection is the lack of data on the macro level construction expenditure for the sub categories under residential buildings. Although this study has found it prudent to split the residential buildings category into multiple sub categories, the data on annual construction expenditure in this category is reported as a lump sum by the U.S. Census Bureau. This makes it difficult to compute the macro level fire expenditures for each of the sub categories using the established procedure.
- The EU FireStat project (EU FireStat 2021) provides a comprehensive overview on the collection and organization of fire statistics in Europe. Similar conclusions can be drawn for other countries around the world. However, the fire statistics are not homogenized worldwide, and many key parameters are rarely collected, as highlighted by Manes et al. (Manes et al. 2021). To carry out comprehensive cost-benefit analyses using a statistics-based approach, there is a need to collect fire statistics of higher quality in a more structured manner. Only in this way, the effect of different fire protection systems can be associated with different frequencies and severities of fire events, as well as well different direct and consequential losses. In the absence of such data, a modelling-based approach is used.

6 Case studies – background and discussion

6.1 Introduction

This Section applies the methodology for evaluating the total benefits and costs related to fire protection features in buildings to five case studies. The calculations are completed in Jupyterlab scripts which are provided together with this report (one for each case study). This Section describes the main data, inputs, and assumptions used in the calculations, and provide the results of the Present Net Value analyses. Sensitivity analyses are also provided for illustration of the effect of some key assumptions. Coding of the methodology in the Jupyterlab environment allows for easy modification of the inputs and assumptions in the case studies. This also allows easy updating of inputs as data becomes updated (e.g., on building construction costs), additional data becomes available (e.g., on indirect costs), and other case studies are considered.

The case studies provide a demonstration of the prototype methodology. Since the goal is to demonstrate application of the methodology, their outcomes should not be readily generalized to draw definite conclusions on effectiveness of particular fire protection measures for broad classes of buildings. In the following, the input and output of the case studies are presented. The calculations themselves are performed in a JupyterLab (Python) environment which has been made available together with this report. Interested readers can readily modify input values within the JupyterLab, or even add cost components in the assessment, to explore the effect on the cost-benefit evaluation. The cost-benefit calculations themselves are quasi-instantaneous. For case studies 4 and 5 advanced structural fire engineering (SFE) calculations have been performed. The output of these SFE calculations is taken into account within the JupyterLab, but the SFE calculations themselves are not part of the workflow (i.e., inputs cannot be readily updated by the reader).
All case studies are executed from the perspective of a code-maker and thus adopt a societal perspective on costs and benefits. This is of importance notably with respect to (i) the valuation of risk to humans; (ii) the discount rate; (iii) indirect costs; and (iv) subjective cost components. Also, insurance effects are thus not considered. Through parameter studies, the initial societal evaluation is extended to a possible private assessment. Note however that it is fully acceptable for a private assessment to consider a very high discount rate (reducing the lifetime benefit of upfront fire safety investments), or to consider additional subjective costs for specific fire safety solutions (such as an aesthetic cost) or very high/low indirect costs. The code-maker perspective also implies that (a) the FRS capabilities are considered a given, and are outside the optimization (i.e., the code-maker cannot make a trade-off between investments in the FRS and investments in compartmentation); (b) trade-offs allowed by existing guidance documents do not result in costs or benefits; and (c) that business interruption costs are generally limited as the code-maker takes a broad societal approach whereby the economic losses by some parties are compensated by gains for other parties. On a private level or at the level of a community, however, the aftermath of a fire can have important consequences on (e.g.,) employment.

The above also implies that the cost evaluation is for an "average" (prototype) building, and that location-specific costs can be different. For example, it is acknowledged that the detailed cost evaluation of sprinkler systems is a complicated procedure which will depend on the goal of the system (life safety versus property protection). As part of the case studies, reference values have been adopted. Similar comments apply to e.g., detection systems and compartmentation. Thanks to the JupyterLab implementation readers can readily explore the impact of adjusted assessments.

The case studies start from the existing level of fire protection in society. This allows for the consideration of fire statistics (which can be considered a direct observation of the effectiveness of existing fire protection measures). Thus, the question asked is (notably in case studies 1-2-3) whether additional fire safety investments are cost-effective. This framing of the cost-effectiveness evaluation implies that it can be expected upfront that many proposals for additional investments in fire safety will be found to be not cost effective. The opposite finding (i.e., that many proposals for additional investments are indeed cost effective) would indicate that the current level of fire protection should be increased. It is expected that the optimum level of fire safety investment increases over time, but also that this has already been considered in the past through trial and error approaches and more subjective decision making by code making bodies.

All relevant upfront and recurring costs are deemed to be included in the installation and maintenance costs (in other words: discussion on the inclusion yes/no of any such cost-item is equivalent to a discussion of the magnitude of the cost-item). No detailed costing has been done, both for generality and practicality. It is nevertheless highlighted that, for example, sprinklers naturally need a water supply and possibly booster pumps to operate.

Other case studies can be considered, e.g., high-rise office occupancy. The case studies below are not intended to be exhaustive.

6.2 Case 1 – Residential single-family dwelling: net benefit of sprinkler protection

Case 1 applies the prototype methodology to the assessment of the net benefit of sprinkler protection for wood light-frame single-family residential buildings (RES1). The assessment is done considering statistical data. The building prototype is a two-story townhouse inspired by the case study in (Butry, 2009), and has a total floor area of 210m^2.

Figure 5: Example single-family residential building considered in Case Study 1.

6.2.1 Input

6.2.1.1 *Building characteristics*

Construction, demolition and disposal costs are assessed through the RSMeans database (Gordian, 2022), considering national averages. These costs are summarized in Table 7. The reconstruction cost is the combined cost of demolition, disposal and (renewed) construction.

6.2.1.2 *Discount rate and obsolescence rate*

A discount rate of 3% is adopted, based on (Fischer, 2014). Obsolescence is neglected (i.e., an obsolescence rate of 0% is adopted).

6.2.1.3 *Cost of fire protection, and macro-level cost multiplier*

A basic fire detection system is considered to be the standard fire protection in the building. The cost of sprinklers is evaluated for consideration within the CBA. The costs are assessed through the RSMeans database (Gordian, 2022) as detailed in Table 8. The costs for the smoke detectors are unexpectedly high. This influences the obtained fire protection cost multiplier. The cost multiplier can be readily updated considering improved cost information. The sprinkler cost has been assessed taking into account the cost evaluation of (Butry et al., 2007). An annual maintenance cost of 5% has been adopted as in (Hopkin et al., 2019). This maintenance cost is assumed to include the replacement cost of parts to allow for indefinite lifetime extension.

Table 7 – Construction, demolition and disposal costs.

Construction cost	
Construction cost (Residential single-family house, 2 story brick veneer – wood frame, includes smoke detector cost)	1,305.5 USD/m^2
Demolition cost	
Volume (considering 8ft floor height)	511.3 m^3
Total demolition cost (0.39 USD/ft^3)	7,041.8 USD
Demolition cost	33.5 USD/m^2
Disposal cost	
Waste from walls, floors, roof.	109 m^3
Total disposal cost (850 USD per 40 yd^3)	3,030 USD
Disposal cost	14.4 USD/m^2
Replacement cost	
Demolition + disposal + (re-)construction	1,349.9 USD/m^2

Table 8 – Cost of fire protection.

Cost of smoke detectors	
Cost for single detector (assumed to include any maintenance cost)	248 USD/detector
Number of detectors (assumed 1 per story + 1 in the kitchen)	3 detectors
Cost of smoke detectors per m²	$248\frac{USD}{detector}\cdot\frac{3\ detectors}{210\ m^2}=3.54\frac{USD}{m^2}$
Cost of sprinkler system	
Cost of sprinkler system installation per m²	11.68 USD/m²
Annual maintenance cost for sprinkler system (assumed to include replacement cost for lifetime extension)	5%
Macro level cost multiplier	
Installation cost multiplier for reference design (detectors only)	$\frac{3.54\ USD/m^2}{1302\ USD/m^2}=0.27\%$
Installation cost multiplier for design with detectors and sprinklers	$\frac{3.54\ USD/m^2+11.68\ USD/m^2}{1302\ USD/m^2}=1.17\%$

6.2.1.4 *Benefit of fire protection (fire risk parameters)*

Fire risk parameters obtained from statistics are listed in Table 9, together with the associated reference. The valuation of the fatality and injury risk is done through the VSL and VSI approach, as discussed in the main document. For the VSI, the moderate injury class is adopted as the average, based on (NFPA, 2017).

Table 9 – Benefit of fire protection (fire risk parameters).

Parameter	Value	Reference
Fire frequency (reported fires)	0.00151 per year	(Manes and Rush, 2019)
Probability of successful fire suppression by sprinklers	0.95	(Vassart et al., 2014)
Civilian fatality rate	7.4 per 1,000 reported fires	(NFPA, 2022)
Civilian injury rate	3 per 100 reported fires	(NFPA, 2022)
Firefighter fireground fatality rate	2.4 per 100,000 reported fires	(Fahy and Petrillo, 2021)
Firefighter response fatality rate	2.2 per 100,000 reported fires	(Fahy and Petrillo, 2021
Firefighter fireground injury rate	1.62 per 100 reported fires	(Campbell and Evarts, 2021)
Firefighter response injury rate	0.37 per 100 reported fires	(Campbell and Evarts, 2021)
Average damage area without sprinkler suppression	35.69 m²	(Manes and Rush, 2019)
Average damage area with sprinkler suppression	4.92 m²	(Manes and Rush, 2019)
Content loss factor	1.5	(FEMA, 2015)
Indirect loss factor	1.1	(Ramachandran and Hall, 2002)

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 value adopted from (Manes and Rush, 2019) is within the same order of magnitude as the value listed, for example, in PD 7974-7:2003 for dwellings and in (Butry, 2009).

Successful sprinkler suppression relates to the situation whereby the sprinkler system operates and manages to control the fire. This manifests itself through markedly different average fire losses (Table 9).

The civilian fatality rate considers 2,761 residential fire deaths in the USA on a total of 377,399 reported fires (average values for 2015-2019), based on (NFPA, 2022). Considering (Fahy and Petrillo, 2021), a distinction can be made between firefighter deaths at the location of the fire, and deaths while responding to or returning from alarms. The civilian injury rate is assessed through (NFPA, 2022), taking into account 11,582 injuries reported for 377,399 fires (averages 2015-2019). The firefighter fireground injury rate is listed by (Campbell and Evarts, 2021). These constitute 35% of the total firefighter injury rate, while response injuries constitute 8%. The reduction of fatalities and injuries for sprinkler suppressed fires is elaborated as part of the fire risk model, as these are considered to be modelling assumptions (limited statistical data is available).

The property loss areas are obtained from (Manes and Rush, 2019), which is based on 2014 USA fire statistics. In accordance with (FEMA, 2015), the replacement cost for the contents of a residential single-family dwelling is valued at 50% of the construction cost of the property. For residential properties the indirect loss was estimated as 10% of the direct loss in (Ramachandran and Hall, 2002). This indirect loss value is added to the total property loss.

6.2.2 Fire risk evaluation for the design alternatives

6.2.2.1 *Scenario definition*

Risk reduction is the net benefit obtained from fire safety systems. This risk reduction is assessed by comparing the risk level without the investigated fire safety systems (i.e., the risk level for the reference design), with the risk level for the design with the fire safety systems. Risk assessments can be very complex. Often however, a simple model and appropriate sensitivity analyses suffice to draw conclusions on the net benefit of a proposed fire safety scheme.

Figure 6 visualizes the event tree for the considered case. The event tree defines two scenarios: (i) “no sprinkler suppression”, and (ii) “successful sprinkler suppression”. The consequences for each scenario are assessed in the following. The risk associated with a design considers these scenario consequences together with their probabilities. This is done within the PNV evaluation.

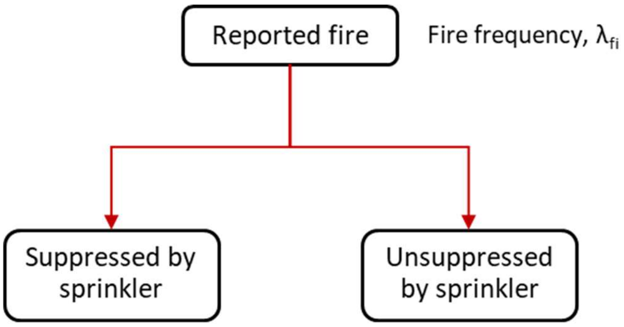


Figure 6 – Event tree defining scenarios for Case 1.

6.2.2.2 *Consequence evaluation for scenario "no sprinkler suppression"*

For the scenario "no sprinkler suppression", fatality and injury rates for civilians and firefighters (both fireground and response) are considered as listed in Table 8. Also, the average damage area is listed in Table 8.

6.2.2.3 *Consequence evaluation for scenario "successful sprinkler suppression"*

Successful fire suppression results in a reduction of the fatality and injury rate. Civilian injuries are reduced by 57%, based on (Butry, 2009), while the fatality rate is considered to be reduced to very low levels (modelled as a fatality rate of zero), also based on (Butry, 2009). Similarly, firefighter fireground fatalities and injuries are considered to be reduced to negligible levels. The firefighter response fatalities and injuries are however not affected. The average damage area is based on statistics listed by (Manes and Rush, 2019), see Table 8.

6.2.3 PNV evaluation

The PNV evaluation is done considering the prototype methodology. See the JupyterLab implementation for the step-by-step calculation. Considering the inputs as listed above, the total PNV investment cost (i.e., including maintenance and obsolescence) is 6,450.8 USD. The PNV net benefit of sprinkler implementation is 5,722.6 USD. As the benefit is smaller than the cost, the safety measure is not recommended for implementation on a cost-benefit basis. The obtained cost-benefit indicators are listed in Table 10. As only a single alternative design is considered, the BCR/CBR indicators and the PNV evaluation both give the same conclusion: for the considered case sprinkler installation is not beneficial on economic grounds.

Table 10 – Cost-benefit indicators for Case 1.

Parameter	Value	Conclusion
BCR	0.87	Investment not recommended
CBR	1.14	Investment not recommended
PNV	-823 USD	Investment not recommended

6.2.4 Cost visualization and parameter study

6.2.4.1 *Cost visualization*

The PNV evaluation of 6.2.3 concludes the demonstration of the prototype methodology. To grasp the background to the cost-benefit conclusion, however, it is valuable to do a cost breakdown for both design alternatives. Figure 7 highlights how the sprinkler system considerably reduces the fire-induced costs compared to the design without sprinklers. The installation and (especially) the maintenance costs are however of such a magnitude that sprinkler installation is not recommended. Note that the PNV maintenance cost will reduce in case a larger discount rate or a smaller annual maintenance cost is considered. The discount rate of 3% is recommended for societal decision-making (see 2.3.2). Private decision-makers may prefer a higher discount rate.

This analysis shows that, while with the current assumptions the installation of sprinklers in single-family dwellings is not economically justified in terms of cost-benefit, it is possible that in the future with a reduction in the cost of maintenance of sprinkler systems the PNV might become positive, and therefore the installation of sprinklers in single-family houses beneficial from a societal point of view.

6.2.4.2 *Parameter study*

A parameter study is conducted whereby the VSL, indirect cost ratio and the sprinkler success rate are changed. Results are visualized in Figure 8. On the horizontal axis, the magnitude of the indirect cost is listed. As the indirect cost increases, the net benefit Z increases for all investigated cases. The investigated cases are grouped for 3 different VSL values (in millions of USD), i.e., a value of 11.6 based on (NFPA, 2017), 5.7 based on ISO 2394:2015, and a lower value of 2.8 for comparison. Figure 8 highlights how the decision on the VSL is very important for the cost-effectiveness conclusion in this specific case. If the VSL of 11.6 million USD is adopted, sprinklers are found to be cost-effective irrespective of the magnitude of the indirect cost. In case of a VSL of 2.8 million USD, the calculation indicates that sprinklers are only cost-effective if the indirect cost is very high (much higher than what is commonly expected for residential housing). The situation with VSL of 5.7 million USD is intermediate, with cost-effectiveness being achieved at intermediate indirect cost percentages. For each VSL value, 3 different sprinkler reliabilities are considered: 0.92, 0.95, and 0.98, based on (Vassart et al., 2014). Within the considered range, the precise value of the sprinkler reliability however has less impact. See the JupyterLab implementation for the underlying code. The parameter study highlights that the conclusion on cost-effectiveness of sprinklers in dwellings is not clear cut. It is recommended to clarify the costs and benefits in further detail, paying attention also to the costs of inadvertent sprinkler activation and possible user meddling with sprinkler effectiveness if such inadvertent sprinkler activation would happen to occur.

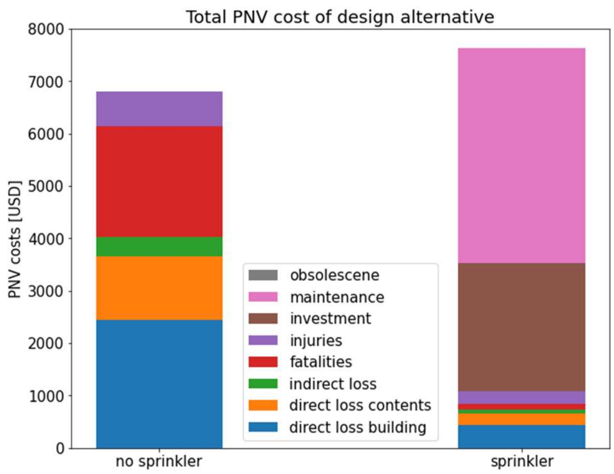


Figure 7 – PNV breakdown for Case 1.

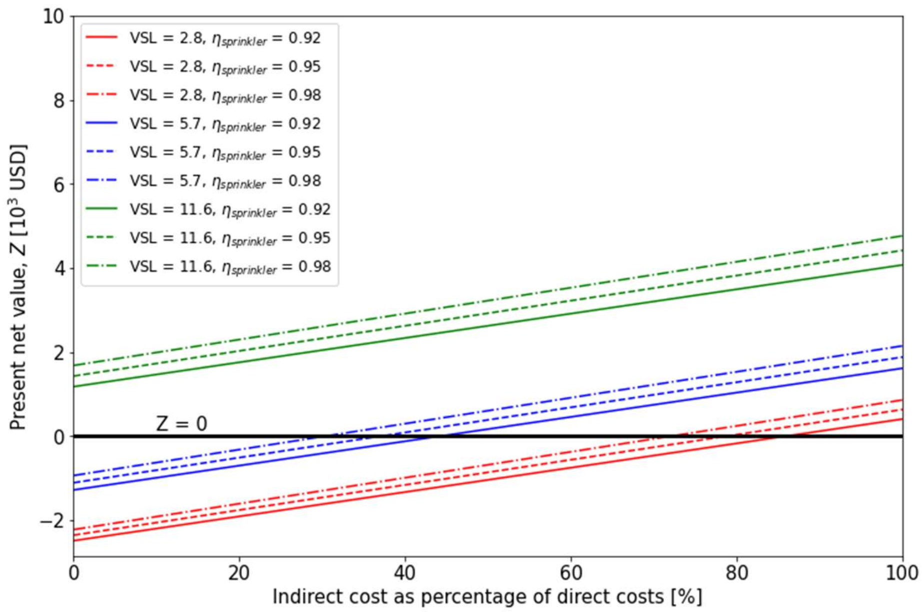


Figure 8 – Parameter study for Case 1.

6.3 Case 2 – Warehouse: net benefit of sprinkler protection and compartmentation

Case 2 applies the prototype methodology to the cost-benefit evaluation of sprinkler protection and compartmentation in a low-rise steel moment frame commercial warehouse (COM2). A total floor area of 6000 m^2 is considered, with a ground plan of 60 m by 100 m. This warehouse classifies as medium-sized, considering (BRE Global, 2013). The case study is developed for a remote location whereby FRS intervention before flashover is unlikely. A parameter study is included whereby early FRS intervention (i.e., well connected location) is considered.

6.3.1 Input

6.3.1.1 *Building characteristics*

Construction, demolition and disposal costs are assessed through the RSMeans database (Gordian, 2022). These costs are summarized in Table 11.

Table 11 – Construction, demolition and disposal costs.

Construction cost	
Construction cost (Single story warehouse, 100 m x 60 m x 7 m; includes smoke detector cost)	1,075.2 USD/m^2
Demolition cost	
Total demolition cost (0.39 USD/ft^3)	608,160 USD
Demolition cost	101.36 USD/m^2
Disposal cost	
Disposal cost	10.7 USD/m^2
Replacement cost	
Demolition + disposal + (re-)construction	1,187.3 USD/m^2

6.3.1.2 *Discount rate and obsolescence rate*

A discount rate of 3% is adopted, based on (Fischer, 2014). Obsolescence is neglected (i.e., an obsolescence rate of 0% is adopted). The considered discount rate can be considered typical for a societal decision-maker (i.e., a code-making body). Private decision-makers are free in their decision on the discount rate. Commercial constraints may likely result in a higher discount rate. 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 cost and higher maintenance costs (relative to other fire protection measures which rely on a higher upfront investment and lower maintenance costs).

6.3.1.3 *Cost of fire protection, and macro-level cost multiplier*

A basic fire detection system is considered to be the standard fire protection in the building. The cost of sprinklers and compartmentation are evaluated for consideration within the CBA. The costs are assessed through the RSMeans database (Gordian, 2022) as detailed in Table 12. An annual maintenance cost of 5% has been adopted for the sprinklers as in (Hopkin et al., 2019). This maintenance cost is assumed to include the replacement cost of parts to allow for indefinite lifetime extension. As sprinkler systems require a water supply for their operation, the installation and maintenance costs are deemed to include these. The compartmentation considers the minimum length needed for dividing the warehouse in the listed number of compartments (all compartments are of equal size). A compartment wall buildup of concrete blocks with gypsum plaster coating (both sides) has been considered. The fire rating of the concrete wall (thickness 6 inch or approximately 15cm) is considered to exceed 30 minutes. It is assumed that no maintenance cost applies to the compartmentation (i.e., that any occasional costs for maintaining the compartmentation are negligible relative to the other cost components).

6.3.1.4 *Benefit of fire protection (fire risk parameters)*

Fire risk parameters obtained from statistics are listed in Table 13, together with the associated reference.

The fire frequency is evaluated considering the area-dependent formulation for storage buildings (USA data) listed by (Manes and Rush, 2019) and is considered to already include early suppression by occupants. The fire brigade success rate relates to a professional fire and rescue service with (expected) arrival time within 10 minutes (Vassart et al., 2012). The civilian fatality and injury rates relate to 34 deaths and 292 injuries being reported for 22,439 fires in “storage” properties (2015-2019 annual averages) according to (NFPA, 2022). Firefighter fatalities for storage fires are assessed in accordance with (Fahy and Petrillo, 2021). No warehouse-fire specific injury rates were found. The same general injury rates as for case 1 have been adopted.

The warehouse damage area in case of successful sprinkler suppression and in case of successful fire brigade suppression (i.e., excluding cases with suppression by sprinklers) are assessed based on the analysis by Manes and Rush (2019) for “storage” buildings. As a modelling assumption, the averages listed by Manes and Rush are considered to exclude suppression failure (technically: suppression failure is considered not to influence the average considerably). In case of failure to suppress the fire, the full compartment is assumed to reach burnout.

Table 12 – Cost of fire protection.

Cost of smoke detectors	
Cost for single detector (assumed to include any maintenance cost)	258 USD/detector
Number of detectors	1 detector / 60 m^2
Cost of smoke detectors per m^2	4.3 USD/m^2
Cost of sprinkler system	
Cost of sprinkler system installation per m^2	61.67 USD/m^2
Annual maintenance cost for sprinkler system (assumed to include replacement cost for lifetime extension)	5%
Cost of compartmentation	
Unit cost compartment wall	1050 USD/m
Total compartmentation wall length and cost - 2 compartments - 3 compartments - 4 compartments - 6 compartments - 8 compartments	 60 m; 63,000 USD 120 m; 126,000 USD 160 m; 168,000 USD 220 m; 231,000 USD 280 m; 294,000 USD
Macro level cost multiplier	
Installation cost multiplier for reference design (detectors only)	0.4%
Installation cost multiplier for design with detectors and sprinklers	6.1%
Installation cost multiplier for design with detectors and compartmentation - 2 compartments - 3 compartments - 4 compartments - 6 compartments - 8 compartments	 1.4% 2.3% 3.0% 4.0% 4.9%

Table 13 – Benefit of fire protection (fire risk parameters).

Parameter	Value	Reference
Fire frequency (reported fires)	0.00156 per year	(Manes and Rush, 2019)
Probability of successful fire suppression by sprinklers	0.95	(Vassart et al., 2014)
Probability of successful fire suppression by the fire and rescue service	0.10 (remote location) 0.95 (well-connected location)	Remote location as demonstration value; 0.95 based on (Vassart et al., 2014)
Civilian fatality rate	1.5 per 1,000 reported fires	(NFPA, 2022)
Civilian injury rate	1.3 per 100 reported fires	(NFPA, 2022)
Firefighter fireground fatality rate	2.8 per 100,000 reported fires	(Fahy and Petrillo, 2021)
Firefighter response fatality rate	2.5 per 100,000 reported fires	(Fahy and Petrillo, 2021
Firefighter fireground injury rate	1.62 per 100 reported fires	(Campbell and Evarts, 2021)
Firefighter response injury rate	0.37 per 100 reported fires	(Campbell and Evarts, 2021)
Average damage area without sprinkler suppression, but with successful fire brigade suppression	41.30 m^2	(Manes and Rush, 2019)
Average damage area with sprinkler suppression	22.59 m^2	(Manes and Rush, 2019)
Average damage area in situations without successful fire suppression	Full compartment	Modelling assumption
Content loss factor	2.0	(FEMA, 2015)
Indirect loss factor	1.65	(Ramachandran and Hall, 2002)

6.3.2 Fire risk evaluation for the design alternatives

6.3.2.1 *Scenario definition*

Figure 9 visualizes the event tree for the considered case. The event tree defines three scenarios: (i) “suppression by sprinkler”, (ii) “not suppressed by sprinklers, suppressed by fire and rescue service”, and (iii) “not suppressed”. The assessed consequences for each scenario are elaborated in the following.

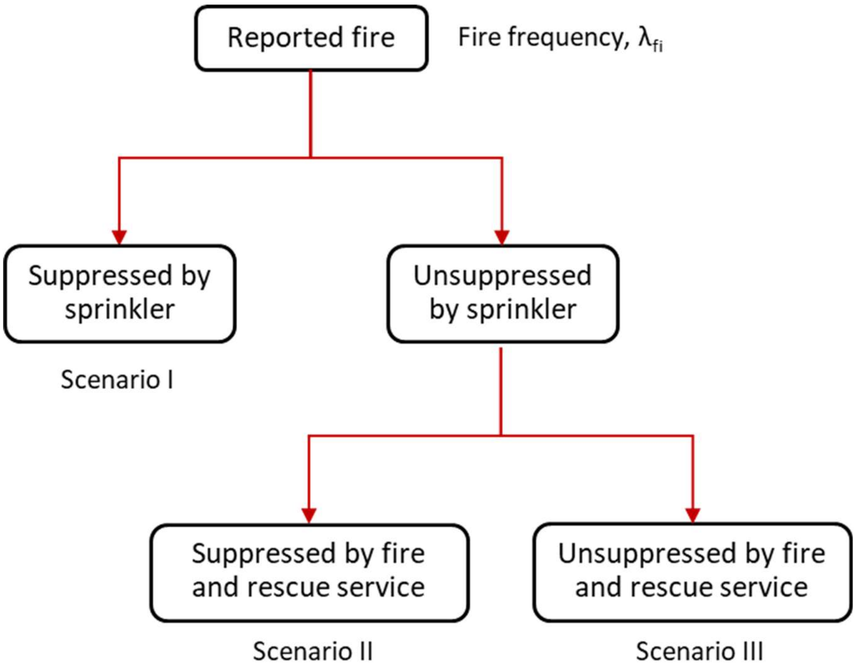


Figure 9 – Event tree defining scenarios for Case 2.

6.3.2.2 *Consequence evaluation for scenario "suppression by sprinklers"*

For the scenario "suppression by sprinkler", fatality and injury rates for civilians and firefighters (both fireground and response) are considered as for case 1: civilian injuries are reduced by 57%, while the fatality rate is considered effectively reduced to zero. Similarly, 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 13.

6.3.2.3 *Consequence evaluation for scenario "no suppression by sprinklers, suppression by fire and rescue service"*

For this scenario, full fatality and injury rates for civilians and firefighters are considered (i.e., as listed in Table 13). Also, the average damage area is listed in Table 13.

6.3.2.4 *Consequence evaluation for scenario "no suppression"*

Full fatality and injury rates for civilians and firefighters are considered, and the damage area is assessed as the total compartment area. Smaller compartment areas (i.e., compartmentation into a higher total number of compartments) thus reduces the material damage for this scenario. 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.

6.3.3 PNV evaluation

The PNV evaluation is detailed in the JupyterLab implementation. The net PNV for the design alternatives is listed in Table 14, 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. 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. Note that the difference in PNV between the optimum design (6 compartments) and the design with maximum BCR (2 compartments) is approximately 200,000 USD. 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.

Table 14 – Cost-benefit indicators for Case 2 (remote location: probability of successful FRS intervention of 0.10 adopted).

Design alternative	PNV [USD]	BCR	Conclusion
Alternative a: sprinkler system only	55,463	1.06	Investment cost-effective
Alternative b: compartmentation only			Investment cost-effective
- 2 compartments	487,035	8.73	
- 3 compartments	607,380	5.82	
- 4 compartments	657,052	4.91	6 compartments (no sprinkler system) as optimal solution
- 6 compartments	685,725	3.97	
- 8 compartments	668,561	3.27	
Alternative c: sprinkler system and compartmentation			Investment cost-effective only for 2 compartments and sprinkler protection; not for higher number of compartments
- 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	

6.3.4 Parameter study

When the probability of successful FRS intervention is adopted for a well-connected location (see Table 13), the fire protection investments are no longer cost-efficient. This result is readily obtained in the JupyterLab implementation by modifying the value of p_frs and rerunning the code. 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.

Nevertheless, it can be hypothesized that also in situations with a high likelihood of successful FRS intervention (i.e., probability of the FRS preventing a fully developed fire, here: 0.95), additional fire protection investments will be cost-effective as the indirect cost, or value of the content, increases. Warehouses 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. This is investigated as part of the parameter study described here. As the cost factors are multiplicative, the parameter study also gives a view of the impact of changing the content value.

Figure 10 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 15 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 in 2.2.2.3, the BCR should not be used to compare cost-effective design alternatives.

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

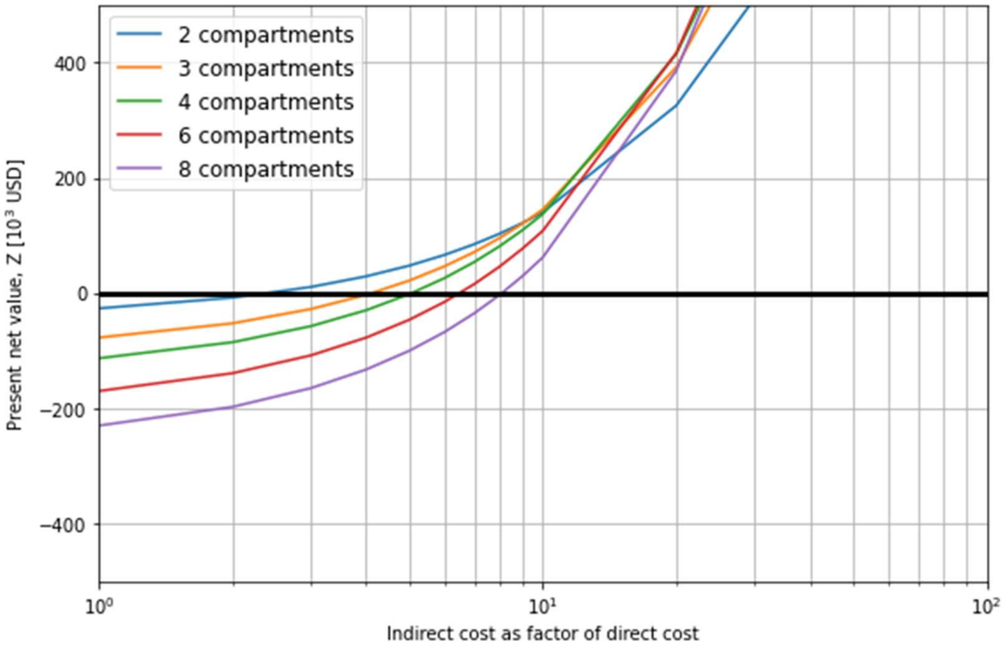


Figure 10 – Parameter study for Case 2 (probability of successful FRS intervention equal to 0.95).

Table 15 – 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			
- 2 compartments	325,914	6.17	Investment cost-effective; optimum for 6 compartments
- 3 compartments	392,551	4.12	
- 4 compartments	415,370	3.47	
- 6 compartments	417,189	2.81	
- 8 compartments	386,599	2.31	

6.4 Case 3 – Governmental general services: net benefit of detection system and extra staircase

Case 3 applies the prototype methodology to an assessment of the cost-effectiveness fire safety investments for a government office building. Specifically, three alternative designs are considered with

(a) an advanced fire detection system; (b) an additional staircase; and (c) both an advanced fire detection system and an additional staircase.

The benefits of early detection and improved evacuation routes can be assessed using advanced modelling tools. Before such an assessment is made however, it is worthwhile to determine the conditions under which the proposed alternative designs can be cost-efficient. If the early stage assessment shows that the investment is highly cost-efficient, then detailed modelling may not be required in order to decide on the safety measure's implementation. If on the other hand the early stage assessment indicates that the proposed safety measure is highly inefficient, then similarly detailed modelling may not be needed to conclude that the investment is not cost effective.

In the following, the evaluation is done for a 6000 m^2 (6 floors of 1000 m^2) office building, inspired by the case study in (Yung et al., 1997). Note that the cost-effectiveness is evaluated relative to a reference design which is considered to be representative for the current building stock. This allows to take into account current fire loss statistics for the evaluation of the reference case fire losses. It is therefore not readily possible to clarify to what extent the current fire protection measures have reduced the fire risk relative to a building stripped from all fire safety features. The calculation of the risk profile associated with such a building without fire safety features is possible by application of engineering principles (either evaluating the risk profile from the ground up, or by evaluating the effect of removing the available fire protection measures). While most interesting and likely to demonstrate the great societal benefit of existing fire protection measures, such evaluation is not considered here considering the goal of the project to establish and demonstrate the application of the prototype methodology.

6.4.1 Input

6.4.1.1 *Building characteristics*

Construction, demolition and disposal costs are assessed through the RSMeans database (Gordian, 2022). These costs are summarized in Table 16. The reconstruction cost is the combined cost of demolition, disposal and (renewed) construction.

Table 16 – Construction, demolition and disposal costs.

Construction cost	
Construction cost (Concrete moment frame, mid-rise)	3,903 USD/m^2
Demolition and disposal	
Percentage of construction cost	3% (assumed considering Case 1)
Demolition and disposal cost	117 USD/m^2
Replacement cost	
Demolition + disposal + (re-)construction	4,020 USD/m^2

6.4.1.2 *Discount rate and obsolescence rate*

A discount rate of 3% is adopted, based on (Fischer, 2014). Obsolescence is neglected (i.e., an obsolescence rate of 0% is adopted).

6.4.1.3 *Cost of fire protection, and macro-level cost multiplier*

The current level of fire protection in this type of building is considered as a baseline. Thus, a basic fire detection system is considered to be present. This allows to adopt fire-induced losses obtained from statistics as part of the reference evaluation. The (additional) cost of a more advanced detection system is considered within the CBA. The costs are assessed through the RSMeans database (Gordian, 2022) as detailed in Table 17. This maintenance cost is assumed to include the replacement cost of parts to allow for indefinite lifetime extension. The cost for the additional staircase considers the footprint of the building to be constant (i.e., the construction cost is not increased). The additional staircase however results in a loss of usable floorspace, and thus an annual cost equal to the rent value of the lost floorspace is considered, as indicated in section Table 17.

Table 17 – Cost of fire protection for Case 3.

Cost of detection system	
Cost for basic fire detectors	4 USD/m^2 (considering case 1 and case 2)
Cost of advanced fire detection system (addressable system with fire alarm command center and voice alarm)	19.8 USD/m^2
Excess cost of advanced fire detection system	15.8 USD/m^2
Annual maintenance cost (assumed to include replacement cost for lifetime extension)	5%
Cost of additional staircase	
Floor area usage	5.4 m^2
Annual rental cost	430 USD/m^2
Macro level cost multiplier	
Installation cost multiplier for reference design (basic detectors only)	$\frac{4\,USD/m^2}{3903\ USD/m^2} = 0.001\%$
Installation cost multiplier for advanced detection system	$\frac{19.8\ USD/m^2}{3903\ USD/m^2} = 0.005\%$

6.4.1.4 *Benefit of fire protection (fire risk parameters)*

Fire risk parameters obtained from statistics are listed in Table 18 together with the associated reference.

The average damage area in the reference 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 (here, an advanced fire detection system). The much lower damage area adopted in case of a detected fire successfully suppressed by the occupants is based on case 1 to allow for the early stage evaluation. Together, these assumptions within the early stage assessment are considered generous with respect to the benefit of the detection system.

The life risk reduction factors for the additional staircase, early warning (detection), and suppression are adopted within the early stage evaluation to assess the potential for cost-efficiency of the proposed alternative designs. Their application is described further.

Table 18 – Benefit of fire protection (fire risk parameters).

Parameter	Value	Reference
Fire frequency (reported fires)	0.002 per year	(Manes and Rush, 2019)
Probability of successful detection and alarm	0.9	PD 7974-7:2019
Probability of successful fire suppression by the occupants	0.5	(Albrecht and Hosser, 2010)
Civilian fatality rate	0.9 per 1,000 reported fires	(NFPA, 2022)
Civilian injury rate	1.4 per 100 reported fires	(NFPA, 2022)
Firefighter fireground fatality rate	6.9 per 100,000 reported fires	(Fahy and Petrillo, 2021)
Firefighter response fatality rate	6.3 per 100,000 reported fires	(Fahy and Petrillo, 2021
Firefighter fireground injury rate	1.62 per 100 reported fires	(Campbell and Evarts, 2021)
Firefighter response injury rate	0.37 per 100 reported fires	(Campbell and Evarts, 2021)
Average damage area reference situation	97.34 m^2	(Manes and Rush, 2019)
Average damage area with suppression by occupants	5 m^2	Modelling assumption exploratory study
Content loss factor	2.0	(FEMA, 2015)
Indirect loss factor	1.25	(Ramachandran and Hall, 2002)
Life risk reduction in case of an additional staircase, k_{SC}	0.3	Modelling assumption exploratory study
Life risk reduction in case of early warning (detection), k_{det}	0.4	Modelling assumption exploratory study
Life risk reduction in case of occupant suppression, k_{sup}	0.5 (injuries only; fatalities considered effectively zero)	Modelling assumption exploratory study

6.4.2 Fire risk evaluation for the design alternatives

6.4.2.1 *Scenario definition*

The scenarios are defined through the event tree of Figure 11: (i) no detection system warning; (ii) detection system warning, no occupant suppression; and (iii) detection system warning and successful suppression by occupants. The event tree itself does not make a distinction between case 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 scenarios the consequences are assessed both with/without the additional staircase.

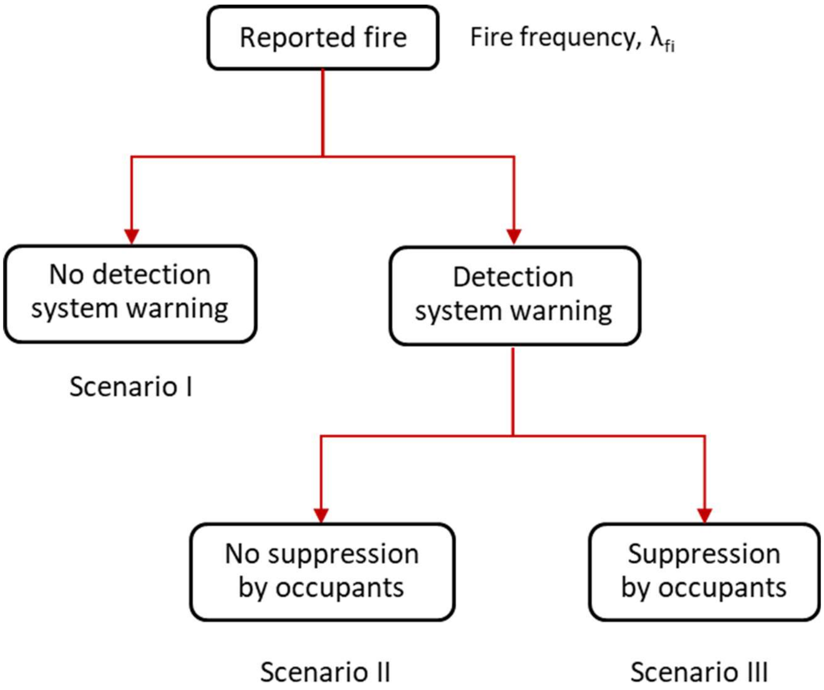


Figure 11 – Event tree defining scenarios for Case 3.

6.4.2.2 *Consequence evaluation for scenario "no detection system warning"*

This scenario, without the additional staircase, constitutes the reference case for which the consequences are based on statistics. Full risk to life (civilian and fire and rescue service fatalities and injuries) are considered, as well as full material damages.

When an additional staircase is foreseen, evacuation is easier and thus the civilian risk to life is reduced by the fraction k_{sc} listed in Table 18. The residual risk to life is (1-k_{sc}) times the reference value. The considered fraction is a preliminary number allowing for parameter studies. The additional staircase is considered not to result in a lower property risk, nor a lower risk for the fire and rescue service.

6.4.2.3 *Consequence evaluation for scenario "detection system warning, no occupant suppression"*

When the advanced detection system results in an earlier detection, this reduces the civilian risk to life due to an earlier onset of the evacuation. This effect is modelled by the factor k_{det}. When also an additional staircase is present, the effects are considered cumulative (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 measures together). The material losses and the fire and rescue service risk is the same as in the reference situation.

6.4.2.4 *Consequence evaluation for scenario "detection system warning and successful suppression by occupants"*

This scenario results in an early fire suppression. The civilian fatality risk is considered effectively zero, while the civilian injury risk is reduced with the factor k_{sup}. 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 18.

6.4.3 PNV evaluation

The JupyterLab implementation details the PNV evaluation. Considering the input values as listed above, none of the design alternatives are considered cost-effective (Table 19). The net benefit of the additional staircase is particularly low, resulting in a BCR of $3.4 \cdot 10^{-4}$ such that it is clear that this fire safety measure is not cost effective for the case at hand. It is therefore concluded that there is no need for detailed evacuation calculations for the additional staircase as the early-stage investigation already provides a conclusive answer. Only with respect to alternative design a, a further assessment is done.

Table 19 – Cost-benefit indicators for Case 2.

Design alternative	PNV [USD]	BCR	Conclusion
Alternative a: advanced fire detection system	-264,504	0.10	Investment not recommended
Alternative b: additional staircase	-515,824	0.00	Investment not recommended
Alternative c: advanced fire detection system and additional staircase	-780,438	0.04	Investment not recommended

6.4.3.1 *Parameter study*

In order to explore under what conditions the advanced fire detection system may be cost effective, a generous assessment is done whereby the detection system is considered to be 100% effective, resulting in 100% successful fire suppression by the occupants, and a complete reduction of the civilian life risk. The indirect loss factor is further varied between 0% and 2,000% (i.e., between no indirect loss and factor 20 indirect loss). Results are visualized in Figure 12, indicating that even under the generous reliability and loss reduction assumptions, the advanced detection system only becomes cost-effective in case of an indirect cost factor exceeding (approximately) 6.

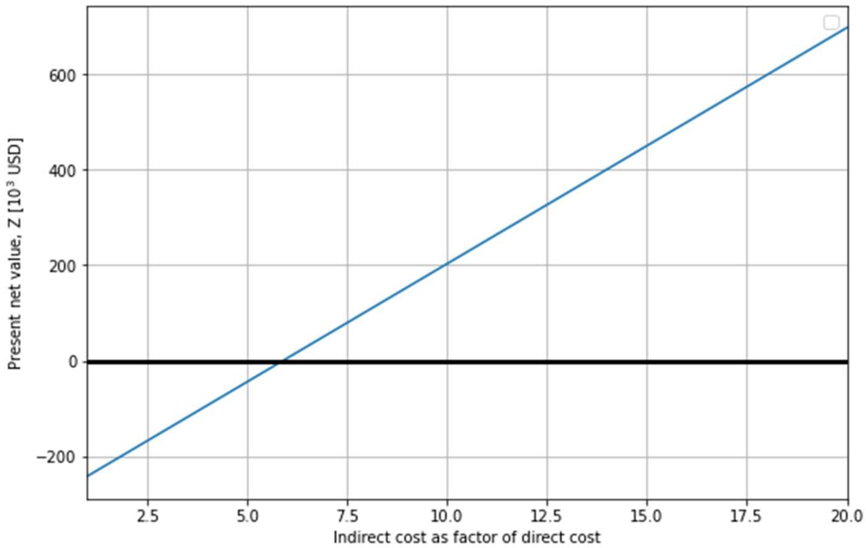


Figure 12 – Parameter study for Case 3.

6.5 Case 4 – Commercial office building: net benefit of passive fire protection

Case 4 applies the prototype methodology to the assessment of the net benefit of passive fire protection for steel moment-frame commercial professional services buildings (COM4). The assessment is done considering a combination of statistical data and numerical simulations. The building prototype is a nine-story steel-concrete composite building with a floor plan area of 2090 m^2 for a total floor area of 18810 m^2. The building design is based on the FEMA/SAC project for the Boston area post-Northridge (SAC, 2000).

The steel members of the interior gravity frames of the building (beams and columns) are protected with Sprayed Fire Resistive Material (SFRM). The evaluation considers different thickness of SFRM corresponding to 1-hour, 2-hour, and 3-hour of protection from qualified UL assemblies.

6.5.1 Inputs

6.5.1.1 *Building characteristics*

Construction, demolition and disposal costs are assessed through the RSMeans database (Gordian, 2022). These costs are summarized in Table 20. The reconstruction cost is the combined cost of demolition, disposal and (renewed) construction.

Table 20 – Construction, demolition and disposal costs.

Construction cost	
Construction cost (Multi-story office building, include structural and nonstructural)	1674.43 USD/m^2
Demolition cost	
Volume	77706.2 m^3
Total demolition cost (0.41 USD/ft^3)	1125109.11 USD
Demolition cost	59.82 USD/m^2
Disposal cost	
Waste from building demolition.	145.74 m^3
Disposal cost (steel frame) (13.45 per yd^3)	1682.19 USD
Disposal cost (concrete floors- assuming 2.5 in. thick concrete floor) (15.90 USD per yd^3)	1042.4 USD
Total disposal cost	2724.59 USD
Disposal cost	0.145 USD/m^2
Replacement cost	
Demolition + disposal + (re-)construction	1734.39 USD/m^2

6.5.1.2 *Discount rate and obsolescence rate*

A discount rate of 3% is adopted, based on (Fischer, 2014). Obsolescence is neglected (i.e., an obsolescence rate of 0% is adopted).

6.5.1.3 *Cost of fire protection, and macro-level cost multiplier*

The cost of the SFRM passive fire protection is evaluated for consideration within the CBA. The costs are assessed through the RSMeans database (Gordian, 2022) as detailed in Table 21. No maintenance cost is considered for the SFRM. For comparison purposes, the cost for installing a fire sprinkler system is listed. To determine the cost of the sprinkler system, the building is classified into the light hazard category for sprinkler systems. Although listed to compare costs with those of the SFRM, sprinklers are not considered within the current case study in analyzing the cost benefit of the fire protection.

Table 21 – Cost of fire protection.

Cost of sprinkler system (per m^2 of building floor area)	
Cost of sprinkler system installation per m^2	35.16 USD/m^2
Cost of SFRM (per m^2 of building floor area)	
Cost of SFRM installation per m^2 - 1-hour fire resistance rating - 2-hour fire resistance rating - 3-hour fire resistance rating	 13.66 USD/m^2 23.76 USD/m^2 40.99 USD/m^2
Macro level cost multiplier	
Sprinkler system	$\frac{35.16\ USD/m^2}{1674.43\, USD/m^2} = 2.1\%$
Installation cost for 1-hour fire resistance rating	$\frac{13.66\ USD/m^2}{1674.43\, USD/m^2} = 0.82\%$
Installation cost for 2-hour fire resistance rating	$\frac{23.76\ USD/m^2}{1674.43\ USD/m^2} = 1.42\%$
Installation cost for 3-hour fire resistance rating	$\frac{40.99\ USD/m^2}{1674.43\ USD/m^2} = 2.45\%$

6.5.1.4 *Benefit of fire protection (fire risk parameters)*

Fire risk parameters obtained from statistics are listed in Table 22, together with the associated reference. The valuation of the fatality and injury risk is done through the VSL and VSI approach, as discussed previous sections. 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 FRS 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.

Average fire losses depend heavily on the occurrence of major structural failure of a frame member. Indeed, such failure would result in a breach of compartmentation and severe structural damage. 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. In contrast, in cases where the structural frame collapses during the fire, the entire building is considered lost.

The fatality and injury rates shown in Table 22 and used in the subsequent cost benefit analysis are obtained from the published sources listed. These values are from recent data collected on both the civilian and firefighter casualties and injuries from fires across the United States.

The property loss areas are obtained from (Manes and Rush, 2019), which is based on 2014 USA fire statistics. In accordance with (FEMA, 2015), the replacement cost for the contents of a commercial office building is valued at 100% of the construction cost of the property. For office buildings, the indirect loss was estimated as 25% of the direct loss in (Ramachandran and Hall, 2002). This indirect loss value is added to the total property loss, to obtain the total monetary losses from a fire incident.

Table 22 – Benefit of fire protection (fire risk parameters).

Parameter	Value	Reference
Fire frequency (reported fires)	0.00423 per year	(Manes and Rush, 2019)
Civilian fatality rate	0.89 per 1,000 reported fires	(NFPA, 2022)
Civilian injury rate	1.4 per 100 reported fires	(NFPA, 2022)
Firefighter fireground fatality rate	6.9 per 100,000 reported fires	(Fahy and Petrillo, 2021)
Firefighter response fatality rate	6.3 per 100,000 reported fires	adapted from (Fahy and Petrillo, 2021): same as case studies 1 and 2
Firefighter fireground injury rate	1.62 per 100 reported fires	(Campbell and Evarts, 2021)
Firefighter response injury rate	0.37 per 100 reported fires	(Campbell and Evarts, 2021)
Average damage area without structural failure	83.5 m^2	Compartment of fire origin
Average damage area with structural failure	18,810 m^2	Entire building
Content loss factor	2.0	(FEMA, 2015)
Indirect loss factor	1.25	(Ramachandran and Hall, 2002)

6.5.2 Numerical simulations to estimate the effect of fire protection measures

The simulation-based method utilizes numerical modeling to predict the expected damage in case of fire. The objective is to complement statistics when data is unavailable and/or not provided at a level of granulometry that would allow analysis of the effects of variations in the design. In this case study, the effect of thickness of fire protection on the structural frame member is investigated. As there is no detailed data on the expected losses in case of fire as a function of the design of fire protection, numerical modeling is used to fill this gap.

6.5.2.1 *Building model*

A numerical model of the building is constructed in the nonlinear finite element software SAFIR (Franssen and Gernay, 2017). The building is a nine-story structure with 5 bays of 9.14 m (30 ft) in each direction (Figure 13). The design and dimensions of the frame members are detailed in a previous study (Gernay and Elhami-Khorasani, 2020); it is based on the FEMA/SAC prototype for the post-Northridge design in the Boston area. A 2D frame model is considered.

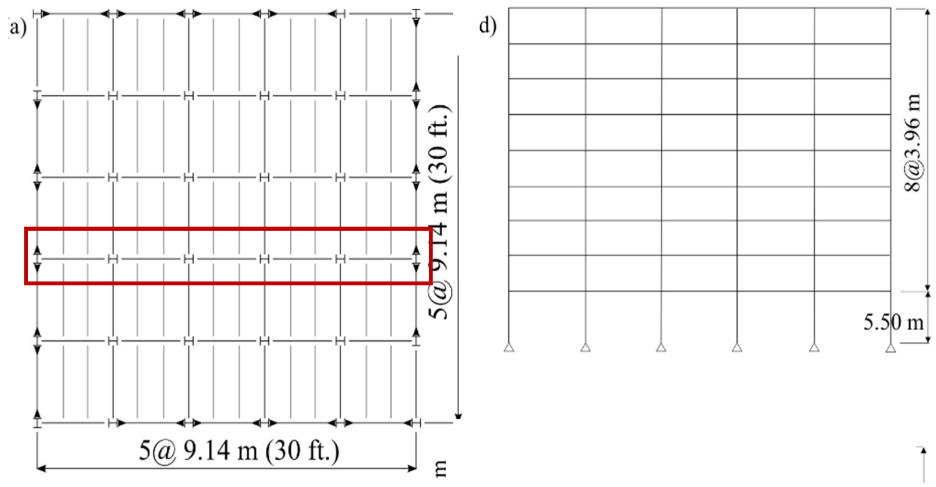


Figure 13 – Gravity frame analyzed as part of the multi-story office building.

The building is classified as Type I B. Therefore, the ICC fire resistance rating requirement for the primary structural frame members is 2-hour. 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-hour and 3-hour 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 23.

Table 23. Gravity frames: member sections and SFRM insulation thickness.

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

The distributed dead load on the floors is 4.60 kN/m². The typical live load for office occupancy is 2.40 kN/m² (50 psf). The reduced live load is 0.96 kN/m². These values are unfactored. For ambient temperature design, the ASCE load combination leads to a distributed load of 7.05 kN/m² (taking into account reduced live load). For fire situation, the ASCE load combination leads to a distributed load of 5.99 kN/m². 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 review in (Jovanovic et al., 2021). The total load effect is described by $K_E(G+Q)$, where K_E is the model uncertainty with expected value of 1.0, G is the permanent load with expected value equal to the nominal value (i.e., 4.60 kN/m²), and Q is the imposed load with expected value equal to 0.2 times the nominal value (i.e., 0.48 kN/m²). As a result, the beams are subjected to a uniformly distributed load of (1.0*4.60 + 0.2*2.40) = 5.08 kN/m² multiplied by the tributary width of 9.14 m, i.e., 46.4 kN/m.

6.5.2.2 *Probabilistic inputs of the model*

There are many uncertainties associated with a fire event and thermal-structural response. The objective is to quantify the expected response of the structure in case of an uncontrolled fire, to infer the expected losses. To capture the effects of uncertainties, key parameters of the model are taken as probabilistic. These include: (i) the fuel load, (ii) the opening factor in the compartment, (iii) the thermal properties of the SFRM, and (iv) 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 the recent NFPA study by Elhami-Khorasani et al. (2021). The conducted survey measured a mean of 1116 MJ/m² with a standard deviation of 604 MJ/m² 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/m², and μ of 847 MJ/m². The second distribution is adopted from the Eurocode EN1991-1-2 for office occupancy. It is a Gumbel distribution with average 420 MJ/m² and 80% fractile 511 MJ/m².

For the opening factor, the distribution is calculated according to the formula provided by (JCSS, 2001): $O = O_{max}(1-\zeta)$. The factor O_{max} is the opening factor calculated from Eurocode EN1991-1-2:2002. It is 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/m³, 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. (2015) and is implemented in SAFIR as SFRM_PROBA.

For the steel yield strength, a probabilistic temperature-dependent model is adopted from Elhami-Khorasani et al. (2015). The steel 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. The material is implemented in SAFIR as STEC3PROBA.

6.5.2.3 *Results of the numerical simulation: probability of failure*

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 significantly more frequent than multi-compartment fires. One compartment is studied as representative of the structural fire response, as the dimensions, fuel load, and load level are similar for all compartments within the building. The fire scenario that is modeled is an uncontrolled fire in a compartment of the fourth story, see Figure 14. The structural model focuses on the gravity frame members and analyzes the nine-story structure.

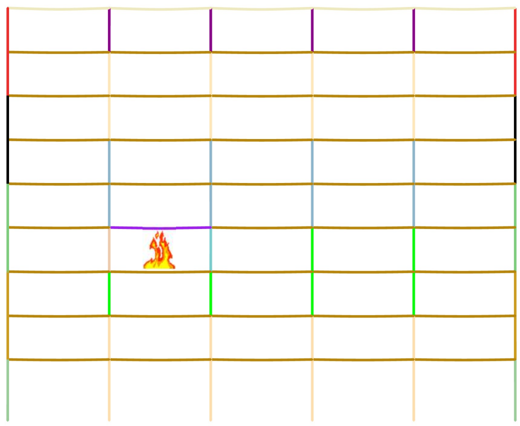
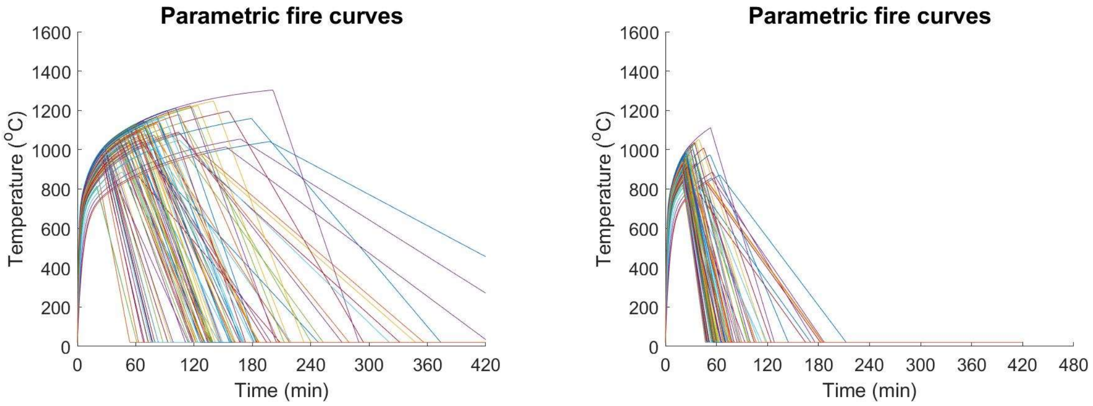


Figure 14. Numerical model of the steel frame structure, with fire in one compartment of the fourth story. Colors represent different steel section types.

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 parametric Eurocode EN1991-1-2 fire model. The fire curves obtained by running 100 realizations with random fuel loads and opening factors are plotted in Figure 15, for the NFPA and Eurocode fuel load distributions, respectively. The NFPA fuel load distribution yields significantly more severe fires than the Eurocode fuel load distribution, as expected given the much larger values of fuel loads in the former than in the latter.

The results are given in Table 24. 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 hours of the fire event). It is verified that these lacks of numerical convergence correspond with a rapid increase in deflections in the frame members, indicative of a loss of stability. Failure initiates in the beams. Figure 16 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 (1h fire protection, NFPA fuel load, #10) and the case that survives (2h fire protection, Eurocode fuel load, #100). 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 significantly larger fuel load values reported in the former study. When adopting the Eurocode distribution, the probability of failure for the prescriptive 2-hour design is 0.15 in case of uncontrolled structurally significant fire.

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



(a) NFPA fuel load distribution (b) Eurocode fuel load distribution

Figure 15. Gas temperature-time curves considered in the building simulations, based on two fuel load distributions for office occupancy.

Table 24 – Probability of failure (P_f) for the steel frame structure subjected to fire. These P_f are obtained by Monte Carlo Simulation with 100 runs of a nonlinear Finite Element Model in SAFIR.

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

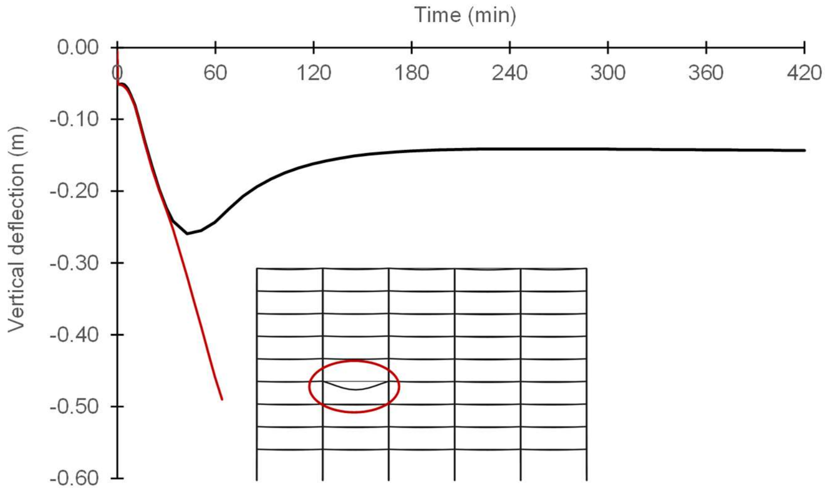


Figure 16. Evolution of the vertical deflections at mid-span of the beam in the fire compartment, for a case that fails and a case that survives the fire.

6.5.3 Fire risk evaluation for the design alternatives

6.5.3.1 *Scenario definition*

Risk reduction is the net benefit obtained from fire safety systems. This risk reduction is assessed by comparing the risk level with the three levels of passive fire protection corresponding to 1-hour, 2-hour, and 3-hour of prescriptive design, respectively.

Figure 17 shows the event tree for the Case Study 4. For each design, the event tree defines two scenarios: (i) "no structural failure", and (ii) "structural failure". The probability associated with each branch of the event tree is obtained from the numerical simulations, as discussed in the previous section. The consequences for each scenario are assessed based on statistics. The following section details the calculation of the probabilities and consequences for each design and scenario. The risk associated with a design considers the scenario consequences together with their probabilities. This is done within the PNV evaluation.

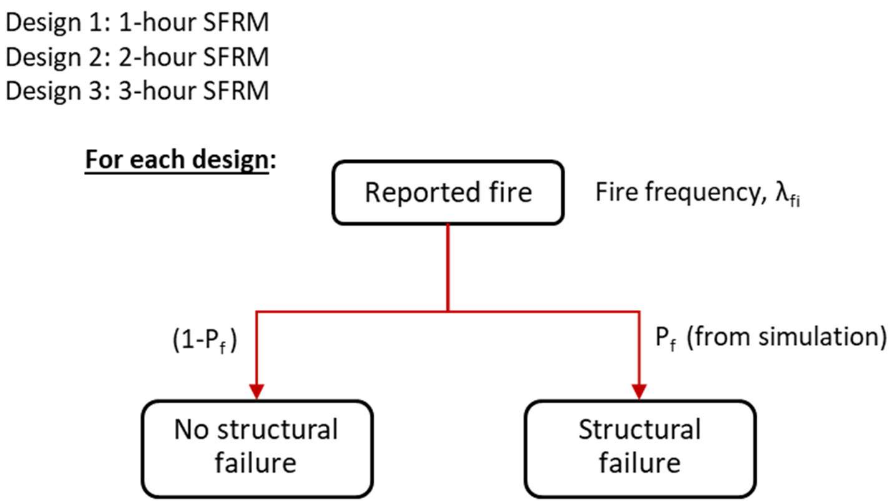


Figure 17 – Event tree defining the scenarios for Case 4.

6.5.3.2 *Evaluation of the probability of structural failure*

The probability of failure has been assessed through numerical simulations (see results in Table 24).

6.5.3.3 *Consequence evaluation for scenario "no structural failure"*

In case of "no structural failure", the structure is able to resist to full fire burnout. Therefore, it is assumed that the use of SFRM over the structural members as a fire protection strategy is successful and the fire does not spread beyond the compartment of origin, which has a surface area of 83.5 m^2, see Table 22. The average damage area is taken as that of the compartment.

6.5.3.4 *Consequence evaluation for scenario "structural failure"*

In case of structural failure of the primary frame, consequences can reasonably be expected to be much more severe. No detailed statistics are available on fire losses specifically for cases of major structural failure of the primary loadbearing system. Here, it is assumed for simplification that the entire building area would suffer some degree of damage, as a building experiencing a breach of compartmentation and large deformations associated with a local failure would be likely to necessitate remediation well beyond the compartment of origin. No increase in civilian and firefighter casualties is assumed, considering that the structural failure is after the evacuation and rescue time for this structure. This is an assumption to allow for a first evaluation.

6.5.4 PNV evaluation

The PNV evaluation is done considering the prototype methodology. See the JupyterLab implementation for the step-by-step calculation. Considering the inputs as listed above, the total PNV for the different fire resistance ratings are as shown in Table 25. Using both prescribed fuel load distribution models, the PNV for each prescriptive SFRM rating returns a positive value (benefit exceed than cost). As such, under the simulated conditions, these safety measures can be recommended as beneficial from an economic perspective. Both the NFPA fire load density model and the Eurocode fire load density model indicate a 3 hour fire resistance rating as being the optimal solution. This is noteworthy in that it correlates with current prescriptive guidance which often require up to 2 hours of fire resistance rating. However, more detailed modelling is recommended to investigate the possibility of load redistribution following failure of one of the primary beams, which may change the failure rates.

Table 25 – Cost-benefit indicators for Case 4.

Design fire rating	NFPA Study		Eurocode	
	PNV	BCR	PNV	BCR
SFRM prescriptive 1-hour	86,522	1.34	2,834,258	12.03
SFRM prescriptive 2-hour	1,957,343	5.38	9,284,639	21.77
SFRM prescriptive 3-hour	3,350,582	5.35	9,761,966	13.66

6.5.5 Parameter study

A parameter study shows the effect on the present net value 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, one can vary the damage area when the building remains stable, as large deformations and smoke could still affect parts of the building outside the fire compartment. The damaged areas are determined as a percentage of the total floor area and the present net values computed for each prescribed protection level using both the NFPA and the Eurocode fuel distribution models. Results are visualized in Figure 18. See the JupyterLab implementation for the underlying code.

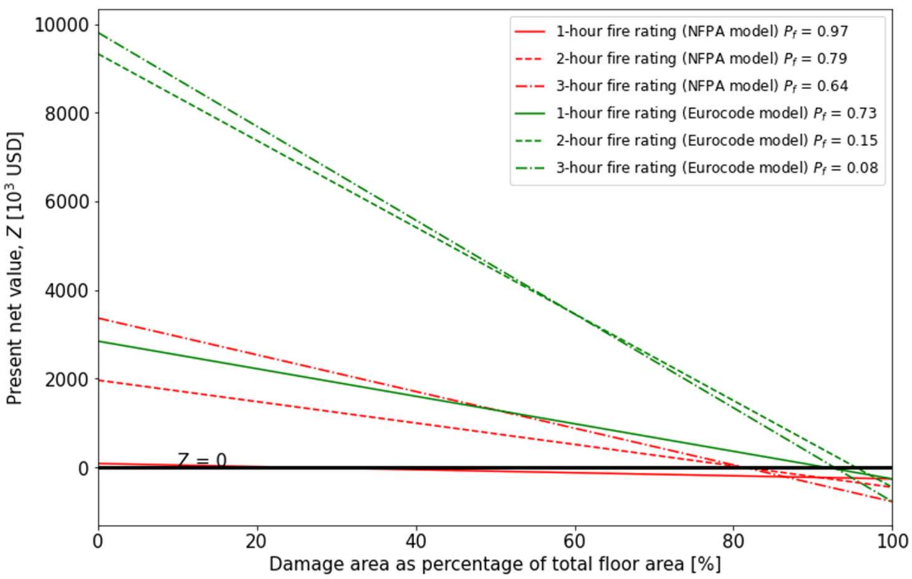


Figure 18 – Parameter study for Case 4.

From the results in Figure 18, it can be observed that the assumption of the damage area when structural failure is avoided has a significant effect on the determined present net value. In the baseline case, it is assumed that the damage area remains limited to the fire compartment when the simulation shows no major structural failure. Assuming a larger damaged area in the absence of failure reduces the beneficial effect of the fire protection, because it assumes that even when the fire protection saves the structure from failing, a large part still needs to be repaired. As expected, increasing damaged areas lead to reduced value of the fire protection measure. However, even with the unavailability of accurate information on the exact damage area due to a fire outbreak, it can be observed that the sprayed fire resistant material as a passive fire protection does provide good value, even with extensive damage. The PNV remains positive even after postulating that nearly 80% of the total floor area is damaged, indicating that this fire protection measure does help prevent structural failure, and provides good value for the money.

6.6 Case 5 – Residential multi-family timber building: net benefit of sprinklers and passive fire protection

Case 5 applies the prototype methodology to the assessment of the net benefit of sprinklers and passive fire protection for mass timber multi-family dwellings (RES3E). The assessment is done considering a combination of statistical data and numerical simulations. The building prototype is a ten-story mass-timber building with a floor plan area of 909.52 m^2. The building design is based on an NSF project focusing on the seismic performance of tall mass-timber buildings, and designed by KPFF (NHERI-Tallwood Homes, n.d.).

The timber glulam members of the interior gravity frames of the building are protected with gypsum encapsulation. The evaluation considers the presence or absence of sprinklers, and either no gypsum encapsulation, encapsulation with one layer of gypsum, or two layers of gypsum.

6.6.1 Inputs

6.6.1.1 *Building characteristics*

Construction cost of this building is based on square foot cost for the mass-timber building T3 in the US. The square foot construction cost of T3 was 1,511.81 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 1,797.54 USD/m^2. The demolition and disposal costs are assessed through the RSMeans database (Gordian, 2022). The RSMeans database does not contain cost information for mass timber structures, and thus the disposal cost of a steel frame structure was assumed for this analysis. These costs are summarized in Table 26. The reconstruction cost is the combined cost of demolition, disposal and (renewed) construction.

Table 26 – Construction, demolition and disposal costs.

Construction cost	
Construction cost (Multi-story office building, include structural and nonstructural)	1797.54 USD/m^2
Demolition cost	
Volume	3146.87 m^3
Total demolition cost (0.39 USD/ft^3)	43340.96 USD
Demolition cost	47.65 USD/m^2
Disposal cost	
Waste from building demolition.	421.49 m^3
Disposal cost (mass timber, including frame, wall and floor, 13.45 USD per yd^3)	6502.67 USD
Disposal cost (concrete top for the composite floor system, assuming 2.25 in. thick concrete floor, 15.90 USD per yd^3)	1078.02 USD
Total disposal cost	7580.69 USD
Disposal cost	8.34 USD/m^2
Replacement cost	
Demolition + disposal + (re-)construction	1853.52 USD/m^2

6.6.1.2 *Discount rate and obsolescence rate*

Similar to the previous case studies, a discount rate of 3% is adopted based on (Fischer, 2014). Obsolescence is neglected (i.e., an obsolescence rate of 0% is adopted).

6.6.1.3 *Cost of fire protection, and macro-level cost multiplier*

The cost of the gypsum passive fire protection and the fire sprinkler system is evaluated for consideration within the CBA. The costs are assessed through the RSMeans database (Gordian, 2022) as detailed in Table 27. Light hazard level is used in computing the cost of the sprinkler system for the building, and an annual maintenance cost of 5% has also been adopted for the sprinkler system. This maintenance cost is assumed to allow for indefinite lifetime extension at the same level of performance. It is assumed that the gypsum boards encapsulating the timber members will require no maintenance, hence no maintenance cost has been assumed for this passive fire protection measure.

Table 27 – Cost of fire protection.

Cost of sprinkler system (per m^2 of building floor area)	
Cost of sprinkler system installation per m^2	48.85 USD/m^2
Annual maintenance cost for sprinkler system (assumed to include replacement cost for lifetime extension)	5%
Cost of encapsulation (per m^2 of building floor area)	
Unit cost - 1 layer - 2 layers	 52.66 USD/m^2 90.48 USD/m^2
Total cost - 1 layer - 2 layers	 47896.15 USD 82297.76 USD
Total cost of fire protection	
- 1 layer + sprinklers	101.51 USD/m^2
- 2 layers + sprinklers	139.33 USD/m^2
Macro level cost multiplier	
Installation cost multiplier for design with sprinkler system	$\frac{48.85\ USD/m^2}{1797.54\, USD/m^2} = 2.72\%$
Installation cost multiplier for design with encapsulation (1 layer)	$\frac{52.66\ USD/m^2}{1797.54\, USD/m^2} = 2.93\%$
Installation cost multiplier for design with encapsulation (2 layers)	$\frac{90.48\ USD/m^2}{1797.54\, USD/m^2} = 5.03\%$

6.6.1.4 *Benefit of fire protection (fire risk parameters)*

Fire risk parameters obtained from statistics are listed in Table 28, together with the associated reference. The valuation of the fatality and injury risk is done through the VSL and VSI approach, as discussed in previous sections.

Table 28 – Benefit of fire protection (fire risk parameters).

Parameter	Value	Reference
Fire frequency (reported fires)	0.00151 per year	(Manes and Rush, 2019)
Civilian fatality rate	7.4 per 1,000 reported fires	(NFPA, 2022)
Civilian injury rate	3 per 100 reported fires	(NFPA, 2022)
Firefighter fireground fatality rate	2.4 per 100,000 reported fires	(Fahy and Petrillo, 2021)
Firefighter response fatality rate	2.2 per 100,000 reported fires	(Fahy and Petrillo, 2021
Firefighter fireground injury rate	1.62 per 100 reported fires	(Campbell and Evarts, 2021)
Firefighter response injury rate	0.37 per 100 reported fires	(Campbell and Evarts, 2021)
Average damage area without sprinkler suppression, and without structural failure	23.8 m^2	Compartment of fire origin
Average damage area without sprinkler suppression, and with structural failure	909.52 m^2	Entire building
Average damage area with sprinkler suppression	4.92 m^2	(Manes and Rush, 2019)
Content loss factor	1.5	(FEMA, 2015)
Indirect loss factor	1.1	(Ramachandran and Hall, 2002)

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. The values listed for the other parameters are adopted from previous published studies, as elaborated in the previous case studies.

Average fire losses depend heavily on the occurrence of major structural failure of a frame member. Indeed, such failure would result in a breach of structural integrity and result in severe structural damage. It is assumed that, in cases where the structural frame withstands the fire through full burnout, losses remain contained within the compartment of fire origin (here considered to be the compartment where the fire starts). In contrast, in cases where the structural frame collapses during the fire, the entire building suffers losses.

6.6.2 Numerical simulations to estimate the effect of fire protection measures

The simulations of fire incidences in this mass timber model utilizes numerical modeling to predict the expected damage in case of fire, with the aim of complementing statistics and analysis of the effects of variations in the design. Particularly in this case study, the effect of thickness of fire protection on the structural frame member is investigated.

6.6.2.1 *Building model*

A numerical model of the building is constructed in the nonlinear finite element software SAFIR (Franssen and Gernay, 2017). The building is a 10-story structure (Figure 19). The height of the first floor is 4 m and the height of the other floors are 3.4 m each. Each floor has a total area of 90.95 m^2.

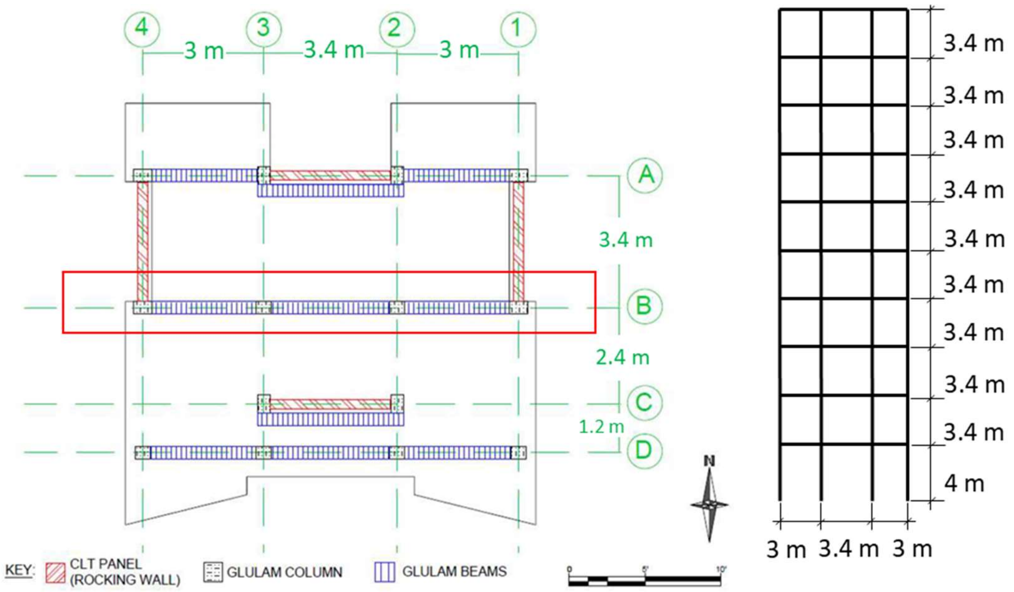


Figure 19 – *Gravity frame analyzed as part of the multi-story office building (NHERI-Tallwood Homes, n.d.).*

The building is classified as Type IV-B. Therefore, the ICC fire resistance rating requirement for the primary structural frame members is 2-hour. The insulation material is type X 5/8'' gypsum boards for all the structural members. The member sections are listed in Table 29.

Table 29. Gravity frames: member sections.

Member	Size, mm x mm (in. x in.)
Column (Floor 1-2)	311x381 (12.25x15)
Column (Floor 3-6)	311x343 (12.25x13.5)
Column (Floor 7-10)	311x305 (12.25x12)
Beam	311x343 (12.25x13.5)

The distributed dead load on the floors is 5.27 kN/m² (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/m². For fire situation, a uniformly distributed load on the beams is determined and applied similar to case study 4, resulting in the beams being subjected to a uniformly distributed load of (1.0*5.27 + 0.2*3.11) = 5.89 kN/m² multiplied by the tributary width of 3.5 m, i.e., 20.6 kN/m.

6.6.2.2 *Probabilistic inputs of the model*

To capture the effects of uncertainties, key parameters of the model are taken as probabilistic, including the fuel load and the opening factor in the compartment. For the fuel load, the probability distribution is adopted from Eurocode EN1991-1-2 for residential occupancy. This distribution is a Gumbel distribution with average 780 MJ/m^2 and 80% fractile 948 MJ/m^2. Note that 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 case study 4.

6.6.2.3 *Results of the numerical simulation: probability of failure*

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 36.28 kN/m. Therefore, the expected loading in the fire situation is 20.6/36.28 = 57% 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 significantly more frequent than multi-compartment fires. One compartment is studied as representative of the structural fire response, as the dimensions, fuel load, and load level are similar for all compartments within the building. The fire scenario that is modeled is an uncontrolled fire in a compartment of the second story, see Figure 20. The structural model focuses on the gravity frame members and analyzes the ten-story structure.

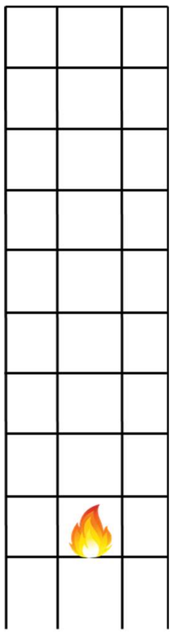


Figure 20 – Numerical model of the mass-timber frame structure, with fire in one compartment of the second story.

50 simulations are run for each design (i.e., layers of gypsum boards) and each fuel load distribution. The fire curves are evaluated using the parametric Eurocode EN1991-1-2 fire model. The fire curves obtained by running 50 realizations with random fuel loads and opening factors are plotted in Figure 21.

The results are given in Table 30. 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. It is verified that these lacks of numerical convergence correspond with the collapse of the frame. The columns' failure at the second story due to fire damage leads to the collapse of the building. The probability of failure is computed by dividing the number of simulations that failed over the 50 simulations realized. As expected, the probability of failure decreases with an increase in the layers of gypsum boards. If the frame is not protected, the probability of failure is 24%. The probability of failure will decrease to 2% if frame is protected by one layer of 1/2'' type X gypsum boards and 0% if protected by 2 layers.

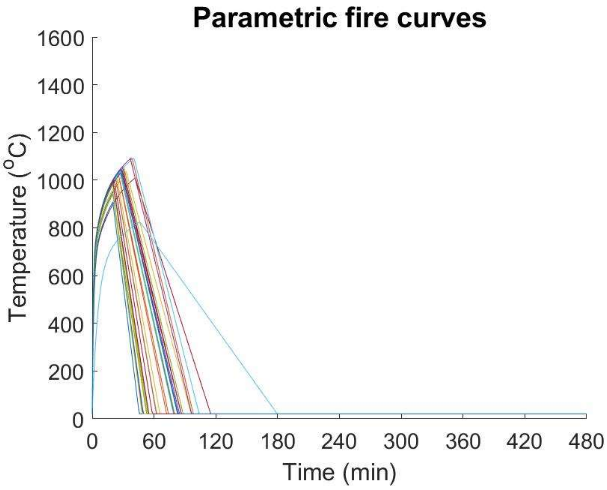


Figure 21 – Gas temperature-time curves considered in the building simulations, based on the fuel load distribution for residential occupancy.

Table 30 – Probability of failure (P_f) for the mass-timber frame structure subjected to fire. These P_f are obtained by Monte Carlo Simulation with 50 runs of a nonlinear Finite Element Model in SAFIR.

Layer of gypsum boards	Probability of failure (P_f)
Without gypsum boards	0.24
1 layer 1/2'' type X gypsum board	0.02
2 layer 1/2'' type X gypsum board	0

6.6.3 Fire risk evaluation for the design alternatives

6.6.3.1 *Scenario definition*

Risk reduction is the net benefit obtained from fire safety systems. This risk reduction is assessed by comparing the risk level of a building with no protection to one with fire protection measures (either with sprinklers or encapsulation or a combination of both).

Figure 22 shows the event tree for the Case Study 5. For each design, the event tree defines three scenarios: (i) suppressed by sprinklers, (ii) “no structural failure”, and (iii) “structural failure”. The probability associated with two branches under “Unsuppressed by sprinkler” is obtained from the numerical simulations, as discussed in the previous section. The consequences for each scenario are assessed based on statistics. The following section details the calculation of the probabilities and consequences for each design and scenario.

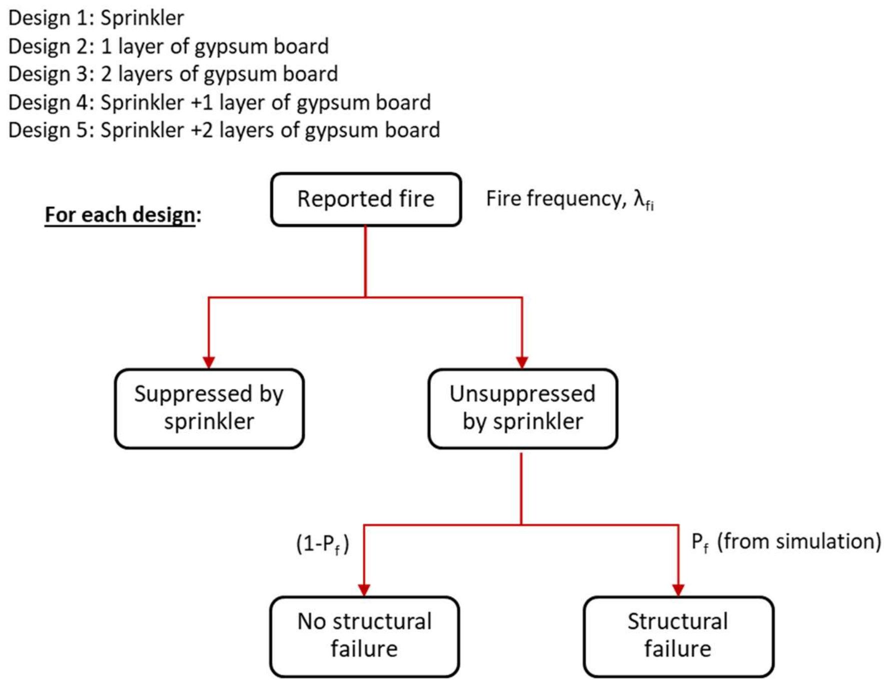


Figure 22 – Event tree defining the scenarios for Case 5.

6.6.3.2 *Evaluation of the probability of structural failure*

The numerical model designed as discussed in the previous section is used to simulate the possible outcomes of fire in terms of structural failure as outlined above.

6.6.3.3 *Consequence evaluation for scenario “suppression by sprinkler”*

For the scenario “suppression by sprinkler”, fatality and injury rates for civilians and firefighters (both fireground and response) are considered as for case 1: civilian injuries are reduced by 57%, while the fatality rate is considered effectively reduced to zero. Similarly, firefighter fireground fatalities and injuries are effectively reduced to zero, while response fatalities and injuries are not affected. The average damage area with the successful suppression by sprinklers is 4.92 m^2 as listed in Table 28.

6.6.3.4 *Consequence evaluation for scenario "no suppression by sprinklers, no structural failure"*

In case of "no structural failure", the structure is able to resist to full fire burnout. It is assumed that the encapsulation strategy is successful and the fire does not damage the structural members. It is also assumed that the fire does not spread beyond the compartment of origin, which has a surface area of 23.8 m^2 (see Table 28). Thus, the average damage area is taken as the area of the compartment. Civilian and firefighter injuries and casualties are assumed based on statistics collected from fire incidences around the U.S as shown in Table 28.

6.6.3.5 *Consequence evaluation for scenario "no suppression by sprinklers, structural failure"*

In case of structural failure of the primary frame, consequences can reasonably be expected to be much more severe, both in terms of expected losses and casualties. No detailed statistics are available on fire losses specifically for cases of major structural failure of the primary loadbearing system. Here, it is assumed for simplification that the entire building collapses, as a building experiencing column failure at a low story would likely lead to the collapse of a building. Civilian and firefighter casualties' assumptions are based on previously collected statistics as listed in Table 28. This allows for a first level evaluation, assuming that structural failure occurs after finalization of the evacuation and rescue operations.

6.6.4 PNV evaluation

The PNV evaluation is done considering the prototype methodology. See the JupyterLab implementation for the step-by-step calculation. Considering the inputs as listed above, the total PNV investment cost (i.e., including maintenance and obsolescence) for the different design alternatives (sprinkler system only, encapsulation of structural members only, and a combination of both) are as listed in Table 31. For the different alternatives tested, investment can be recommended for cases where the benefits exceed the cost and thus have a positive PNV, otherwise the investment in the safety feature cannot be recommended.

Table 31 – Cost-benefit indicators for Case 5.

Design alternative	PNV [USD]	BCR	Conclusion
Sprinkler system	-82,248	0.31	Investment not recommended
1 layer gypsum board	-17,900	0.63	Investment not recommended
2 layers of gypsum board	-49,571	0.40	Investment not recommended
Sprinkler system + 1 layer of gypsum board	-128,643	0.23	Investment not recommended
Sprinkler system + 2 layers of gypsum board	-162,905	0.19	Investment not recommended

From Table 31, the net negative PNV of the sprinkler system makes it not recommendable for use in such buildings. In a similar vein, the net negative PNV of the encapsulation system makes it not recommendable as a fire protection measure in this type of building. Beyond each individual fire protection system, a combination of both the sprinkler system and the encapsulation using gypsum boards is also not recommendable as the installation costs are of such magnitude that the costs exceed the benefits. This PNV evaluation concludes the demonstration of the prototype methodology.

6.6.5 PNV parameter study

A limited parameter study is conducted by changing the indirect cost ratio and number of encapsulation layers. Results are visualized in Figure 23Figure 23. From the results, it can be deduced that with increasing indirect cost of fires in buildings, the value of having encapsulation layers increases. Complementing previous conclusions drawn, a single encapsulation layer is economically justifiable at relatively high indirect costs. However, even as the indirect costs of a fire increases, having more encapsulation layers (in this case 2 layers) is still not viable even if these costs reached 100% of the direct costs. This is similar to the cases with the sprinkler system. Although the value of having sprinklers in the building increases as the indirect costs increases, this value does not increase enough to overcome the costs and thus the net value remains negative, making a fire protection system of sprinklers or sprinklers with the encapsulation of structural members economically unjustifiable for this type of structure. These observations illustrate the importance of the definition of indirect costs on the viability or otherwise of the protection systems, highlighting the necessity of accurately characterizing these indirect costs in a cost benefit analysis.

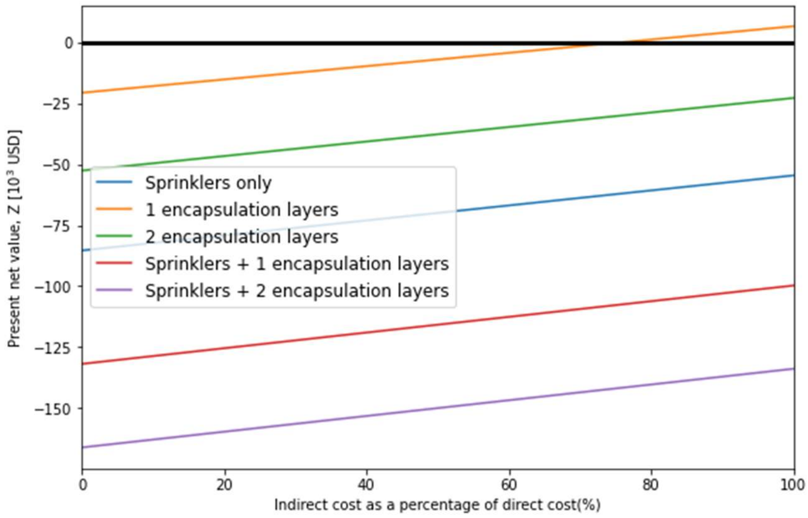


Figure 23 – Parameter study for Case 5.

7 Identified gaps and areas for future research

7.1 Costs and benefits for retrofitting existing buildings

Fire safety costs incurred as part of the retrofit of existing buildings were not considered in this report. This is considered as an important limitation. On the one hand, the total cost of fire protection misses these fire safety investments. On the other hand, the lack of insight in fire protection costs during retrofitting hinder the cost-effectiveness evaluation of such measures. In some jurisdictions, no fire safety guidance exists for existing buildings. Cost-effectiveness studies could however provide a basis for a model code on fire safety requirements in existing buildings. It is hypothesized that such a model code could have considerable positive societal impact.

7.2 Cost-benefit evaluations on the community level

The report applies the cost-benefit assessment to private decision-makers (i.e., for decisions related to specific buildings), and societal decision-makers at the level of code-makers (state or national level). This leaves a gap for cost-benefit assessments at the community level. Such an evaluation may potentially indicate that an investment which is not cost-effective for a building owner (e.g., shop), and neither cost-effective to be mandated in guidance documents, is nevertheless cost-effective at the local level. This possibility is hinted at within Case study 2, where compartmentation was found cost-effective for warehouses in remote locations without the possibility of FRS intervention on-time to avoid flashover. Similarly, it may be hypothesized that in small communities which rely on a limited number of employers (such as a single large industrial facility), the business continuity of said facility is key for the community.

7.3 Assessment of indirect costs

The assessment of indirect costs has been done through a multiplier applied to the direct costs. Parameter studies as part of the case studies provide a generalized view on how conclusions on cost-effectiveness change in function of the magnitude of the indirect costs. There appears to be, however, limited guidance available for decision makers to assess the indirect costs in a specific situation. In order to develop such guidance, detailed evaluations of a number of case studies are recommended. As this report did not focus on indirect costs, it is currently not clear if adequate case study data or other guidance is available. A research project to establish the state-of-the-art in this regards, with special emphasis on differences in function of stakeholder perspectives (see also 7.2 can be recommended). For example, based on reviewer comments, indirect costs can differ greatly from listed expected values for manufacturing locations and societal contexts. Possibly, indirect costs can be (partially) linked to an evaluation of the required reconstruction time post-fire.

7.4 Cost optimization including FRS funding

The FRS availability and performance was considered as beyond the scope of the cost-benefit evaluation within this report. On a societal level, however, a more holistic approach to fire safety whereby investments in fire protection measures are optimized together with investments in FRS may indicate considerable benefit in a fire safety approach which is tailored to the local community. In hypothesis, a professional and well-funded FRS may be very cost-effective in urban areas (potentially allowing to reduce other fire safety measures), while in remote areas increased investment in building specific fire safety measures may be the more cost-effective solution. Indirectly, this is already considered through the existence of volunteer fire brigades, but the authors of this report are not aware of studies which have holistically assessed such decisions in fire safety investments.

7.5 Environmental costs and benefits

Fire protection investments can imply an environmental cost (i.e., environmental effects in production and possible environmental effects in case of operation). On the other hand, fire protection investments which limit the extent of fires will consequently also help in limiting the environmental adverse effects of fires. These costs and benefits have not been elaborated within this report. Adverse environmental effects resulting from fires are lumped within the term “indirect costs”. Adverse environmental effects due to the installation and maintenance of fire protection measures are considered small (associated dollar costs can be considered lumped within the installation and investment costs).

7.6 Valuation of injuries

Within the case studies presented above, the valuation of injuries was not found to be a determinative factor. However, both from the studied references and the feedback received from the project panel, it is clear that the valuation of injuries is a topic which currently lacks consensus. Currently, the valuation of injuries is done as a fraction of the valuation of fatalities.

7.7 Granularity of cost multipliers

Within this report, a prototype methodology has been developed which allows evaluating fire protection cost-multipliers per building category. These multipliers are based on a reference building within the category which is considered representative. The variability within a category is however not known. Application of the prototype methodology to a large number of (real) buildings will allow to assess this variability, and thus to determine whether a finer granularity of building categories is advantageous. Considering reviewer feedback, it is for example expected that a finer granularity is recommendable for manufacturing premises.

7.8 Cost-benefit evaluation taking into account insurance effects

Insurance effects have not been considered within the prototype methodology. For societal decision making, this is recommended as insurance constitutes the transfer of funds within society. For private decision making, insurance may have an important impact. For example, if insurance is purchased because of tolerability reasons, then this may affect the cost-effectiveness of further investment in fire protection measures. On the other hand, insurance companies may require certain fire protection, or may provide premium discounts in function of the protection level. The elaboration of these effects would provide clarity on the application of CBA to private actors and may highlight inefficiencies (i.e., where insurance effects provide a driver towards societally sub-optimal fire protection levels).

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9 Appendix – Building information and characteristics

9.1 Building occupancy

Table 32 - Building occupancy classes from (FEMA, 2003).

Label	Occupancy Class	Example Descriptions
Residential		
RES1	Single Family Dwelling	House
RES2	Mobile Home	Mobile Home
RES3	Multi Family Dwelling RES3A Duplex RES3B 3-4 Units RES3C 5-9 Units RES3D 10-19 Units RES3E 20-49 Units RES3F 50+ Units	Apartment/Condominium
RES4	Temporary Lodging	Hotel/Motel
RES5	Institutional Dormitory	Group Housing (military, college), Jails
RES6	Nursing Home	
Commercial		
COM1	Retail Trade	Store
COM2	Wholesale Trade	Warehouse
COM3	Personal and Repair Services	Service Station/Shop
COM4	Professional/Technical Services	Offices
COM5	Banks	
COM6	Hospital	
COM7	Medical Office/Clinic	
COM8	Entertainment & Recreation	Restaurants/Bars
COM9	Theaters	Theaters
COM10	Parking	Garages
Industrial		
IND1	Heavy	Factory
IND2	Light	Factory
IND3	Food/Drugs/Chemicals	Factory
IND4	Metals/Minerals Processing	Factory

IND5	High Technology	Factory
IND6	Construction	Office
Agriculture		
AGR1	Agriculture	
Religion/Non/Profit		
REL1	Church/Non-Profit	
Government		
GOV1	General Services	Office
GOV2	Emergency Response	Police/Fire Station/EOC
Education		
EDU1	Grade Schools	
EDU2	Colleges/Universities	Does not include group housing

9.2 Building structural system

Model building types from (FEMA, 2003) (Table 5.1) with detailed description (Section 5.2.1). Since mass timber buildings are not included in this list, structural systems based on mass timber has been added according to (Breneman et al., 2021).

Table 33 - Model building types, after (FEMA, 2003).

No.	Label	Description	Height			
			Range		Typical	
			Name	Stories	Stories	Feet
1 2	W1 W2	**Wood, Light Frame (≤ 5,000 sq. ft.)** **Wood, Commercial and Industrial (>5,000 sq. ft.)**		1 - 2 All	1 2	14 24
3 4 5	S1L S1M S1H	**Steel Moment Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
6 7 8	S2L S2M S2H	**Steel Braced Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
9	S3	**Steel Light Frame**		All	1	15
10 11 12	S4L S4M S4H	**Steel Frame with Cast-in-Place Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156

13 14 15	S5L S5M S5H	**Steel Frame with Unreinforced Masonry Infill Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 13	24 60 156
16 17 18	C1L C1M C1H	**Concrete Moment Frame**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
19 20 21	C2L C2M C2H	**Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
22 23 24	C3L C3M C3H	**Concrete Frame with Unreinforced Masonry Infill Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
25	PC1	**Precast Concrete Tilt-Up Walls**		All	1	15
26 27 28	PC2L PC2M PC2H	**Precast Concrete Frames with Concrete Shear Walls**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
29 30	RM1L RM1M	**Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms**	Low-Rise Mid-Rise	1-3 4+	2 5	20 50
31 32 33	RM2L RM2M RM2H	**Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms**	Low-Rise Mid-Rise High-Rise	1 - 3 4 - 7 8+	2 5 12	20 50 120
34 35	URML URMM	**Unreinforced Masonry Bearing Walls**	Low-Rise Mid-Rise	1 - 2 3+	1 3	15 35
36	MH	**Mobile Homes**		All	1	10
37 38 39	MTL MTM MTH	**Mass Timber Frame**	Low-Rise Mid-Rise High-Rise	1 - 6 7 - 12 13+		

9.3 Fire safety strategy and characteristics

Additional information and details about the building characteristics and fire safety strategy:

- Design Strategy
  - ☐ Prescriptive
    - ☐ No rating
    - ☐ 30 min rating
    - ☐ 1h rating
    - ☐ 90 min rating
    - ☐ 2h rating
    - ☐ 3h rating
    - ☐ 4h rating
  - ☐ Performance-based

- Active Fire Protection
  - ☐ Detection & Alarm
  - ☐ Emergency Lighting
  - ☐ Fire Extinguishers
  - ☐ Sprinklers/Water Mist
  - ☐ Ventilation & Extraction Systems
  - ☐ Stairs Pressurization
  - ☐ Oxygen Depletion Systems
- Passive Fire Protection
  - ☐ Means of Escape
  - ☐ Compartmentation (Doors, Separating Walls, Penetrations)
  - ☐ Structural Fire Protection (Fire Ratings)
- Other Specific Information
  - ☐ Storage of Dangerous Goods
  - ☐ …?

9.4 Construction cost

Table 34 - Mean construction cost per square foot associated with occupancy classes and estimated using the RSMeans 2022 database (RSMeans, 2022).

HAZUS Occupancy Description		Sub category	Means Model Description (Means Model Number)	Means Cost/SF (2022)
RES1	Single Family Dwelling	-	-	-
RES2	Manufactured Housing	Manufactured Housing	Manufactured Housing (N/A)[1]	57
RES3	Multi Family Dwelling-small	Duplex	SFR Avg 2 St. MF adj. 3,000 SF	115.23
		Triplex/Quads	SFR Avg 2 St. MF adj. 3,000 SF	131.93
	Multi Family Dwelling-medium	5-9 units	Apt 1-3 st, 8,000 SF (M.010)	303.71
		10-19 units	Apt., 1-3 st., 12,000 SF (M.010)	255.03
	Multi Family Dwelling - large	20-49 units	Apt., 4-7 st., 40,000 SF (M.020)	220.63
		50+ units	Apt., 4-7 st., 60,000 SF (M.020)	195.57
			Apt., 8-24 st., 145,000 SF (M.030)	226.5
RES4	Temp. Lodging	Hotel, medium	Hotel, 4-7 st., 135,000 SF (M.350)	194.14
		Hotel, large	Hotel, 8-24 st., 450,000 SF (M.360)	208.7
		Motel, small	Motel, 1 st., 8,000 SF (M.420)	163.02
		Motel, medium	Motel, 2-3 st., 49,000 SF (M.430)	184.58
RES5	Institutional Dormitory	Dorm, medium	College Dorm, 2-3 st., 25,000 SF (M.130)	201.28
		Dorm, large	College Dorm, 4-8st., 85,000 SF (M.140)	193.44
		Dorm, small	Frat House, 2 st., 10,000 SF (M.240)	206.18

RES6	Nursing Home	Nursing home	Nursing home, 2 st., 25,000 SF (M.450)	225.26
COM1	Retail Trade	Dept Store, 1 st	Store, Dept., 1 st., 110,000 SF (M.610)	131.59
		Dept Store 3 st	Store, Dept., 3 st., 95,000 SF (M.620)	152.28
		Store, small	Store, retail, 8,000 SF (M.630)	161.13
		Store, medium	Supermarket, 44,000 SF (M.640)	151.21
		Store, convenience	Store, convenience, 4,000 SF (M.600)	137.88
		Auto Sales	Garage, Auto Sales, 21,000 SF (M.260)	133.5
COM2	Wholesale Trade	Warehouse, medium	Warehouse, 30,000 SF (M.690)	136.74
		Warehouse, large	Warehouse, 60,000 SF (M.690)	113.41
		Warehouse, small	Warehouse, 15,000 SF (M.690)	183.39
COM3	Personal and Repair	Garage, repair	Garage, repair, 10,000 SF (M.290)	146.14
	Services	Garage, Service sta.	Garage, Service sta., 1,400 SF (M.300)	222.29
		Funeral Home	Funeral home, 10,000 SF (M.250)	177.24
		Laundromat	Laundromat, 3,000 SF (M.380)	263.54
		Car Wash	Car wash, 1 st., 800 SF (M.080)	309.15
COM4	Prof/Tech/Business Services	Office, medium	Office, 5-10 st., 80,000 SF (M.470)	214.75
		Office, small	Office, 2-4 st., 20,000 SF (M.460)	199.87
		Office, large	Office, 11-20 st., 260,000 SF (M.480)	172.26
COM5	Banks	Bank	Bank, 1 st., 4,100 SF (M.050)	264.34
COM6	Hospital	Hospital, medium	Hospital, 2-3 st., 55,000 SF (M.330)	362.47
		Hospital, large	Hospital, 4-8 st., 200,000 SF (M.340)	301.7
COM7	Medical office/Clinic	Med. Office, medium	Medical office, 2 st., 7,000 SF (M.410)	248.7
		Med. oOffice, small	Medical office, 1 st., 7,000 SF (M.400)	243.88
COM8	Entertainment & Recreation	Restaurant	Restaurant, 1 st., 5,000 SF (M.530)	221.06
		Restaurant, fast food	Restauant, fast food, 4,000 SF (M.540)	236.71
		Bowling alley	Bowling alley, 20,000 SF (M.060)	178.29
		Country club	Club, country, 1 st., 6,000 SF (M.100)	243.99
		Social club	Club, Social, 1 st., 22,000 SF, (M.110)	174.03
		Racquetball Court	Racquetball court, 30,000 SF (M.510)	187.19
		Hockey Rink	Hockey Rink, 30,000 SF (M.550)	179.36

COM9	Theaters	Movie Theater	Movie Theater, 12,000 SF (M.440)	179.63
		Auditorium	Auditorium, 1 st., 24,000 SF (M.040)	178.18
COM10	Parking	Parking garage	Garage, Pkg, 5 st., 145,000 SF (M.270)	74.56
		Parking garage, Underground	Garage, UG Pkg, 100,000 SF (M.280)	90.75
IND1	Heavy	Factory, small	Factory, 1 st., 30,000 SF (M.200)	139.2
		Factory, large	Factory, 3 st., 90,000 SF (M.210)	154.06
IND2	Light	Warehouse, medium	Warehouse, 30,000 SF (M.690)	136.74
		Factory, small	Factory, 1 st., 30,000 SF (M.200)	139.2
		Factory, large	Factory, 3 st., 90,000 SF (M.210)	154.06
IND3	Food/Drugs/Chemicals	College laboratory	College lab., 1 st., 45,000 SF (M.150)	197.49
		Factory, small	Factory, 1 st., 30,000 SF (M.200)	139.2
		Factory, large	Factory, 3 st., 90,000 SF (M.210)	154.06
IND4	Metals/Minerals/Processing	College laboratory	College lab., 1 st., 45,000 SF (M.150)	197.49
		Factory, small	Factory, 1 st., 30,000 SF (M.200)	139.2
		Factory, large	Factory, 3 st., 90,000 SF (M.210)	154.06
IND5	High technology	College laboratory	College lab., 1 st., 45,000 SF (M.150)	197.49
		Factory, small	Factory, 1 st., 30,000 SF (M.200)	139.2
		Factory, large	Factory, 3 st., 90,000 SF (M.210)	154.06
IND6	Construction	Warehouse, medium	Warehouse, 30,000 SF (M.690)	136.74
		Warehouse, large	Warehouse, 60,000 SF (M.690)	113.41
		Warehouse, small	Warehouse, 15,000 SF (M.690)	183.39
AGR1	Agriculture	Warehouse, medium	Warehouse, 30,000 SF (M.690)	136.74
		Warehouse, large	Warehouse, 60,000 SF (M.690)	113.41
		Warehouse, small	Warehouse, 15,000 SF (M.690)	183.39
REL1	Church	Church	Church, 1 st., 17,000 SF (M.090)	183.84
GOV1	General services	Town hall, small	Town hall, 1 st., 11,000 SF (M.670)	147.77
		Town hall, medium	Town hall, 2-3 st., 18,000 SF (M.680)	201.04
		Courthouse, small	Courthouse, 1 st., 30,000 SF (M.180)	219.07

		Courthouse, medium	Courthouse, 2-3 st., 60,000 SF (M.190)	233.15
		Post office	Post office, 13,000 SF (M.500)	145.13
GOV2	Emergency response	Police station	Police station, 2 st., 11,000 SF (M.190)	235.4
		Fire station, small	Fire station, 1 st., 6,000 SF (M.220)	174.45
		Fire station, medium	Fire station, 2 st., 10,000 SF (M.230)	193.16
EDU1	Schools/Libraries	High school	School, high, 130,000 SF (M.570)	214.98
		Elementary school	School, Elementary, 45,000 SF (M.560)	184.96
		Jr. High School	School, Jr. high, 110,000 SF (M.580)	194.1
		Library	Library, 2 st., 22,000 SF (M.390)	182.36
		Religious school	Religious education, 1 st., 10,000 SF (M.520)	195.14
EDU2	Colleges/Universities	College classroom	College class., 2-3 st., 50,000 SF (M.120)	180.24
		College laboratory	College lab., 1 st., 45,000 SF (M.150)	197.49
		Vocational school	School, Vocational, 40,000 SF (M.590)	173.1