RISK AND PERFORMANCE ASSESSMENT FRAMEWORK FOR A SUSTAINABLE AND FIRE RESILIENT BUILDING ENVIRONMENT (SAFR-BE)

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Risk and Performance Assessment Framework for a Sustainable and Fire Resilient Building Environment (SAFR-BE)

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About the SFPE Foundation

The Society of Fire Protection Engineers (SFPE) established the SFPE Educational and Scientific Foundation in 1979. The Foundation is a charitable 501c(3) organization incorporated in the state of Massachusetts in the United States of America. It supports a variety of research and educational programs in service of its mission to enhance the scientific understanding of fire and its interaction with the social, natural, and built environments.

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Executive Summary

Increasingly, buildings are becoming complex “systems of systems” with many materials and attributes combining to create a whole that aims to meet a variety of design objectives including but not limited to functionality, aesthetic appeal, sustainability, safety, and security. We are now seeing this complexity move from commercial buildings and iconic structures to encompass even the residential sector. Such buildings are typically designed by professionals seeking to produce stunning, environmentally friendly, healthy, safe, and operationally efficient artifacts. They are engineered by experts from diverse disciplines, using innovative materials and technologies, that do not necessarily interact, but focus on their piece of the whole design picture. They are constructed within regulatory boundaries which largely align with the major systems or components of a building (e.g., structure, mechanical systems), albeit sometimes missing important interactions between systems, i.e., these complex designs sometimes result in important points of interaction between design objectives being outside of any individual designer’s responsibility.

While this can result in rather spectacular buildings, with state-of-the-art technologies as part of the building (e.g., building-integrated photovoltaics) and within the building (e.g., automated systems for improved indoor environments or improved user comfort), if the design is not holistic and well-integrated, and the building is not adequately maintained within operational parameters, there can be unintended consequences that may not manifest until well after construction. In recent years, there have been a series of rather significant fire losses associated in one way or another with choices made to meet societal objectives to be more environmentally sustainable and minimize the potential for climate change. These include numerous high-rise exterior façade fires around the world, notably the Grenfell Tower fire in London, the Dietz &

Watson cold storage warehouse in Delanco, and a spate of fires in buildings under construction using lightweight timber framing.

The work presented in this report represents an overview of risk methodologies, an investigation of state-of-the-art publications concerning the nexus between fire safety and sustainability, and the latest proof-of-concept and development of a model to foster sustainable and fire resilient choices in the design process of a building. The literature review has shown that while little is presently published concerning the nexus of sustainability and fire safety, some interesting investigations of sustainable and fire safe solutions have been found. Further, while the development of a complex hierarchical model to assess the sustainability and fire resiliency of different design choices is difficult, we have been able to make the first steps towards creating a framework to support decision making in the design of sustainable and fire resilient *buildings* as part of a larger framework to create a sustainable and fire resilient *built environment* (SAFR-BE). But rather than the whole built environment, the focus is on sustainable and fire resilient buildings (SAFR-B).

The framework is built on an analysis of regulatory requirements (for fire safety) and green building systems (for sustainability), as well as the creation of an analytical hierarchy process (AHP) risk assessment methodology. The resultant scores in the SAFR-B framework are based on generous input from international experts in the field of fire safety and sustainability, while the weighting between attributes has been based on the project team's expert input. The resultant proof-of-concept framework has been applied to a fictive case study of an apartment building from Malmö. The building itself is perhaps not particularly representative of US buildings, but the application of the framework could easily be generalized to US structures should such a case exist.

The results of the study show that the framework can give guidance to the designer of the importance of various choices for fire safety and sustainability, in a relative sense. The model is not absolute. The comparisons are not expressed as absolute numbers, and comparisons between different buildings are neither possible at the moment (the model has been developed specifically for apartment buildings), nor recommended due to the inherent differences between different applications and buildings. Relative comparisons are really the only comparison that makes sense at this point.

The development of the model and application to apartment buildings is a first proof-of-concept. More developmental work is needed, and several suggestions have been forwarded at the end of the report concerning future improvements. Perhaps most importantly, more expert input is needed. The more experts that give their input and the broader range of experts involved, the better the overall scoring of relative importance of different survey items will be. Greater expert input will improve the robustness of the model and can ultimately provide sufficient information to make comparisons between different buildings or different building contexts. Finally, the model has specifically been developed for apartment buildings. While this is a good starting point, there is a need to add different types of buildings and to expand apartment buildings to both low-rise and high-rise examples. Expanding the application of the model will also expand its usefulness and range. Ideally, future buildings should be designed with the SAFR-B framework as an obvious step (or multiple steps) in the design process.

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Acronyms, Abbreviations and Selected Definitions

AHP	Analytical Hierarchy Process, a multi-attribute decision-support framework that helps one think about and address complex interactions and interdependence amongst decision factors in a simple way.
MADM/ MCDM/ MODM	Multi-Attribute Decision Method / Multi-Criteria Decision Method / Multi-Objective Decision Methods are formal mathematical treatments of decision problems with multiple criteria (objectives/attributes) and include multi-objective programming and vector optimization.
MAUT	Multi-Attribute Utility Theory (MAUT) is a procedure for evaluating objects, wherein a set of attributes is developed that characterizes the objects, and each object is evaluated on each attribute.
Resilient	There are many definitions of resilient (or resiliency). As used in this report, it is defined as the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.
Resilient buildings	Resilient buildings are those which are designed for long life. Resilience can be achieved in many ways, from use of durable and highly reliable components, to ease of repair and renovation, to high level of resistance to expected hazard impacts. Attributes can include reduced susceptibility to single points of failure, increased robustness, redundancy and reliability of systems and components, and flexibility and adaptability.
SAFR-B	Sustainable and Fire Resilient Buildings (structures) are those which are designed to both be sustainable in terms of reducing or eliminating negative impacts on our climate and natural environment, and resilient in terms of their ability to safeguard people, property, operations, and the environment from unwanted fire.
SAFR-BE	A Sustainable and Fire Resilient Built Environment includes the built environment in the SAFR-concept, i.e. not simply isolated to buildings.
Sustainable	There are many definitions of sustainable (or sustainability). As used in this report, it is defined as responsibly interacting with the planet to maintain natural resources and avoid jeopardizing the ability for future generations to meet their needs.
Typology	As used in this report, typology refers to apartment buildings in general, while mid-rise apartment buildings are a specific classification within this typology.

1. Introduction

1.1. Background

Increasingly, buildings are becoming complex "systems of systems" with many materials and attributes combining to create a whole that aims to meet a variety of design objectives including but not limited to functionality, aesthetic appeal, sustainability, safety, and security. While this has perhaps been the case in complex commercial or multifunctional buildings previously, today we are seeing this complexity extend into the residential sector. Such buildings are typically designed by professionals seeking to produce stunning, environmentally friendly, healthy, safe, and operationally efficient artifacts. They are engineered by experts from diverse disciplines, using innovative materials and technologies, that do not necessarily interact, but focus on their piece of the whole design picture. They are constructed within regulatory boundaries which largely align with the major systems or components of a building (e.g., structure, mechanical systems), albeit sometimes missing important interactions between systems, i.e., these complex designs sometimes result in important points of interaction between design objectives being outside of any individual designer's responsibility. In particular, commercial or multifunctional buildings are used by people who are likely not cognizant of the importance of operating and maintaining the building in a manner that continues to achieve all societal, regulatory, design, and operational objectives as outlined during the design process, throughout its lifecycle. A recent handbook on fire and the environment discusses these and other issues [1] without operationalizing how to solve the question of multi-attribute optimization.

While this can result in rather spectacular buildings, with state-of-the-art technologies as part of the building (e.g., building-integrated photovoltaics) and within the building (e.g., automated systems for improved indoor environments or improved user comfort), if the design is not holistic and well-integrated, and the building is not adequately maintained within operational parameters, there can be unintended consequences that may not manifest until well after construction. These concerns can be amplified when new materials and technologies are integrated into existing buildings without appropriate consideration of the potential impacts as part of major renovations or rebuilds. This can happen for a variety of reasons, including ignorance of potential interactions between the existing building and newly introduced technologies, a regulatory system that imposes less oversight on renovation of existing buildings as compared with new construction, and underlying lack of tools to support risk and performance analyses.

In recent years, there have been a series of rather significant fire losses associated in one way or another with choices made to meet societal objectives to be more environmentally sustainable and minimize the potential for climate change. These include numerous high-rise exterior façade fires around the world, notably the Grenfell Tower fire in London [2-5], the Dietz & Watson cold storage warehouse in Delanco [6], and a spate of fires in buildings under construction using lightweight timber framing [7-10]. Additional non-fire-related incidents have happened, such as the Champlain Towers collapse in 2021 [11, 12]. While these other failures are also important, the impact of fire as the failure mode is the focus of the work presented in this report.

The challenge in addressing such fire safety issues with "green" buildings and attributes can be readily understood when one considers the number of attributes and scenarios that exist. A recently completed Fire Protection Research Foundation (FPRF) commissioned project [13] identified some 100 materials, technologies, or features that can be considered "green" or sustainable in the context of buildings. Associated with these are some 22 potential sources of hazard or risk of concern if not mitigated. As a visualization of the extent of potential attribute and hazard conditions, a relative risk matrix was developed, see Figure 1.

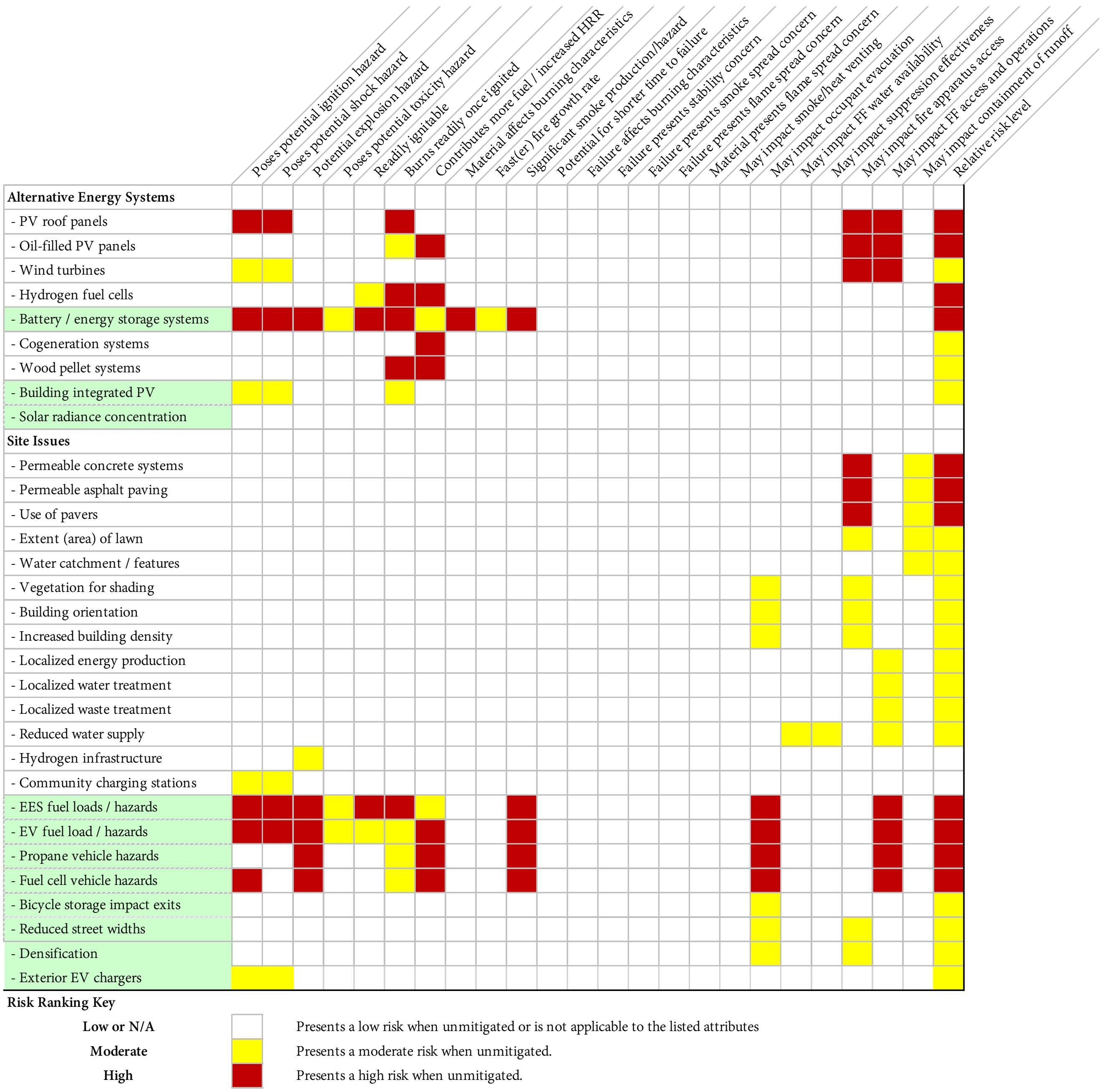


Fig. 1. Matrix summarizing relationship between "green" attributes (rows) and potential hazards (columns). Reproduced from Meacham and McNamee [13].

The focus of this previous work was understanding the fire safety implications of choices made to meet sustainability objectives, but this is only half of the optimization needed to properly balance both sustainability and fire safety. It is also necessary to consider the sustainability implications of choices made to meet fire safety objectives. To consider multiple ‘green’ attributes and multiple potential hazards and risks, both in terms of their impact on sustainability objectives and fire safety objectives, a much greater level of data and information are needed. This will ultimately require significant research, testing, and tool development. The work presented in this report represents initial scoping and proof of concept of such research and development.

1.2. Broadening Traditional Risk-based Methods

Risk-based methods offer a systematic approach to assessing complex systems. Fundamentally, risk is a function of decision-making under uncertainty. It is most often characterized, at least in engineering, as being a function of some unwanted event, the likelihood of that event occurring, and the associated consequences should the event occur; although there are many other ways to characterize, analyze or assess risk. Broadly, risk-based approaches exist within a range from qualitative, semi-quantitative, and quantitative, each of which encompasses various levels of granularity and complexity. Selection of a method is most often related to the needs of a particular problem and the required robustness of the risk estimate, taking into account available data, level of uncertainty, how uncertainty is treated, and factors affecting decisions about risk acceptability and tolerability. Numerous resources exist for identifying appropriate risk assessment methods across many areas, including fire safety. The qualitative framing of the fire performance risks associated with “green” building attributes that has been developed previously has been used as a starting point for the development of a broader risk-based approach that attempts to incorporate an understanding of the complex interplay between sustainability and fire safety risks while taking sustainability and fire safety objectives as their starting point.

1.3. Importance to Fire Protection Engineers

The work presented in this report is important to fire protection engineers (FPEs) as it relates specifically to choices that will be made as part of the building design process, some of which may seemingly have competing objectives depending on the perspective of the different stakeholders involved. Understanding, defining, and addressing stakeholder objectives is a significant part of the performance-based design (PBD) process. So too are the aspects of defining fire scenarios, quantifying design fires, and postulating and evaluating trial design options. To facilitate good discussion and understanding between stakeholders who may have a focus on sustainability (e.g., architects, mechanical systems designers, energy systems designers, etc.) and those who may be more focused on fire safety (e.g., fire service, insurers), it is important to understand both sustainability and fire safety objectives, how those objectives may be realized in terms of building materials, technologies, and features, what if any fire safety challenges might exist with proposed sustainability-oriented materials, technologies, and features, and how one might aim to balance sustainability and fire safety objectives. While it is not suggested that every design will need to go through a detailed process such as outlined here, the framework that is presented provides an approach for understanding the potentially differing perspectives and how they might be balanced. The question of how to achieve this balance is complex. It is important to keep in mind the fact that while accident costs are reduced by the inclusion of prevention costs, this is not included in the present iteration of the framework as accidents are not explicitly included. Future iterations could endeavor to bridge this gap through the inclusion of statistical models to estimate the benefits gained through the inclusion of prevention costs. The work herein is a first step in achieving a decision support tool. In the future, additional research can lead to simpler applications and more robust decision-support tools for sustainable and fire resilient building design.

1.4. Project Aim and Objectives

The project aims to facilitate the creation of sustainable and fire resilient buildings (SAFR-B) in the future through the development of a framework for assessing and aligning design choices made to attain both sustainability and fire resiliency design objectives. The objectives in this project are to develop said framework and test the proof-of-concept on a representative building typology. The framework builds on previous and new research and incorporates input from international experts on fire safety and sustainability. The proof-of-concept is based on a generic, simplified mid-rise apartment building type.

1.5. Expected Project Impact

The research has focused on advancing and framing the scientific and engineering understanding of risk and decision tradeoffs that are part of balancing sustainability and fire resiliency decisions in a building design project. This was done: (a) through research into the fire performance of “green” building attributes, (b) through research into how fire involving green building attributes impacts the risk to building occupants, and secondarily to the environment, and (c) through the development of a framework for a risk-informed performance-based decision framework aimed at delivering more sustainable and fire resilient buildings.

There are policies in many countries to make buildings more environmentally sustainable. This includes making buildings more energy efficient, which often involves adding thermal insulation, some types of which are combustible. It also means reducing the carbon footprint of the materials used, which can include using more timber, which is combustible, or reducing other materials, such as the amount of concrete or steel. Each of these can have fire consequences. It also means integrating alternative energy systems, including photovoltaics and energy storage systems into buildings, each of which has fire ignition and other risks. This research effort has the potential to have a significant impact on identifying fire risks that may result from the confluence of sustainability measures and lead to the design and construction of buildings that include sustainability features more resilient to fire.

1.6. Project Tasks

To support the research, the project was divided into the following tasks:

- **Task 1.** Literature review and refinement of research objective.
- **Task 2.** Identification of “green” attributes and risk factors for consideration in the methodology.
- **Task 3.** Review of potential methodology(ies) for risk characterization and assessment.
- **Task 4.** Collection of expert and non-expert stakeholder input.
- **Task 5.** Development of framework for risk-informed performance-based assessment methodology for sustainable and fire resilient buildings.

1.7. Project Limitations (Scope)

The project was framed as a proof-of-concept concerning the development of a framework to assess sustainable and fire resilient buildings. In this context, sustainability is restricted to environmental sustainability, i.e., economic and social sustainability are outside of the scope of the project. Furthermore, the scope of sustainable materials, technologies, and systems have been restricted in the first instance to “high-level” attributes, such as different material typologies (e.g., concrete and timber), technologies (e.g., photovoltaic panels generally, and not roof-based or building-integrated specifically), and so forth. Likewise, fire safety attributes are generalized in terms of fire resistive construction, detection and suppression systems, egress systems, and the like. Future iterations can go into much more detail.

Buildings have a variety of bespoke design features depending on their intended use. These features are difficult to combine in a single framework because uses vary significantly, and thus the sustainability and fire safety objectives also vary. Therefore, a single building typology has been selected for the development of the framework in this first iteration (i.e., apartment building). Given that most fire deaths occur in the home, and that many residential buildings are designed today with sustainable objectives in addition to regulatory requirements such as fire safety, the proof-of-concept application has focused on apartment buildings. To further narrow the focus of application, the apartment building has been defined as midrise with an attic and all floors used for domestic occupation.

Objective data on fire performance of sustainable materials, technologies, and systems – for use in fire engineering analyses – is lacking. In part, this is a function of the standard fire test methods, which often yield only index-based output, but is also a function of the limited history of fire loss data in buildings with sustainable materials, technologies, and systems. This means that there is a need for use of largely subjective data in the first instance, mostly (but not exclusively) from sustainability and fire risk experts. Use of such data comes with significant uncertainty and variability, which must be understood in the initial framework, but which can be reduced in future iterations.

Expert and non-expert opinions were convenience sampled, meaning that experts were recruited through contacts in the author group. In all cases either fire safety, risk, or sustainability experts were chosen. In most cases, the experts were experts in their particular field and could be seen as non-experts in the other, i.e., sustainability experts were typically non-experts in fire safety and vice versa.

1.8. Project and Report Structure

To guide the research, a number of steps were identified as associated with the required research tasks. The report is structured in alignment with these tasks as illustrated in Table 1.

TABLE 1. APPROXIMATE REPORT STRUCTURE JUXTAPOSED WITH PROPOSED PROJECT TASKS

Task	**Chapter**
Task 1: Literature review and refinement of research methodology	Chapter 2. Literature Review
Task 2: Identification of "green" attributes and risk factors for consideration in the methodology	Chapter 1. Introduction Chapter 2. Literature Review
Task 3: Review methodologies for Risk characterization and assessment	Chapter 2. Literature Review Chapter 3. A Framework for a Sustainable and Fire Resilient Building (SAFR-B)
Task 4: Collection of expert and non-expert stakeholder input	Chapter 3. A Framework for a Sustainable and Fire Resilient Building (SAFR-B)
Task 5: Development of framework for a risk-informed performance-based assessment method	Chapter 3. A Framework for a Sustainable and Fire Resilient Building (SAFR-B) Chapter 4. Application of SAFR-B to Apartment Building Chapter 5. Discussion Chapter 6. Conclusions Chapter 7. Future Work

2. Literature Review

2.1. Methodology

A literature search was conducted using Web of Science. A broad variety of key words were used in each of the databases, e.g., multi-attribute, sustain*, fire, "risk index", evaluat*, "risk assessment", rating, AHP, and application. See Table 2 for search term combinations and hits. Publications were not restricted to peer review, allowing the inclusion of reports, conference proceedings, magazine articles, and other grey literature, in addition to peer reviewed journal articles. The definition of key words and the literature search followed approximately the process outlined in Figure 2.

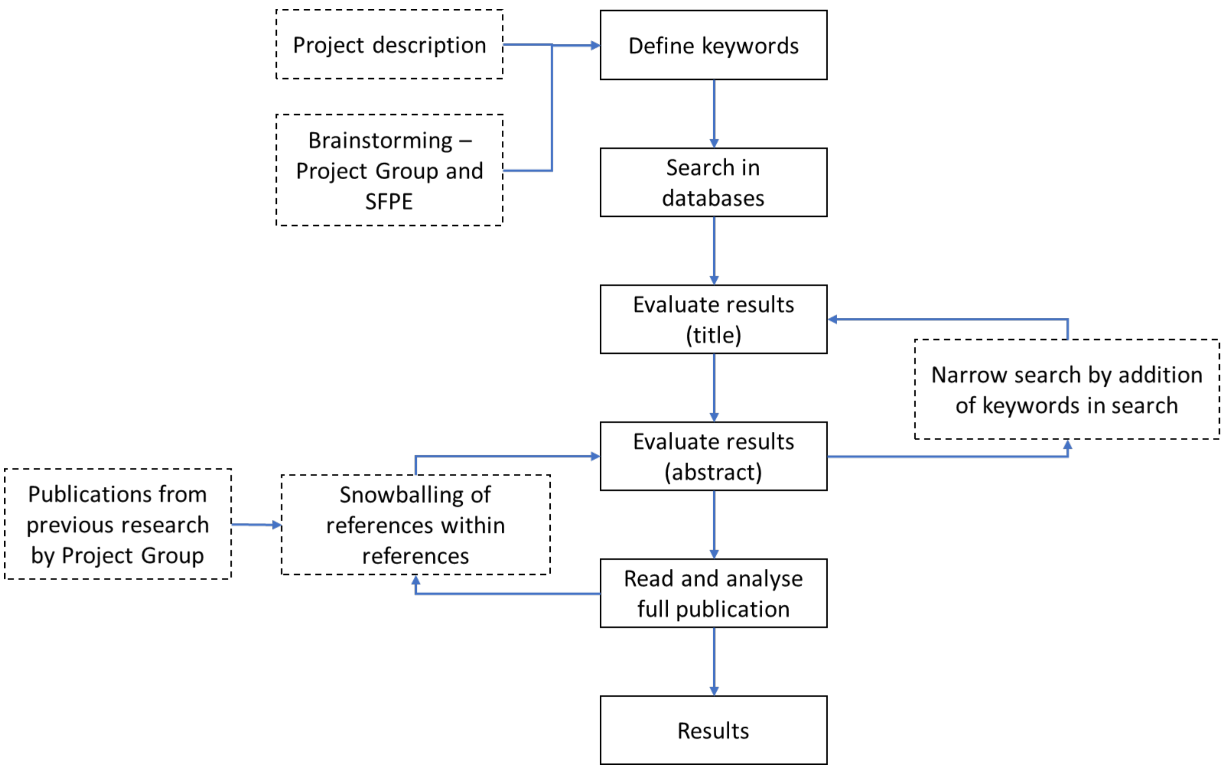


Fig. 2. Schematic overview of literature search process.

TABLE 2. SUMMARY OF KEYWORDS AND HITS

Keywords	Hits	Comments
Fire + "Risk index"	181	Additional keywords were included to reduce hits
Fire + "Risk index" + rating	30	Titles and abstracts reviewed
Fire + "Risk index" + application	19	Titles and abstracts reviewed
Fire + "Risk index" + AHP	7	Titles and abstracts reviewed
Fire + "Risk index" + AHP + sustain*	1	Titles and abstracts reviewed
Fire + "Risk index" + sustain*	14	Titles and abstracts reviewed
Fire + Risk + index + sustain*	235	Additional keywords were included to reduce hits
Fire + Risk + index + sustain* + Topic: sustainable science + safety & maintenance	13	Titles and abstracts reviewed
Fire + risk + index + AHP	70	Titles and abstracts reviewed
"Risk assessment" + rating	26 000	Additional keywords were included to reduce hits
"Risk assessment" + rating + AHP	115	Titles and abstracts reviewed
"Risk assessment" + rating + AHP + sustain*	8	Additional keywords were included to reduce hits
Multi-attribute + Risk + index	112	Additional keywords were included to reduce hits
Multi-attribute + "Risk index"	12	Titles and abstracts reviewed
Multi-attribute + AHP	605	Additional keywords were included to reduce hits
Multi-attribute + AHP + sustain*	89	Titles and abstracts reviewed

2.2. Risk Assessment

2.2.1. Introduction

Risk means different things to different people. It can be challenging to characterize due to the breadth of perceptions, conceptualizations, and definitions that exist [14]. For many people, risk is related to the uncertainty around some future decision, action, or event, where all relevant knowledge and information that may impact the outcome is not known or available. What is the risk of losing money in the stock market? What is the risk of flight cancellation? What is the risk of developing cancer? What is the risk of fire in a particular building? What is the risk of *not* reducing the human caused release of carbon into the environment? Every such framing includes querying some future possibility, often under significant uncertainty, to inform current decisions / actions, often for the purpose of reducing the potential for an unwanted future outcome. This uncertainty necessitates considering the possibility or likelihood that different outcomes might occur. The framing of a risk decision is also dependent on how those involved perceive and value the potential outcomes (e.g., those imposing the risk or those at risk). Risk can also be characterized as individual or societal (impacting the one or the many).

There are different types of risks which may be considered, such as health risks, safety risks, environmental risks, economic risks, and political risks, and the interpretation and measurement of risk is often a function of the context of the risk problem that is being addressed. As a result, specific taxonomies and tools for discussing and assessing risk grew out of the context of the various problem areas for which risk analysis was being applied [15, 16]. An example of the diversity of risk framing is illustrated in Table 3 [15, 16].

TABLE 3. SYSTEMATIC CLASSIFICATION OF RISK PERSPECTIVES (FROM [16], AS ADAPTED FROM [15])

	Integrated Approaches (e.g., Social Amplification of Risk)						
	Actuarial Approach	Toxicology Epidemiology	Probabilistic Risk Analysis	Economics of Risk	Psychology of Risk	Social Theories of Risk	Cultural Theory of Risk
Base Unit	Expected Value (EV)	Modelled Value	Synthesized Expected Value	Expected Utility (EU)	Subjective Expected Utility	Perceived Fairness and Competence	Shared Values
Predominant Method	Extrapolation	Experiments	Fault Tree and Event Tree Analysis	Risk Benefit Analysis	Psychometrics	Surveys	Grid-Group Analysis
		Health Surveys				Structured Analyses	
Scope of Risk Concept	Universal	Health & Environment	Safety	Universal	Individual Perceptions	Social Interests	Cultural Clusters
	One-dimensional	One-dimensional	One-dimensional	One-dimensional	Multi-dimensional	Multi-dimensional	Multi-dimensional
	Averaging over space, time, context			Preference Aggregation		Social Relativism	
Basic Problem Areas	Predictive Power	Transfer to Humans	Common Mode Failure	Common Denominator	Social Relevance	Complexity	Empirical Validity
		Intervening Variables					
Major Application	Insurance	Health	Safety Engineering	Decision Making	Policy making and regulations		
		Environmental			Conflict resolution		
					Risk communication		
Instrumental Function	Risk sharing	Early warning		Resource allocation	Individual Assessment	Equity Fairness	Cultural identity
		Standard setting	Improving systems			Political acceptance	
Social Function	Assessment	Risk reduction and policy setting (coping with uncertainty)					Political legitimization

Engineers tend to idealize risk as a numerical value that is a function of likelihood and consequences. A more robust framing is the risk triplet [17], in which one should: identify what can go wrong (events / scenarios), determine what can happen if something goes wrong (the consequences of the events / scenarios), and assess how likely is it that something will go wrong (estimate the likelihood / probability / frequency). Inherent in this framing is that there are many possible outcomes, each of which have different likelihoods of occurrence, but all with some level of uncertainty. The level at which the uncertainty needs to be understood, quantified, and addressed depends on the risk decision, context, and data availability, as well as other factors discussed below.

By contrast, some social scientists view risk as a social construct, not dependent on numerical values, but dependent upon the social situation and conditional knowledge [18]. Another view is held by some psychologists who believe that "risk" does not exist outside of our minds, but that it is simply a concept humans developed to deal with uncertainties of life [19]. There are also some who have suggested that the selection of a definition of risk is a political one, chosen to express someone's views regarding the importance of different adverse effects in a particular situation [20]. In the latter case, several dimensions define the issue, including objectivity (objective versus subjective probability and/or risk), dimensionality (there are usually benefits as well as consequences), data, statistics and units of measure, time impacts, values, and perceptions. Add to the mix various cultural and other viewpoints on risk, and other important considerations [14], then numerous definitions and classifications of risk can result [15-17, 21].

Although an ideal definition of risk may not be possible, it is still helpful to aim for a definition of risk that encompasses the key attributes of risk, that are particular to the context of the risk decision. Drawing from those who have considered what is needed in a well-rounded definition of risk, particularly around what can be considered "hazard-related risk," it has been suggested that key attributes to be considered in any definition of risk are [16, 22]:

- The concept of hazard or hazard event,
- The consequences of the hazard event (including all relevant consequences and the valuation of the consequence, including off-setting benefits),
- Differences in risk perception,

- Social and cultural experience,
- Judgement(s) regarding the likelihood (probability) of the consequence occurring, and
- Consideration of uncertainty and variability.

One definition of risk that includes the above factors is [14, 16]: "the possibility of an unwanted outcome in an uncertain situation, where the possibility of the unwanted outcome is a function of three factors: loss or harm to something that is valued (consequence), the event or hazard that may occasion the loss or harm, and a judgement about the likelihood that the loss or harm will occur (probability)." In this definition, the valuation of loss or harm is intended to consider physical, technical, social, cultural, and psychological factors, and an event or hazard is intended to consider any act or phenomenon that has the potential to produce loss or harm. Loss or harm to something that is valued includes such things as loss of life, injury, disease, reduced quality of life, inability to carry on economic activity (the inability of an individual to work, or the inability of a business to carry on operations), property damage, and damage to the environment [14, 16].

Given the variability in the framing of risk as a concept, it should come as no surprise that the notion of risk assessment has many framings as well. Since risk can be characterized as anything from a psychological construct to a quantitative representation of hazard scenarios and their likelihoods of occurrence, risk assessment definitions and approaches are equally as broad. There is a further complication with the presence of the concepts of risk analysis, risk assessment, and risk estimation, generally considered in the context of risk management. Discussions, definitions, and debates over the various terms can be found in the literature [e.g., [14-17, 21-24].

For the purpose of this research, the following broad definitions / framing were adopted:

Risk management – activities associated with the managing of risks to some acceptable or tolerable level, generally through either accepting the risk, avoiding the risk, mitigating the risk, transferring the risk, or some combination. At its core, risk management involves decisions about the risk and its acceptability or tolerability. This follows the framing that the acceptability of risk should be viewed as an attempt to solve or manage a problem, and whether the risk is acceptable will be dependent on whether the approach to managing the risk problem is acceptable [20]. The fundamental argument is that an acceptable risk problem is a decision problem, where different solutions to a risk problem provide different benefits, and acceptability is a function of the options available, and the option(s) selected. Because values, perceptions, and available information may affect evaluation of the options, there are no universally accepted or acceptable risks.

Risk assessment – involves identification of hazard(s) of concern, analysis of the risk (the quantification / estimation component of likelihood and consequence), and the comparison of the risk against some benchmark level. This generally follows the ISO 31000 [23] framing. The outcome of a risk assessment is generally to inform and/or to respond to risk management decisions. Risk assessments can be framed as qualitative, semi-quantitative, or quantitative, depending on the risk estimation (analysis) approach, as discussed below. The levels of analysis, quantification, treatment of uncertainty, and representation of outcomes should be appropriate to the risk (management) decision.

Risk analysis – the process for developing risk estimates that support risk assessment and management decisions by (1) identifying and grouping every type of unwanted events that can lead to adverse consequences, (2) characterizing the severity of those consequences, and (3) characterizing the likelihood of those types or groups of events. Risk analysis (estimation / quantification) can be qualitative, semi-quantitative, or quantitative, ranging from descriptive (e.g., low, medium, high), to semi-quantitative, to fully quantitative / probabilistic expressions (e.g., see [14]). Data, tools, and methods for risk estimation / analysis exist across an equally broad spectrum. A variety of methods have been applied over the years to create such risk estimation evaluation methodologies (see e.g. [25-32]). The choice of underlying method has depended largely on the researcher's preference and available data. Likewise, quantification and treatment of uncertainty in the analysis and assessment varies greatly (e.g., Paté-Cornell [33]), largely driven by the method of analysis and the level of support needed for the risk management decision.

Approaches for fire risk analysis are widely discussed in the literature and not detailed here (see e.g., Meacham, et al. [14], Meacham [16], Meacham [24], Brzezińska and Bryant [25], Brzezińska and Bryant [26], Watts Jr [28], Watts and Kaplan [31], Koutsomarkos, et al. [32], Hasofer, et al. [34], Yung [35], Ramachandran and Charters [36], ISO [37], SFPE [38], NFPA [39], SFPE [40], BSI [41]). Table 4 provides a summary framing of the different categories of risk analysis (adapted from NFPA 551 [39], Table 5.1.2.1).

TABLE 4. SUMMARY FRAMING OF RISK ANALYSIS CATEGORIES (ADAPTED FROM NFPA 551, 2022)

Category	Definition	Type of Output	Examples
Qualitative	Treats likelihood and consequence qualitatively	Tabulation of outcome and relative likelihood of various scenarios and how they are affected by various protection options	• What if analyses • Risk matrices • Risk indices • Fire Safety Concepts Tree
Semi-quantitative likelihood	Treats likelihood quantitatively and consequences qualitatively	Determination of frequency of occurrence of different types of fires and/or fires with different types of protection	• Actuarial/loss statistical analyses • Stand-alone event tree analyses
Semi-quantitative consequence	Treats likelihood qualitatively and consequences quantitatively	Deterministic fire model outputs with qualitative representation of likelihood	• Enclosure fire models for specific scenarios
Quantitative	Treats likelihood and consequences quantitatively	1. Determination of loss expectancy OR 2. Determination of probability of flashover OR 3. Determination of probability of fatalities in other rooms or floors of building OR 4. Plot of frequency versus number of fatalities OR 5. Plot of frequency versus size of loss OR 6. Determination of likelihood of injuries, fatalities, property damage, and business interruption OR 7. Determination of individual risk (to building occupants) and of societal risk (to entire population)	• FRAs to determine probability of reactor core melt due to fire at a nuclear power plant • Event tree analysis combined with fire models
Cost-benefit	Include determination of costs of alternative approaches to limit consequences and/or likelihoods	1. Determination of costs required to achieve various levels of risk reduction OR 2. Determination of "optimum" level of fire protection based on minimizing "overall risk" or some other risk criterion	• Computational models that incorporate probability, consequences, and cost data in an integrated manner

As noted in the Introduction, research into the fire safety challenges of green buildings and attributes included the development of a relative risk matrix, which illustrated the relative risk posed by a green building attribute, in terms of a fire hazard, if not mitigated [13, 42]. In that research, it was noted that the data needed for a quantitative risk assessment did not yet exist, and that efforts to collect data and perspectives on the intersection of fire risk and sustainability would be needed.

At present, data remain lacking for fire risks of green or sustainable building attributes – both for likelihood of fire events and consequences thereof – and on perceptions of fire risk associated with sustainable building attributes – that is, the importance of fire risk in comparison with benefits of sustainable construction. As such, a first attempt to address both aspects suggests that a qualitative or semi-quantitative approach to risk assessment, coupled with a decision support method to gauge importance, would be most appropriate. As a next step beyond the qualitative relative risk matrix approach outlined in previous research, it was decided to proceed with a combination of the fire safety concepts tree [43] and a risk-index approach. While still qualitative, the fire safety concepts tree provides a set of building fire safety strategies for consideration, and a risk index approach takes a step towards risk quantification.

The fire safety concepts tree illustrates the elements that must be considered in building fire safety and the interrelationships among those elements, which then enables a building to be analyzed or designed by progressively moving through the various concepts in a logical manner [44]. The fire safety concepts tree considers seven strategies:

1. Prevent fire ignition
2. Control combustion process

3. Control fire by construction

4. Detect fire early and provide notification

5. Automatically suppress fire

6. Manually suppress fire

7. Manage exposed (people or physical objects)

These strategies fit under two main decision choices – *Prevent Fire Ignition* or *Manage Fire Impact*, under the latter of which sits *Manage Fire* and *Manage Exposed*. The top levels of the fire safety concept tree decision structure are illustrated in Figure 3. For this initial approach, it has been determined that the fire safety concepts tree provides a reasonable starting point for considering the fire safety aspects to be considered.

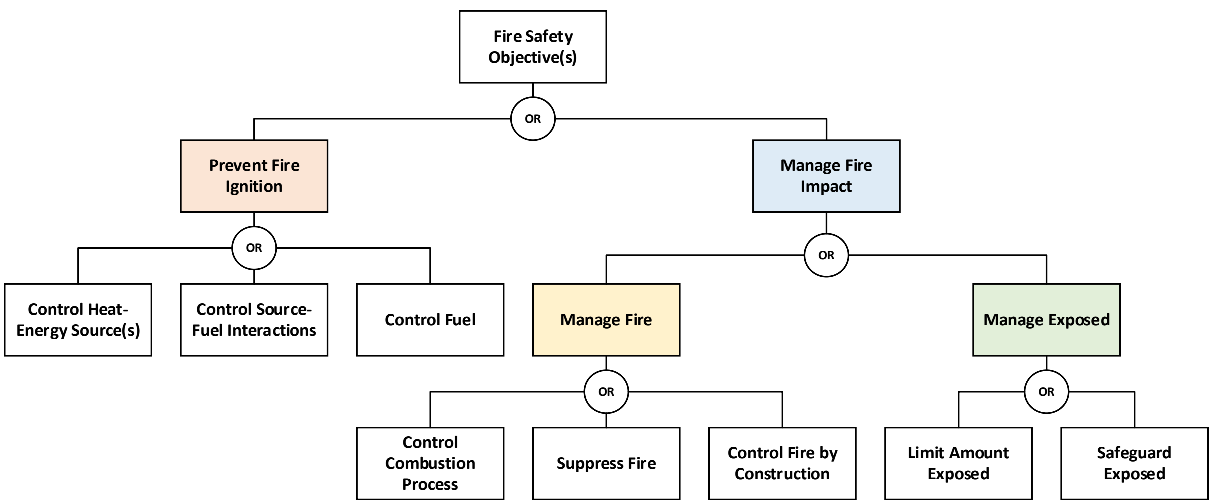


Fig. 3. Top Branches of the Fire Safety Concepts Tree. Reproduced with permission of NFPA from NFPA 550, *Guide to the Fire Safety Concepts Tree*, 2022 edition. Copyright© 2021, National Fire Protection Association. For a full copy of NFPA 550, please go to www.nfpa.org.

Given this starting point, and given the lack of data, it has been concluded that a risk indexing approach is appropriate as a first step toward risk quantification. Koutsomarkos, et al. [32] describe fire risk indexing (FRI) methods as heuristic models of fire safety. They define heuristics as procedures that, in the absence of a formal underlying physical theory, provide a practical approach to solving problems, and are typically defined as efficient rules or procedures for converting complex problems into simpler ones; and suggest that such methods reflect a problem solving approach that employs a practical method that is not guaranteed to be optimal or perfect, but is instead considered (by the method's designers) *sufficient* for reaching an immediate goal.

In keeping with Koutsomarkos, et al. [32], we adopt the approach that a risk index is a multi-attribute evaluation used to develop risk assessments where the results are aggregated into a single number. The process of creating a fire risk index includes a procedure of scoring the causal, and mitigating, fire safety attributes – with the result being a rapid and relatively simple fire safety evaluation. The scoring process is typically undertaken by allocation of points to each attribute. There are numerous examples of fire risk indexing in the literature (e.g., Brzezińska and Bryant [25], Brzezińska and Bryant [26], Watts Jr [28], Watts and Kaplan [31], Koutsomarkos, et al. [32]). The same approach is taken for assessing the sustainability level for a particular building, i.e. to allocate points to attributes that focus on meeting sustainability objectives. The approach for this project will be discussed in more detail in the next chapter. It has been noted above that the context of the risk decision matters [45]. This will be explored more below for the specific context of the framing of a *sustainable and fire resilient building* (SAFR-B). It has also been noted that framing as individual risk or societal risk matters for risk assessment and management. Another attribute that is important is scale. While a factor of the individual versus societal framing, at the societal scale there are also geographic and socio-political differences. Fire, for example, can impact an individual in close contact with initial materials burning (e.g., gas fueled cooking stove or campfire), as one of many in large building with numerous occupants (e.g., large apartment building or convention center), or as someone living along with many others in a region that is prone to wildland fire. In the large occupancy building scenario, there is a societal risk component due to the number of people, but the geospatial scale is small. In the wildland fire scenario, there can be both a large number of people and a large land area at risk.

Risks to the environment vary as well, but here the scale is generally larger, for example starting at a local habitat level [46], increasing to an ecosystem level [47], and ultimately impacting the entire world [48-51]. As a broad generalization, hazard events occur locally, but in many different forms, and their effects can extend beyond the local. This includes ecological damage due to raw material extraction, climate impacts due to materials transportation, fabrication and use, and ecological and climate impacts associated with waste, aspects of which are dealt with in life-cycle assessments [52] or using life cycle thinking [53, 54]. Societal risk can be assessed in terms of social resilience [55].

Because they are both risk problems, assessing and managing risks associated with unwanted fire impacts and risks associated with unwanted environmental impacts can use the same general processes and approaches [56, 57]. However, the contexts, effects, scale, and impacts vary considerably. This makes a one-to-one comparison at the largest scales, societally and geographically, extremely difficult and perhaps unhelpful. Carbon contribution to the atmosphere from human intentional activities (e.g., raw material extraction, processing, manufacturing, combustion of fossil fuels, etc.) dwarfs some human caused accidental fires in buildings [58]. At the building scale, though, much can be done to decrease the risk of fire and the risk of impact on the environment. Measures to reduce both sets of risk are often incorporated into building regulation and building design practice, and can be externally influenced as well (e.g., insurance for fire and ‘green’ building certifications for environment, such as LEED, BREEAM and others). This will be discussed further later in this chapter.

Unfortunately, research has found that because the risks are treated differently, mitigation in one area can result in unintended consequences for the other. In particular, this has been shown to be the case when combustible thermal insulation is installed to control energy usage from fossil fuel sources and is not adequately protected against contributing to a higher fire load and therefore increases fire risk [13, 59-65].

It is this confluence of fire risk management and environmental risk management objectives for buildings, particularly where they create the potential for competing objectives, which is a driver of this research effort [25, 26, 56, 57, 66-69]. More specifically, it is the introduction of technological means for risk mitigation of environmental and fire risks in buildings, how the risks may interact, and how one might understand the preferences and implications of choices between risk mitigation options that is of interest.

The objective of facilitating *sustainable and fire resilient buildings* needs to consider risks to the environment and how they can be mitigated, and it needs to consider fire risks to people (and the environment) and how they can be mitigated. Thus, the risk framing, for practical purposes, needs to be focused on the building scale (at least in this first application). While it is fully recognized and accepted that risks to the environment, which have triggered environmentally sustainable measures for said risk mitigation, are broader than any single building, the potential conflicts between environmental risk reduction and fire risk reduction become apparent largely at the building level. Thus, the geographical and societal scale are most accessible when limited to the building and the plot of land it sits upon.

Broadly, then, the risks to the environment can be framed as contribution of building technologies to reducing the impact on the environment. This can manifest as circular building materials [70], energy systems [71], and more (e.g., Anand, et al. [72]). Fire risks are framed largely as those attributes of a building that impact the ability of occupants to remain safe in the case of fire. This includes means to prevent fire occurrence or manage the fire and manage the exposed (occupants) should fire occur.

Even with such bounding conditions, the risk assessment challenges are significant due to the number of factors involved, difficulty in understanding risk tolerability limits in such a framing, and general lack of data that are specific and/or useful to this framing. This argues for keeping the risk assessment component relatively simple. For this reason, a risk indexing approach has been selected. Since all acceptable risk problems are decisions problems, a decision support approach is needed as well. In this research, the decision support approach should help to identify the relative importance of both the fire and sustainability attributes to risk reduction, along with the relative weights of building attributes to reducing the risk. Decision support / analysis methods are presented in the next section.

2.2.2. Decision Analysis and Decision Making

Every person makes myriad decisions every day. Some are simple, but many are complex. In either case, many of the decisions rely on one's best judgment, as people often have incomplete, uncertain, and sometimes competing information [73]. How and why people make decisions have been the foci of philosophical study for centuries, but it was not until the late nineteenth century that empirical studies into human judgment began, and not until the midtwentieth century that quantitative analysis of decision-making began to take shape [74, 75]. Since then, the field of study called 'decision sciences' has emerged to create a better understanding of how individuals, groups, organizations, and society make decisions, and to help improve the decision-making process [76].

Decision-making is often separated between individual and group. The distinction is important for several reasons. Decision making by groups is much more complex than individual decision-making, and group decision-making should not be characterized simply as extrapolations of values and beliefs of individual members in the group [73, 76]. Groups are subject to a variety of social dynamics that can lead to worse decisions than might be expected from a simple belief that "two heads are better than one." When all members of a group are friends or close associates, and on good terms with each other, a desire to maintain group harmony can lead to a form of "self-censorship." If this occurs, divergent ideas may never be voiced and thus never considered. Furthermore, when such a dynamic exists, and is combined with a strongly voiced and respected opinion, such as that of the group leader or respected "expert," a single opinion of the leader or expert can shift the group's opinion, even when an opposing viewpoint is raised. Such a tendency to "follow the leader" can lead to what is known as "groupthink," a situation wherein few options other than those posed by the leader are considered, and reasonable alternatives are not discussed. Groups also exhibit a tendency to polarize and seem to be more influenced by the way a problem is framed than are individual decision-makers [76]. When positively framed (e.g., *there is a 90% chance of preventing severe fires from occurring*), groups tend to make riskier choices than their individual members would. Alternatively, when negatively framed (e.g., *there is a 10% chance that fire protection measures would not prevent a severe fire from occurring*), groups make more cautious choices than their individual members would. There are various strategies that can be employed to help avoid group decision-making problems, including use of the Delphi process, in which members of a group are polled individually and anonymously; building sufficient trust amongst group members so that everyone feels comfortable in voicing their opinions; and using a group facilitator to elicit opinions without a defined group leader [76]. The iterative nature of the Delphi process then allows the benefit of opportunities to bounce understanding off other participants interpretation of ranking or survey questions, without the underlying pressure to conform. The drawback can be that the Delphi panel may have difficulties reaching a consensus agreement resulting in uncertainty about the outcome decision.

Most discussions on the decision-making process, for either an individual or for a group, characterize it as involving several distinct but interrelated steps beginning with “identifying the problem” and ending with “implementation of a solution selected from a set of options” [73]. The degree to which one decomposes the process into individual steps depends on the nature of the problem, the number of factors involved, the alternatives available, the certainty of outcome, and the formality or rigidity with which one chooses to proceed. Chechile and Carlisle [77] has described “the ideal processing steps involved in decision making” as including: (1) identify the problem and define the goal; (2) identify alternatives including the status quo; (3) gather and analyze information about alternatives, probabilities, implementation plans, risks, and benefits; (4) apply a decision tool; (5) make a decision; and (6) implement the decision. If the alternative selected is from a thorough set of alternatives, and is efficacious, implementable, ethical, and “optimal,” then a “good” decision has been made. Kleindorfer, et al. [76] describe a similar process, that involves (1) identifying the problem context; (2) identifying, accepting, and representing the problem; (3) legitimizing the decision process; and (4) solving the problem.

Numerous others have described similar processes as well, some simpler and some more complex [77-84]. Combining key elements, we can describe the process as follows for the purpose of this study:

1. Identify the problem context.
2. Identify the problem and define the goal.
3. Identify alternatives, including the status quo.
4. Gather and analyze information on alternatives, probabilities, implementation plans, risks, and benefits.
5. Solve the problem (i.e., make a decision) within the problem context (e.g., framing, boundary conditions, data limitations, etc.), using a decision-support tool as appropriate to aid the decision.
6. Legitimize the decision.
7. Implement the selected alternative.

As noted above, if the alternative selected is from a thorough set of alternatives, and is efficacious, ethical, and implementable, then a good decision can be said to have been made. For some, the decision can be considered "better" if shown to be optimal, which could be tested through application of an optimization technique. If cost is a significant driver in the decision problem, benefit-cost analysis or related approaches may be used (e.g., [83, 84].

As intimated above, there are different theories and approaches that can be applied depending on whether the decision-maker is an individual or group, where optimization is a critical factor, or whether cost is a driving concern. In general, Decision Theory focuses on how an individual makes decisions under uncertainty [73]. Most decision theory is based on Bernoulli's concept that choice depends on the probabilities of various consequences of a decision and on the utility of those consequences to the individual (the decision-maker). These theories utilize the von Neumann-Morgenstern axioms of rationality and Bayesian probability theory and are often referred to as Expected Utility or Subjective Expected Utility Theory (e.g., [76, 82, 85]. In utility theory, an individual's decision problem is solved by evaluation of a set of outcomes that result from the choice of an alternative and the occurrence of some state of nature with a given probability. A utility function can be constructed if the axioms of completeness, transitivity, continuity, independence, and reduction of compound lotteries are satisfied [76]. The actual construction of a simple utility function requires making indifference judgments between a certain outcome and a two-outcome lottery whose outcomes straddle the certain outcome, with probabilities of occurrence p and $1 - p$. Either the value of the certain outcome (known as the certainty equivalence) or the value of the probability (known as the probability equivalence) can be elicited. Bayesian probability theory is used to calculate the "expected value" of the lottery. An individual's utility function will reflect attitudes toward risk as well as the person's values for the outcomes under certainty.

Moving from individual to group decision-making, there are several theories and approaches as well. Social Choice Theory, for example, focuses on the normative and logical questions of how individuals should, and could, aggregate information about views, interests, or preferences, into group decisions [74, 86, 87]. The decision problem is created when there are significantly different perspectives of participants, such as 'value' experts or 'fact' experts [76]. The overall aim is to rationally synthesize the preferences of the collective of individuals who will be affected by the decision [81]. Social Judgement Theory (SJT) is a subset, which had its origins in the challenges of synthesizing science and policy decisions [86, 88]. To overcome some of the polarization that can exist, deliberative approaches focus on how to bring different information and perspectives into a decision through an iterative process of learning, considering, and coming to agreement (e.g., see [22]). Deliberative decision making and SCT are often associated with policy decisions. Consensus decisions are a form of this [73]. Negotiation is also a form of coming to agreement on different perspectives, but with a third-party facilitator.

Cost-Benefit Theory is the basic theory underlying cost-benefit analyses (benefit-cost analyses) and is based on the premise that alternatives should be selected according to a systematic comparison of the advantages (benefits) and disadvantages (costs) that result from making a choice (decision). It is an economic based theory that does not presume the participation of a social decision-maker with special responsibility for the decision. Rather, it identifies a “best” alternative in terms of an efficiency criterion (often a Pareto optimality) and uses an individual’s “willingness to pay” to value consequences [74, 89-91].

2.2.3. Multi-Criteria Decision Methods (MCDM)

Regardless of the specific scenario or set of conditions for which a decision is needed, addressing multiple decision variables and participant values and preferences is a challenge. To address this challenge, a variety of decision-support tools are applicable, including Multi-Criteria Decision Methods (MCDMs) (sometimes known as Multi-Objective Decision Methods (MODMs) or Multi-Attribute Decision Methods (MADMs)), Multi-Attribute Utility Theory (MAUT), various Cost-Benefit Analyses (CBA/BCA), and more. Indeed, a recent review summarized numerous multi-criteria optimization methods which have been developed and published through a thorough review of almost 300 peer reviewed publications [92], see Figure 4.

Multi-Criteria Decision Methods (MCDMs) are formal mathematical treatments of decision problems with multiple criteria (objectives/attributes) and include multi-objective programming and vector optimization. In general, the concept is to maximize (or minimize) an objective function subject to constraints which define feasibility, where the objective function and the constraints are mathematical functions of decision variables and parameters (e.g., [78, 81, 84, 92, 93]).

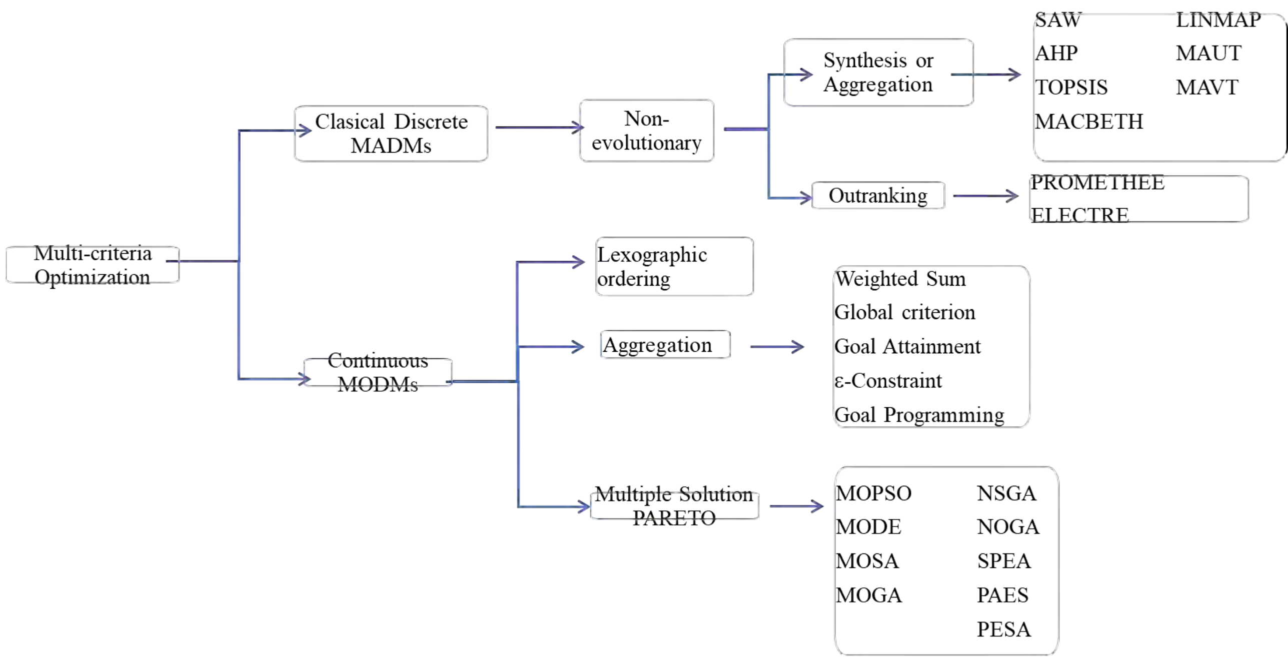


Fig. 4. Summary of types of multi-criteria optimization methods, redrawn from Syan and Ramsoobag [92].

An objective function is a mathematical statement of an objective, stated in terms of the decision variables of a problem, where objectives are operationally useful statements that are consistent with some underlying ideal. Economic efficiency, equity, and “acceptable” risk, for example, are objectives that could be tied to the underlying ideal of social welfare. From these, minimizing costs for a particular building fire safety design, providing access to people with disabilities, providing all persons with adequate time to reach a place of safety in the event of a fire, providing an energy efficient building, are possible objective functions that could be developed.

Constraints are often required to ensure physical feasibility [73]. For example, minimizing the cost of a design might lead one to consider omitting elevators. However, without elevators, access for the disabled may not be provided. Thus, the requirement for elevators would be one possible constraint on the cost minimization objective. Similarly, construction of a building all at grade level would minimize the need for elevators, but the size of the site may be limited by neighboring buildings.

Decision variables are those aspects of a problem that can be changed, while parameters are givens [73]. For a particular building fire safety problem, possible decision variables might include interior finishes, contents, occupant loading, and fire safety system options, while parameters might include building layout and proximity to other buildings. For building sustainability design, decision variables might be energy systems, insulation, and construction materials, while parameters might include building layout and proximity to other buildings or even maximum climate loading. Given that MCDMs are mathematical treatments of decision problems, a solution to a MCDM is a collection of mathematically generated values for the decision variables. A solution that satisfies all the constraints is considered a feasible solution. The feasible solution which gives the best value of an objective function is the optimal solution.

Multi-Attribute Utility Theory (MAUT) is a procedure for evaluating objects, wherein a set of attributes is developed that characterizes the objects, and each object is evaluated on each attribute [73]. The resulting judgments are then aggregated by formal algebraic processes that reflect the relative importance of each attribute so as to produce an overall utility of each object.

In applications of MAUT to Social Choice Theory, the attributes are typically preferences of various interest groups, and the aggregation function reflects a judgment of relative importance of the preferences of each group [81]. The application of MAUT depends on six key points [94]:

1. When possible, evaluations should be comparative.
2. Programs normally serve multiple constituencies.
3. Programs normally have multiple goals, not all equally important.
4. Judgments are inevitably a part of any evaluation.
5. Judgments of magnitude are best when made numerically.
6. Evaluations typically are, or at least should be, relevant to decisions.

The application of MAUT to a decision problem entails seven steps:

1. Identify the objects of evaluation and the function or functions that the evaluation is intended to perform.
2. Identify the stakeholders.
3. Elicit from stakeholder representatives the relevant attributes (value dimensions) and organize them into a hierarchical structure (value tree).
4. Assess for each stakeholder group the relative importance of each of the values identified in Step 3.
5. Ascertain how well each object of evaluation serves each value at the lowest level of the value tree.
6. Aggregate location measures with measures of importance.
7. Perform sensitivity analyses.

As noted previously, expected utility theory, on which MAUT is based, utilizes the von Neumann-Morgenstern axioms of rationality and Bayesian probability theory. For some, the rigidity of the von Neumann-Morgenstern axioms is a source of some concern [76]. Key concerns include observations of intransitivity, preference reversal, and concern of regret if one makes “the wrong” decision (e.g., the Allais paradox and the Ellsberg paradox). To address these concerns, some have offered “general utility” theories, which permit nonlinear weightings of probability within the expected utility structure. An example of this is Prospect Theory as advanced by Kahneman and Tversky [95, 96].

Because people do not have a good ability to correctly assess probabilities, modifications to expected utility theory (e.g., regret models, prospect theory, and generalized utility models such as weighted utility and anticipated utility) introduce alternative axioms, or weaken the axioms of expected utility, in an attempt to create a self-consistent model of an individual’s utility function that correlates with descriptive observation. The modifications suggested can be extremely mathematical and applicable only to narrowly specified regimes of behavior. As remarked by two critics of utility theory, the observed violations of utility theory axioms have led its proponents to “bizarre attempts” to modify the original theory without “rigorous justification” [97]. Because of problems such as the above, critics of Expected Utility Theory and MAUT have argued for alternative approaches altogether, such as the Analytical Hierarchy Process (AHP) [79, 97-100]. Some recent reviews [92, 101-103], indicate that AHP is by far the most popular approach corresponding to almost 40% of all published methods.

The Analytical Hierarchy Process (AHP) is described as an organized framework that helps one think about and address complex interactions and interdependence amongst decision factors in a simple way [79]. One of its strengths is the integration of both deductive (focus on parts) and systems (focus on the whole) approaches to solving problems into a common framework. It does this by breaking down complex, unstructured problems into component variables, arranging the variables into a hierarchical order, assigning numerical values to subjective judgments of the relative importance of each variable, and synthesizing the judgments to determine which variables have the highest priority and should be addressed.

The AHP is applicable to single or multiple decision-makers. It provides a means to integrate facts with subjective judgments, incorporate judgments of several people, and resolve conflicts. The flexibility of the system permits the use of complementary decision support tools and methods, such as cost-benefit or risk minimization approaches, and helps the decision maker(s) to better understand explicit tradeoffs.

The structure of the AHP has at least three levels [73, 79]: the focus (or goal), which is the main objective of the decision problem; criteria levels (criteria and sub-criteria), which describe key components of the decision problem; and alternatives (decision options). In a building fire safety application problem, the focus might be life safety during a fire, criteria could be systems options, cost, and risk, and alternatives could be fire prevention, passive fire protection systems, active fire protection systems, or some combination of systems (various combinations could be proposed). Priorities are established so that the criteria or sub-criteria in each level are comparable to each other with respect to the next highest level. (If criteria in a level do not seem to be comparable, additional levels (or sublevels) may be required). The priorities are then weighted, again with respect to the criteria in the next higher level. Finally, the weights are evaluated to determine the overall priority of alternatives to support a decision.

The process for setting priorities involves pairwise comparison of elements in a particular level against a given criterion. The comparisons can be expressed in one of three ways: as the degree of importance of one criterion over another, as the degree of likelihood of occurrence of one criterion over another, or as the degree of the decision-maker's preference for one criterion over another. The scale for the pairwise comparisons is 1-9, which seems to reflect the degree to which people can discriminate the intensity of relationships between elements [73, 79]. It should be noted that this is a ratio scale, not an interval scale, with the levels expressed as 1: equal importance (or preference, or likelihood), 3: weak importance of one over another, 5: essential or strong importance, 7: very strong or demonstrated importance, 9: absolute importance. For decisions with multiple criteria and/or alternatives, the criteria or alternatives should be clustered into sub-groups that have qualities with no greater preference intervals than can be expressed by the one-to-nine ratio scale.

In structuring a decision hierarchy, the following steps are generally followed [100]:

1. Identify the overall goal. (What are you trying to accomplish: what is the main question?)
2. Identify sub-goals of the main goal, and if relevant, any time horizons.
3. Identify criteria that must be satisfied to fulfil the sub-goals.
4. Identify sub-criteria under each criterion.
5. Identify in descending levels, as needed, actors, actor objectives, and actor policies.
6. Identify alternatives or outcomes.
7. For yes-no decisions, include doing and not doing the alternative.
8. If cost is a criterion, construct separate hierarchies for costs and benefits.

The mathematical foundation for the AHP is matrix algebra, wherein each of the criteria is included in at least one comparison to another criterion. This means that for n criteria, the minimum number of pairwise comparisons required is $n - 1$, and the maximum possible number of comparisons is $n(n-1)/2$. As a general rule, the more paired comparisons made among the criteria, the better the final decision made should be. However, the more comparisons one makes, the greater the potential for inconsistency.

Inconsistency, as used here, refers primarily to the transitivity of decisions required by expected utility theory (i.e., if option A is preferred to B, and B is preferred to C, then option A should be preferred to C). There is a need to be careful of large inconsistencies, as they will impact the decision outcome, even though it has been shown that people can indeed prefer option A to B, and B to C, and yet prefer C to A [104]. Inconsistency is assessed in the AHP as the ratio of a consistency index (CI), $\frac{\lambda_{max}-n}{n-1}$, to a random index (RI) indicating the consistency expected for a randomly generated square matrix of n by n, where λ_{max} is the maximum or principal eigenvalue of a positive, reciprocal, square (i.e., n by n) matrix containing pairwise comparisons among n criteria. For a perfectly consistent n by n matrix, λ_{max} will be n. For an inconsistent n by n matrix, λ_{max} will be greater than n. It has been proposed that an inconsistency ratio of more than 10% should prompt the decision maker to re-examine the model, attempting to express more pairwise comparisons if fewer than the maximum were initially defined, or looking for pairwise comparisons that are not truly representative of the decision maker's attitudes [79].

When fewer than the maximum possible number of pairwise comparisons are made, inference can determine the comparisons not explicitly stated. For example, if criterion 1 is considered two times as important as criterion 2, and criterion 2 is three times as important as criterion 3, it can be inferred that criterion 1 is six times as important as criterion 3. The AHP is also able to incorporate numerical data when they exist. In concept, the approach of AHP is not all that different than that of MAUT: they are both decision support tools, and as with MAUT, AHP has mathematical underpinnings, including basic definitions, theorems, and axioms on which the theory is based [79, 100]. In the underlying theory, however, there are some significant differences, which may drive selection of one approach over another. In assessment of available methods, the project team selected AHP as the most appropriate method to build the decision-making framework proposed for this project, both due to the fact that it is theoretically appropriate and due to name recognition among those experts recruited to participate in a Delphi development of relative significance of attributes within the AHP structure. This choice was confirmed by using the MCDA Methods Selection Software of Cinelli, et al. [105], which is available on http://mcdamss.com. Input choices for the software are provided in Appendix A.

2.2.4. The Index Approach

There is a long tradition in fire safety engineering of heuristic models of fire safety, i.e., engineering models that convert complex models to simple ones [32]. Complex problems such as the evaluation of numerous design objectives simultaneously call for the development of simplified models. Indeed, even multi-criteria decision assessment methods such as AHP are simplifications of reality. The methodology defined by Koutsomarkos, et al. [32] provides a sound basis for the development of an engineering assessment of sustainability and fire resiliency in a multi-criteria framework, even though they focused on multiple facets of fire safety only. The only modification to their methodology is to adjust the terminology slightly to suit the approach that has been used to create the SAFR-B framework. According to Koutsomarkos, et al. [32]; an index can be developed using the following general steps:

1. Identify hierarchical levels of [fire safety] specification.
2. Specify items comprising each level.
3. Construct and assign values to matrices of each sequential pair of levels.
4. Combine (multiply) matrices to yield importance ranking of items.

5. Verify the results.

Once this has been done, there are three main judgements which are needed in development of an index:

- *Identification* – a decision must be made about which [fire safety] attributes are going to be evaluated by the [fire safety] index.
- *Weighting* – a decision must be made about the use of relative weights for each attribute or the group in which they belong, along with which weighting method is used.
- *Index calculation* – a decision must be made about the mathematical functions (or calculation style) used to calculate the final index based on the attributes chosen, and each attribute's relative weighting produced.

An index is typically structured in a hierarchy built up from a number of different levels, e.g., Level 1. Policy, Level 2. Objectives, Level 3. Strategies, Level 4. Attributes, Level 5. Sub-attributes, Level 6. Survey items. Levels can be eliminated, although the top three levels are generally used. The fewer the levels the simpler the model.

2.3. Sustainability Assessment

2.3.1. Introduction

The latest IPCC reports state that observed increases in greenhouse gases since 1750 are undoubtedly due to human activity [106-108]. The observed warming of global surface temperature over the past 200 years is unprecedented when compared to temperature estimates over more than 2000 years. It is urgent to reduce emissions of greenhouse gases, which has resulted in numerous initiatives in recent decades, e.g.,:

- 1987 the work of the United Nations World Commission on Environment and Development (UN WCED) creates its report on sustainable development - Our Common Future [109].
- 1992 the first UN conference on environment and development is held in Rio de Janeiro, Brazil – Earth Summit, creates the Rio agreement, formally known as the United Nationals Framework Convention on Climate Change (UNFCCC) and Agenda 21 [110].
- 1994 the UNFCCC entered into force, calling for all parties to the convention to prevent dangerous human interference with the climate system (https://unfccc.int/).
- 1995 Conference of Parties (COP) initiated, official meeting of UNFCCC, continues until the present day (https://en.wikipedia.org/wiki/United_Nations_Climate_Change_conference).
- 1997 the Kyoto protocol extended the UNFCCC, committing the 192 ratifying nations to reduce greenhouse gas emissions [111].
- 2015 Paris accord adopted as a legally binding international treaty on climate change, to hold the increase of global average temperature to well below 2°C above pre-industrial levels (https://unfccc.int/process-and-meetings/the-paris-agreement).
- 2015 UN adopts Agenda 2030 and the 17 global sustainability goals [112].
- 2019 the EU and US presents separate but similar activities to foster “green” industrial development and the creation of a sustainable future [113].
- 2021-2023 the IPCC released a series of new working group reports [48-50], including the 6th Synthesis report [114], confirming that climate change due to human activities is already visible and that we can expect increased weather volatility in the future.

Common among these initiatives is the realization that there is a clear need for sustainable goals and models to support them. As part of these initiatives, some effort has been made to identify common terminology to ensure that we are all on the same page concerning what we mean by *sustainability* and *sustainable development*. In the context of this work, we have used the definition of sustainability included in the report from the UN World Commission on Environment and Development that a sustainable society "meets the needs of the present without compromising the ability of future generations to meet their needs" [110]. Attention to sustainability does not imply that our present needs to design buildings are not met, rather that they are met in a way that does not pose undue burden on future generations to meet their needs. In the wake of the work of the UN WCED, Agenda 21 was developed as an outcome of the 1992 Conference on Environment and Development where the need for a multi-dimensional approach to sustainability was central. In Agenda 21, economic, environmental, and social dimensions were suggested [110]. In the ensuing decades, arguments have been made for the addition of dimensions to this model [115]; but the pervasiveness of the original three dimensions is a testament to the fact that they encompass at least most of what is needed to break down sustainability into conceptually manageable parts. Combinations of the various dimensions of sustainability help us to identify pathways to reach equitable, viable, and bearable societies at the intersection between these dimensions, see Figure 5.

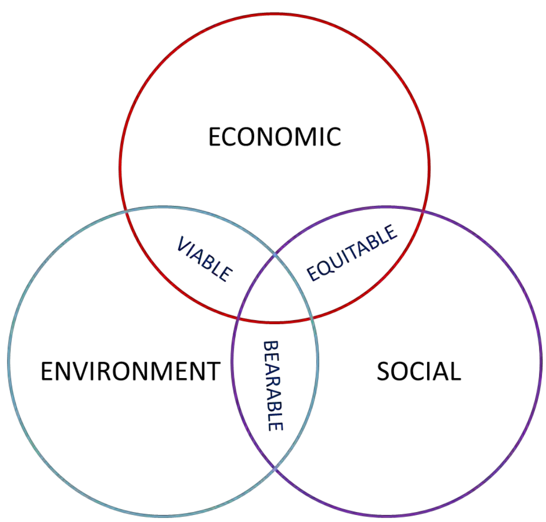


Fig. 5. Overview of dimensions of sustainability.

The construction sector has great potential to positively influence sustainable development by reducing energy use and/or material use, but historic examples have shown that such efforts are not wholly without fire safety implications. It is worth noting that there is an opportunity to influence both through various materials and construction choices in new construction and in the renovation or remodeling of existing buildings. In the UK, it has been estimated that approx. 80% of the buildings that will exist in 2050 have already been built [116].

2.3.2. Life Cycle Thinking

The need to understand the environmental impact of products and materials became pressing in the aftermath of the industrial revolution. Impacts of manufacturing in terms of reduced air quality were the topic of a select committee of the House of Lords in London UK as early as 1862 [117]; but recognition of the need to consider environmental impacts from the cradle to the grave, or across the whole product life cycle emerged first in the 1960's. The first academic papers concerning life cycle assessment (LCA) began to emerge in the 1970's. Guinée, et al. [118] denoted the first two decades (1970's-1980's) as the *decades of conception*. Life cycle assessments from this period lack much necessary data and are characterized as dealing with parts of the life cycle. The period immediately after (1990's) could be denoted as the *decade of standardization*, with the emergence of ISO standards and LCA databases (e.g., that developed by the Society of Environmental and Toxicological Chemistry (SETAC)). The present age of LCA is that of *elaboration*. During the past decades, the concept of life cycle thinking has emerged to encompass all aspects of efforts to understand sustainability. In 2002, the United Nations Environment Programme (UNEP) and SETAC launched the Life Cycle Initiative (LCI) [119], with the aim to "build international consensus and access to science-based life cycle knowledge." The LCI fosters Life Cycle Thinking (LCT) as a way to move beyond the environmental dimension of sustainability to include all dimensions of sustainability.

Using the approach set out in the documents developed by UNEP, LCT works to develop and spread information about all aspect of sustainability, see Figure 6. Methods have been developed to investigate the environmental impact of a product, material, or service using Life Cycle Assessment (LCA). Similarly, methods have been developed to assess the economic impact of a product, material or service using Life Cycle Costing (LCC). Assessment of the social dimension of sustainability is less well developed but in recent years, a methodology has emerged for Social-Life Cycle Assessment (S-LCA) designed to assess the social impact of products, materials, and services.

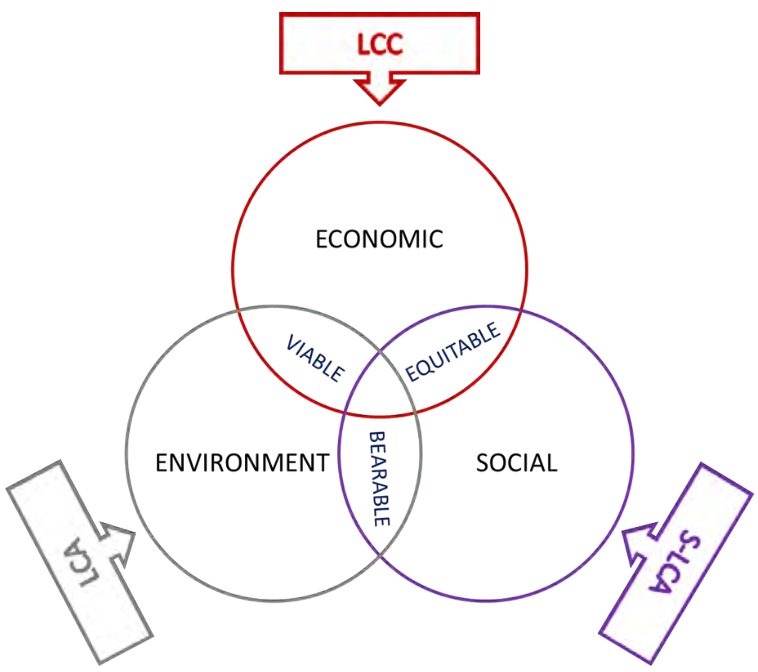


Fig. 6. Illustration of tools developed to consider the various dimensions of sustainability.

To introduce the concept of LCT, it is necessary to consider what the life cycle of a product, material, or service entails. Figure 7 gives an overview of a product life cycle, with red indicating input of virgin resources or removal of resources at the end of a life cycle, blue indicates movement of resources within the life cycle and green indicates circular strategies that close the loop of the full life cycle [53].

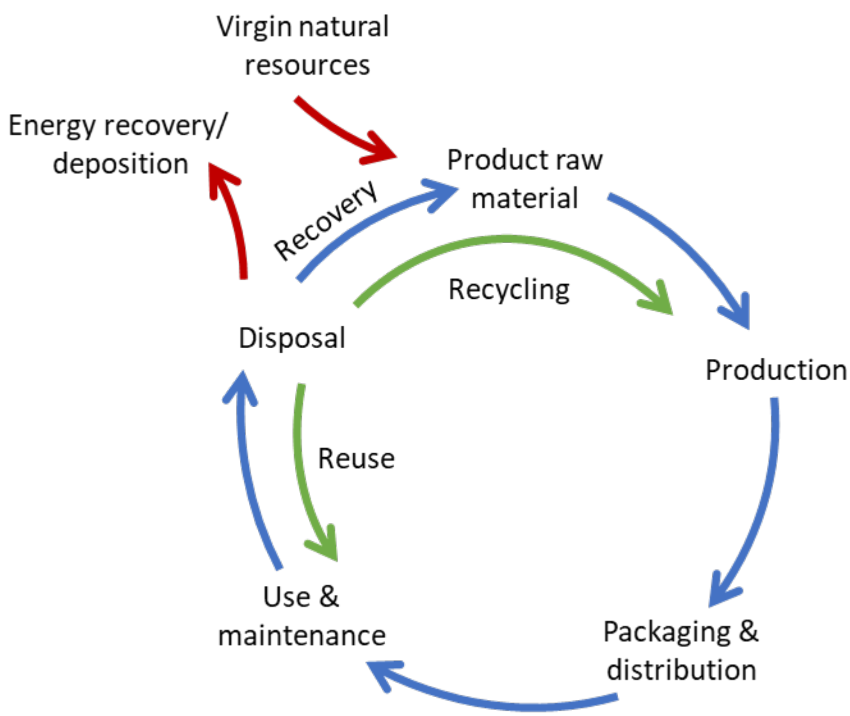


Fig. 7. Schematic of a product life cycle. Redrawn and slightly updated based on UN EP Life Cycle Initiative [53].

At each stage of a life cycle there is the potential to reduce the impact of the product, material, or service. In practice there are five main levers that can be used to minimize impacts from a life cycle perspective: life-time extension, dematerialization, manufacturing efficiency, substitution, and recovery [54]. Considering one or more of these aspects in terms of their environmental impact can lead to unintentional tradeoffs in terms of cost or social consequences which is why LCT is important. By considering all three dimensions of sustainability, we have the option to highlight such trade-offs between them. This requires us to build new ways of looking at the world. As this field is still to some degree in its infancy, the three dimensions of sustainability are still often modelled separately. LCT tends then to become more of a philosophy, a way of observing and reflecting, rather than a single methodology. Life Cycle Sustainability Assessment (LCSA) is a direction in which LCA is developing to produce a cohesive model of sustainability assessment in the sense that $\mathrm{LC}SA = \mathrm{LCA} + \mathrm{LCC} + \mathrm{Soc.LCA}$ [120]. Depending on where the user is in the full life cycle (or the supply chain) LCT may offer different benefits. Mazzi [54] highlighted this in a recent chapter by identifying how LCT helps different stakeholders promote sustainable behavior and avoid unsustainable behavior.

The Sustainable and Fire Resilient Building (SAFR-B) framework that is presented through this work aims to support building designers, owners, and regulators in making sustainable *and* fire safe decisions. By using an LCT based approach, the designer is encouraged to conduct comprehensive, complete, and consistent analysis of all the factors that contribute to the sustainability and fire safety of their building. At the same time, this discourages from a partial analysis of the environmental, economic, and social impacts associated with single phases of a product's life cycle. The SAFR-B model is, however, in its infancy and much developmental work remains even after this project before the lofty ideals of full LCT are implemented.

2.3.3. Green Building Certification Schemes

Green building certification schemes are a set of rating systems and tools that are used to assess building performance from a sustainability and environmental perspective [121]. Such certification schemes aim to improve the overall quality of buildings and infrastructures, integrate a life cycle approach in their design and construction. Buildings that have been assessed and are deemed to meet a certain level of performance and quality receive a certificate proving this achievement. Not all “green” buildings are certified as green. “Green” buildings mean different things to different people. According to the Egypt Green Building Council (WGBC), “a ‘green’ building is a building that, in its design, construction or operation, reduces or eliminates negative impacts, and can create positive impacts, on our climate and natural environment. ‘Green’ buildings preserve precious natural resources and improve our quality of life” [122].

Efforts to facilitate green or sustainable building design can be traced back to the launch of the first green building assessment method in 1990 by the English Building Research Establishment [123]. The US Green Building Council followed in 2000 with the launch of the LEED system [124]. Since the establishment of these systems, others have followed and continue to be developed.

Buildings and construction activities together contribute to 36% of the global energy use and 39% of carbon dioxide (CO_2) emissions [125]. A recent report from Dodge Data & Analytics in collaboration with the World Green Building Council [126], indicated that the majority of new construction expects to be green by 2021 although only a small number of these buildings will actively seek certification. The most high-level green projects are, however, consistently seeking recognition through certification.

The major drivers globally to using green attributes in buildings are (in order of priority) client demands, environmental regulations, and an aspiration to create healthier buildings, although the relative importance of these drivers varies from country to country. The highest barriers to increasing green building activity appears to be higher (perceived or actual) initial investment costs and lack of political support or incentives, although lack of training and an inability to prove the business case for green buildings through lowering life-time costs were cited in just over 20% of responses. There is a risk that perceptions of green building certification being reserved for the most high-profile cases may slow the broad acceptance of such certification schemes. It is, however, reasonable to assume that even projects which do not actively seek certification look to the most common schemes seeking guidance concerning how to improve the carbon footprint of their building. In this project, the sustainability objectives have taken the most common green building certification schemes as the starting point for their development, i.e., LEED and BREEAM. These two building certification schemes have been selected due to their relative market dominance in many parts of the world and the fact that many other schemes are based on them [127]. In addition, we have considered the World Building Design Guide (WBDG). While WBDG is not a certification scheme, the design objectives within the WBDG relate well to the concept of sustainability objectives.

Leadership in Energy and Environmental Design (LEED)

LEED was created in 2000 by the US Green Building Council (US GBC) for rating design and construction practices. It is used in North America as well as in more than 150 countries with over 100,000 *projects* registered and certified globally [128]. Certification is based on points awarded in nine categories, see Table 5 (based on LEED for building design and construction). The total number of points that can be awarded is 110. Platinum rating is awarded for >80 points, Gold 60-79 points, Silver 50-59 points and Certified 40-49 points. Projects with less than 40 points are not eligible for LEED certification. The LEED system is actually a collection of specific rating systems, adapted to a variety of projects, e.g. New Construction, Existing Buildings, Commercial Interiors, Core & Shell, Schools, Retail, Healthcare, Homes, Cities, and Communities. The focus of LEED is on operational and embodied carbon but there are some points awarded which are relevant to social and economic aspects of sustainability [129].

TABLE 5. SUMMARY OF LEED CATEGORIES AND THEIR INTENT (TAKEN FROM THE GUIDELINES FOR BUILDING DESIGN AND CONSTRUCTION)

Category	Points	Intent
Integrative process	1	Maximize opportunities for integrated, cost-effective adoption of green design and construction strategies, emphasizing human health as a fundamental evaluative criterion for building design, construction, and operational strategies. Utilize innovative approaches and techniques for green design and construction.
Location & Transportation	16	To avoid development on inappropriate sites. To reduce vehicle distance traveled. To enhance livability and improve human health by encouraging daily physical activity.
Sustainable Sites	10	To reduce pollution from construction activities by controlling soil erosion, waterway sedimentation, and airborne dust that disproportionately impact frontline communities.
Water Efficiency	11	To reduce outdoor potable water consumption and preserve no and low-cost potable water resources.
Energy & Atmosphere	33	To support the design, construction, and eventual operation of a project that meets the owner’s project requirements for energy, water, indoor environmental quality, and durability.
Materials & Resources	13	To reduce the disproportionate burden of landfills and incinerators that is generated by building occupants’ waste hauled to and disposed of in landfills and incinerators through reduction, reuse, and recycling service and education, and to conserve natural resources for future generations.
Indoor Air Quality	16	To contribute to the comfort and well-being of all building occupants by establishing minimum standards for indoor air quality (IAQ).
Innovation	6	To encourage projects to achieve exceptional or innovative performance to benefit human and environmental health and equity. To foster LEED expertise throughout building design, construction, and operation and collaboration toward project priorities.
Regional Priority	4	To provide an incentive for the achievement of credits that address geographically specific environmental, social equity, and public health priorities.

Building Research Establishment's Environmental Assessment Method (BREEAM)

BREEAM is the world's first sustainability rating scheme for the built environment and while launched originally for the UK, it is now an international standard that is available in locally adapted versions. At the time of writing, the system has been applied in nearly 600,000 building assessments across over 80 countries worldwide [123]. Certification is based on 10 categories, see Table 6. The total number of points that can be awarded is 150. An Outstanding rating is awarded for ≥85% score of total 150 points, Excellent for ≥70% score, Very Good for ≥55% score, Good for ≥45% score and Pass for ≥30% score. Projects with less than 30% score are not eligible for BREEAM certification. Identically to the LEED system, the BREEAM system is actually a collection of specific rating systems, adapted to a variety of projects, e.g., New Construction, Refurbishment and fit out, In-use structure, Communities and Infrastructure. Focus in BREEAM is broader than that of LEED with more points allocated to, e.g., Health & Well-being.

TABLE 6. SUMMARY OF BREEAM CATEGORIES AND THEIR INTENT (TAKEN FROM THE GUIDELINES FOR NEW CONSTRUCTION)

Category	Points	Intent
Management	20	This category encourages the adoption of sustainable management practices in connection with design, construction, commissioning, handover, and aftercare activities to ensure that robust sustainability objectives are set and followed through into the operation of the building.
Health & Well-being	22	This category encourages the increased comfort, health, and safety of building occupants, visitors, and others within the vicinity.
Energy	32	This category encourages the specification and design of energy efficient building solutions, systems, and equipment that support the sustainable use of energy in the building and sustainable management in the building's operation.
Transport	11	This category encourages better access to sustainable means of transport for building users.
Water	9	This category encourages sustainable water use in the operation of the building and its site.
Materials	14	This category encourages steps taken to reduce the impact of construction materials through design, construction, maintenance, and repair.
Waste	13	This category encourages the sustainable management (and reuse where feasible) of construction and operational waste and waste through future maintenance and repairs associated with the building structure.
Land Use & Ecology	5	This category encourages sustainable land use, habitat protection and creation, and improvement of long-term biodiversity for the building's site and surrounding land.
Pollution	12	This category addresses the prevention and control of pollution and surface water run-off associated with the building's location and use.
Innovation	10	The innovation category provides opportunities for exemplary performance and innovation to be recognized that are not included within, or go beyond the requirements of the credit criteria. This includes exemplary performance credits, for where the building meets the exemplary performance levels of a particular issue. It also includes innovative products and processes for which an innovation credit can be claimed.

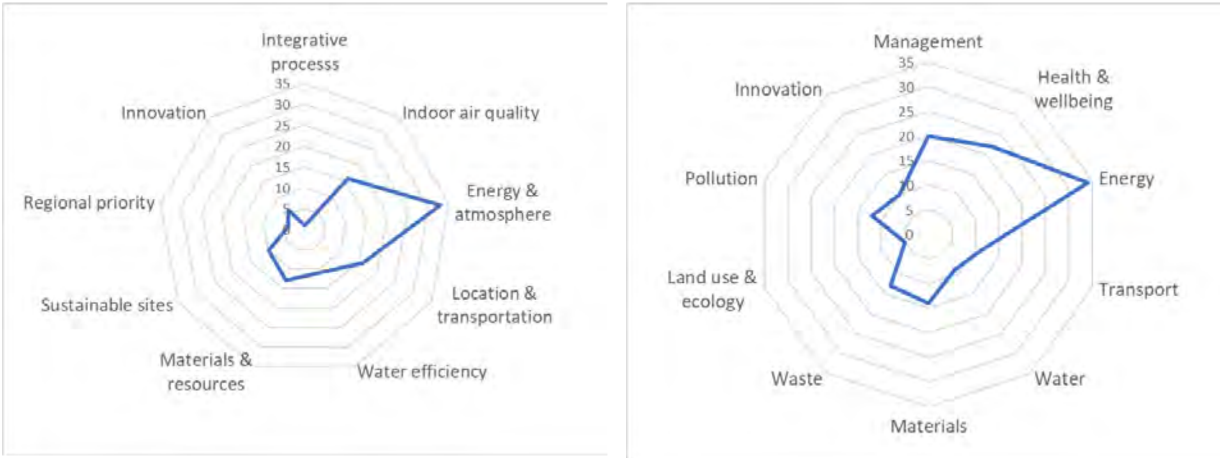
Whole Building Design Guide (WBDG) – Design objectives

The Whole Building Design Guide (WBDG) is created by the US National Institute of Building Sciences (NIBS). The WBDG aims to be an entrance to up-to-date information on the whole building in terms of design techniques and technologies. The goal of the system is to support the development of successful high-performance buildings by integrated design using recommendations based on *Design Objectives*, *Building Types*, *Space Types*, *Design Disciplines*, *Guides & Specifications*, and general *Resource Pages*. In this project we have focused on the *Design Objectives*, which include: Accessible, Aesthetics, Cost-Effective, Functional/Operational, Historic Preservation, Productive, Secure/Safe, and Sustainable. These Design Objectives do not have a scoring system like LEED and BREEAM, rather each design objective is important in any project. The focus is on identifying relevant project goals early and ensuring that a proper balance between them is maintained throughout the design process. The interrelationships and interdependencies between the design objectives are understood, evaluated, appropriately applied, and coordinated concurrently during the planning phase, see Figure 8. Implicit in this methodology is the concept that a high-performance building cannot be achieved unless the integrated design approach is employed.

Fig. 8. Overview of the connection between the design objectives as defined by the WBDG and the development of a high-performance building.

2.3.4. Developing Sustainability Design Objectives

The green building systems – LEED, BREEAM, and WBDG design objectives – were compared to identify relevant sustainability objectives. The sustainability categories best align with environmental sustainability and the SAFR-B framework will be developed first for environmental sustainability. The sustainability categories identified by LEED and BREEAM each have different numbers of points associated with them, in some way defining the relative importance of the categories. Figure 9 gives a comparison between the relative importance of the categories using radar graphs.



(a) LEED (b) BREEAM

Fig. 9. Comparison between relative importance of various sustainability categories.

It can be clearly seen in the comparison between LEED and BREEAM in Figure 9, that there is considerable alignment in prioritization of the sustainability categories even if the two schemes use slightly different nomenclature and weight (i.e., number of points) for each category. In both cases, energy is most highly prioritized followed by indoor air quality or health and well-being. In terms of the WBDG objectives, sustainable, accessible, functional all relate well to the categories in LEED and BREEAM, albeit without a points scheme. Overall analysis of the categories indicates that relevant design objectives for sustainability could include such terms as “energy,” “material,” “site specification,” and “water use,” or combinations of these.

3. A Framework for a Sustainable and Fire Resilient Building (SAFR-B)

3.1. Concept

Fire impacts to the environment come from both natural and human sources. Managing both often requires different strategies and can be pursued without consideration of the interface between the natural and technological worlds. However, as society has looked to minimize its impact on the natural world by implementing sustainability strategies, and more recently has recognized the need to make human settlements resilient as well as sustainable, the need to create sustainable and resilient human development has emerged. When one further considers the interrelationships between carbon emissions, climate change, and climate impacts, this need becomes pervasive. While this is true for many hazards, fire is a particular hazard of concern, since fire as a natural hazard is increasing in frequency and intensity due to climate change caused or exacerbated extreme weather leading to, e.g., drought conditions and high temperatures. Further, fire as a technological hazard can be inadvertently increased by implementation of energy sustainability measures, such as localized energy sources (e.g., photovoltaics) creating potential ignition hazards, and/or thermal insulation (specifically combustible materials) creating additional fuel load. To comprehensively address and mitigate the increasing fire risk it is necessary to adopt the concepts of a Sustainable and Fire Resilient Built Environment (SAFR-BE). In this context, the built environment includes buildings (structures, facilities), infrastructure, and communities.

Much of standard building design is based on prescriptive codes which describe the way a building should be constructed, rather than describing the performance that is required. Prescriptive design is built on experiential knowledge where code requirements are based on what we know to be effective in building design. Prescriptive requirements are traditionally updated based on input from incidents where a particular solution has been found to be unsafe relative to some design parameter, e.g., fire. While prescriptive codes are suitable for standard design solutions, they are often unable to keep up with rapid technological achievements and product and material developments. In support of the development of sustainable solutions for buildings, new material and products are being developed rapidly, and their implementation often suits a performance-based design (PBD) process. In performance-based design, a series of design objectives are developed for performance parameters, e.g., structural integrity, chemical safety, sustainability, and fire resilience, just to name a few. It has been suggested that PBD for fire safety emerged in the 1990s [130] together with the introduction of performance-based regulations in several countries [131, 132]. The basis for PBD include:

- Research into compartment fire dynamics in the 1950s-70s (e.g., Kawagoe [133])
- Concepts of reliability-based design (e.g., Cornell [134]) and quantitative risk analysis from the 1960s-70s (e.g., Rasmussen and Svedung [135], Rasmussen [136], Rasmussen [137])
- The application of these concepts to fire design of structures in 1970s-80s (e.g., Pettersson, et al. [138], Lie [139])
- Systems constructs and design approaches introduced in the 1970s-80s (e.g., Fitzgerald [140]), and
- The introduction of computer modeling applications for fire in the 1970s-80s (e.g., Quintiere [141]).

By the late 1980s, the results of research into fire safety science and engineering, structural fire engineering, fire systems components, and reliability- and risk-based design began to be integrated into structural fire performance design, fire safety engineering (FSE) frameworks, and ultimately into frameworks/process descriptions for PBD for fire safety. Although some differences exist between the various frameworks, they all follow the general structure and process flow as illustrated in Figure 10.

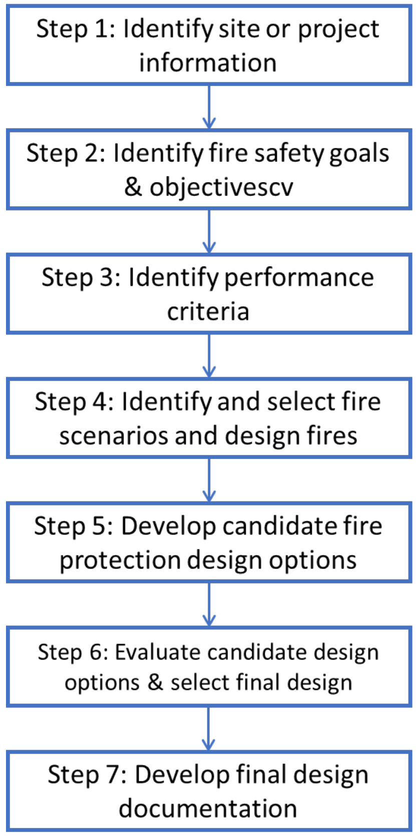


Fig. 10. Overview of performance-based design process (for fire). Adapted from Meacham [130].

Fundamental to performance-based design is that framing of the problem starts with the development of performance objectives. These are often qualitative statements intended to describe an intended function of a system or desired outcome. In performance-based design for fire safety, the objective of *fire safety* is typically expressed in terms of the underlying strategies *prevent ignition* and *prevent fire spread* [43]. In terms of the objective *sustainability*, there are no generally agreed strategies to attain this objective, although we made the case in the previous chapter that there are some common themes in green building schemes which can be exploited to define sustainability strategies that could allow us to develop methods to achieve building sustainability. Applying performance-based design to the dual objectives of fire safety and sustainability is more complex than focusing on one objective at a time, but it is possible using a framework that includes both fire safety objectives and sustainability objectives connected to their various strategies in a hierarchical structure.

This chapter introduces the concept of Sustainable and Fire Resilient Buildings (SAFR-B) and how such holistic thinking can be applied to better understand the sustainability implications of fire safety and the fire safety implications of design choices motivated by sustainability objectives.

3.2. Method

3.2.1. Identification and Recruitment of Experts and Non-experts

To assist in the development of the SAFR-B framework, it was necessary to recruit a pool of fire safety and sustainability experts. The experts were identified through personal contacts of the authors of the study. The core of the group of fire experts was the SFPE Risk group (17 people). In addition, approximately 20 experts from fields with expertise ranging from fire to risk to sustainability. In some cases, experts had experience from more than one field. Table 7 and Figure 11 summarize the geographical distribution and approximate experience of the experts invited to participate in the development of the SAFR-B framework. Of these, 50% provided input to the structure of the framework and seven of those participated in the rating of the attributes and strategies.

TABLE 7. SUMMARY OF LOCATION, EXPERTISE, AND PARTICIPATION OF EXPERTS AND NON-EXPERTS

Expert #	Geographical location	Expertise F=fire; R=risk; S=sustainability	Participated in evaluation of structure of SAFR-B	Participated in pairwise evaluation of attributes and strategies
1	North America	F; R	X	
2	North America	F		
3	Australasia	F	X	X
4	North America	F; R		
5	Europe	R		
6	Australasia	F; R		
7	Australasia	F; R		
8	Europe	F		
9	North America	R		
10	North America	R		
11	Europe	R	X	
12	North America	R		
13	Europe	F; R	X	X
14	Australasia	F; R	X	
15	North America	R		
16	Europe	F; R	X	
17	Australasia	F; R		
18	North America	F; R	X	X
19	North America	F	X	
20	North America	F	X	
21	Europe	F; S		
22	North America	R		
23	North America	R	X	
24	Europe	F; R	X	X
25	Europe	F; R; S	X	
26	Europe	F; R; S	X	
27	Europe	S		X
28	Europe	S	X	
29	Europe	S		
30	Europe	S		
31	Australasia	F; R	X	
32	Europe	F; R	X	X
33	Europe	F; S	X	X
34	Europe	F; R; S	X	
35	North America	F		
36	Europe	F; S		

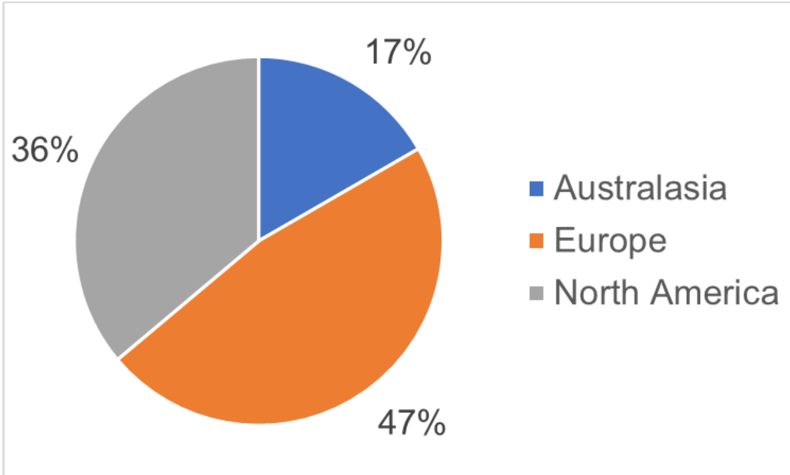


Fig. 11. Geographical distribution of experts and non-experts contacted as part of this study.

3.2.2. Development of SAFR-B Framework

At the outset of the project, there was an intention that the SAFR-B framework would probably be based on an Analytical Hierarchy Process (AHP) methodology as this is the approach that was recently used by ARUP when creating a façade evaluation tool for the National Fire Protection Association (NFPA) [142]. Nonetheless, it was determined that it is necessary at the outset to conduct a literature survey of available risk assessment and decision analysis literature to determine whether there might be alternatives to this approach. To this end, the literature study described in section 2.1 was conducted. The literature survey indicated a number of different approaches could have been chosen, but that the AHP approach was favorable for the proof-of-concept development proposed in this project, as confirmed by checking recommendations on the MCDA Methods Selection Software of Cinelli, et al. [105], which is available on http://mcdamss.com.

The framework has been developed through a multistep engagement of the identified experts and non-experts. The first stage was to develop the hierarchy of the method in support of a policy of creating a sustainable and fire resilient building (SAFR-B), by breaking this down into the sustainability and fire safety objectives, identifying a restricted number of strategies with associated attributes and sub-attributes or survey items, see Figure 12. The choice of sub-attribute or survey item depends on the granularity associated with a specific attribute. In some cases, these are not broken down other than into the survey items which are weighed against each other in the expert evaluation. In other cases, the attributes are first broken down into sub-attributes before the sub-attributes are then broken down into survey items. In each case, survey items are at the base of the hierarchy.

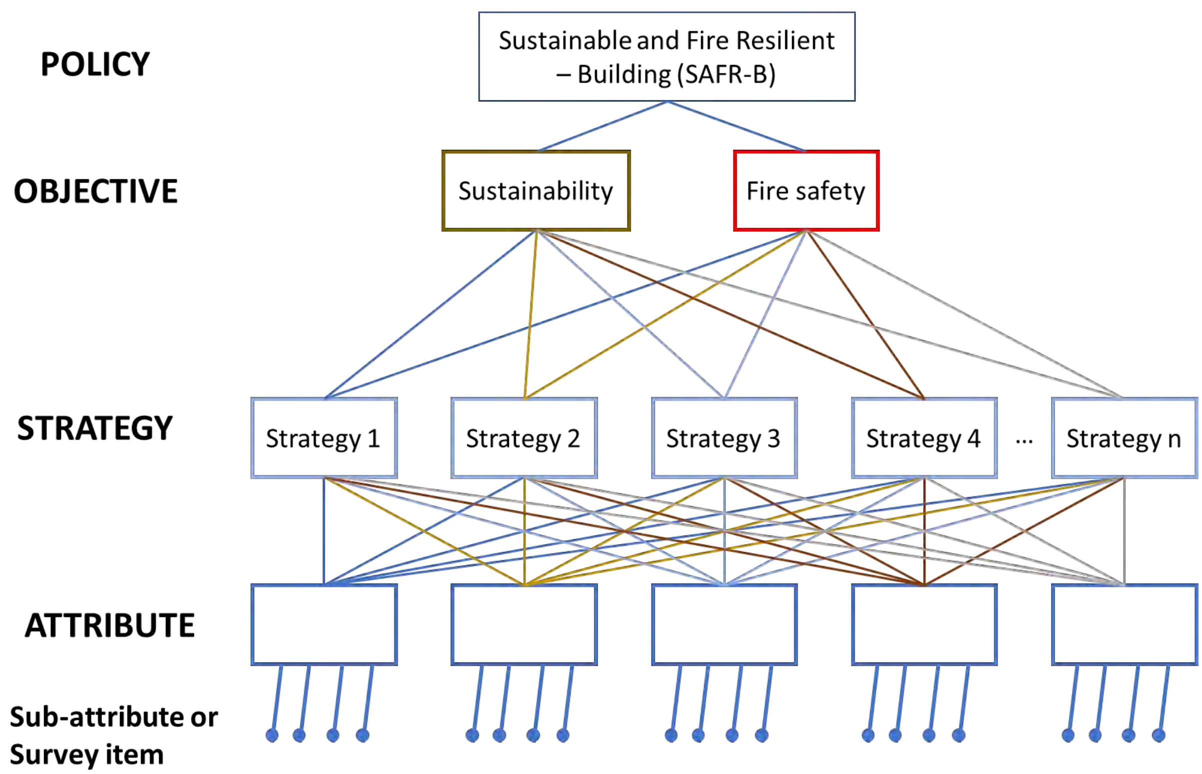


Fig. 12. Conceptual overview of the SAFR-B methodology.

The experts and non-experts were approached first to provide feedback on the structure as such. Changes to the overall structure (e.g., names and descriptions of the strategies, attributes, and sub-attributes) were made based on this external input. In a second stage, the experts and non-experts were asked to perform a pairwise evaluation of attributes using the Analytical Hierarchy Process (AHP). The experts provided input to the AHP using a Delphi procedure [143]. This means that the experts do the evaluation independently and each expert has an opportunity to review an initial assessment in a final evaluation step, knowing the combined assessment from all experts, see Figure 13.

Strategy 1.	Attribute 1	Attribute 2	Attribute 3	Attribute 4	...	Attribute n
Attribute 1	1 : 1	5 : 1	1 : 7	4 : 1	:	1 : 7
Attribute 2	1 : 5	1 : 1	1 : 3	1 : 5	:	1 : 2
Attribute 3	7 : 1	3 : 1	1 : 1	1 : 9	:	1 : 5
Attribute 4	1 : 4	5 : 1	9 : 1	1 : 1	:	1 : 5
	0 : 0	0 : 0	0 : 0	0 : 0	1 : 1	1 : 3
Attribute n	7 : 1	2 : 1	5 : 1	5 : 1	3 : 1	1 : 1

Fig. 13. Structure for pairwise comparisons of relative importance of various attributes in support of strategy 1. Note, numbers in the grey, red, and green fields are fictive.

Numbers were entered into the fields shown in Figure 13 based on relative importance of the attributes in achieving the strategy according to the methodology developed by Saaty [79], where 1:1 represents that the attributes are equally important, 1:3 that the second attribute is moderately more important, 1:5 that the second attribute is strongly more important etc., up to a maximum relative value of 1:9 to designate that the second attribute is extremely more important that the first. Note that all the numbers in the red and green cells were entered by the experts manually while the grey cells were entered automatically.

3.3. SAFR-B Structure and Application

The intention with SAFR-B is that it should provide a framework for using a risk index approach for grading aspects relevant for the building which are important for sustainability and fire resilience. Since different building uses many have different importance levels associated with sustainability and fire safety objectives, the initial development of this framework has focused on one building typology. The initial selected typology is an apartment building.

A hierarchical decision tree approach was used to guide the decision process, and this was initially developed by the project team as a starting point for expert input. The initial hierarchy was then subjected to a peer review by experts and subsequently updated in the final version. The hierarchy shape methodology was adopted to facilitate use of the Analytical Hierarchy Process (AHP) for weighting as recommended based on the literature review. The final version of the hierarchical tree is presented in Figure 14.

The hierarchy for the SAFR-B framework is based on the definition of guiding policy, i.e., the development of a *Sustainable and Fire Resilient Built Environment*; design objectives, i.e., *Sustainability* and *Fire Safety*; strategies to attain these objectives, i.e., *Manage Energy Use*, *Manage Embodied Carbon*, *Manage Site Specifications*, *Manage Hazard Exposure*, *Prevent Fire Ignition*, *Manage Fire,* and *Manage Exposed* (to fire). Finally, several attributes were identified associated with the strategies, i.e., *Building Structure, Internal Material and Design, Building Envelope*, *Building Services*, *Alternative Energy System*, *Site Properties, Fire Extinguishing, Building Management*, and *Means of Egress*.

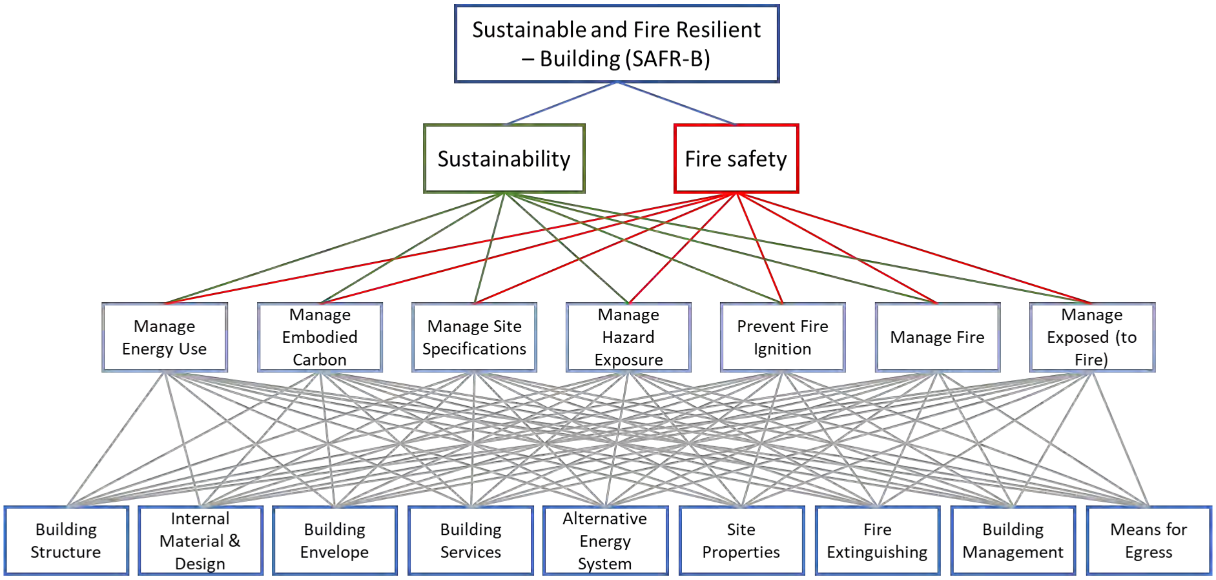


Fig. 14. Hierarchical structure for the SAFR-B framework.

There are two branches (objectives) of the hierarchical SAFR-B assessment tree: sustainability and fire resilience. These objectives are supported by seven strategies which have been defined to be associated with sustainability or fire resilience. The wording of these strategies took its starting point from sustainability documentation [123, 124, 144] and fire safety documentation [43] in an effort to promote recognizability to both communities.

At the bottom of the tree, we have nine attributes, which are aspects that are important for the sustainability and fire resilience strategies. These attributes are differently important for each strategy used to reach the ultimate objectives of environmental sustainability and fire resilience. For the method to work, it is necessary to determine the importance of each attribute and the relative grade of each attribute from both the sustainability and fire resilience perspectives. The importance value, together with the grade for each attribute, will be used to derive the sustainability index and the fire resilience index, i.e., how well the proposed building design meets these two objectives. Indeed, this relative grade (and to a certain degree importance) of each attribute of the proposed framework is determined by expert users through a survey of the building. The model will ultimately allow the user to develop a grading of the attributes for a specific project which will then allow them to develop two performance measures, one for environmental sustainability and one for fire resilience.

As mentioned, the current version of SAFR-B has nine attributes which represent nine aspects that are important to describe the building’s sustainability level and fire safety level. Each attribute is associated with several survey items, which are aspects that are thought to be important for the attribute and which can be graded during a survey of a particular building. While it is possible to have more attributes, the AHP works best with a limit of nine. To accommodate this, more complex attributes can be divided into sub-attributes to better capture details.

Each of these will be described and defined below. We should note that these definitions have also been reviewed by the experts and the final definitions are those presented.

3.4. SAFR-B Assessment

When applying the framework, the attributes are used to reflect something about the building's overall goal for sustainability and fire resilience. The intermediate levels are included to explain the structure and to develop the method numbers going into the assessment of the objectives and the policy.

SAFR-B is based on the building's sustainability and fire resilience performance being evaluated on many properties, each of which has a contribution to maintaining the building's sustainability and fire resiliency performance. These properties are described using the attributes and how these are graded with respect to sustainability properties and fire resilience properties, i.e., the survey items for the two topics. Each attribute has several survey items, and they are graded so that, when the framework is used, the attribute receives an assessment value or grading, corresponding to a grade, usually on a scale of 1 – 10.

Furthermore, the attributes are of different importance (different weights) to maintain the desired sustainability level and fire resilience level, which means that the grading of each attribute is weighted with regards to their respective importance for the level of sustainability and fire resilience.

The SAFR-B index (in this case broken down into the objectives for sustainability and fire resilience) is defined as a sum of all (*n* pieces) attributes, expressed as the product of a grading and an importance (weight):

$$Sustainability = \sum_{i=1}^{n} score_i^{sust} \cdot importance_i^{sust}$$

$$Fire\ resilience = \sum_{i=1}^{n} score_i^{fire} \cdot importance_i^{fire}$$

Using this method, it is also possible to calculate an overall SAFR-B performance index by combining the two individual indices. This index will then give an indication of the Policy performance. This is illustrated in the application in the next chapter.

3.5. Defining the Importance Metrics

There are several ways to define the weights to be used in the assessment. In developing the framework SAFR-B it was initially decided to use the AHP approach as it provides a consistent result. Regardless of the technique used to determine the weights, it should be done step by step using the hierarchical tree-like structure. The weights for each attribute are thus determined in three steps:

1. The importance values of the attributes in relation to different sustainability and fire resilience strategies are assessed,
2. The importance estimations of the strategies for the objectives are assessed, and
3. The importance of the objectives for the building's overall sustainability and fire resilience policy is assessed.

This work to assess the importance metrics was performed by the seven experts, see Table 7. The task given to them was to perform a pairwise comparison of the aspects on each level in the hierarchy tree with respect to the next higher-level aspects. As an example, all nine attributes on the attribute level were compared to each other with respect to each of the seven strategies. This means that there were in total almost 300 pairwise comparisons performed by the experts.

To strengthen the estimations conducted by the experts, a Delphi procedure was applied [143]. The Delphi procedure is a formal procedure for expert elicitation. In practice, mean values of all the pairwise comparisons the experts submitted in the first round were sent back to the experts in a second round, asking them to review their initial estimation, with knowledge of the total group mean estimations. This gives the opportunity for the experts to make an informed revision of their initial estimations of the importance assessments. The pairwise comparisons from the second round were used to derive the final weights for the framework. This means that the Delphi process stopped after only two rounds even if a true consensus was not reached. It should be noted that all experts were treated in the same way with respect to their competence, irrespective of whether they had mainly sustainability and/or fire safety expertise. This means that experts on fire safety also evaluated pure sustainability aspects and vice versa. This means that there is a natural bias included in the assessment as no distinction was made between experts' knowledge. The main reason for this approach was the limited number of experts participating in this task.

The weights or importance values originating from the estimations done by the experts were derived according to the hierarchical tree structure. This means that the estimations from attribute level are combined with the estimations on strategy level, on objectives level, and finally on policy level. This is done by matrix multiplication from one level to the next. But before this can be done, the relative weights at each level need to be derived, i.e., the AHP estimates must be converted to importance measures.

On each level, the importance values for each aspect (for example an attribute) are derived by calculating the geometrical mean for each aspect. The attribute importance values are derived for one attribute at a time, see Figure 15.

Fig. 15. Schematic overview of method to derive the importance values based on the AHP estimations.

The importance value for the first attribute is calculated as the geometrical mean, suggested by Saaty [79], using the values on the first row 1/1, 2, 7/2, 3, 2/3 etc. It would also be possible to calculate the arithmetic mean value, but in this case the method by Saaty [79] was followed. In the Fig. 15 example, the importance value for the attribute “Building structure” with respect to the strategy “Manage hazard exposure” is calculated as the geometrical mean as:

$$\left[\frac{1}{1}\cdot\frac{2,7}{2,3}\cdot\frac{2}{3}\cdot\frac{2,5}{3,3}\cdot\frac{2}{2,3}\cdot\frac{2}{5,3}\cdot\frac{3}{3}\cdot\frac{2}{3,8}\cdot\frac{2,3}{4,8}\right]^{\frac{1}{9}} = 0,71$$

This is repeated for all aspects in the hierarchical tree to obtain the importance values for each aspect with respect to the aspects in the next higher level in the hierarchical tree. For each strategy there is a vector containing the importance values for the attributes. When combining the vectors for all strategies, the result is a matrix “attribute to strategy.”

The procedure is repeated for all levels and the result will be three matrixes, i.e., attribute-strategy, strategy-objectives, and finally objective-policy. The importance values for attribute to objective or for attribute to policy is obtained by a matrix multiplication using the three matrixes as in Figure 16. Normally the importance values are normalized so values are between 0 and 1 and that the sum of the importance values are 1,0.

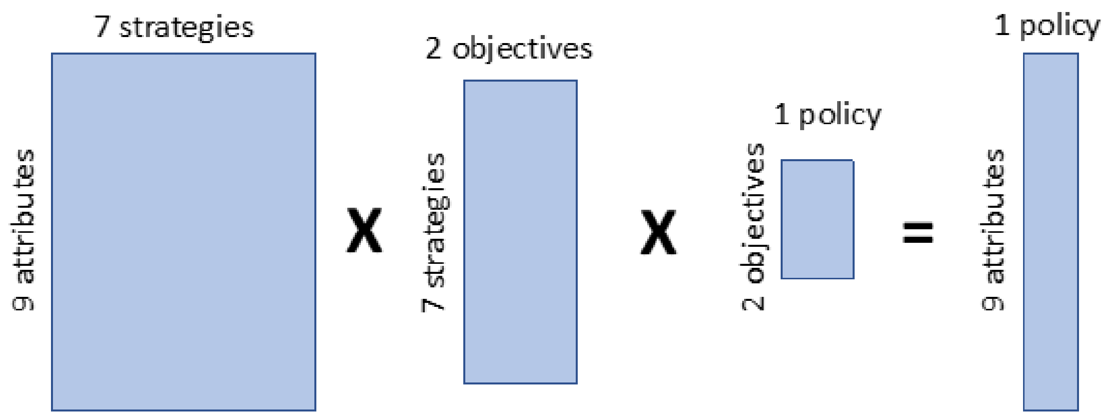


Fig. 16. Illustration of matrix multiplication used in the SAFR-B model.

The numbers used to develop the importance values are presented in Appendix B.

3.6. Grading the attributes

Each attribute was divided into a limited number of survey items. Each attribute, therefore, needed to be graded according to these survey items. Each survey item represents an aspect that is considered important to describe the performance for attributes. The combined effect of different survey item grades is combined into the attribute grade. The attribute grade is the measurable aspect in the method and is used to calculate the index values.

As the basis for using the risk index approach is to combine aspects that may be very different in the way they are evaluated, much of the grading is made by subjective judgement. The definitions of alternatives resulting in a specific grade were, however, also exposed to the expert panel review.

3.7. Hierarchy description

The section provides a more detailed description of all aspects in the hierarchy tree.

3.7.1. Policy

The policy is the main goal which the framework is to describe. It shall be a general description of what is the general aim and is defined by the boundary definitions for the framework.

SAFR-B policy: The building shall be sufficiently sustainable and provide a satisfactory level of fire resilience.

3.7.2. Objectives

The objectives are used to further explain the intention with the policy. In this case there are two objectives related to sustainability and to fire resilience, see Table 8. Additional objectives could potentially be relevant, like preservation of the cultural heritage and facilitation of production continuation. In the current case, the framework focuses on apartment buildings and is therefore limited to the two objectives selected.

TABLE 8. LIST OF OBJECTIVES IN THE SAFR-B FRAMEWORK

Objective	Description
Environmentally sustainable building	Environmentally sustainable building seeks to reduce negative impacts from building materials, systems, and features on the environment and on the health and comfort of building occupants, thereby improving building performance throughout the building's expected lifetime. Other aspects of sustainability (e.g., economic and social) could be included in later versions of the framework.
Fire resilient building	Fire resilient building seeks to reduce the negative impacts of fire in a building on occupants, emergency responders, and the environment, and facilitate a rapid response to ensure timely and efficient post-fire use of the building (i.e., improved resilience as opposed to traditional improved fire safety).

3.7.3. Strategies

The strategies describe how the objectives are supposed to be achieved. Different ways to meet the objectives are possible and there may also be a differentiation between how important they are for each of the objectives. The strategies are in this case divided into ones related to fire resilient building and others to environmentally sustainable construction, see Figure 14. Strategies should use a verb to define the intention of each strategy. A strategy should describe a means used for obtaining or striving for a desired sustainability (environmental) or fire resiliency status of the building.

TABLE 9. LIST OF STRATEGIES IN THE SAFR-B FRAMEWORK

Strategy	Description
Manage energy use	Refers to actions aimed at limiting the use of non-sustainable energy use. This could include the implementation of renewable energy sources and/or reduction of energy needs during building use, e.g., through the implementation of zero-energy (or positive energy) building strategies.
Manage embodied carbon	Refers to actions aimed at limiting the amount of embodied carbon in the building both during construction and use. This could include the implementation of lightweight materials; increased use of renewable materials, e.g., wood products; and/or increased recycling and reuse of material in the construction of the building.
Manage site specification	Refers to actions aimed at improving the environmental sustainability of the building, specifically in terms of their implications for fire resiliency. This includes the evaluation of site accessibility, e.g., for FRS; evaluation of recipient sensitivity; and/or water management and availability.
Manage hazard exposure	Refers to actions aimed at minimizing the exposure to a variety of hazards. This could include the reduction of toxic substances which are dangerous to human health and the environment (including species health); improve preparedness for natural hazards (e.g., flooding or wildfire); and/or improved building security.
Prevent fire ignition (in NFPA550)	Refers to actions aiming at limiting risk of ignition, such as excluding materials with risk of autoignition, heat sources etc.
Manage fire (in NFPA550)	Refers to limiting fire from spreading, both by construction (i.e. compartmentation, etc.) but also by extinguishing fire. Fire department and sprinklers can be linked to this strategy, i.e., to control the fire process.
Manage exposed (in NFPA550)	Refers to affording occupants to safe evacuation, through notification, wayfinding, and smoke control. Can also affect damage to the building as such.

3.7.4. Attributes

Attributes refers to the different aspects of the building. Each attribute is given a fire safety and a sustainable credit, which is obtained by weighting different survey items for that attribute against each other. The attributes will then be given a direct importance value for each of the strategies i.e., the attributes will not be weighed against each other. What is not part of the survey is how to consider the design phase and principles for design, e.g., planning for end-of-building use. To some degree, design phase principles are considered because recycled material can be used and is part of the current survey. Each attribute is further described in the following section and the full grading of all attributes is presented in Appendix C. The attribute descriptions and gradings in Appendix C are mainly based on subjective judgements. There is still much work to be done to present a well-founded structure on how to grade each attribute, and the material in the report is a starting point for such a work.

3.8. Attributes

Attributes refer to different aspects of the building that are important for the sustainability and for the fire resilience of the building. Each attribute is graded separately with respect to fire resilience and sustainability. Each attribute usually consists of several survey items which are the measurable features for the attribute. The survey items measure the relative performance for the aspect being graded from low performance (value = 1) to high performance (value = 10). The survey items are combined into an attribute grade by a relevant procedure, usually by weighting the survey items with respect to each other given the objective for each attribute for sustainability and fire resilience.

The grades will later be used to grade the building's total performance in relation to the strategies for sustainability and fire resilience, and in relation to the overall index value for a joint score for sustainability and fire resilience.

3.4.1. Building Structure

This attribute describes how the building structure is designed and what materials are being used. The attribute refers to features that are related to the building´s structural members. These include both interior and exterior load-bearing walls, i.e., walls separating apartments are described as being part of the building structure. The design of the building´s structure can influence its stability during a fire as well as its recovery afterwards. The presence of cavities in the structure can impact the likelihood of fire spreading throughout the building. The use of fire barriers within such cavities can impact the overall fire safety of the building. The attribute has four survey items:

- Material
- Building height
- Construction method
- Fire protection level

The material used for the building structure has a high importance for both fire resilience and sustainability. Selecting the material will have a huge impact on many other aspects of the building. The higher the building is, the more material is needed, which will affect the sustainability grade in combination with the amount of toxins emitted by structure members and will indicate how much energy is used during production of the material. The height of the building is also important for the ability to handle a fire. Circularity will affect the grading.

Fire spread in the building structure depends on the type of material but also on the presence of voids or cavities within the structure. To avoid structural fires, fire stoppers are included as a measure to control the fire risk, and in this case proper control and documentation is also needed for a better fire safety performance grade.

The overall fire protection level, expressed as the structure fire rating, is an essential part of fire resilience of the building. A higher fire rating will, however, also increase the amount of material used.

The four survey items are combined to result in an attribute grade. In this weighting it is assumed that *Material* and *Fire safety protection level* are most important for fire resilience while *Material* and *Building height* are the two most important aspects for sustainability.

3.4.2. Internal Material and Design

"Internal material and design" refers to the overall interior design of the building. This includes not only the material used as surface layer within the apartments but also the material and design features for the fire compartmentation of the building. The attribute has four survey items:

- Surface material
- Interior design
- Attic
- Stairwell

The surface material is related to the finishing material on ceilings, walls, and floors in the apartments. The selection of lining material can have a significant effect on the fire development in the apartment. It will also affect the indoor environmental quality as materials emit substances like VOC and other toxins. Circularity in terms of re-using material shall be considered for all types of material.

The indoor design reflects how the apartments are separated from each other, and if the apartment has an open floor plan or is designed with separate closable rooms. Having walls in the apartment will limit the fire spread even if walls are not fire rated which is beneficial for fire resilience. The quality of an open floor plan is on the other hand higher from a living perspective. An open floor plan is also positive for light spread in the apartment.

The attic can have separate fire compartments to prevent large fire spread consequences. Openings to vent the attic are considered, because vents are needed to prevent moisture in the attic but can also spread fire from the top apartment to the attic.

To limit fire smoke spread between the stairwell and apartments, the stairwell can be equipped with a smoke venting functionality. Additional protection from smoke spread is achieved if doors between apartments and stairwells are equipped with door closing devices. The venting system may also be part of the climate control of the building as it can release warm air during the summer. This is beneficial for the building's sustainability because it may reduce the need for cooling the air. Smoke venting can use natural ventilation or mechanical ventilation.

The four survey items are combined to result in an attribute grade. In this weighting it is assumed that *Interior design* and *Stairwell* are most important for fire resilience while *Surface material* and *Interior design* are the two most important aspects for sustainability.

3.4.3. Building Envelope

"Building envelope" refers to the description of the outer covering of the building, which includes its façade and roof outside features. The use of combustible materials in combination with having cavities in the façade system can increase the risk of fire spreading both inside the façade construction and along the outside of the façade material. Fire spread along the façade also depends on the façade structure, such as the presence of canopies or balconies and the vertical distance between windows. Vertical fire spread in the current framework is only considered based on material selection and vertical distance between windows. Additional complexity could be added to future versions.

The materials and insulation used in the building´s envelope can impact its energy efficiency and the amount of carbon dioxide during production and other harmful substances it releases during its lifetime. The attribute has six survey items:

- Façade
- Cavities in façade
- Insulation material
- Windows
- Roof covering
- Roof insulation

Material properties play an important role in the façade, both for the outer protecting shield and for the insulation material. From a fire resilience perspective, combustible material on the façade may contribute to significant fire spread in the building and is therefore an important part in the grading of the fire performance. Material in the façade is also related to thermal insulation, which contributes to the overall energy use for heating and cooling the building. The selection of material for heat insulation will also impact the fire performance. Circularity of material is also included in judging the grade for sustainability aspects, as is the amount of material used. There is a conflict of interest when looking at the amount of insulation materials to have in the building. It is assumed that it is more beneficial from a sustainability perspective that better heat insulation is more important than use of extra material.

The façade can be designed in different ways, but it is common to have a void between the weather shield and the insulation material to remove any moisture. Having combustible material as one of the surfaces in this cavity can result in significant fire spread. Preventing this is part of the grading of the façade system. So called fire stoppers are used as a means for limiting fire spread and especially above windows to prevent fire spread from an apartment to the façade.

Windows in the façade may have many positive contributions to the building performance. More windows contribute to more light in the apartment, which is positive from a sustainability perspective. At the same time windows may contribute to fire spread, especially if the vertical spacing between them is short and if the windows can be opened.

The roof material and insulation are two aspects that are important for sustainability and fire resilience. The outer surface material can contribute to fire spread if combustible but may also be vital for the heat balance in the building and can be used to absorb rainwater which both are positive for the sustainability. As for other material properties, re-use of material is favorable.

From a fire safety perspective, it is assumed the façade and handling cavities are the most important for grading. For the sustainability grading, material in the façade and insulation material on the outer walls and on the roof is assumed to contribute mostly to the sustainability grade.

3.4.3. Building Services

The attribute “Building services” refers to the technical systems installed in the building that provide services like heating and ventilation. The design choices made for these systems can impact both the risk of a fire starting and the energy efficiency of the building. The attribute has six survey items:

- Ventilation system
- Heating system
- Cooling system
- Energy recovery
- Stoves
- Fireplace

The ventilation system refers to the normal system for providing ventilation in the building to control indoor climate. The system can either be natural ventilation or mechanical ventilation and if the latter there is also a selection if fire smoke spread is prevented by dampers or not. From a sustainability point the natural ventilation system is the one resulting in a better performance.

The building can be designed with different heating and cooling systems and use different energy sources for the heating. It is assumed that district heating is the most optimal for both sustainability and fire resilience reasons. In this context, district heating is a system for distributing heat generated in a centralized location through a system of pipes to users. Such heat generation can be produced efficiently and with low emissions. A wood stove/pellet burner is assumed to provide a higher fire risk and will also provide a poorer solution from an emissions point of view. However, wood is a circular energy source and is therefore graded relatively high. This is a typical example of conflicting aspects within an attribute that need further attention. Electrical resistance heating has the lowest performance for both aspects. The type of cooling system (if installed) will also affect the grading, as will any heat recovery system.

Local heat sources like the kitchen stove and any wood/pellet stove or fireplace in an apartment will also contribute to the fire risk and to sustainability, the latter primarily due to emissions and dependent on type of fuel.

The total attribute grades (sustainability and fire resilience) differ in significance in the survey items. Fire safety is primarily based on the type of stove because kitchen related fires are not uncommon. The sustainability grade depends mostly on the type of ventilation, heating, and cooling systems.

3.4.4. Alternative Energy System

"Alternative energy system" refers to the amount of electricity that is not externally provided to a building. This includes the installation of facilities that can produce and store electricity, as well as the installation of EV-charging stations for those occupants who choose to use electric vehicles. The attribute has three survey items:

- Electricity generation
- Energy storage
- EV-charging

It is assumed that the amount of energy generated within the building has an importance for both sustainability and fire resilience. The more energy locally generated, the better it is from a sustainability perspective, even if the storage capacity also may have to be increased. An idea of self-sufficiency is seen as positive. However, it is also slightly negative from a fire resilience perspective because higher capacities for generation and storage mean a higher fire risk, i.e., a risk to initiate a fire. A fire in photovoltaic (PV) panels is also quite difficult to suppress because electricity is continuously generated as long as the panels are exposed to light. Other means for electricity generation are also supported, e.g., wind generators.

Charging stations for electrical vehicles may be part of the building facilities and is beneficial from a sustainability perspective. Having the charging stations located indoors in a garage or similar may pose a fire risk when connected to a vehicle.

Both from a sustainability perspective and a fire resilient perspective, the grade is mostly related to generation and storage.

3.4.5. Site Properties

The attribute "Site properties" refers to the characteristics of the area surrounding the building. These characteristics can impact both the potential spread of fires to the building, as well as the ability of fire fighters to effectively operate in the area. The attribute has three survey items:

- Ground characteristics and access
- Separation distance
- Access to water

Ground characteristics depend on the ability of rescue services to reach the building, if there are obstacles, slopes or similar obstructions, and if the ground is hard or soft. Vegetation can also be seen as an obstacle but is desirable from a sustainability point of view. Vegetation can provide shade to the building resulting in less demand for artificial cooling. Obviously, there is a conflict of interest in the use of the ground outside the building. It is preferred to have space around the building, much daylight, and large green areas around the building for sustainability purposes. However, the ground can be used more efficiently if not much space is reserved for green areas. It is not clear what aspect is most important.

Separation distances are determined by looking at the distance between the building and nearby buildings. Short distances indicate that there may be fewer green areas around the building. It is also appreciated to have access to a wildland area, at least from a sustainability aspect.

Access to water and the potential for re-use of water are important aspects to include. Re-used water, i.e., gray water, is considered for fire extinguishing purposes.

Ground characteristics and access are considered most important for both sustainability and fire resilience when assessing the attribute grade.

3.4.6. Fire Extinguishing

The “Fire extinguishing” attribute refers to the capability of limiting the fire development if a fire starts. This can impact whether the people inside the building are able to control a fire from spreading on their own. The attribute has two survey items:

- Portable extinguishing systems
- Automatic extinguishing systems

Portable extinguishers can be in each apartment and/or in common areas. A short delay to start fighting the fire requires that extinguishers are in each apartment. This will, however, result in more extinguishers in the entire building. Also, the type of hand-held extinguisher is important, specifically the extinguishing media. The least environmentally impacting media are preferred and graded higher from a sustainability point of view. The environmental friendliness of chemicals is continually updated, and this ranking will also need to be updated over time. As the ranking is coarse, the present evaluation is expected to be applicable as proof-of-concept. Also, the extinguishing properties can follow the same grading structure.

Given a generic assessment of automatic sprinklers, the efficiency of the automatic sprinkler system mainly depends on the proportion of the building that has this protection system.

The importance of the attribute grade depends on the two perspectives. In the present application, the sustainability grade is mostly dependent on the properties (material) of the hand-held extinguishers, while the fire resilience grade mostly depends on the automatic system.

3.4.7. Building Management

In most buildings there must exist a management system that ensures fire safety and promotes sustainable behavior among occupants while the building is in use. It also encompasses the routines for inspecting and cleaning the building's systems. The "Building management" attribute has three survey items:

- Information
- Waste management
- Inspection and maintenance routines

Information to new residents can be used to increase the likelihood that residents are aware of procedures for sustainability and fire resilience. Different aspects are important for the two perspectives, and evacuation related factors and how to prevent fires are important for fire safety. The sustainability view is more focused on the use of resources like electricity, energy for heating and cooling, and water. Lastly, it is important to make sure the administrative procedures work as intended and, therefore, maintenance and inspection routines are important.

The attribute grades, both for sustainability and for fire resilience, focus on the importance of maintenance and routines. Therefore, this score will be the most dominant for the attribute grades.

3.4.8. Means for Egress

The attribute "Means for egress" refers to the systems and design elements within the building that facilitate safe evacuation of occupants in the event of a fire. The attribute has five survey items:

- Fire detection systems
- Fire notification
- Wayfinding
- Exit routes
- Mobility impairment

The aspects related to this attribute focus on the safety of the residents in the case of a fire. Occupant safety is achieved by aspects of this attribute in combination with other attributes, e.g., related to grading the lining material in apartments and the presence of an automatic sprinkler system, which both will influence the fire development. To facilitate a safe evacuation, the notification system is important. What type of detection and alarm system is available is important for attribute grading. Also, provision for the mobility impaired may contribute to safety, such as the presence of a safe refuge area. On the sustainability interpretation, the focus is basically related to the amount of material needed to facilitate different means for egress.

The attribute grade is mostly dependent on the scores for detection and alarm systems, in combination with the mobility impairment aspects.

4. Application of SAFR-B to Apartment Building

4.1. Introduction

The SAFR-B framework has been applied to a mid-rise apartment building to illustrate how it might be used to inform decision making when weighing sustainability and fire safety attributes as part of the initial building design. Calculations were performed in Excel using the weights and scoring summarized in Appendix B and Appendix C. The framework allows users to select building options for each survey item, and then to compare different building choices based on fire safety and environmental sustainability. The example is based on a typical multi-story multi-family residential building in Sweden. Building 1 is an actual building (see Figure 17) while Buildings 2 and 3 are variations of this construction using different attribute choices.

4.2. Application

4.2.1. Building 1

The building selected as the basis of comparison in this case study is a 6-story building in central Malmö, built in 1934 with concrete construction, see Figure 17. As seen from Figure 17, the building is connected to other buildings, although the model calculations have been for this part of the full city block only. The apartments have gypsum walls and ceiling surfaces, with wooden floor surfaces. The façade is covered in plaster while the material used for insulation is unknown and non-fire rated. The building lacks an active fire protection system, with only single detectors installed in the stairwell, attic, and cellar. The building management is mostly done by residents, and maintenance routines and information about fire safety and sustainability are weak or nonexistent. The heating of the building uses district heating.

Fig. 17. Photo of Building 1 which is a 6-story residential building containing multiple apartments located in central Malmö, Sweden. Photo: Erik Kimblad.

4.2.2. Building 2

Building 2 is a modern 8-story construction built with precast concrete planar elements. The building is single standing and 13 meters from the closest neighbor. The building has wooden inner linings and a façade of wood insulated with fire rated rigid polyurethane foam. There is no attic in the building, and the stairwells are fire rated with a door closing system and mechanical ventilation. The building has both active fire extinguishing systems and detectors connected to a central alarm system. The residents are provided with general information about fire safety and sustainability, and the building management tests and maintains building systems frequently. The heating and cooling of the building is done by a heat pump integrated with a mechanical ventilation heat recovery system.

4.2.3. Building 3

Building 3 is identical to Building 2, with the addition of solar panels on the roof and a lithium-ion battery energy storage system.

4.3. Results

Figure 18 illustrates the differences between the three buildings using the SAFR-B framework. The building method from 1934 is the least favorable option in terms of fire safety *and* sustainability. Installing electricity storage and generation proved beneficial for sustainability but detrimental for fire safety, due to decreasing energy use and increasing the risk of fire ignition.

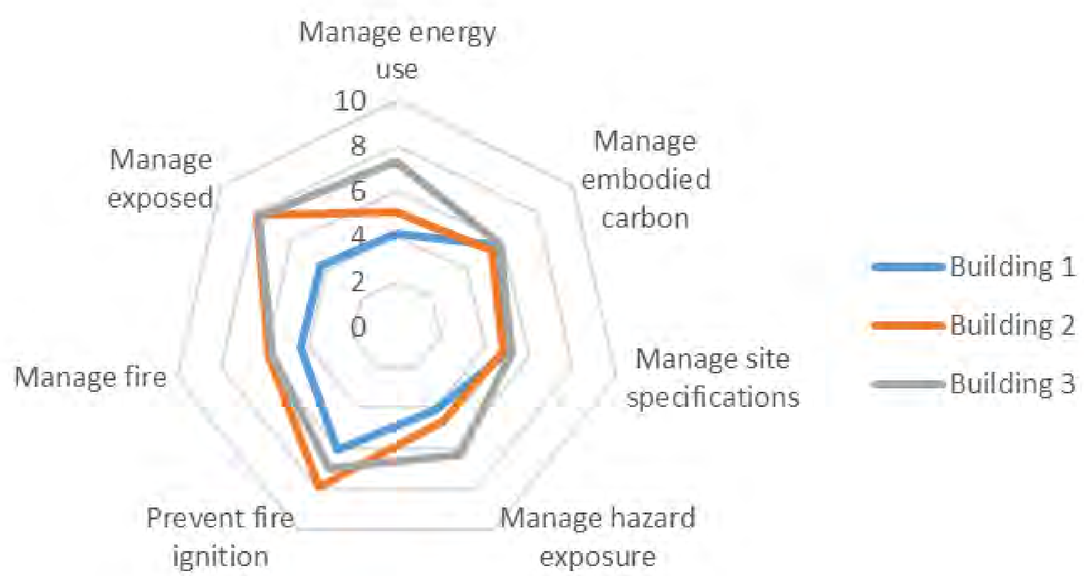


Fig. 18. Comparison between SAFR-B scores for the various strategies in buildings 1-3.

When considering the relative importance of fire safety and environmental sustainability, the SAFR-B framework indicates that installing electricity generation and storage is the more favorable option, see Figure 19.

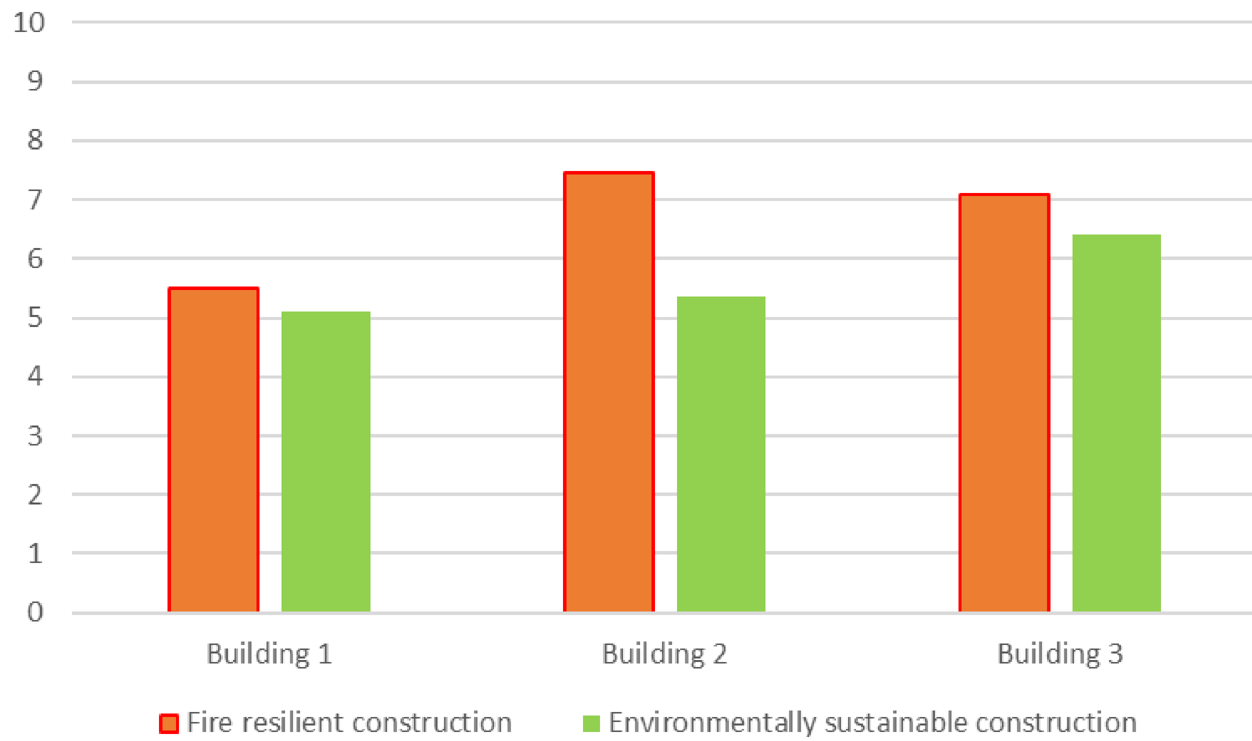


Fig. 19. Comparison between the SAFR-B objectives for the three buildings.

Finally, the objectives can be numerically combined to give an indication of how well each alternative achieves the policy of a sustainable and fire resilient building, see Figure 20.

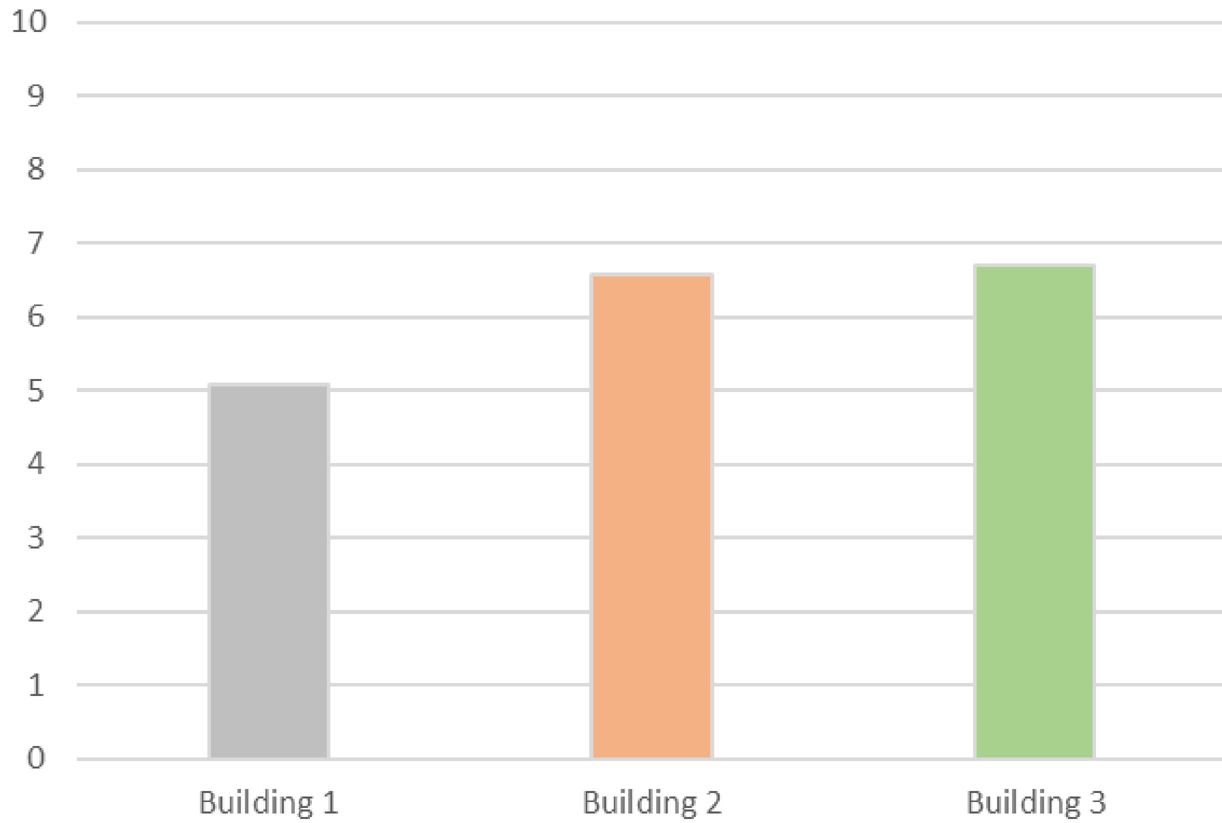


Fig. 20. SAFR-B evaluation of the three building alternatives which clearly shows that Building 1 is the least attractive option for a sustainable and fire resilient built environment.

5. Discussion

The intention of the SAFR-B framework is to compare aspects of a building as input to design choices relative to their environmental sustainability and fire resilience. As part of this project, a review of the literature has been made with two main aims, to: 1) identify which risk methodology would be most suitable to develop the framework (using AHP as a starting point), and 2) identify which strategies are relevant to support the design objectives of sustainability and fire resilience. The literature review supported the initial suggestion to use AHP as the basic structure of the SAFR-B framework. This means that the framework was structured in levels, starting at the policy level, and moving through design objectives, strategies, attributes, and sub-attributes (or survey items). The hierarchy for the SAFR-B framework has, therefore, been developed based on the definition of guiding policy of the development of a *Sustainable and Fire Resilient Built Environment*; the design objectives of *Environmental Sustainability* and *Fire Safety*; the underlying strategies of *Manage Energy Use*, *Manage Embodied Carbon*, *Manage Site Specifications*, *Manage Hazard Exposure*, *Prevent Fire Ignition*, *Manage Fire,* and *Manage Exposed* (to fire); and the attributes associated with these strategies of *Building Structure*, *Internal Material and Design*, *Building Envelope*, *Building Services*, *Alternative Energy System*, *Site Properties*, *Fire Extinguishing*, *Local User Attitudes,* and *Means of Egress*. In most cases these attributes have been sub-divided into survey items. In some cases, the attributes have been divided into sub-attributes and the sub-attributes have been divided into survey items.

Expert input was used to establish the relevance of the strategies, attributes/sub-attributes, and survey items of the model. It should, however, be noted that not all input could be included in the model structure given the limited number of experts and sometimes conflicting input. In particular, expert input was used in the definition of attributes/sub-attributes and survey items.

Once the structure for this first version of the model was established, the Delphi method was used to obtain expert input to the development of scores and weights in the model [143]. Finally, an application of the model to a case building with a variety of features was conducted to illustrate how the framework might be applied for decision making in early phases of the overall design process, as exemplified by a mid-rise apartment building.

The method has undergone significant development as part of this project, but important aspects remain for future development and are summarized here as input to such development. Experts repeatedly asked for further definition of what is meant by sustainability. In the first feedback stage, it was clarified that the model presently focusses on the environmental dimension of sustainability, but even that requires further definition to facilitate the development of scores and weights in the AHP framework. Whether we define “environmental sustainability” in terms of climate impact or eco-toxicity of compounds will impact on the pairwise comparisons. Ultimately, the project team determined that it is easiest to leave this ambiguous because the comparison is made based on the individual expert’s point of view; nevertheless, further definition would facilitate improved similarity between input from different experts. The choice of definition of sustainability will impact which sub-attributes are most important, e.g., some choices that will improve the carbon-footprint of a structure might be toxic. A definition will help to rank these choices.

Related to this question of the definition of sustainability is the question of the difference between sustainability and resilience. As noted previously by Meacham and McNamee [67], these terms are both ubiquitous and difficult to define as their definition has often been related to the context of their application. While sustainability and resiliency are arguably different concepts, they are interconnected, in particular when concerning protection of the environment and human settlements. Given that the SAFR-B framework presented in this report has chosen to exemplify the method using a mid-rise apartment building, one could argue that the model development has its start at the nexus of this intersection between sustainability and resilience. Nonetheless, as experts point out, a definition of what is meant by sustainability (or environmental sustainability) and what is meant by resiliency is required for future development. Concisely put, environmental sustainability in the context of this project has focused on carbon footprint and resiliency has focused on fire safety. Future versions of the framework could expand these definitions as building typology is developed and expert input is expanded.

When developing the framework, there was a concern that there would be a bias towards resiliency because the authors all have their background within that discipline. Some input from experts indicate that the result may instead have been biased towards sustainability. More expert input is needed to improve this balance. Related to this comment, the question of the importance of the building structure has been raised. We know from a sustainability perspective that the structure is the part of the building that has the greatest potential to impact the sustainability of the building. The importance of this feature is rather lost when it appears first at the attribute level. Perhaps it should be raised in importance and directly related to a strategy, instead, in future versions of the model.

As part of this work, an effort has been made to discuss the fact that fire safety is part of the regulated built environment while building sustainability has largely been developed through extra-regulatory means. Experts have expressed that there is a need to better relate the pairwise comparisons to what is required from a purely regulatory point of view. Because this will vary between countries and contexts, it is important to develop guidance concerning how a user can incorporate evaluation of the framework output against the regulatory backdrop provided in their country of application.

Particular effort has been given to defining various strategies and attributes. Nonetheless, much of the expert input was related to the difficulty in assessing the relative importance of attributes and definition or identification of sub-attributes without precise definitions, e.g., below is a selection of expert queries collated during the evaluation process:

- Do we include equality aspects in the attributes relating to site accessibility? (We don’t.)
- How do we include questions of regulatory evaluation of reused products? (We assume that products must be compliant with appropriate regulations.)
- Do we include well-being aspects in site specifications, such as the impact of improved greening of surroundings on well-being? (We don’t.)
- There is some potential overlap between attributes and experts experienced “Where should I put this?” moments when considering sub-attributes and survey items. How can we be sure that this is done the same way between experts? (We cannot be sure, but the problem is mitigated by robust descriptions of the attributes/sub-attributes and survey items.)
- There is great variation between buildings, e.g., even a mid-rise apartment building may have multiple underground floors for parking, or none at all. How do we generalize the importance for various building typologies? (This is countered by increasing the number of experts providing input.)

- How do we include the functionality of fire protection in the model? It can improve the fire resiliency of the building but will add environmental costs in terms of material and installation. Should we take the fact that they reduce the number and size of fires into our grading? (No, at this stage the building is not thought to participate in a fire during its life cycle. The reason for this is that both sustainability and fire resilience are considered as objectives in the methodology. Fires are relatively rare events. Had we assumed that the building was involved in a fire, then all fire safety precautions are automatically important sustainability installations, which oversimplifies the situation. The model endeavors to incorporate sustainability and fire safety thinking in a realistic manner, giving value to both objectives in real world applications.)
- How do we account for, e.g., that a fire cell boundary may also be necessary for acoustic reasons? In this case it will not be an increased environmental cost as it is needed in the building anyway. (In the framework, this would be included implicitly as the building must adhere to all regulatory requirements. The fire cell boundary only has an additional sustainability implication if it could be eliminated if not for the fire resiliency objective.)
- Some terminology is not very self-explanatory, could you give explanations? (The documentation associated with the framework needs further development.)
- How do we account for extreme hazards? (The scores developed in this first development of the framework are built based on typical hazards. If it is common

that there is a flood or forest fire, the model can take this into account. If this is a freak event, the model is not able to include this hazard.)

- Why do you include "embodied carbon" but not "operational carbon"? (Embodied carbon was used as a general method to account for how much material is needed for the building. Operational carbon is dealt with partially through "manage energy use.")

These questions, and others, require that robust documentation be associated with the framework. A more detailed explanation of the attributes/sub-attributes and survey items would assist decisions concerning the development of scores in the future. Indeed, the attributes associated with *Manage Site Specifications* raised many questions and have been rewritten several times. This strategy was also noted to include some inbuilt conflicts, e.g., space should be given around the building for fire service access and lighting, but this space is then not "used optimally." Both aspects relate to environmental sustainability and can be difficult to prioritize, the priority being in the eye of the beholder. While additional detail will need to be developed over time for all strategies and attributes and some will be very country or project specific, one strength of the method (provided large numbers of experts provide input) is that grading will ultimately be quite robust. It was noted, however, that even experts who are familiar with the approach need to understand how the model has been designed to ensure that their input is in line with the intentions of the framework. This can only be achieved through improved clarity in component definition.

While life cycle thinking lies behind the development of the model, life cycle analysis is not explicitly used in the framework and the comparisons are somewhat subjective. The design phase develops the basis for all aspects of the building life cycle, i.e., design choices will affect recyclability of products and material in the building, and the explicit inclusion of life cycle assessment (LCA) as input to grading between choices will improve the application of the framework. As it becomes more mainstream in the future to include LCA calculations as part of the design process, such information could also be used to develop robust scoring of attributes or weighting between attributes.

Fire safety engineering (FSE) and performance-based design (PBD) are at the heart of resiliency in the built environment. The development of engineering methods to weigh sustainability and fire resiliency in building design has the potential to impact on design choices as part of the PBD process. The example given in the case study compares three building alternatives. In all three cases, the buildings have the same function, but make different design choices to achieve that function. The SAFR-B framework provides a methodology to weigh how sustainability and fire safety choices can be optimized and evaluated. In the example chosen, the traditional building method from the 1930's represented the poorest design solution of the three, while the other two alternatives had similar overall SAFR-B performance. The detailed investigation illustrated that building 2 represented the best alternative from a fire safety point of view but building 3 represented the best compromise between fire safety and sustainability. The framework is not in its final form but even in this first application, the output provides interesting input to design choices.

6. Conclusions

A first application of the SAFR-B framework has been made as part of this study, and the methodology developed has been applied to a case study of a six-floor apartment building. The framework has proven to give valuable input to comparisons between design choices.

Expert input has identified the need for more careful definition of sustainability and fire resilience. As part of this improved definition, it will be necessary to define boundaries for comparisons between survey items associated with the various attributes. Many experts were included in the development of the model and the scores, and weighting associated with the AHP model. While the project team is very appreciative of the time and input from all experts, more input is needed for further development of the model moving forward.

When working on development of the framework, one expert input particularly highlighted the difficulty of weighing two desirable outcomes against each other, i.e., sustainability and fire resiliency. Improved fire safety can, directly or indirectly, lead to reduced sustainability when considering material use and maintenance needs. If we do not consider the fact that the building may burn down if safety needs are not met, which will then require additional material use to replace products, we risk missing an important impact on sustainability. The issue is complex, but this does not mean that we should not at least try to provide some design input. It is important to understand that the comparisons between parts of the framework are relative and not absolute. Absolute differences may be both large and small.

The framework aims to improve both sustainability *and* fire resiliency, not one at the cost of the other. To improve the ability of the model to reflect this, it is necessary to broaden it to include the impact of fire safety choices on a reduction in the number and size of fires. This inclusion requires models to be developed of the statistical number of buildings associated with a fire as a function of the choices made. This has been outside of the scope of the present study.

7. Future Work

The present study represents a literature survey and proof-of-concept of the SAFR-B methodology. For the SAFR-B framework to reach the broader engineering community, it will be necessary to continue with the following main activities (without internal ranking):

- More expert input should be solicited to ensure the scoring and weighting is robust and represents a broad range of expertise.
- The Framework should be implemented into an engineering tool to facilitate its application as part of the design process.
- Increased definition of objectives, strategies, and survey items is necessary to ensure that application of the model provides input which can then be compared between projects and applications.
- The framework has been developed and applied specifically to a medium-rise apartment building. The application should be expanded to include other apartment building designs, additional types of buildings, and perhaps even other types of construction, e.g., critical infrastructure.
- New versions of the framework should consider including “waste management.”
- New versions of the framework should consider including “manage operational carbon” as strategy, potentially instead of “manage energy use.”

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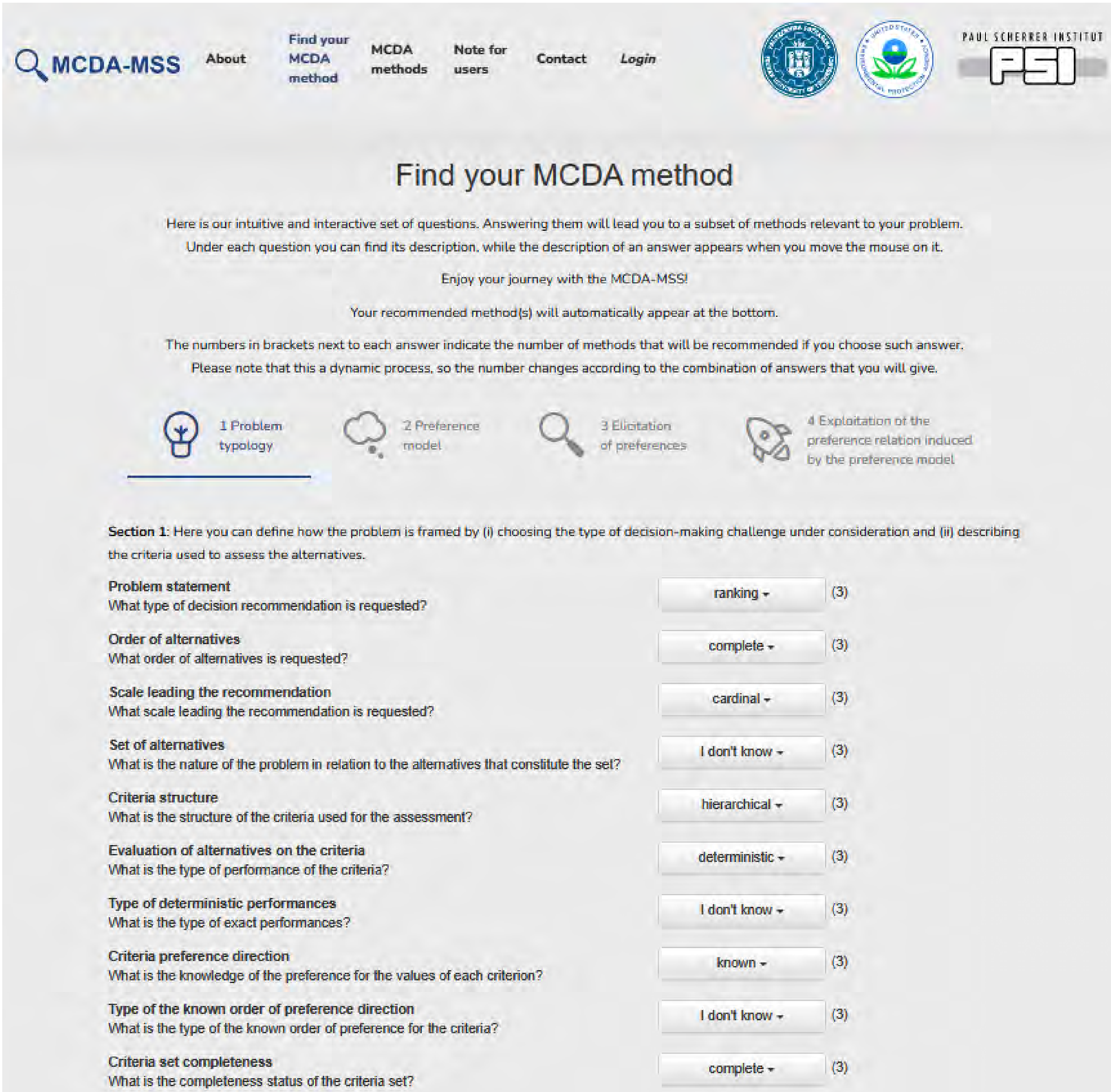
Appendix A. Input Values for Method Evaluation



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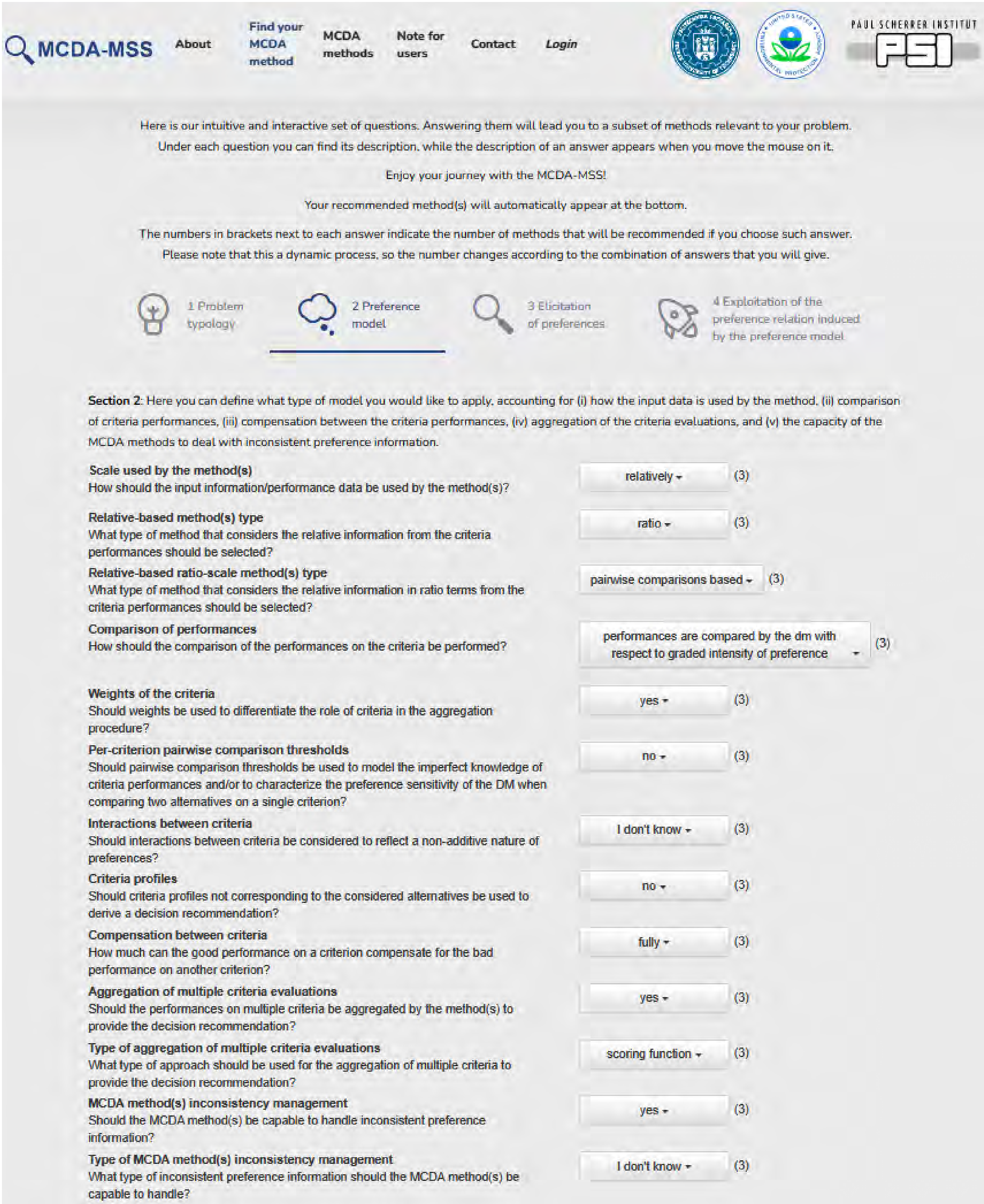
1 Problem typology | 2 Preference model | 3 Elicitation of preferences | 4 Exploitation of the preference relation induced by the preference model

Section 1: Here you can define how the problem is framed by (i) choosing the type of decision-making challenge under consideration and (ii) describing the criteria used to assess the alternatives.

Problem statement What type of decision recommendation is requested?	ranking	(3)
Order of alternatives What order of alternatives is requested?	complete	(3)
Scale leading the recommendation What scale leading the recommendation is requested?	cardinal	(3)
Set of alternatives What is the nature of the problem in relation to the alternatives that constitute the set?	I don't know	(3)
Criteria structure What is the structure of the criteria used for the assessment?	hierarchical	(3)
Evaluation of alternatives on the criteria What is the type of performance of the criteria?	deterministic	(3)
Type of deterministic performances What is the type of exact performances?	I don't know	(3)
Criteria preference direction What is the knowledge of the preference for the values of each criterion?	known	(3)
Type of the known order of preference direction What is the type of the known order of preference for the criteria?	I don't know	(3)
Criteria set completeness What is the completeness status of the criteria set?	complete	(3)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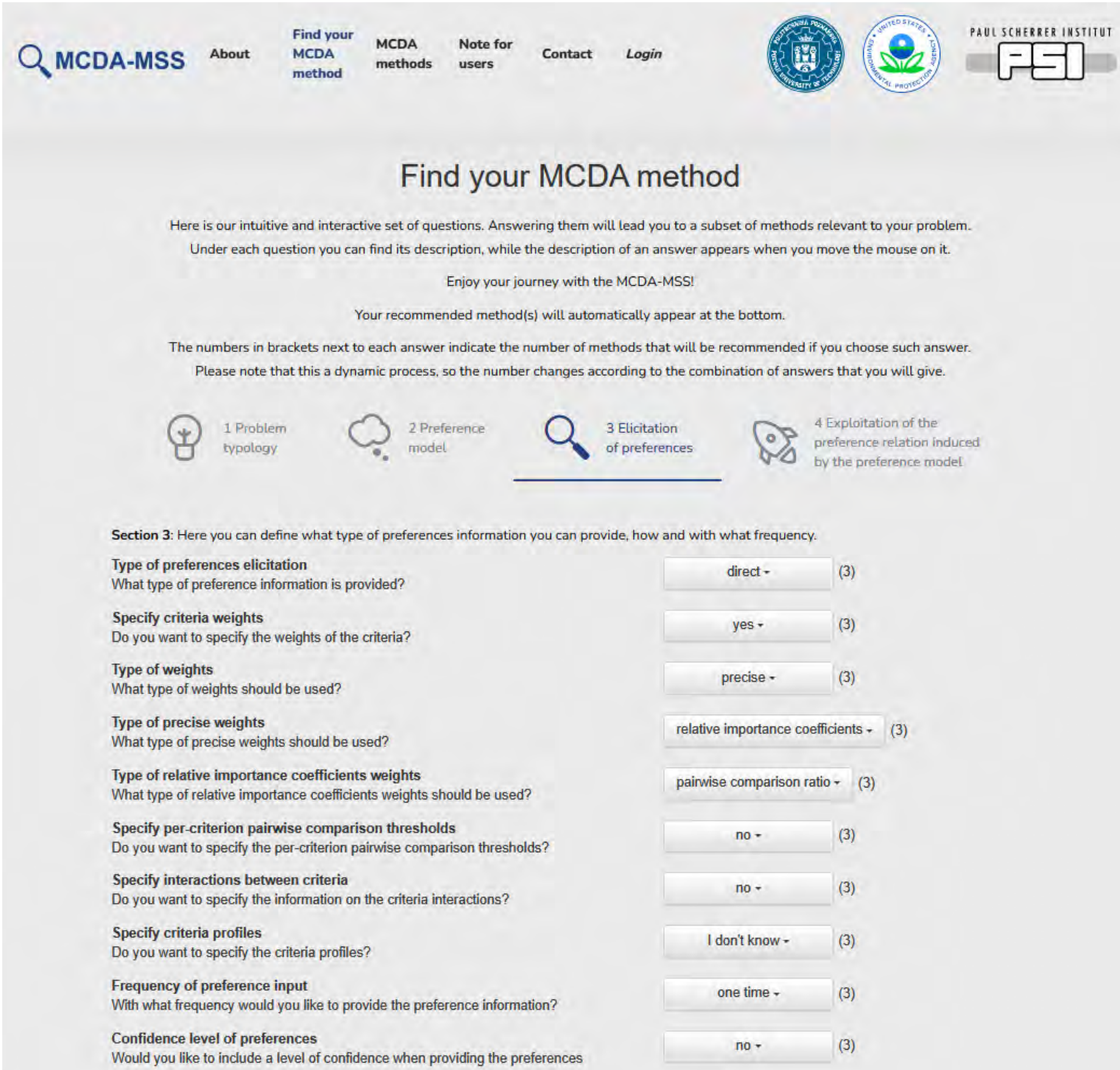
Please note that this a dynamic process, so the number changes according to the combination of answers that you will give.
1 Problem typology
2 Preference model
3 Elicitation of preferences
4 Exploitation of the preference relation induced by the preference model
Section 2: Here you can define what type of model you would like to apply, accounting for (i) how the input data is used by the method, (ii) comparison of criteria performances, (iii) compensation between the criteria performances, (iv) aggregation of the criteria evaluations, and (v) the capacity of the MCDA methods to deal with inconsistent preference information.
Scale used by the method(s)
How should the input information/performance data be used by the method(s)?
relatively (3)
Relative-based method(s) type
What type of method that considers the relative information from the criteria performances should be selected?
ratio (3)
Relative-based ratio-scale method(s) type
What type of method that considers the relative information in ratio terms from the criteria performances should be selected?
pairwise comparisons based (3)
Comparison of performances
How should the comparison of the performances on the criteria be performed?
performances are compared by the dm with respect to graded intensity of preference (3)
Weights of the criteria
Should weights be used to differentiate the role of criteria in the aggregation procedure?
yes (3)
Per-criterion pairwise comparison thresholds
Should pairwise comparison thresholds be used to model the imperfect knowledge of criteria performances and/or to characterize the preference sensitivity of the DM when comparing two alternatives on a single criterion?
no (3)
Interactions between criteria
Should interactions between criteria be considered to reflect a non-additive nature of preferences?
I don't know (3)
Criteria profiles
Should criteria profiles not corresponding to the considered alternatives be used to derive a decision recommendation?
no (3)
Compensation between criteria
How much can the good performance on a criterion compensate for the bad performance on another criterion?
fully (3)
Aggregation of multiple criteria evaluations
Should the performances on multiple criteria be aggregated by the method(s) to provide the decision recommendation?
yes (3)
Type of aggregation of multiple criteria evaluations
What type of approach should be used for the aggregation of multiple criteria to provide the decision recommendation?
scoring function (3)
MCDA method(s) inconsistency management
Should the MCDA method(s) be capable to handle inconsistent preference information?
yes (3)
Type of MCDA method(s) inconsistency management
What type of inconsistent preference information should the MCDA method(s) be capable to handle?
I don't know (3)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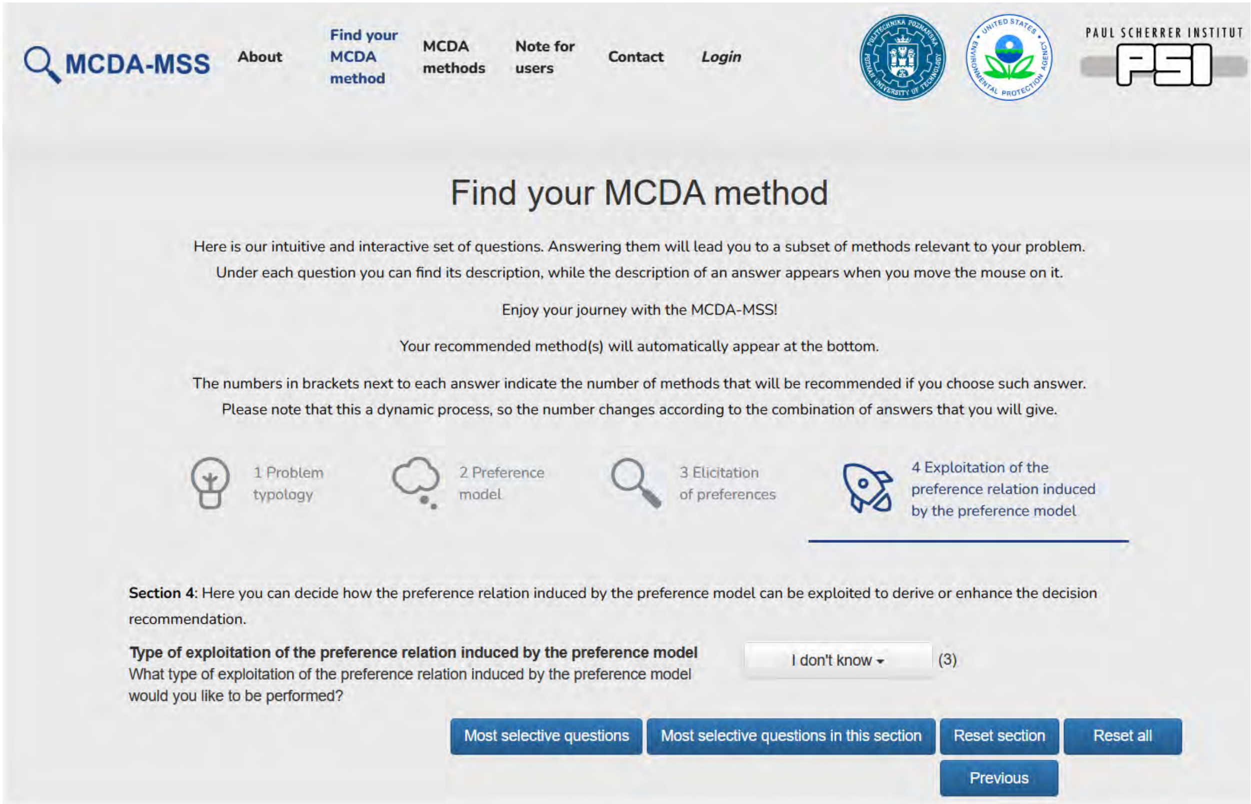
Your recommended method(s) will automatically appear at the bottom.
The numbers in brackets next to each answer indicate the number of methods that will be recommended if you choose such answer.
Please note that this a dynamic process, so the number changes according to the combination of answers that you will give.
1 Problem typology
2 Preference model
3 Elicitation of preferences
4 Exploitation of the preference relation induced by the preference model
Section 3: Here you can define what type of preferences information you can provide, how and with what frequency.
Type of preferences elicitation
What type of preference information is provided?
direct (3)
Specify criteria weights
Do you want to specify the weights of the criteria?
yes (3)
Type of weights
What type of weights should be used?
precise (3)
Type of precise weights
What type of precise weights should be used?
relative importance coefficients (3)
Type of relative importance coefficients weights
What type of relative importance coefficients weights should be used?
pairwise comparison ratio (3)
Specify per-criterion pairwise comparison thresholds
Do you want to specify the per-criterion pairwise comparison thresholds?
no (3)
Specify interactions between criteria
Do you want to specify the information on the criteria interactions?
no (3)
Specify criteria profiles
Do you want to specify the criteria profiles?
I don't know (3)
Frequency of preference input
With what frequency would you like to provide the preference information?
one time (3)
Confidence level of preferences
Would you like to include a level of confidence when providing the preferences
no (3)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Please note that this a dynamic process, so the number changes according to the combination of answers that you will give.
1 Problem typology
2 Preference model
3 Elicitation of preferences
4 Exploitation of the preference relation induced by the preference model
Section 4: Here you can decide how the preference relation induced by the preference model can be exploited to derive or enhance the decision recommendation.
Type of exploitation of the preference relation induced by the preference model
What type of exploitation of the preference relation induced by the preference model would you like to be performed?
I don't know
(3)
Most selective questions
Most selective questions in this section
Reset section
Reset all
Previous

Appendix B. Deriving Weights for SAFR-B

One of the key aspects of the scoring technique is to grade different aspects with regards to their respective importance in order to derive a higher-level aspect. In SAFR-B, the attributes are individually weighted in relation to each strategy, each strategy is then weighted in relation to the objectives. Finally, the objectives are weighted in relation to the top policy indicating the building's general performance on fire safety and environmental sustainability.

In the following tables, the results from the AHP process are presented. The tables contain the average values based on the experts' evaluations. As an example, each expert compares each attribute in relation to all other attributes for a single strategy. This results in a vector containing the importance values for the attributes in relation to the selected strategy. The work is then repeated with the attribute comparison, but for the next strategy, resulting in a new vector. The values in each vector are derived according to the calculation technique presented in section 3.5. As a result, we get a matrix with importance values for attributes in relation to strategies. The work is then repeated for the next level evaluation, i.e., from strategies to objectives.

As this work is done independently by the experts, each expert has his/her own matrix, which is a result from the pairwise comparison. To derive a single matrix including all experts' evaluations, the mean value was derived for the elements in the experts' matrices.

In total there are three matrices containing the mean values resulting from the work performed by the seven experts, cf. Figure 16. These matrices are presented below.

Attr-Strat	Manage energy usage	Manage embodied carbon	Manage site specifications	Manage hazard exposure	Prevent fire ignition	Manage fire	Manage exposed
1. Building structure	0,061	0,358	0,081	0,090	0,050	0,059	0,056
2. Internal material and design	0,067	0,182	0,045	0,119	0,250	0,164	0,110
3. Building envelope	0,254	0,210	0,055	0,094	0,124	0,169	0,056
4. Building services	0,210	0,078	0,051	0,088	0,124	0,085	0,119
5. Alternative energy system	0,258	0,055	0,050	0,049	0,231	0,039	0,022
6. Site properties	0,034	0,041	0,362	0,194	0,033	0,034	0,023
7. Fire extinguishing	0,020	0,032	0,129	0,094	0,031	0,373	0,134
8. Building management	0,080	0,029	0,148	0,096	0,136	0,044	0,088
9. Means for egress	0,015	0,016	0,078	0,176	0,022	0,032	0,392
TOTAL	1,000	1,000	1,000	1,000	1,000	1,000	1,000

Fig. B1. Collective results of importance evaluations between attributes and strategies.

Strat-Obj	Environmentally sustainable construction	Fire resilient construction
1. Manage energy use	0,321	0,078
2. Manage embodied carbon	0,199	0,060
3. Manage site specification	0,086	0,053
4. Manage hazard exposure	0,115	0,071
5. Prevent fire ignition	0,116	0,205
6. Manage fire	0,104	0,247
7. Manage exposed	0,060	0,287
Total	1,000	1,000

Fig. B2. Collective results of importance evaluations between strategies and objectives.

Obj-Pol	SAFR
1. Environmentally sustainable cons	0,320
2. Fire resilient construction	0,680

Fig. B3. Collective results of importance evaluations between objectives and policy for SAFR-B.

Having these matrices, the importance measures for attributes to objectives and attributes to policy can be calculated according to the principle in Figure 16. The results after this are presented in figure B4.

Attribute-SAFR			
	1. Environmentally sustainable construction	2. Fire resilient construction	SAFR
1. Building structure	0,123	0,078	0,092
2. Internal material and design	0,128	0,150	0,143
3. Building envelope	0,174	0,125	0,141
4. Building services	0,128	0,111	0,116
5. Alternative energy system	0,136	0,093	0,107
6. Site properties	0,081	0,060	0,066
7. Fire extinguishing	0,085	0,154	0,132
8. Building management	0,081	0,087	0,085
9. Means for egress	0,064	0,144	0,118
Totalt	1,000	1,000	1,000

Fig. B4. Collective results of importance evaluations for attributes to objectives and for attributes to policy for SAFR-B.

Using the grading for each attribute together with the weight value for the corresponding attributes in the figure above will result in indices indicating the building's performance with respect to environmental sustainability, fire resilience, or the joint sustainability and fire resilience performance. The difference depends on which of the columns is selected in the figure. Each index value is calculated using the generic equation below. A higher value is better.

$$Performance\ index = \sum_{i=1}^{9} grade_i \cdot weight_i$$

Appendix C. Grading Scheme for the Attributes

It should be mentioned that the grading and weights for grading different survey items are based on a subjective assessment and need to be refined in the future. Some of the survey items also contain conflicting aspects which have not been fully considered. Using a grading tool will never capture all relevant aspects or relations, because the purpose is to present a general assessment of sustainability and fire resilience, and it can never replace a more detailed design procedure. The intention with the description is to illustrate the principle behind the technique, and many issues remain to be solved and verified.

C.1. Building structure

C.1.1. Description

The attribute “Building structure” refers to features that are related to the building´s structural members. These include both interior and exterior load-bearing walls, e.g., walls separating apartments are described as being part of the building structure. The attribute considers material used, building height, and construction strategy. The latter is important as it is an indicator of the presence of cavities in the structure. Cavities in the structure can impact the likelihood of the fire spreading throughout the building. The use of fire barriers within such cavities can impact the overall fire safety of the building. The attribute has four survey items:

- Material
- Building height
- Construction methods
- Fire protection level

C.1.2. Survey Items

Each survey item is rated based on its “fire safety grade” and “sustainability grade”:

Fire safety grade	F
Sustainability grade	S

All grades are integers between 1-10.

Material (M)

- The survey item “Material” refers to the material used for the building structure.
- If circular materials are used, add 2 to $\mathbf{S_M}$.

Material	$\mathbf{F_M}$	$\mathbf{S_M}$
Concrete	10	3
Light weight concrete	9	5
Light timber	8	7
Mass timber	9	8
Light weight steel	7	5
Structural steel	8	4
Brick	9	4

Building Height (BH)

The survey item “Building height” refers to the number of stories the building has. This will affect the quantity of materials required for the structure, corresponding to a decrease “sustainability grade” as the number of floors increases. Note that the fire risk is assumed to increase with building height which means that the fire safety grade decreased with increasing height.

Building height	$\mathbf{F_{BH}}$	$\mathbf{S_{BH}}$
4 - 6 floors	10	10
7 - 8 floors	5	5
$\leq$ 9 floors	2	2

Justification:

Choice of material will contribute differently to fire resilience and sustainability. Typically, wooden based material is beneficial for the sustainability properties of the building but poorer for fire resilience and vice versa. A low building is good for both aspects as easier to access the building and less material use. Use of circular material is considered separately.

Construction Methods (C)

The survey item “Construction methods” refers to the method as such (primarily for the sustainability grade), but also to cavities in the structure, i.e., the open and usually narrow spaces within the building´s structure which is a result of the construction method. The method used to construct the building can result in unwanted cavities inside the building that may contribute to air movement and fire spread. Controlling the cavities and using appropriate barriers can impact the building fire safety and sustainability integrity (acoustic, thermal, etc.). The sustainability grading refers partly to where the building is constructed, on site or prefabricated. It is assumed prefabricated can be performed more efficiently considering material and energy use.

The aspect “Construction method” refers to method used for the building structure.

Construction method	F_{C1}	S_C
The construction is designed to prevent cavities in separating structures. Examples of this type include cast-in-place concrete and massive planar elements made of wood or concrete.	10	6
The construction is built on-site, and cavities may be present that can allow fire to spread. To prevent this, specially designed connections called fire stops are used to limit the spread of fire within the construction.	8	7
The construction is built with prefabricated planar elements and cavities may be present that can allow fire to spread. To prevent this, specially designed connections called fire stops are used to limit the spread of fire within the construction.	6	7
The construction is built with prefabricated volumetric elements and cavities may be present that can allow fire to spread. To prevent this, specially designed connections called fire stops are used to limit the spread of fire within the construction.	4	10
Unknown or no prevention of fire to spread in cavities.	1	1

The aspect "control of cavities" refers to the process of controlling cavities and verifying the effectiveness of potential barriers within them.

Control of cavities in the structure	F_{C2}
The construction has no need for fire stops.	10
Fire stops will be constructed using non-combustible materials and will be subject to external control. Documentation will be provided to verify proper execution.	9
Fire stops will be constructed using non-combustible materials and will be subject to self-control. Documentation will be provided to verify proper execution.	7
Fire stops will be constructed using combustible materials and will be subject to self-control. No documentation will be provided.	4
Unknown	1

$$F_C = 0.5F_{C1} + 0.5F_{C2}$$

Fire Protection Level (FPL)

This survey item refers to the fire protection level the building is designed for. The time (in minutes) refers to the time the structure is designed to withstand fire before structural integrity is compromised. The FPL will also influence the amount of materials used in the building for protecting the structure, e.g., gypsum board.

Fire protection level	F_{FPL}	S_{FPL}
No protection level	1	10
<30 min	5	8
<60 min	7	5
<90 min	9	4
>90 min	10	1

Justification:

The difference between having no protection level at all or having some level of protection is deemed more critical for the fire safety than having slightly better protection level.

C.1.3. Attribute grade

Fire safety grading

The fire protection level is determined to be most important for fire safety in the building.

$w_M = 0{,}3$

$w_{BH} = 0{,}15$

$w_C = 0{,}15$

$w_{FPL} = 0{,}4$

$$F_1 = (F_M * 0.3) + (F_{BH} * 0.15) + (F_C * 0.15) + (F_{FPL} * 0.4)$$

Justification:
In terms of fire safety, the construction method features are deemed slightly more critical than the material used, while the building height is considered the least important factor.

Sustainability grading

The material is determined to be most important for the sustainability of the building. The construction method is considered least important.

w_M=0.35

$w_{BH} = 0.3$

$w_C = 0.15$

$w_{FPL} = 0.2$

$$S_1 = (S_M * 0.35) + (S_{BH} * 0.3) + (S_C * 0.15) + (S_{FPL} * 0.2)$$

Justification:
In terms of sustainability, the choice of building material and building height are considered more crucial than the fire protection level and cavity characteristics. This is because the building material is used extensively throughout the entire structure, and the building height will have a significant impact on the amount of material required.

C.2. Internal Material and Design

C.2.1. Description

The “Internal material and design” attribute refers to the overall interior design of the building. This includes not only the material used as surface layer within the apartments but also the material and design features for the fire compartmentation of the building. The attribute has four survey items:

- Surface material
- Interior design
- Attic
- Stairwell

C.2.2. Survey Items

Each survey item is rated based on its “fire safety grade” and “sustainability grade”:

Fire safety grade	**F**
Sustainability grade	**S**

All grades are integers between 1-10.

Surface Material (SM)

The survey item “Surface material” refers to the material used on the inside surface of apartments. However, since the wall and ceiling materials are more significant for fire safety, the grading for “Surface material” is determined by using the following equation. The example 'wood' in the tables below assumed untreated wood.

$$\mathbf{F_{SM} = 0{,}6F_{Ce} + 0{,}3F_{Wall} + 0{,}1F_{Fl}}$$
$$\mathbf{S_{SM} = 0{,}33S_{Ce} + 0{,}33S_{Wall} + 0{,}33S_{Fl}}$$

The aspect “ceiling surface layer (Ce)” refers to the material used on the ceilings of apartments. If circular materials are used, add 2 to S_{Ce}.

Ceiling surface material	**F_{Ce}**	**S_{Ce}**
Concrete	10	2
Wood	3	8
Painted gypsum	8	5
Plastic board	1	1

The aspect “Wall surface layer (Wall)” refers to the material used on the walls of apartments. If circular materials are used, add 2 to S_{Wall}.

Wall surface material	**F_{Wall}**	**S_{Wall}**
Concrete	10	2
Wood	3	8
Painted gypsum	8	5
Brick	10	3
Plastic board	1	1

The aspect “Floor surface layer (Fl)” refers to the material used on the floor of apartments. If circular materials are used, add 2 to S_{Fl}.

Floor surface material	**F_{Fl}**	**S_{Fl}**
Concrete	10	2
Wood	3	8
Ceramic tiles	8	2
Carpet	1	4
Plastic material	1	1

Justification:

Fire is known to spread more rapidly on the surface of walls and ceilings than on floors.

Concrete is known to emit large amount of CO_2 in production, while building with wood generally has a lower carbon-footprint. Therefore, concrete has a higher fire safety, but lower sustainability grade than wood.

Interior Design (ID)

The survey item "Interior design" refers to features related to the fire compartmentation of apartments as well as the layout of these areas.

Apartment separation	F_{ID1}	S_{ID1}
Apartments are separated with fire rated walls.	10	1
Apartments are not separated with fire rated walls.	1	10

Apartment layout	F_{ID2}	S_{ID2}
Apartments have an open floor plan with little partitioning walls and few rooms.	1	10
Apartments have a more closed floor plan with multiple partitioning walls.	10	1

$$F_{ID} = 0.8*F_{ID1} + 0.2*F_{ID2}$$

$$S_{ID} = 0.5*S_{ID} + 0.5*S_{ID}$$

Justification:

Apartments with an open floor plan are believed to experience faster flame spread within the compartment when compared to a more partitioned apartment with multiple rooms. Though it is not considered as critical as separating adjacent apartments with fire rated walls.

Attic (Attic)

The survey item "Attic" refers to features related to the building attic. It reflects how the attic is constructed, ventilated, and divided into compartments.

Attic	F_{Attic}	S_{Attic}
The building has no attic.	10	10
The building attic is divided into multiple compartments with the eaves of the roof closed.	7	6
The building attic is divided into multiple compartments with eaves of the roof open.	5	8
The building attic is one single compartment with the eaves of the roof closed.	5	8
The building attic is one single compartment with the eaves of the roof open.	3	10

Justification:

Attics with open eaves are at a higher risk of façade fires spreading to the attic. When there is only one compartment in the attic, fires can spread faster within the space. Open eaves directly above a window no closer than X meters can be graded as closed eaves. Open eaves equipped with fire stoppers activated by the fire can be graded as closed eaves.

On the other hand, open eaves can be incorporated into the building design to avoid moisture damage. Additionally, having fewer compartments in the attic means that fewer materials are required for construction.

It is assumed that the attic has heat insulation either on the attic floor or attached inside to the slope roof. Amount of insulation is not covered by the gradings.

Stairwell (Stair)

The survey item “Stairwell” refers to systems to manage fire spread to the stairwell.

The aspect “Smoke ventilation” refers to the ability to remove smoke from the stairwell in the case of a fire. This can be achieved either naturally through an opening such as a window or a hatch in the top of the stairwell, or through mechanical means. Smoke ventilation is not assumed to contribute to apartment heat ventilation, because it is supposed to operate only if there is a fire in the building. However, it may be used to release heat from the stairwell during the hot season.

The “Door closing system” aspect refers to whether there are mechanisms in place to automatically close the doors in the stairwells.

	Alternatives					
Smoke ventilation	Mechanical ventilation		Natural ventilation		None	
Door closing system	Yes	No	Yes	No	Yes	No
F_{Stair}	10	7	8	5	3	1
S_{Stair}	8	10	3	8	1	1

Justification:

The implementation of door closing systems reduces the probability of smoke filling the stairwell. Alternatively, a smoke ventilation system can extract smoke from the stairwell. The smoke ventilation system is considered more dependable due to factors such as the possibility of residents altering the function of the door closing system for their convenience, which may compromise its effectiveness.

C.3.1. Attribute Grade

Fire Safety Grading

The interior design of the apartment is determined to be most important for the fire safety of the building, followed by systems to manage smoke in the stairwell.

$w_{SM} = 0{,}2$

$w_{ID} = 0{,}35$

$w_{Attic} = 0{,}15$

$w_{Stair} = 0{,}3$

$$F_2 = (F_{SM} * 0.2) + (F_{ID} * 0.35) + (F_{Attic} * 0.15) + (F_{Stair} * 0.3)$$

Justification:

When it comes to fire safety, the most critical aspect is the compartmentation of apartments. This is because compartmentation greatly affects the risk of fire spreading throughout the building. The compartmentation of stairwells is also important but it is considered slightly less critical in comparison.

Sustainability Grading

The surface material is determined to be most important for the sustainability in the building, followed by floorplan of the apartment.

$w_{SM} = 0{,}4$

$w_{ID} = 0{,}3$

$w_{Attic} = 0{,}15$

$w_{Stair} = 0{,}15$

$$S_2 = (S_{SM} * 0.4) + (S_{ID} * 0.3) + (S_{Attic} * 0.15) + (S_{Stair} * 0.15)$$

Justification:

The choice of surface materials is considered crucial for sustainability because it will be used extensively throughout the building.

C.4. Building Envelope

C.4.1. Description

The “Building envelope” refers to the description of the outer covering of the building, which includes its façade and roof outside features. The use of combustible materials in combination with having cavities in the façade system can increase the risk of fire spreading. The materials and insulation used in the building´s envelope can impact its energy efficiency and the amount of carbon dioxide during production and other harmful substances it releases during its lifetime. The attribute has six survey items:

- Façade
- Cavities in façade
- Insulation material
- Windows
- Roof covering
- Roof insulation

C.4.2. Survey Items

Each survey item is rated based on its “fire safety grade” and “sustainability grade”:

Fire safety grade	**F**
Sustainability grade	**S**

All grades are integers between 1-10.

Façade (FM)

The survey item “Façade” refers to the characteristics of the building component (wall) separating the building from the outside. It focuses on what material it uses, whether there are cavities, and what type of heat insulation material is used. This excludes the interior wall outer cladding of the exterior wall, i.e., not the exterior wall itself. The survey item grades different aspects for fire resilience and sustainability to focus on important aspects.

The fraction combustibles on the façade are important for fire resilience and used to specify likelihood of fire spreading on the outside of the building.

Fraction combustibles	$\mathbf{F_{FM}}$
0%	10
< 20%*	6
20 – 40%*	4
> 40 %*	2

*If combustibles directly over window, subtract 2 for $\mathbf{F_{FM}}$

Justification:

The quantity of combustible materials on the building’s façade affects the likelihood of flame spread, particularly if combustibles are situated between windows.

The façade material is important for building sustainability and refers to the material used in the cladding of the exterior of the building.

If circular materials are used, add 2 to $\mathbf{S_{FM}}$.

Calculate mean value of $\mathbf{S_{FM}}$ from the fraction of materials of the facade.

Façade Material	**S_{FM}**
Concrete	3
Wood	8
Brick	5
Plaster	4
Metal composite	5

Justification:

The environmental impact from producing wood material is substantially less than other materials. Concrete is the alternative with the largest carbon footprint in production.

Cavities in Façade (C)

The survey item “Cavities in façade” refers to cavities usually constructed in the façade to facilitate ventilation of moist air in the façade. In most cases the cavity is narrow.

Cavities in façade	F_C	S_C
There are no cavities inside the exterior wall system.	10	1
Both sides of the cavities are constructed with non-combustible materials.*	8	10
Cavities have at least one combustible surface, but measures have been taken to prevent fire spread with horizontal and vertical separation in place (fire stops).*	6	10
Cavities has at least one combustible surface, but measures have been taken to prevent fire spread with horizontal separation in place (fire stops).*	4	10
Continuous cavities without separation where at least one surface is combustible.*	1	10

*If cavities are sealed with fire stops in connection to window frames, add 2 to $\mathbf{F_C}$

Justification:

The presence of combustibles within cavities increases the risk of flame spread. However, if there are separating fire stops in place, this risk can be reduced.

Insulation Material (Ins)

The survey item "Insulation material" refers to the material that is used to insulate the façade of the building and its thickness.

-	F_{Ins}	S_{Ins}*
Stone wool	10	8
Glass wool	8	8
PIR (fire rated)	8	3
PIR (non-fire rated)	6	5
PUR (Fire rated)	7	4
PUR (non-fire rated)	3	6
Other (fire rated)	7	1
Other (non-fire rated)	1	1

If insulation is > 30 cm, add additional 2 to $\mathbf{S_{Ins}}$

Justification:

The material and the thickness of the insulation will impact the buildings heat efficiency, and the amount of flammable materials within the building. Although PUR and PIR are typically combustible materials, they may or may not have some level of fire rating. When exposed to fire, PUR will liquify and burn as a pool fire, whereas PIR will form char, which makes it less likely to cause a risk for fire to spread.

Windows (W)

The survey item “Windows” refers to choices regarding windows on the building exterior.

The aspect “Fraction of façade” refers to the fraction of the façade which is made up of windows.

The aspect “Placement” refers to the vertical distance between windows on different floors of the building, specifically whether the distance is more or less than 1.5 meters apart.

The aspect “Operability” refers to whether windows in the building can be opened or not. This factor can have an impact on the potential behavior of fire in the building.

If windows are using circular material, add 2 to $\mathbf{S_W}$.

	Alternatives											
Fraction of facade	<15%				<30%				>30 %			
Spacing	<1.5 m*		>1.5 m		<1.5 m*		>1.5 m		<1.5 m*		>1.5 m	
Operability	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N
$\mathbf{F_W}$	8	7	10	9	5	4	7	6	2	1	4	3
$\mathbf{S_W}$	8	5	8	5	8	4	8	3	6	2	6	1

*If glass is fire rated, grade as <15% and >1.5 m

Justification:

The fraction of window area is considered the most important for both the risk of fire to spread and the amount of material used. Although the possibility to open the windows can impact the fire dynamics and make it easier for firefighters to rescue people using ladders, it is not as critical as the spacing between windows on different floors. It is further assumed it is sustainable not to have too much windows for cooling/heating even if large areas result in much daylight. Non-operational windows cannot be used for controlling indoor climate.

Roof Covering (Cov)

The survey item "Roof covering" refers to the building features for the outer protection shield (roof material).

The aspect "Covering" refers to the material used as covering of the roof.

If covering uses circular material, add 2 to $\mathbf{S_{Cov}}$.

Material	$\mathbf{F_{Cov}}$	$\mathbf{S_{Cov}}$
Ceramic	10	2
Steel	10	2
Asphalt roofing felt	6	5
Green roof	6	8

Roof Insulation (RoofIns)

The survey item "Roof insulation" refers to two things: (1) the type of material used to insulate the roof of the building, and (2) the thickness of the insulation material.

If roof insulation is using circular material, add 2 to $\mathbf{S_{RoofIns}}$, but not if Type is "Other."

Type	$\mathbf{F_{RoofIns}}$	$\mathbf{S_{RoofIns}}$*
Mineral wool	10	4
PIR (fire rated)	8	5
PIR (non-fire rated)	6	6
PUR (Fire rated)	7	5
PUR (non-fire rated)	3	6
Other (fire rated)	7	1
Other (non-fire rated)	3	1

*If insulation is > 30 cm, add additional 2 to $\mathbf{S_{RoofIns}}$

Justification:

The material and the thickness of the insulation will impact the buildings heat efficiency, and the amount of flammable materials within the building. Although PUR and PIR are typically combustible materials, they may or may not have some level of fire rating. When exposed to fire, PUR will liquify and burn as a pool fire, whereas PIR will form char, which makes it less likely to cause a risk for fire to spread.

C.4.3. Attribute Grade

Fire Safety Grading

The cavity characteristics are determined to be most important for the fire safety of the building, followed by façade material.

$w_{FM} = 0.3$

$w_{C} = 0.3$

$w_{Ins} = 0,2$

$w_{W} = 0,05$

$w_{Cov} = 0,1$

$w_{RoofIns} = 0,05$

$$F_5 = (F_{FM} * 0.3) + (F_{FC} * 0.3) + (F_{Ins} * 0.2) + (F_W * 0.05) + (F_{Cov} * 0.1) + \left(F_{RoofIns} * 0.05\right)$$

Justification:

The fraction of combustibles on the façade and the characteristics of cavities are considered the most crucial factors for fire safety. This is because the choices made regarding these factors can greatly impact the risk for fire spreading throughout the building. In contrast, the importance of windows and roof insulation for fire safety is much lower.

Sustainability Grading

The facade material is determined to be most important for the sustainability in the building, followed by façade insulation material.

$w_{FM} = 0.25$

$w_C = 0{,}1$

$w_{Ins} = 0{,}25$

$w_W = 0{,}05$

$w_{Cov} = 0{,}2$

$w_{RoofIns} = 0{,}15$

$$S_5 = S_{FM} * 0.25 + S_{FC} * 0.1 + S_{Ins} * 0.25 + S_W * 0.05 + S_{Cov} * 0.2 + S_{RoofIns} * 0.15$$

Justification:

The materials used for the façade and the type and amount of façade insulation are considered the most vital factors for sustainability. This is because of the large extent to which they are used throughout the building.

C.5. Building Services

C.5.1. Description

The attribute “Building services” refers to the technical systems installed in the building that provide services like heating and ventilation. The design choices made for these systems can impact both the risk of a fire starting and the energy efficiency of the building. The attribute has six survey items:

- Ventilation system
- Heating system
- Cooling system
- Energy recovery
- Stoves
- Fireplace

C.5.2. Survey Items

Each survey item is rated based on its "fire safety grade" and "sustainability grade":

Fire safety grade	**F**
Sustainability grade	**S**

All grades are integers between 1-10.

Ventilation System (Vent)

The survey item "Ventilation system" refers to the continuously operating system in the building aimed at controlling the indoor climate in the apartments and other common areas.

The aspect "Type of ventilation" refers to whether the building has natural or mechanical ventilation installed in the building.

The aspect "Fire dampers" refers to whether ventilation ducts have fire dampers installed. Fire dampers are used to close the ducts in case of a fire. Note that mechanical ventilation designed as part of the smoke spread protection is not considered.

	Alternatives		
Type of ventilation	Natural	Mechanical	
Fire dampers	-	Yes	No
F_{Vent}	5	10	1
S_{Vent}	10	1	5

Justification:

Not having fire dampers with mechanical ventilation is deemed the least safe for fire safety because smoke can spread quickly through the supply vent. However, if fire dampers are installed in the mechanical ventilation system it can be regarded as safer against fire than natural ventilation.

Heating System (Heat)

The survey item "Heating system" refers to what type of system is used to heat the building. If flammable heating elements are used, there is a risk of fire.

Heating syste	**F_{Heat}**	**S_{Heat}**
Geothermal	8	9
Oil	4	1
LNG	4	1
Bio-gas	4	4
Electric resistance heating	2	2
Wood pellets	3	8
District heating	10	10
Heat pump	9	9

Cooling System (Cool)

The survey item "Cooling system" refers to whether the building has a system in place for cooling and, if so, whether it is a standalone system or integrated with the heating system. The cooling system per se can be local or part of a district cooling system; no difference is made between them.

Cooling system	**F_{Cool}**	**S_{Cool}**
Integrated	10	7
Standalone	10	4
None	1	10

Energy Recovery (Recov)

The survey item "Heat-/cooling recovery" refers to whether the building has a heat recovery system (HRV) installed or not. A HRV system transfers heat from the outgoing extracted air to the incoming supply air, which can affect the amount of energy required to heat the building.

Heat-/cooling recovery	**F_{Recov}**	**S_{Recov}**
Yes	10	10
No	1	1

Justification:

Heating systems that utilize combustible materials like gas or oil, or generate heat of sufficient to ignite materials in contact with the heating source, are considered the worst for fire safety.

Heating systems that consume high levels of energy are considered the least sustainable. Furthermore, cooling systems that are integrated into the heating system are deemed more sustainable than using two separate systems because they require less material usage.

Stoves (Stove)

The survey item "Stoves" refers to the type of stoves that are commonly installed in the kitchens of apartments.

Type	F_{Stove}	S_{Stove}
Induction	10	10
Gas	1	1
Electrical heating	5	5

Justification:

Gas stoves pose a greater fire risk compared to induction stoves because they cook food over an open flame. In addition, gas stoves are considered less environmentally friendly compared to induction or electrical heating stoves, which use electricity. Because electric heating stoves generate a lot of heat they are considered to have a higher risk of igniting materials in contact with the stove compared to induction stoves.

Fireplace (FP)

The survey item "Fireplace" refers to whether apartments have fireplaces installed and, if they do, what kind of fuel they use.

Fuel	F_{FP}	S_{FP}
None	10	10
Liquid	5	2
Wood	1	6
Coal	3	1
Gas	7	3
Electrical	9	7

Justification:

In terms of preventing fire, wood is regarded as the worst fuel because of the risk for spot fires. Gas on the other hand is the most easily controllable fuel and is therefore considered the best option.

In terms of sustainability, the production of firewood is known to emit less energy compared to the production and transportation of gas.

C.5.3. Attribute Grade

Fire Safety Grading

The choice of stove is determined to be most important for the fire safety of the building, followed by fireplace.

$w_{Vent} = 0{,}05$

$w_{Heat} = 0{,}05$

$w_{Cool} = 0{,}05$

$w_{Recov} = 0{,}05$

$w_{Stove} = 0{,}6$

$w_{FP} = 0{,}2$

$$F_5 = (F_{Vent} * 0{,}05) + (F_{Heat} * 0{,}05) + (F_{Cool} * 0{,}05) + (F_{Recov} * 0{,}05) + (F_{Stove} * 0{,}6) + (F_{FP} * 0{,}2)$$

Justification:

Many fires are in the kitchen, and only a few are related to the heating/cooling installation. Having a fireplace is also considered of importance for fire safety due to risk for fire ignition.

Sustainability Grading

The heating system is determined to be most important for the sustainability in the building, closely followed by cooling system and recovery of energy.

$w_{Vent} = 0{,}2$

$w_{Heat} = 0{,}3$

$w_{Cool} = 0{,}2$

$w_{Recov} = 0{,}2$

$w_{Stove} = 0{,}05$

$w_{FP} = 0{,}05$

$$S_5 = (S_{Vent} * 0{,}2) + (S_{Heat} * 0{,}3) + (S_{Cool} * 0{,}2) + (S_{Recov} * 0{,}2) + (S_{Stove} * 0{,}05) + (S_{FP} * 0{,}05)$$

Justification:

In terms of sustainability, the type of heating and cooling systems used in the building is crucial because they are among the most energy-intensive systems. Similarly, ventilation is also a significant aspect to sustainability as it can also require a lot of energy.

C.6. Alternative Energy System

C.6.1. Description

The "Alternative energy system" refers to the amount of electricity that is not externally provided to a building. This includes the installation of facilities that can produce and store electricity, as well as the installation of EV-charging stations for those occupants who choose to use electric vehicles. The attribute has three survey items:

- Electricity generation
- Energy storage
- EV-charging

C.6.2. Survey Items

Each survey item is rated based on its "fire safety grade" and "sustainability grade":

Fire safety grade	**F**
Sustainability grade	**S**

All grades are integers between 1-10.

Electricity Generation (Prod)

The survey item "Electricity generation" refers to whether there are any systems installed on the building that generate electricity.

The aspect "Type of production" refers to what type of electricity generating system is installed. The types include photovoltaic panels (solar panels) or wind turbines.

The aspect "Capacity" refers to whether the generator installed on the building can produce more or less electricity than what the building requires.

≥100%	The electricity generated is more than the building's demand, which means extensive installations that cover a large area of the building.
<100%	The electricity generated meets less than the building's demand, which means installations cover a smaller area of the building.

The aspect "placement" refers to whether the photovoltaic panels are placed on the roof, the façade, or both.

Type of Production	**Capacity**	**Placement**	**F_{Prod}**	**S_{Prod}**
Photovoltaic	≥100%	Roof	4	9
		Facade	3	9
		Both	1	9
	<100%	Roof	6	6
		Facade	5	6
		Both	1	7
Wind turbine	≥100%	-	5	10
	< 100%	-	6	8
None	-	-	10	1

Justification:
The size of the facility will be influenced by the capacity of energy produced, which in turn will affect the fire load. Additionally, where the production system is placed will impact the risk of fire spreading and the accessibility of emergency rescue services to the building´s façade. The capacity of electricity that the building can generate will determine the amount of non-sustainable energy that must be purchased to meet its energy demand. Therefore, even if the external energy comes from renewable sources, it is considered more sustainable for a building to generate its own electricity.

Energy Storage (Store)

The survey item "Energy storage" refers to whether there are installations for storing electricity inside the building.

The aspect "Type of storage" refers to the specific type of storage system that is installed in the building. Examples of storage systems include lithium-ion batteries or power-to-gas systems that store hydrogen gas (H_2) or other types of gas.

The aspect "Capacity" refers to the amount of electricity that can be stored by the installation. The capacity of storage will determine the size of the installation.

High	The amount of electricity that can be stored will meet the building's demand for <u>more</u> than 1 day.
Medium	The amount of electricity that can be stored will meet the building's demand for <u>less</u> than 1 day.
Low	The amount of electricity that can be stored will meet the building's demand for <u>less</u> than 12 hours.

Type of storage	Capacity	F_{Store}	S_{Store}
Gas*	High	1	3
	Medium	2	2
	Low	3	1
Li-ion Battery*	High	4	8
	Medium	5	7
	Low	6	6
H_2-storage*	High	0	10
	Medium	1	9
	Low	2	8
None	-	10	1

*If storage has designated protection systems for abnormal conditions (overheating, thermal runaway etc), add 2 to $\mathbf{F_{Store}}$

Justification:

The capacity of energy stored will impact the size of a facility and affect its fire load. With highly ignitable gases, such as H_2, the risk of fire is greater compared to li-ion batteries. However, installing protection systems that can prevent or control fires can significantly improve the safety of the energy storage system.

The production of li-ion batteries is regarded as more environmentally damaging than the production of H_2 systems due to environmental hazards from the mining industry.

EV-charging (EV)

The survey item “EV-charging” refers to whether there are charging stations for electrical vehicles located inside or outside of the building for electric vehicles.

EV charging present	F_{EV}	S_{EV}
Yes, inside the building	3	10
Yes, outside the building	9	10
No	10	1

C.6.3. Attribute Grade

Fire Safety Grading

The method of production of energy is determined to be most important for the fire safety of the building, followed by storage of energy.

$w_{Prod} = 0{,}45$

$w_{Store} = 0{,}35$

$w_{EV} = 0{,}2$

$$F_5 = (F_{Prod} * 0.45) + (F_{Store} * 0.35) + (F_{EV} * 0.2)$$

Justification:

Having energy production systems is considered slightly more important for fire safety than having energy storage systems, but much more important than having EV-charging stations by the building. This is due to the risk of electrical arcs forming and uncertainties about the safety of firefighters when putting out fires.

Sustainability Grading

The method of production of energy is determined to be most important for the sustainability in the building, followed by storage of energy.

$w_{Prod} = 0{,}4$

$w_{Store} = 0{,}35$

$w_{EV} = 0{,}25$

$$S_5 = (S_{Prod} * 0.4) + (S_{Store} * 0.35) + (S_{EV} * 0.25)$$

Justification:

Having energy production systems is considered more important for sustainability than having energy storage systems, but much more important than having EV-charging stations by the building. This is because production systems generate additional renewable energy, as opposed to just storing or transferring possibly non-sustainable energy.

C.7. Site Properties

C.7.1. Description

The attribute “site properties” refers to the characteristics of the area surrounding the building. These characteristics can impact both the potential spread of fires to the building, as well as the ability of fire fighters to effectively operate in the area. The attribute has three survey items:

- Ground characteristics and access
- Separation distance
- Access to water

C.7.2. Survey Items

Each survey item is rated based on its "fire safety grade" and "sustainability grade":

Fire safety grade	**F**
Sustainability grade	**S**

All grades are integers between 1-10.

Ground Characteristics and Access (GA)

This survey item concerns the characteristics of the site that could obstruct or create obstacles for fire fighters to gain access to the building.

Ground characteristics	$\mathbf{F_{Ground}}$	$\mathbf{S_{Ground}}$
The area surrounding the building is mostly covered with hard surfaces, such as concrete and asphalt, with very few green surfaces and little vegetation.	10	1
The area surrounding the building is evenly covered with both hard surfaces, such as concrete and asphalt, and green surfaces such as grass, with some vegetation.	7	5
The area surrounding the building is mostly covered with green surfaces such as grass, with much vegetation and few hard surfaces.	1	10

Access to building	**F_{Access}**	**S_{Access}**
Site features allow firefighters to access around 70-100% of building façade with aerial ladder platform truck.	10	10
Site features allow firefighters to access around 50-70% of building façade with aerial ladder platform truck.	7	8
Site features allow firefighters to access around 30-50% of building façade with aerial ladder platform truck.	4	6
Site features allow firefighters to access less than 30% of building façade with aerial ladder platform truck.	2	3

$$F_{GA} = (F_{Ground} + F_{Access}) \cdot 0{,}5$$

$$S_{GA} = 0{,}7S_{Ground} + 0{,}3S_{Access}$$

Justification:

The accessibility for firefighter operation around the building may be influenced by the presence of green solutions like trees and soft soil, as well as hard solutions such as benches, fences, or other surrounding features which can obstruct firefighting operations such as slopes, big rocks, etc. Diversity in terms of trees, vegetation, slopes, green areas, etc. is beneficial for the sustainability aspects. Sustainability grade reflects the benefit of having vegetation around the building. However, this may result in poor land use (treated in next SI).

Separation Distance (SD)

This survey item concerns characteristics on the site that could pose a risk for fire to spread to the building. The fire safety and sustainability grade depend on both the distance to other buildings and the area where the building is situated:

$F_{SD} = 0{,}8F_{SD1} + 0{,}2F_{SD2}$
$S_{SD} = \max(S_{SD1} + S_{SD2})$

The aspect “distance to other buildings” describes the proximity of the building to nearby buildings.

Distance to other building	**F_{SD1}**	**S_{SD1}**
Connected	5	10
≤ 2 m	1	8
2 - 3 m	2	7
3 - 8 m	5	6
9 - 15 m	10	5
> 15 m	10	1

The aspect “wildland urban interface” refers to the area where the building is situated, which could potentially be at risk from wildfires due to its proximity to natural wilderness area.

Wildland-urban interface	**F_{SD2}**	**S_{SD2}**
Yes	1	10
No	10	1

Justification:

Both the WUI fires and fires in other buildings can spread through spot fires or heat transfer. Therefore, they are considered equally important for fire safety.

The distance between buildings has an impact on sustainability as an indication of using land for development.

Access to Water (Water)

This survey item refers to the availability of water on the building site, which could have an impact on the ability of fire rescue services to access fire water, and in turn, impact their firefighting operation.

The aspect “Water services” refers to whether the building is connected to the municipal water supply system, or if it obtains water from a well or some other source.

The aspect "Gray water recycling" refers to whether the building has any systems to recycle gray water, which includes not only water used within the building but also rainwater. Gray water is assumed to be partly used for fire extinguishing.

	Alternatives			
Water services	Municipal system		Well water or other	
Gray water recycling	Yes	No	Yes	No
F_{Water}	10	10	1	4
S_{Water}	10	3	8	1

Justification:

Whether the building is connected to the municipal water supply system or not is deemed most critical for fire safety as it can affect the effectiveness of both automated sprinkler systems and emergency rescue service operations.

Gray water recycling is considered most important for sustainability as it affects the water usage of the building.

C.7.3. Attribute Grade

Fire Safety Grading

Fire safety is graded with separation distance considered most important and access to the building as least important.

$w_{GA} = 0{,}4$

$w_{SD} = 0{,}2$

$w_{Water} = 0{,}4$

$$F_6 = (F_{GA} * 0.4) + (F_{SD} * 0.2) + (F_{Water} * 0.4)$$

Justification:

Accessibility features are considered the most critical aspect for fire safety as they can significantly impact fire rescue service operations. Fire hydrant access is not considered as crucial for many firefighting operations since many firefighting vehicles carry water storage tanks.

Sustainability Grading

Sustainability is graded with access considered most important and separation distance as least important.

$w_{GA} = 0{,}45$

$w_{SD} = 0{,}25$

$w_{Water} = 0{,}3$

$$S_6 = (S_{GA} * 0.45) + (S_{SD} * 0.25) + (S_{Water} * 0.3)$$

Justification:

The surface and vegetation around the building are the most vital aspect for sustainability, as they contribute to both water runoff management and the ecological life in the area where the building is situated. Additionally, water recycling is also considered important for sustainability.

C.8. Fire Extinguishing

C.8.1. Description

The attribute "Fire extinguishing" refers to whether there are hand-held fire extinguishers inside the building. This can impact whether the people inside the building are able to control a fire from spreading on their own. The attribute has two survey items:

- Portable extinguishing systems
- Automatic extinguishing systems

C.8.2. Survey Items

Each survey item is rated based on its "fire safety grade" and "sustainability grade":

Fire safety grade	**F**
Sustainability grade	**S**

All grades are integers between 1-10.

Portable Extinguishing System (PES)

The survey item "Portable extinguishing system" refers to whether the building has hand held fire extinguisher(s) placed inside the building. This will affect the occupant's ability themself to control a fire from spreading. The fire safety and sustainability grades depend on both the type of fire extinguishers and their placement:

$F_{PES} = F_{PES1} + F_{PES2}$
$S_{PES} = S_{PES1} + S_{PES2}$

If grades for each aspect 'Type' and 'Placement' both are 1, then the grade for portable extinguishing system is set to 1.

The aspect "type" refers to the specific type of fire extinguisher that is placed inside the building. The type of fire extinguisher can impact its effectiveness on fighting fire, as well as whether toxic substances are emitted during use.

Type	F_{PES1}	S_{PES1}
None	1	5
Powder	5	3
Foam (With PFAS)	4	1
Foam (Without PFAS)	4	1
CO_2	1	4
Water extinguisher	2	4
Water extinguisher with additives	4	3
Fixed hoses	3	4

The placement refers to whether hand-held extinguishers are placed inside apartments, common areas or both.

Placement	F_{PES2}	S_{PES2}
Apartment	4	2
Common areas	3	3
Both	5	1
None	1	5

Justification:

Powder extinguishers are regarded as the most effective means of fighting fires manually within a building due to their ease of use and effectiveness in suppressing fires. In contrast, CO_2 extinguishers are considered difficult to use and ineffective against fires. Sustainability affects the amount of material (both for type and placement) and potential chemical substances. Foam with PFAS/PFOS or water with additives are considered the worst option in terms of sustainability.

Automatic Extinguishing System (Auto)

The survey item "Automatic extinguishing system" refers to whether the building has fire sprinkler systems installed inside the building. This will affect the control of fire from spreading as well as materials used for the system.

The aspect "placement" refers to whether a sprinkler system is present inside the building and if it covers apartments, common areas. or both.

Placement	F_{Auto}	S_{Auto}
Apartment	8	5
Common areas	5	7
Both	10	2
None	1	10

Justification:

Having sprinkler coverage in apartments can result in early suppression of fires, thereby reducing the consequences of a fire. However, installing sprinklers requires more pipes to be drawn through the building, which means using more material.

C.8.3. Attribute Grade

Fire Safety Grading

$w_{PES} = 0.3$

$w_{Auto} = 0.7$

$$F_7 = (F_{PES} * 0.3) + (F_{Auto} * 0.7)$$

Justification:

Automatic extinguishing systems are considered significantly more important for fire safety than manual extinguishing systems. This is because they can effectively extinguish a fire without the need for occupants to notice and react to the fire.

Sustainability Grading

$w_{PES} = 0.5$

$w_{Auto} = 0.5$

$$S_7 = (S_{PES} * 0.5) + (S_{Auto} * 0.5)$$

Justification:

Automatic extinguishing systems use significantly more material than manual extinguishing systems.

C.9. Building Management

C.9.1. Description

The attribute "Building Management" refers to management measures that ensure fire safety and promote sustainable behavior among occupants while the building is in use. It also encompasses the routines for inspecting and cleaning the buildings systems. The attribute has three survey items:

- Information
- Waste management
- Inspection and maintenance routines

C.9.2. Survey Items

Each survey item is rated based on its "fire safety grade" and "sustainability grade":

Fire safety grade	**F**
Sustainability grade	**S**

All grades are integers between 1-10.

Information (Info)

The survey item "Information" refers to sustainability and fire safety information given to residents in the building.

Sustainability information:	$\mathbf{S_{Info}}$
Residents are provided with information on measures to reduce their environmental impact. This information could include promoting the use of LED lights, encouraging residents to not use heaters on full during the winter, and providing water-saving information during the summer.	10
No information will be given	1

Fire safety information	$\mathbf{F_{Info}}$
Residents are provided with information on what to do in the event of fire. Mobility-impaired residents will be given specific information.	10
Residents will be provided with general information on what to do in the event of fire.	6
No information will be given	1

Waste Management (Waste)

The survey item "Waste management" refers to how occupant waste is handled in the building. While promoting recycling can help reduce waste usage, it can also pose a fire risk if the recycling station is located inside or near the building.

The aspect “Waste storage” refers to whether non-recycled waste is stored inside or outside of the building.

The aspect “Recycling storage” refers to whether there is a recycling waste station, and whether the recycling waste is stored inside or outside of the building.

Waste storage	**F_{Waste}**	**S_{Waste}**
Waste is not handled in the building or at the site.	1	1
Waste only is stored inside building.	5	5
Waste and recycled storage are stored inside building.	5	10
Waste only is stored in station outside of the building.	10	5
Waste and recycled storage are stored in station outside of the building.	10	10

Justification:

Storing waste inside the building increases the likelihood of a fire in the waste storage area spreading to the inside of the building compared to when waste is stored outside.

Waste facilities that include a recycling station contribute positively to sustainability by reducing the amount of material waste.

Inspection and Maintenance Routines (Inspect)

The survey item “Inspection and maintenance routines” refers to whether there will be established routines for cleaning potential chimneys, ventilation ducts, ventilation systems, electricity production units, etc. Inspection also includes controlling and testing fire protection systems if installed. It also encompasses the frequency with which these systems will be inspected and maintained.

Routines	$\mathbf{F_{Inspect}}$	$\mathbf{S_{Inspect}}$
"Strong" routines are established when building systems are inspected and tested on an annual basis.	10	10
"Ok" routines are established when building systems are tested less frequently, but still at least every three years.	7	7
"Weak" routines are established when building systems are tested less frequently, with intervals exceeding three years.	2	2
No inspections are performed, or routines are not established.	1	1

Justification:

Having any routines in place, even if they are only okay, is considered significantly more important than having no routines at all.

C.9.3. Attribute Grade

Fire Safety Grading

$w_{Info} = 0.15$

$w_{Waste} = 0.35$

$w_{Inspect} = 0.5$

$$F_8 = \left(F_{Info} * 0.15\right) + \left(F_{Waste} * 0.35\right) + \left(F_{Inspect} * 0.5\right)$$

Justification:

Inspection and maintenance routines are considered the most crucial aspect of ensuring fire safety in the building, as they directly affect the building´s protection system. While waste storage is important for fire safety, providing fire safety information is considered slightly more crucial.

Sustainability Grading

$w_{Info} = 0.4$

$w_{Waste} = 0.6$

$$S_8 = \left(S_{Info} * 0.2\right) + \left(S_{Waste} * 0.5\right) + 0{,}3S_{Inspect}$$

Justification:

Providing recycling facilities is considered slightly more beneficial for sustainability than solely providing information to residents about sustainable behavior, since the recycling facilities themselves serve as a reminder for residents to be sustainable.

C.10. Means for Egress

C.10.1. Description

The attribute "Means for egress" refers to the systems and design elements within the building that facilitate safe evacuation of occupants in the event of a fire. The attribute has five survey items:

- Fire detection systems
- Fire notification
- Wayfinding
- Exit routes
- Mobility impairment

C.10.2. Survey Items

Each survey item is rated based on its "fire safety grade" and "sustainability grade":

Fire safety grade	**F**
Sustainability grade	**S**

All grades are integers between 1-10.

Fire Detection System (Detect)

The survey item "Fire detection system" refers to the devices that detect and alert occupants and/or first responders to the presence of smoke, fire, carbon monoxide, and/or other fire-related emergencies.

The aspect "type of detectors" refers to the type of fire detectors that are installed in the building. It also encompasses whether the detectors are connected to a central alarm system.

	Alternatives			
Type of detector	No detectors	Separate detectors	Connected smoke detectors inside apartment	Detectors connected to central alarm system for whole building
$\mathbf{F_{Detect}}$	1	6	8	10
$\mathbf{S_{Detect}}$	10	5	4	1

Justification:

Detectors that are linked to a central alarm system can serve multiple purposes by not only sounding the alarm but also regulating active fire protection systems like fire dampers if a fire is detected.

While more advanced detection systems offer better fire protection, they also require more materials and energy, which makes them less sustainable.

Fire Notification (Alarm)

The survey item "type of alarm system" refers to whether the building has a fire alarm system installed and, if so, what type of system it is. Additionally, it refers to whether any visual alarm system is in place to assist occupants who are deaf and may not perceive audible alarms.

	Alternatives				
Type of alarm	No alarm	Siren		Voice alarm	
Visual alarm	-	Yes	No	Yes	No

F_{Alarm}	1	9	7	10	8
S_{Alarm}	10	1	1	1	1

Justification:

The type of audible alarm is considered more important for fire safety than visual alarms since the likelihood of residents being deaf is relatively low. A voice alarm is considered the most effective fire alarm since it can provide residents with specific information on the actions to take in case of a fire.

While more advanced alarm systems offer better fire protection, they also require more materials and energy, which makes them less sustainable.

Wayfinding (W)

The survey item "Wayfinding" is part of the egressability potential and refers to the building design features that help people evacuate safely during a fire or emergency. These features can include things like clear directions for finding exits, having multiple routes available to exit the building, and systems that help people with disabilities to evacuate safely.

The aspect "Wayfinding" in the survey is concerned with two things. First, it refers to whether the building has exit signs displayed in common areas to assist people finding the way out during an emergency. Second, it refers to whether the building has installed emergency lightning that will turn on in case of a fire to aid with evacuation.

Wayfinding	F_W	S_W
Exit signs and emergency lightning are installed in common areas.	10	1
Exit signs are installed in common areas.	6	6
Emergency lightning is installed in common areas.	5	3
No wayfinding installations in building.	1	10

Justification:

Exit signs are considered more crucial for fire safety than emergency lightning. This is because they provide information to residents about where to go, even in situations where visibility is not yet critical.

The installation of emergency lightning and exit signs requires materials and energy, which makes it less sustainable compared to not having them at all. Material use, however, is not significant.

Exit Routes (Exit)

Another part of egressability refers to the potential alternatives for exiting the building. The survey item "Exit routes" in the survey refers to whether the building has multiple or just a single route designed for people to exit the building in the event of fire.

Exit routes	F_{Exit}	S_{Exit}
Building apartments have <u>multiple</u> routes for egress.	10	1
Building apartments have a <u>single</u> route for egress.	1	10

Justification:

Having multiple egress routes provides redundancy. This means that if one route becomes blocked, such as by a fire, residents can still evacuate through the other route.

Designing a building with multiple egress routes is likely to result in a less efficient layout of the building and require more material usage.

Mobility Impairment (Mob)

The survey item "Mobility impairment assistance" focuses on the ability of people with mobility impairment to evacuate. It encompasses two things: (1) it refers to whether the hallways and doorsteps are accessible for people who use wheelchairs, and (2) it refers to whether the building has designated fire protected refuge areas where individuals with mobility impairments can wait for assistance during an evacuation.

	Alternatives			
Wheelchair accessible	Yes		No	
Refuge areas	Y	N	Y	N
F_{Mob}	10	8	4	1
S_{Mob}	1	5	5	10

Justification:

Wheelchair accessibility is considered more critical than refuge areas for evacuation because it enables residents to quickly move away from the immediate danger.

Both wheelchair accessibility and refuge areas are likely to result in increased material usage.

C.10.3. Attribute Grade

Fire Safety Grading

$w_{Detect} = 0.3$

$w_{Alarm} = 0.3$

$w_{W} = 0.05$

$w_{Exit} = 0.15$

$w_{Mob} = 0.2$

$$F_9 = (F_{Detect} * 0.3) + (F_{Alarm} * 0.3) + (F_W * 0.05) + (F_{Exit} * 0.15) + (F_{Mob} * 0.2)$$

Justification:

Detection systems and fire alarms are considered the most crucial components of fire safety as they notify residents about the fire and prompt them to take action. Wayfinding installations are considered the least important in an apartment complex because residents are likely to already know the egress routes.

Sustainability Grading

$w_{Detect} = 0.2$

$w_{Alarm} = 0.2$

$w_{W} = 0.05$

$w_{Exit} = 0.3$

$w_{Mob} = 0.25$

$$S_9 = (S_{Detect} * 0.2) + (S_{Alarm} * 0.2) + (S_W * 0.05) + (S_{Exit} * 0.3) + (S_{Mob} * 0.25)$$

Justification:

Designing the building with multiple egress routes is likely to have the most significant impact on material usage and, therefore, sustainability. In contrast, wayfinding systems are considered to have little environmental impact since they require minimal materials.