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Reliability-Based Fire Resistance Periods for Buildings in England

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Abstract: The traditional route to achieving adequate structural performance in the event of fire is through ensuring that structural elements attain fire resistance ratings. The magnitude of these ratings typically varies in function of the building use, size, and height. In their genesis, fire resistance ratings were a proxy for the specification required of elements such that they had a reasonable likelihood of surviving the full duration of a fire, i.e., burn-out. As such, fire resistance periods were specified in the function of fire load, which, over time, progressively increased in consideration of the consequences of fire induced structural failure. This ratcheting of fire resistance periods was seemingly done so based on the collective experience of the profession, in response to observations from real fires and, where applicable, resulting disasters. That is, the safety levels associated with current fire resistance recommendations in most global codes and guidance documents are not determined. Therefore, this paper presents a review of reliability-based acceptance criteria for structures, ahead of their application, to determine fire resistance recommendations for buildings in England based on both codified reliability indices and the principle of relative (marginal) lifesaving costs. The study applies a novel form of probabilistic time equivalence, which is augmented by fire occurrence related statistics/parameters, to arrive at risk-informed fire resistance ratings that directly relate to the life safety consequences of fire induced structural failure (i.e., fatalities) to adequate fire resistance ratings. In determining these building fire resistance periods, it is observed that safety targets which implicitly include material damage and building reconstruction costs result in fire resistance recommendations that are well-aligned with National codes and standards. That is, to some extent, the ratcheting of fire resistance periods with time has resulted in some potential resilience to fire. Where safety targets are rationalised in consideration of life safety only, i.e., through the principle of relative (marginal) lifesaving costs, it is shown that fire resistance periods can be optimised, particularly in sprinkler protected buildings. However, this has the potential to introduce vulnerabilities to common mode failures.

Keywords: reliability; fire resistance; failure probability; lifesaving costs; fire safety

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1. Introduction

In traditional structural fire safety design, an 'adequate' level of safety is typically assumed to result from the application of prescriptive design guidance and/or legislation [1]. These prescriptive recommendations have been developed over time, often in response to fire disasters [2], and represent the collective experience of the profession. However, fire safety engineering is closely linked to the concepts of reliability, probability, and risk [3], or, as Watts and Hall state in the SFPE Handbook of Fire Protection Engineering, "every decision related to fire safety is a fire risk decision, whether it is treated as such or not" [4]. In the case of structural fire engineering, or the specification of structural fire safety measures, there is a need to implicitly balance up-front investments in materials (protection or element sizing) with improved performance (loss reductions) in the unlikely event of a fire. For traditional prescriptive or guidance-based fire safety recommendations, the underlying target safety levels are not clear to the designer, nor is the associated balancing of risk and investment costs [5], by virtue of their traditionally reactive nature and the corresponding ratcheting of safety levels with time [6].

In ambient temperature structural engineering, there is a high degree of reliance on and acceptance of reliability-based concepts. Partial load factors, combined with material safety factors, are derived from First Order Reliability Methods (FORM) with the intention of ensuring that structural elements or sub-frame assemblies have an appropriately low probability of failure. The acceptable probability of failure is informed by the likely consequences, often using life-time cost-optimisation concepts, where the utility of a building over its life is maximised considering what investment must be made upfront in safety measures and what losses might be anticipated in the event of an uncertain future failure [7]. It is posited that such concepts, conventionally reserved for ambient temperature structural design, have utility in supporting the rational design and specification of structures to adequately resist the effects of fire.

Therefore, this paper considers how reliability-based concepts can be used to define fire resistance periods for buildings in England, with emphasis on coordinating the safety levels achieved by the ambient temperature design and the elevated temperature design/fire protection provisions. It sets out a concept whereby risk-informed fire resistance periods for buildings can be derived which are explicitly linked to the consequences of fire induced failure through either reference to consequence classes or the number of fatalities that might occur. This is through the process of a novel application of the time equivalence method in a Monte Carlo simulation (MCS) format to generate fire intensity distribution functions for different types of buildings. These are subsequently augmented with fire occurrence statistics ahead of benchmarking against either codified reliability targets or those based on potential fatalities, and society's capacity to commit resources. The outcome is an explicit link between the potential fire induced failure consequences and the fire resistance that must be achieved by elements of structure.

2. Review of Reliability-Based Approaches to Specifying Structural Fire Resistance

For the purposes of discussion in this paper, the definition of reliability per the SFPE International Handbook on Structural Fire Engineering is adopted. Therein, it is stated that, in respect of life safety, reliability can be defined as "the probability that the structure or structural member will maintain its load-bearing function in the event of fire, i.e., reliability is the complement of the failure probability" [8]. Given this definition, the remainder of this section focuses on research studies that have applied reliability-based concepts in the potential derivation of fire resistance periods for buildings. The review of the literature in this Sections 2 and 3 is narrative in nature, with research studies selected in primarily chronological order to reflect the evolving state of the art.

2.1. EN 1991-1-2 and the Natural Fire Safety Concept

The adoption of reliability-based concepts in structural fire safety is an emerging area of research and practitioner interest, albeit it has genesis in the development of the Eurocodes, in particular EN 1991-1-2 [9], and the underpinning natural fire safety concept (NFSC) valorisation project [10]. The former proposes a series of partial factors that are applied to the design fire load density, with the intent of achieving a predefined safety target (a failure probability of c. 1×10^{-6} y^{-1}) corresponding to a reliability/consequence class 2 structure, as defined in EN 1990 [11]. The safety factors were determined in consideration that various fire safety measures, such as detection, suppression, management, and fire service intervention, serve a function in reducing the likelihood of a structurally significant fire. That is, the traditional ambient temperature relationship between the reliability index (β) and failure probability (P_f), as given by Equation (1), can be reformed as a conditional safety target, dependent upon the occurrence of a structurally significant fire, as defined in Equation (2):

$$P_f = \Phi(-\beta) \quad (1)$$

$$P_{f,fi} = \frac{P_f}{p_{fi}} = \Phi\left(-\beta_{fi}\right) \quad (2)$$

With Φ is the standard cumulative normal distribution function, β_{fi} the reliability index in the event of a structurally significant fire, p_{fi} the probability of a structurally significant fire and $P_{f,fi}$ the corresponding target failure probability in the event of a structurally significant fire. Both Equations (1) and (2) can be considered over different reference periods, with the most common being either annually or over the building life.

In appraising $P_{f,fi}$ the NFSC introduces a simple limit state, assuming the primary uncertainty influencing the ability of a structure to withstand a fire to be the fire load energy density (FLED). Given this, Equation (2) can be redefined per Equation (3), where $q_{f,d}$ is the design FLED [MJ/m^2] and $q_{f,a}$ the actual FLED [MJ/m^2].

$$P_{f,fi} = P\left[\left(q_{f,d} - q_{f,a}\right) \leq 0\right] \quad (3)$$

Assuming the FLED to follow a Gumbel minimum distribution, the NFSC introduces a direct connection between the conditional reliability target in fire (β_{fi}), and the design fire load density that should be adopted, i.e.,:

$$q_{f,d} = \gamma_{sD} m_{qf} \left\{ 1 - \frac{\sqrt{6}}{\pi} V_{qf} \left[0.577 + ln\left(-ln\Phi\left(0.9\beta_{fi}\right)\right)\right]\right\} \quad (4)$$

With γ_{sD} a model uncertainty factor (1.05 in the NFSC), m_{qf} the mean FLED [MJ/m^2] of the enclosure contents and V_{qf} the FLED coefficient of variation (COV, taken as 0.3 in the NFSC).

It follows from Equation (4), in consideration of Equation (2), that reducing β_{fi} through mitigating ignitions that develop into structurally significant fires provides a means for a reduction in the design fire load density and, hence, the fire resistance demands placed on the structure or structural fire protection. In the codified format in EN 1991-1-2, Equation (4) is adopted to develop a series of partial factors that apply to a characteristic fire load density (80th percentile) considering the role of enclosure area, ignition likelihood, proficiency of the fire service, efficacy of suppression systems, etc., which can be applied in time equivalence calculation methods to derive a fire resistance period for a building or to generate design fires for the purpose of performance-based assessments.

2.2. *Kirby et al.*

In developing contemporary fire resistance guidance for structures in BS 9999 [12], Kirby et al. [13] adopted a Monte Carlo simulation-based time equivalence study to generate probability density functions (PDFs) and cumulative density functions (CDFs) of fire resistance period for a range of different occupancies, including residential flats, offices, and retail. The study adopted the parametric fire curves in EN 1991-1-2, sampling distributions for key parameters such as: room area, room height, window opening area, window opening height and FLED. Each iteration of the MCS resulted in a parametric fire curve. This was subsequently utilised to calculate the peak temperature attained by a protected steel element which was then benchmarked against ISO 834 exposure to establish an equivalent duration of furnace exposure. Sprinkler protection was considered through a partial factor applied to the FLED from EN 1991-1-2 and as discussed in Section 2.1. This factor, 0.61, corresponded to a sprinkler reliability (ability to control a fire and prevent a structurally significant fire) of 98%. Fire resistance ratings at different trigger heights were assigned to different building types through a simplistic correlation that related building height to a target reliability, as given in Equation (5), albeit expressed alternatively as a failure probability.

$$P_{f,fi} = \frac{64.8}{h^2} \quad (5)$$

where h is the height from the lowest ground floor level to the topmost occupied storey, in m.

Within Equation (5), both the likelihood of fire occurrence and the consequences of fire induced structural failure are represented through the proxy of building height, i.e., taller buildings generally have more area, and thus, a greater prospect of ignitions, and correspondingly, with greater area comes greater potential failure consequences in terms of the quantum of people affected in or around the building. In acknowledging the relationship between failure consequences and evacuation mode, Kirby et al. provide alternative target reliabilities for buildings where people sleep vs. those where they are awake. This is shown in Table 1.

Table 1. Target reliability in function of height from Kirby et al.

Height [m]	Target Reliability (%) for Awake Occupants	Target Reliability (%) for Sleeping Occupants
0–5	20	46.4
5–11	46.4	80
11–18	80	92.8
18–30	92.8	98.2
30–60	98.2	99.6
>60	99.6	99.99

The main outcome of the Kirby et al., study was optimised fire resistance periods for buildings, particularly where sprinklers were provided. The study results have since been incorporated into BS 9999 [14] and BS 9991 [15,16]. The use of height as both a proxy for ignition likelihood and fire induced failure consequences was subject to criticism by Hopkin [17], where it was noted that area was a more credible metric by which to estimate ignition frequency, which was aligned to the view in the NFSC.

2.3. Law et al.

Law et al. [18] built upon the approach of Kirby et al. to identify two possible improvements to the study underpinning BS 9999. First, in large compartments in particular, fires may not develop to flashover and, therefore, any consideration of structural fire resistance should incorporate travelling fires. Second, the use of a partial safety factor to reflect sprinkler intervention (applied to the fire load) distorts the resulting fire dynamics reflected in fire models and, therefore, it is preferable to adjust the reliability target to address the role of sprinklers in mitigating structurally significant fires. Principally, the study adopted the same approach as Kirby et al., i.e., the application of Monte Carlo simulations to derive PDFs and CDFs of time equivalence outcomes. However, the interpretation of these PDFs and CDFs differed through adjustment of the reliability target for cases where sprinklers were included. This was proposed to be addressed through Equation (6):

$$R_p = \frac{R_T - R_s}{1 - R_s} \quad (6)$$

where R_p is the reliability of the structural elements/passive fire protection, R_T is the target reliability established as the complement of Equation (5), i.e., $R_T = 1 - P_{f,fi}$, and R_s is the sprinkler reliability.

Inspection of Equation (6) highlights that, in-principle at least, the reliability required of the structure can be eliminated through the specification of a high performing sprinkler system, i.e., where $R_s > R_T$, giving a reliability of the structural elements/passive fire protection $R_p < 0$.

2.4. Hopkin et al.

Hopkin et al. [5] applied life-time optimisation methods to determine the adequate safety levels of protected steel structures exposed to fire. Within this study, safety targets, expressed as acceptable failure probabilities, are derived in function of a parameter named the Damage to Investment Indicator (DII), discussed further in Section 3.2. Therein, it is noted that as the ratio of cost of damage (including those associated with loss of life and injury) to safety investment increases, the safety target, i.e., target reliability index, must also increase.

Within the DII parameter and in studying the origins of safety targets used in ambient temperature structural engineering, it was identified that traditional expressions of acceptable failure probability inherently include consideration of property and asset protection. That is, the cost-optimisation process has generally involved consideration of the damage costs associated with loss of materials, productivity, and the rebuilding of the asset. Given this, they are inherently conservative when applied in the context of health and safety, which is primarily concerned with mitigating fatalities and injuries.

Through application of a MCS based time equivalence tool [19], the paper presents case studies of the optimal fire resistance period for a model office, where consideration is given to both safety targets incorporating either all damage costs or only those associated with loss of life and injury. It was shown that considerably optimised fire resistance ratings for the exemplar structure were possible when the safety target was limited to consideration of life safety only. When considering the costs associated with loss of life, the study applied the life quality index (LQI) [20] which places a value on the benefits of risk reduction through improved life expectancy, in a similar manner to the work of Fischer et al. [21].

3. Safety Targets and Their Application to Structural Fire Engineering

Van Coile et al. [7] provides a detailed summary on the origins of reliability indices, and how they may apply to structures exposed to fire events. Therein, it notes a trend originating from ISO 2394:1998 [22] through to ISO 2394:2015 [23], where target safety levels have gradually reduced with increasing knowledge of the uncertainties present in the actions acting on structures and the resistance of those structures.

3.1. Ambient Temperature Safety/Reliability Targets

Prior to the publication of EN 1990, ISO 2394:1998 gave reliability targets in function of the consequences of failure and relative costs of safety measures, as given in Table 2. These applied to the lifetime of the building.

Table 2. Target β-values for elements (lifetime), ISO 2394: 1998.

Relative Costs of Safety Measure	Target β-Values for Different Consequences of Failure			
	Small	Some	Moderate	Great
High	0	1.5	2.3	3.4
Moderate	1.3	2.3	3.1	3.8
Low	2.3	3.1	3.8	4.3

The 50 year reference period reliability targets in EN 1990 closely align to the lifetime targets given in ISO 2394:2008, as shown in Table 3. The Eurocode target reliability indices are specified both for a 1 year reference period and a 50 year reference period. However, both sets correspond with the same target reliability level, considering independence of yearly failure probabilities [24], i.e., irrespective of how long a structure has been standing, it is assumed that the per annum failure likelihood is constant. However, Vrouwenvelder [25] notes that the Eurocode independence assumption for yearly failures is unrealistic, and that β = 3.8 for a 50 year reference period (which is the basis of Eurocode's partial factors) corresponds better with β = 4.5 for a 1 year reference period.

Table 3. Target β-values for elements per EN 1990.

Reliability/Consequence Class	Consequences	Target Reliability Index	
		1 Year Ref. Period	50 Year Ref. Period
3	High	5.2	4.3
2	Medium	4.7	3.8
1	Low	4.2	3.3

The Joint Committee on Structural Safety (JCSS) gives target values for a 1 year reference period in the Probabilistic Model Code, which are also reproduced in ISO 2394:2015. The reliability targets are given in function of the ratio of the failure plus reconstruction cost to the construction cost (ξ). This results in the reliability targets given in Table 4.

Table 4. Target β-values for structural systems (1 year) from JCSS Probabilistic Model Code.

Relative Cost of Safety Measures	Consequences of Failure		
	Minor (ξ < 2)	Moderate (2< ξ < 5)	Large (5 < ξ < 10)
High	3.1	3.3	3.7
Moderate	3.7	4.2	4.4
Low	4.2	4.4	4.7

At first glance, the reliability targets from the JCSS might be considered less conservative than those given in EN 1990. However, as has been noted, the Eurocode independence assumption introduces a level of conservatism in translating lifetime to one year reference periods. Furthermore, Van Coile et al. [7] identify that the Eurocode target reliability index is applied in practice to structural elements, while the JCSS targets are applicable to structural systems. Vrouwenvelder clarifies that generally the element target reliability index must be larger than the system target reliability index, except for highly redundant structures.

Finally, Fischer et al. [21] presents optimal and acceptable reliabilities for structural design that are also referenced in ISO 2394:2015. These are considered to represent a boundary condition on cost-optimised reliability targets which are said to be consistent with societal preferences for lifesaving investments. Therein, reliability targets are expressed based upon the "relative (marginal) lifesaving costs" (K_1) as given in Table 5, with K_1 defined in Equation (7).

$$K_1 = \frac{C_1(\gamma + \omega)}{N_F G_\Delta} \tag{7}$$

where C_1 is the marginal cost associated with a change in the central safety factor [$] (note that K_1 can also be expressed per unit area), γ is the discount rate [%], ω is the obsolescence rate [%], N_F is the number of fatalities in the event of a failure, and G_Δ is Societal Willingness to Pay (SWTP) for saving one additional life [$/per].

Table 5. Min. acceptable reliabilities for a 1 year reference period, based on marginal lifesaving costs principle, from Fischer et al.

Relative Marginal Lifesaving Costs	Range for K_1	Min. Acceptable Reliability Target (β)
Large	10^{-3} to 10^{-2}	3.1
Medium	10^{-4} to 10^{-3}	3.7
Small	10^{-5} to 10^{-4}	4.2

ISO 2394:2015 gives an example application relating to Equation (7) and Table 5, which is adapted herein for illustration. If it is assumed that the cost of a safety investment (C_1) is 1% of the overall construction cost (C_0), with the construction cost being $50,000,000, the marginal cost associated with a change in the central safety factor is $500,000. Suppose a structural failure leads to 50 fatalities, adopting an SWTP of $3,000,000, combined with a discount and obsolescence rate of 3%, yields K_1 equal to 2×10^{-4}. This makes the relative marginal lifesaving costs "medium", resulting in a bounding reliability index of 3.7 when cross referencing against Table 5.

Alternatively, when the action and resistance are log-normally distributed and have coefficients of variation (COV) in the range of 0.1 to 0.3, the acceptable failure probability ($P_{f,acc}$) can be approximated as $K_1/5$, i.e., 4×10^{-5} y^{-1} or β of 3.94.

3.2. Reliability Targets for Fire Exposed Structures

Limited research has been dedicated to the topic of reliability targets for fire exposed structures. In consideration of the reliability index that should be used for fire exposed structures, the NFSC valorisation project considered the role of the evacuation mode in mitigating the consequences of fire induced structural failure. Therein, it is considered that the reliability target for a fire exposed structure can be rationalized depending upon the difficulty of evacuation, i.e., for a one year reference period:

- Normal evacuation—β = 3.65
- Difficult evacuation—β = 4.21
- No possible evacuation—β = 4.70

In Hopkin et al., reliability indices are proposed for fire exposed protected steel structures, in function of the previously introduced *DII*, where:

$$DII = \frac{\lambda_{fi}[x_m + x_l]}{\alpha_2(\gamma + \omega)} \quad (8)$$

The terms x_m and x_l are defined via Equations (9) and (10):

$$x_m = \frac{\mu_m + C}{C_o A_f} \quad (9)$$

$$x_l = \frac{\mu_l}{C_o A_f} \quad (10)$$

With μ_m the average material failure costs [£], C the total building construction and maintenance cost [£], C_o the base construction cost [£ per m^2 floor area], A_f the floor area [m^2], and μ_l the average costs associated with loss of life [£]. The discount (γ) and obsolescence rates (ω) have been previously introduced. λ_{fi} is the probability of a significant fire occurrence [y^{-1}], with α_2 a rate parameter [£/mm] related to the cost of passive fire protection (in function of the applied thickness).

From this, optimal reliability ($\beta_{fi,opt}$) targets in function of the *DII* and mean FLED, were proposed as set out in Table 6.

Table 6. $\beta_{fi,opt}$ in function of DII [mm^2] and mean FLED.

Mean FLED	DII = 1000	DII = 10,000	DII = 100,000
$q_{f,nom}$ = 200 MJ/m^2	1.0–1.5	2.0–2.2	2.5–2.8
$q_{f,nom}$ = 400 MJ/m^2	1.0–1.3	1.9–2.2	2.3–2.8
$q_{f,nom}$ = 600 MJ/m^2	0.8–1.1	1.8–2.1	2.3–2.7

Intuitively, as the ratio of the cost of the fire induced damages to the cost of the safety measures (expressed through the DII) increases, so does the reliability index. For the same DII, the reliability index reduces in function of the mean FLED. This is because a larger investment in fire protection would be required upfront to counteract a larger fire load, meaning over the lifetime of a building, a higher probability of failure can be accepted to maximise the utility of the building. This is a similar concept as evident in Section 3.1 where high initial investments in safety measures generally result in reduced reliability targets.

An alternative proposition to the two studies above is through the application of ambient temperature reliability targets, i.e., as introduced in Section 3.1, but with adjustment for the probability of fire occurrence, as expressed previously through Equation (2).

4. Factors Leading to a Structurally Significant Fire

Section 2 has introduced the concept of a conditional safety target or reliability, i.e., the occurrence of a structurally significant fire is a prerequisite for a fire induced structural failure. Given this, to define a reliability target for a fire exposed structure, one has two routes to addressing the safety target:

1. Define the probability of a structurally significant fire.
2. Define a conditional safety target on the presumption that a structurally significant fire will occur, i.e., an evaluation independent of the probability of a significant fire.

Approach (1) is reflected in the NFSC and subsequently EN 1991-1-2, whilst approach (2) is like that adopted by Kirby et al. in developing the fire resistance guidance in BS 9999. It is postulated that route (2) has the limitation that the safety level can only be calibrated against some prescriptive norm and, therefore, it does little to enhance the understanding of the safety level achieved, i.e., it relies upon a collective experience of the profession through response to disasters, which likely then require extrapolation to uncommon building situations. Route (1), therefore, is considered preferable as it permits an explicit evaluation of the safety level, albeit under the constraint of the quality of data available in informing both the frequency of a fire event, and the subsequent physics associated with how the fire develops and how the structure responds. Despite this, route (1) forms the basis of further consideration in this paper.

Limited data is available for the purpose of estimating the probability of a structurally significant fire for any given building or class of buildings. Perhaps the most recognisable source of such data resides in the NFSC Valorisation report, from which methods associated with the data continue to be used across various jurisdictions through the adoption of EN 1991-1-2. Therein, the probability of a structurally significant fire is said to be related to four branches of an event tree, per Equation (11):

$$p_{fi} = p_1 \cdot A \cdot p_2 \cdot p_3 \cdot p_4 \quad (11)$$

where:

- p_1 is the probability of a severe fire occurring including the influence of occupants and standard fire service (per m^2 per year);
- A is the area of compartment/occupancy (m^2);
- p_2 is the probability of unsuccessful fire suppression by FRS intervention (considering improved professionalism/performance);
- p_3 is the probability of unsuccessful fire suppression associated with fire alarm and detection systems;
- p_4 is the probability of unsuccessful fire suppression by active fire protection systems (sprinklers).

These probability parameters can be populated with values from the NFSC as per Table 7, which are adopted for the purpose of study herein and subject to application in Section 6.

Table 7. Selected probability parameters in accordance with the NFSC Valorisation Project.

Occupancy	p_1* [$m^{-2}year^{-1}$]	p_2 †	p_3 ‡	p_4 §
Residential	6.5×10^{-7}	0.2	0.25	1 (0.12)
Office	3.0×10^{-7}	0.2	0.25	1 (0.12)
Retail	4.0×10^{-7}	0.2	0.25	1 (0.12)

* 6.5×10^{-7}, 3.0×10^{-7} and 4.0×10^{-7} are adopted based upon the NFSC report for residential, office. and retail occupancy types, respectively. † 0.2 is adopted based upon the NFSC report assuming a professional fire service is provided to intervene, should a fire occur, in 20 to 30 min after the alarm activation. ‡ 0.25 are adopted for residential and office/retail areas based upon the NFSC report. This assumes that heat detectors are provided. § Values in brackets consider situations where an appropriate sprinkler system is provided, with data taken from PD 7974-7.

5. Probabilistic Assessment of Fire Intensity and Time-Equivalence

5.1. Limit State

To apply reliability targets as previously introduced, it has been established that the frequency of a structurally significant fire must be estimated. However, the probability of a structure failing in the event of that significant fire must be appraised. This will be a function of both the intensity of the resulting fire and the fire resistance of the structural element. To this end, a simplistic limit state is proposed for the purpose of arriving at reliability informed fire resistance periods for buildings in England, as presented in Equation (12):

$$\frac{P_f}{p_{fi}} \leq P\left|FR_{req} < FR_{ach}\right| \tag{12}$$

This is simply stating that the target conditional failure probability (P_f/p_{fi}) must be less than the probability of the fire resistance required (FR_{req}) being exceeded by the fire resistance that is specified/achieved (FR_{ach}). When applied to reliability targets that relate to the structural system, this limit state effectively suggests that failure occurs when the fire resistance of isolated elements is exceeded. The fire resistance that is required is considered from the perspective of the intensity of the fire, i.e., disregarding any uncertainties related to the mechanical action on the structure or in material properties, which is analogous to the approach in the NFSC.

5.2. Probabilistic Assessment of Intensity

The probabilistic assessment of fire intensity has been introduced previously through the studies of both Kirby et al. and Law et al., whereby MCS are utilised to generate a thermal boundary condition to a structural element, via a fire model, which is then subsequently applied to estimate the temperature vs. time history of a protected structural steel element. This temperature vs. time history is then benchmarked against standard furnace heating conditions, i.e., ISO 834, to infer an equivalent duration of furnace exposure or time-equivalence. This same concept is applied herein using a software tool developed by the authors and reported elsewhere, i.e., refs. [19,26]. The simplified workflow is given in Figure 1.

Considering the evaluation of the fire model, enclosure fire dynamics are complex, and the development of fire is dependent upon compartment geometry, lining materials, ventilation, etc. These parameters will ultimately govern whether a fire is able to develop to an extent where all combustible material is near-simultaneously involved (i.e., flashover) or whether the fire moves in search of both available un-burnt fuel and/or oxygen (i.e., a travelling fire [27,28]). This study is premised on both forms of fire development being credible scenarios. The choice of when to transition from one fire model to another is based upon the various parameters including FLED and compartment opening factors, etc., and is addressed within SFEPRAPY via the proposals originally adopted by Hopkin et al. [29].

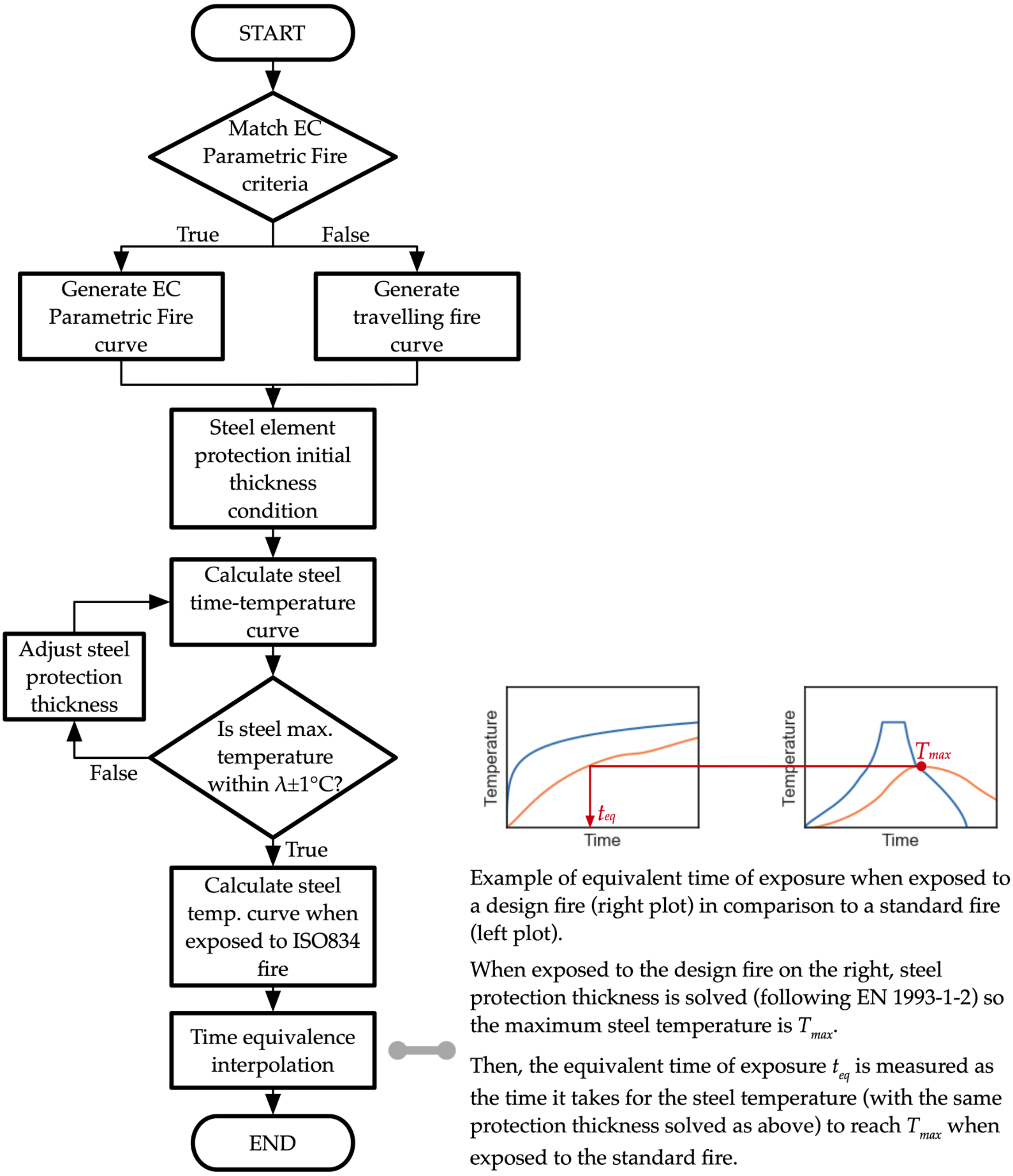

Figure 1. Simplified SFEPRAPY workflow for a single Monte Carlo simulation iteration.

Table 8 summarises the key input parameters used in this study. The data for the FLED and heat release rate (HRR) per unit area is obtained from PD 7974-1:2019 [30] and EN 1991-1-2. It is recognised that not all available fuel will generally be consumed in event of fire; therefore, a uniform distribution has been adopted between the combustion efficiency specified in BS EN 1991-1-2 (80%) and that of PD 6688-1-2 (100%) [31]. Glazing failure in fire has been considered following the principle set out in the JCSS probabilistic model code [32]. The room and window geometry parameters used are as per the work carried out by Kirby, et al.

Table 8. Key parameters adopted for the time equivalence MCS.

Parameter	Distribution	Residential	Office	Retail
Fire load energy density [MJ/m^2]	Gumbel	Mean: 780 SD: 234	Mean: 420 SD: 126	Mean: 600 SD: 180
HRR per unit area ‡ [MW/m^2]	Uniform	(0.32, 0.57)	(0.15, 0.65)	(0.27, 1.00)
Room height [m]	Uniform	2.4 *	(2.8, 4.5)	(4.5, 7.0)
Floor area [m^2]	Uniform	(9, 30)	(50, 1000)	(50, 1000)
Window height to room height ratio [-]	Uniform	(0.3, 0.9)	(0.3, 0.9)	(0.5, 1.0)
Window area to floor area ratio [-]	Uniform	(0.05, 0.2)	(0.05, 0.4)	(0.05, 0.4)
Fuel combustion efficiency ‡ [-]	Uniform	(0.8, 1.0)	(0.8, 1.0)	(0.8, 1.0)
Glazing breakage percentage ‡ [-]	Complementary Lognormal †	Mean: 0.2 SD: 0.2	Mean: 0.2 SD: 0.2	Mean: 0.2 SD: 0.2
Model uncertainty factor § [-]	Lognormal	Mean: 1 SD: 0.25	Mean: 1 SD: 0.25	Mean: 1 SD: 0.25

* Constant is used in lieu of random values based upon a distribution. † Truncated between 0 and 1. ‡ Parameters not considered in Kirby et al. § Truncated between 0 and 3.

Table 8 introduces a model uncertainty parameter that acknowledges there is a general uncertainty that exists in the equating of real fire severity to an equivalent duration of furnace heating, which adopts the proxy of heat transfer to a protected steel element.

5.3. CDF of Time Equivalence for Different Occupancies

For the workflow introduced in Figure 1 and the parameters summarised in Table 8, the tool SFEPRA.py has been applied to generate CDFs of fire intensity (time equivalence) for three different occupancy types, i.e., residential, office, and retail. The resulting CDFs are shown in Figure 2.

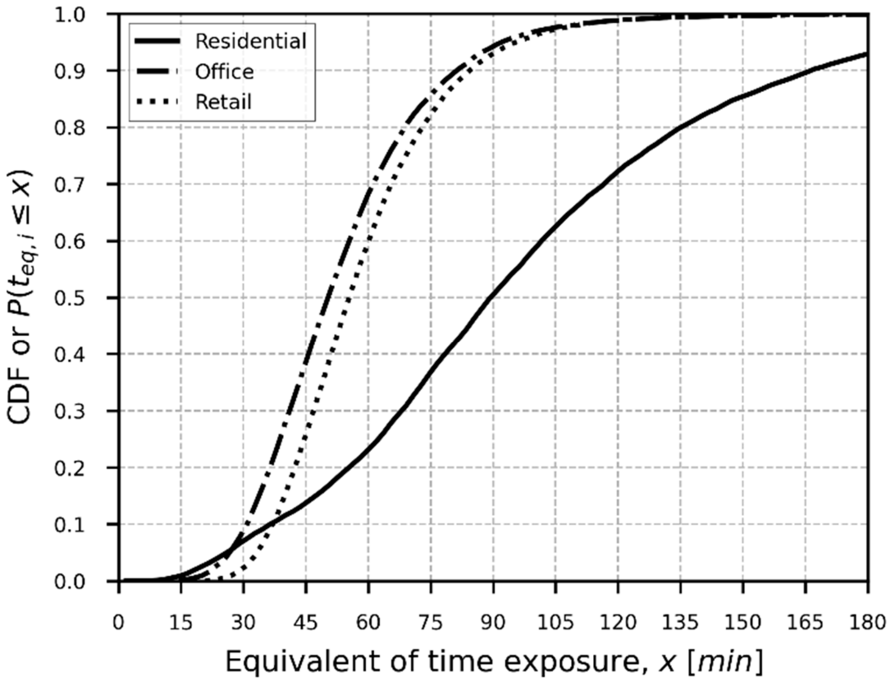

Figure 2. CDF of time equivalence solved from a MCS study using SFEPRAPY.

6. Proposed Reliability-Based Structural Fire Resistance Periods for Buildings in England

6.1. Based upon JCSS Probabilistic Model Code Reliability Targets

Section 3.1 introduced a range of reliability targets in codes and standards, with the most contemporary being those in the JCSS probabilistic model code, as reproduced in ISO 2394:2015. These apply cost-optimisation principles, where material damage not limited to loss of life is considered. To this end, these arguably represent a conservative upper bound on the expected performance of structures as their purview extends beyond just health and safety of those in or around a building. These reliability targets express the failure consequences as the ratio of the failure plus reconstruction cost to the construction cost. These ratios have been tentatively connected to consequence classes, as adopted in Approved Document A [33], with corresponding reliability indices given in Table 9 for "moderate" relative costs of safety measures.

Table 9. Consequence Class, building height (no. of storeys) and allowable failure probability considering residential, retail and office type buildings *.

	Consequence Class (or Building Class)		
	CC2A	**CC2B**	**CC3**
No. of storeys	≤4	>4, ≤15	>15
Reliability index, β [-]	3.7	4.2	4.4
Allowable failure probability ($P_{f,a}$) [year^{-1}]	$\approx 1 \times 10^{-4}$	$\approx 1 \times 10^{-5}$	$\approx 5 \times 10^{-6}$

* Note the Consequence Class (or Building Class) also depends on building usage/characteristics. Specific to residential, retail, and office building types, the only relevant parameter is the number of storeys.

With reference to Figure 2, the fractile of time equivalence (t_{eq}) can be interrogated for a given class of building in consideration that:

$$\frac{P_f}{p_{fi}} \leq 1 - P\left|t_{eq} < x\right| \tag{13}$$

That is, $1 - P_f/p_{fi}$ gives the fire resistance fractile that must be achieved to satisfy the safety target and can be directly interpreted from Figure 2. It follows that for the same consequence class of building there can be differences in the time equivalence fractile that must be achieved owing to potential variations to both the number of storeys and the area of those storeys, with both impacting the probability of a structurally significant fire (p_{fi}). The outcome in recommended fire resistance as a function of the consequence class, number of storeys and, thus, building area is shown in Figure 3. The top row presents results where sprinklers are not provided, the second for cases where sprinklers are included.

Table 10 tentatively maps consequence class-based fire resistance recommendations as given in Figure 3 to height related recommendations as presented in BS 9999:2018. The values in brackets correspond with cases where sprinkler protection is provided.

6.2. Based upon the Principle of Relative (Marginal) Lifesaving Costs

Applying the work of Fischer et al., as summarised in Section 3.1, ambient temperature acceptable reliability indices and failure probabilities can be determined based on the principle of relative (marginal) lifesaving costs.

Based on cost-modelling data, ambient temperature reliability indices (Figure 4) and acceptable failure probabilities (Figure 5) have been calculated via Equation (7), assuming COVs in the resistance and action within the limits of 0.1 to 0.3. As the cost of the safety measure is proportional to the area of the building, for the same number of potential fatalities, a lower reliability index or higher failure probability is justified with increasing total floor area.

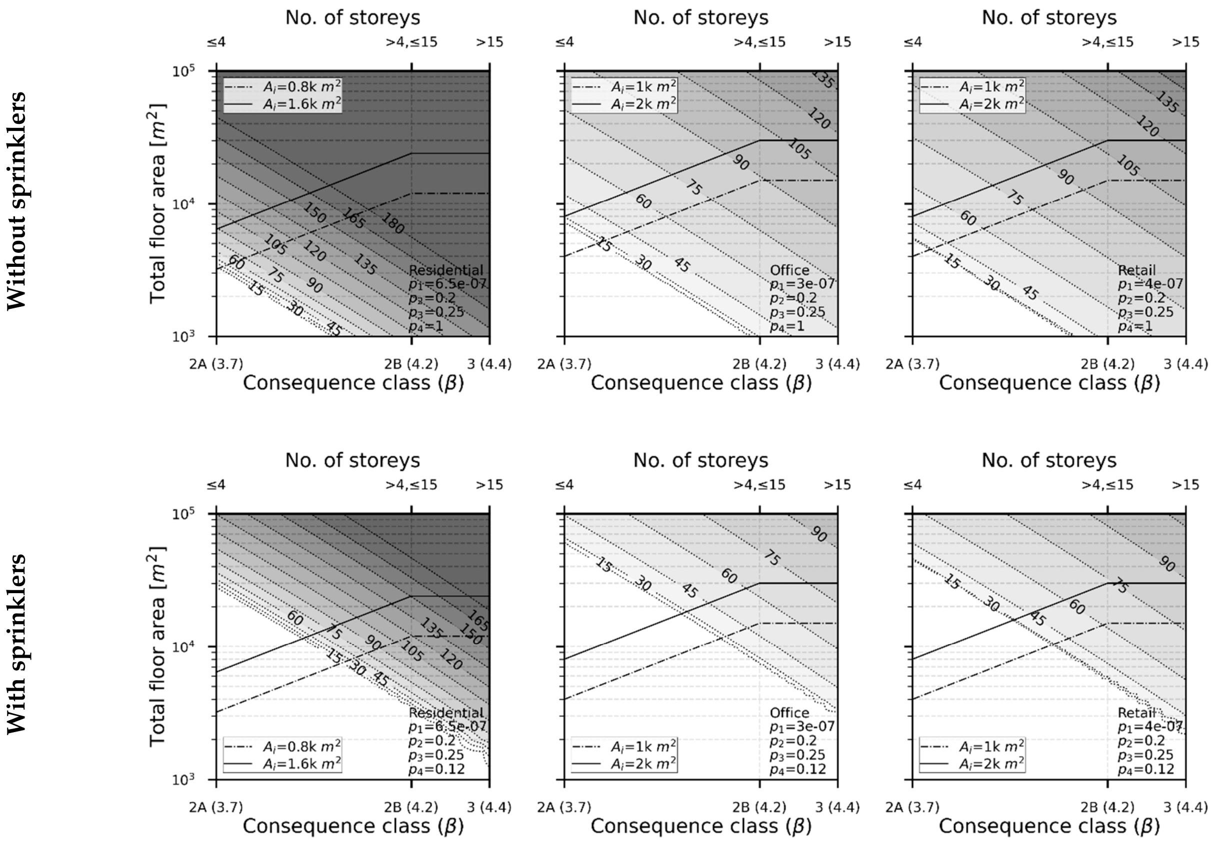

Figure 3. Contour plots of the solved structural fire-resistance rating at various building heights and total floor area (without and with sprinklers); A_i denotes floor area per storey.

Table 10. Minimum required fire resistance periods, a comparison between those derived based on JCSS cost-optimised reliability targets and recommendations in contemporary guidance.

Occupancy	Method	Floor Area per Storey	Fire Resistance Periods Based upon No. of Storeys *S* or Building Height *H* (Values in Bracket Include Sprinklers *) [min] ◊		
			CC2A *S*≤4 5<*H*≤18 m	CC2B 4<*S*≤15 18<*H*≤30 m	CC3 *S*>15 *H*≥30 m
Residential	BS 9999 †	-	60 (60)	90 (60)	120 (120)
	This study	800 m^2	60 (60)	225 (120)	255 (165)
		1600 m^2	90 (60)	240 (165)	270 (195)
Office	BS 9999 ‡	-	60 (30)	90 (60)	120 (120)
	This study	1000 m^2	45 (45)	90 (60)	105 (75)
		2000 m^2	45 (45)	105 (75)	120 (90)
Retail	BS 9999 §	-	60 (60)	90 (60)	120 (120)
	This study	1000 m^2	45 (45)	105 (75)	120 (90)
		2000 m^2	60 (45	120 (75)	135 (90)

* Assuming appropriate sprinkler system specification is provided. † Corresponds to risk profile C1/C2/C3 as defined in BS 9999:2017. ‡ Corresponds to risk profile A1/A2, reduction in fire resistance when sprinkler is provided only applies to A1. § Corresponds to risk profile B1/B2, reduction in fire resistance with sprinklers only applies to B1. ◊ For comparison purposes, the recommendations in BS 9999 are included; however, the building heights defined in BS 9999 do not perfectly align with no. of storeys. For the purposes of this study, the building height bands in BS 9999 (>5, ≤18 m), (>18, ≤30 m) and (≥30 m) are crudely mapped to ≤4, ≤15 and >15 storeys, respectively.

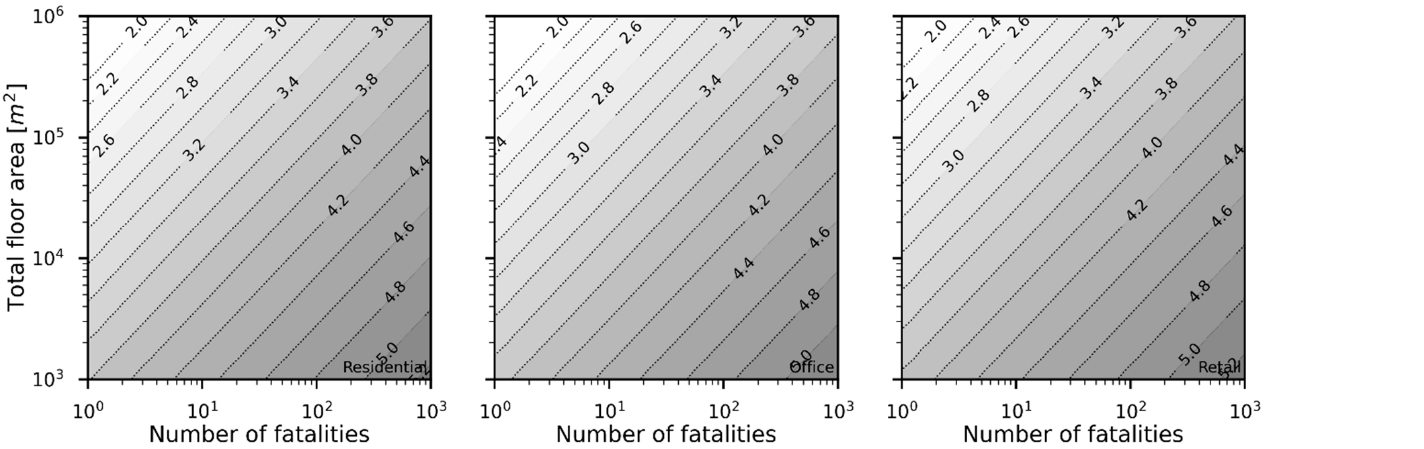

Figure 4. Reliability index in function of the number of fatalities and floor area, for residential, office, and retail use.

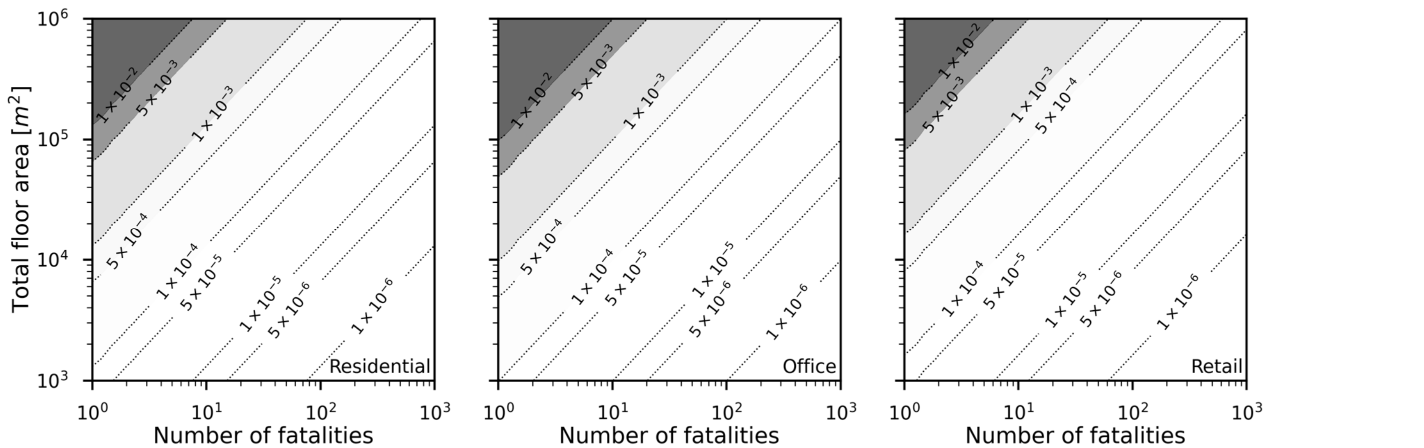

Figure 5. Acceptable failure probability in function of the number of fatalities and floor area, for residential, office and retail use.

Relevant inputs for residential, office and retail use are set out in Table 11. The relative cost of the safety investment is taken as being "normal" per the definition used in ISO 2394:2015, i.e., 1% of the construction cost. In alignment with other cost–benefit-analysis (CBA) studies by the authors [34], the discount and obsolescence rates are taken as 3%.

Table 11. Relevant cost parameters in the determination of acceptable reliability targets based on the principle of relative (marginal) lifesaving costs.

Symbol	Parameter	Unit	Resi.	Office	Retail	Ref (Where Applicable)
C_0	Construction cost	[£/m^2]	2100	2800	1700	[35]
C_1/C_0	Relative cost of safety investment	[-]		0.01		[23]
C_1	Cost of safety measure	[£/m^2]	21	28	17	
$SWTP$	Societal willingness to pay	[£/per]		3,300,000		[34]
γ	Discount rate	[%]		3		
ω	Obsolescence rate	[%]		3		

Given the dependency of the relative (marginal) lifesaving costs (K_1) on the total floor area of a building, Figure 5 can be translated to a conditional failure target in the event of a significant fire through Equation (2), with the resulting $P_{f,fi}$ being independent of total building floor area. This is shown in Figure 6 in function of the number of fatalities for residential, office and retail buildings. Relevant factors influencing the occurrence of a structurally significant fire are as previously defined in Table 7, separate plots are provided with and without sprinklers. Linking Figure 6 to the fire resistance CDF of Figure 2 and the probability parameters in Table 7, a relationship can be established between the number of fatalities and the equivalent duration of furnace exposure (or fire resistance period). This is shown in Figure 7, with the left figure without sprinkler protection and right, including sprinkler protection.

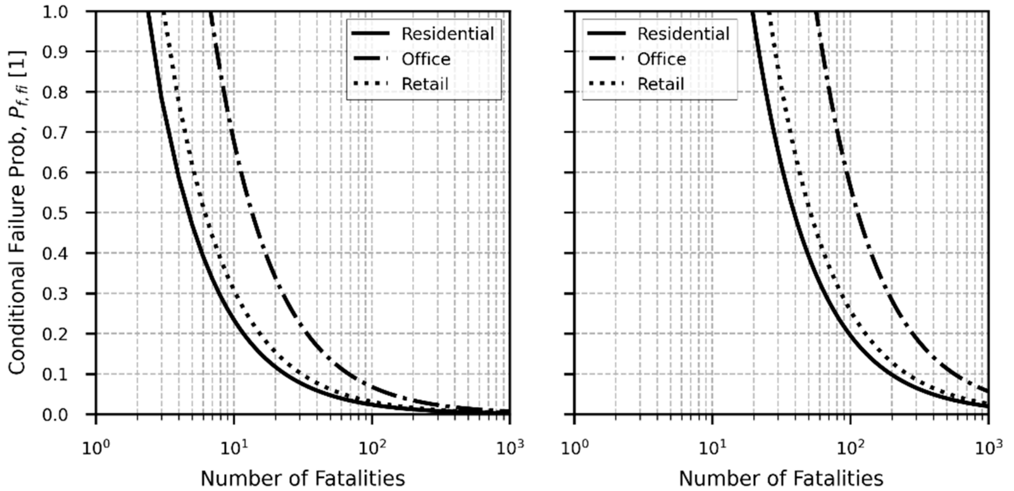

Figure 6. Conditional acceptable failure probability in the event of a structurally significant fire in function of the number of fatalities based on the principle of relative (marginal) lifesaving costs (**left**) without sprinklers, (**right**) with sprinklers.

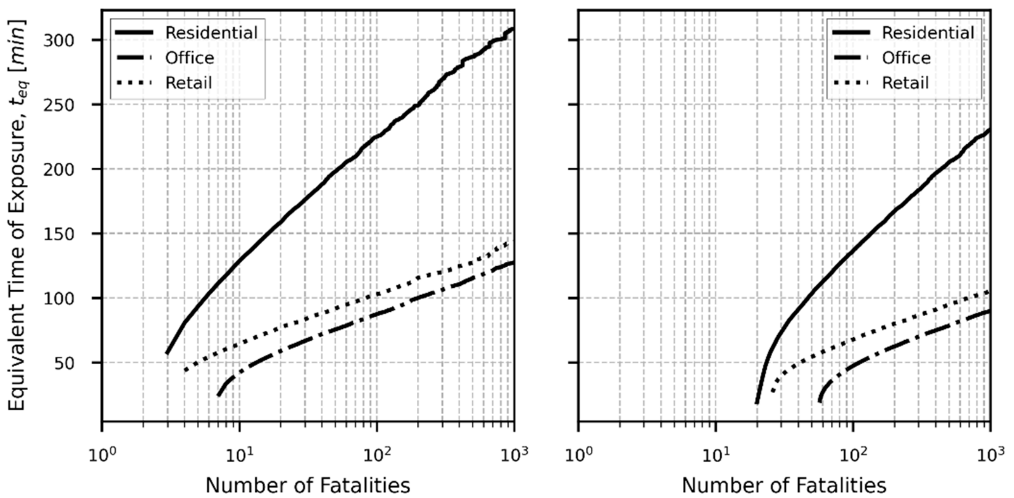

Figure 7. Minimum fire resistance in function of the number of fatalities based on the principle of relative (marginal) lifesaving costs (**left**) without sprinklers, (**right**) with sprinklers.

Table 12 maps the fire resistance determined in function of the number of possible fatalities to the consequence classes in ISO 2394:2015, which have been partly adapted from EN 1991-1-7. Values are mapped to the highest number of possible fatalities in each consequence class.

Table 12. Fire resistance recommendations based on the principle of relative (marginal) lifesaving costs, using ISO 2394:2015 consequence classes.

Class	Example Structures	Expected Number of Fatalities	Fire Resistance without Sprinklers [min]			Fire Resistance with Sprinklers [min]		
			Resi.	Office	Retail	Resi.	Office	Retail
1	Low-rise buildings where only a few people are present	0	0	0	0	0	0	0
2	Smaller buildings and industrial facilities	<5	90	30	60	15 *	15 *	15 *
3	Most residential buildings, larger and hazardous industrial facilities	<50	210	75	90	115	30	60
4	High-rise buildings, grandstands, etc.	<500	300	120	150	210	90	115

* Nominal value introduced to mitigate common mode failures.

It should be acknowledged that these consequence classes are for 'normal' situations, i.e., for application in ambient temperature design. As such, they represent the potential loss of life associated with a structural failure under normal service conditions and not an accident. This means any consequence reduction factors, such as evacuation of a building upon realisation of a fire, are not considered. However, the consequence classes serve to tentatively illustrate how the principle of relative (marginal) lifesaving costs can be applied to derive risk-informed fire resistance ratings for structures.

7. Conclusions

Fire resistance ratings have traditionally been adopted to ensure that buildings can withstand fires. In the past, these ratings were based on the amount of fire load in a building, but these have since been ratcheted with time to increase safety levels based upon the collective experience of the profession. This means that the safety levels for a building in case of a fire are not always clear to the designer and are not readily quantified. There is an increasing need to use resources wisely and to demonstrate what safety levels are achieved. This requires explicit consideration of the balancing of the cost of materials used to protect a building versus the potential damage in the uncertain event of a fire. This paper suggests a way to calculate fire resistance ratings for buildings based on the potential consequences of a fire, such as the number of fatalities that could occur, by making an explicit connection to reliability targets.

In considering fire resistance periods based upon existing consequence classes and associated reliability indices, it is highlighted that the life-time cost-optimisation process considers damage beyond just that related to the health and safety of those in or around a building. Reliability indices in EN 1990, the JCSS Probabilistic Model Code and, by extension, ISO 2394:2015, make allowance for material damage and the cost of reconstruction of a building in considering how the utility of a structure should be maximised over its life. This leads to fire resistance ratings presented in Section 6.1 that, to a large extent, extend beyond just life safety considerations, but also those of property and asset protection. Based upon these results, in benchmarking against design guidance and codes adopted in England, it can be concluded that, at least for common building situations, the fire resistance periods recommended generally surpass the minimum expected for life safety. This is particularly the case where sprinkler protection is included.

A separate consideration of fire resistance periods under life safety only demands has been presented in Section 6.2. This applies the principle of relative (marginal) lifesaving costs, where the value in increasing the life expectancy of occupants is assessed using the life quality index and the associated SWTP metric. Based upon this, for normal safety investment costs, it has been shown that generalised reliability indices can be derived in function of the number of potential fatalities in the event of structural failure. In a fire context, these are adapted through consideration of the probability of a structurally significant fire. Based upon these principles, it is tentatively shown that fire resistance periods for some lower-rise buildings could be substantially optimised where sprinkler protection is provided. However, this does introduce the prospect of common mode failures, where ineffectiveness of the sprinklers leads to instability of the structural system in the event of fire. Therefore, there is merit in providing a minimum fire resistance to all sprinkler protected structures to address any such problems. Very tall buildings, i.e., those defined as Consequence Class 4 in ISO 2394:2015, could warrant higher fire resistance periods versus those recommended in current guidance and codes. However, these are arguably uncommon building situations and, therefore, fall outside of the scope of such guidance regardless.

In considering risk-informed fire resistance periods for buildings that are cost-optimised, whether it be through predefined safety targets in ISO 2394:2015 or through the application of the relative (marginal) lifesaving costs principle, it is apparent that an estimate of the potential fatalities is required in the event of structural failure. Such an estimate is not trivial and will be a function of the fire strategy of a building, i.e., considering its evacuation mode and duration of evacuation period, the provisions for fire and rescue service access and, also, the proximity of a building to other buildings/areas of assembly. Unlike ambient temperature reliability targets, it is generally the case that the fire induced failure consequences of a structure are reducing with time from ignition as occupants in most building types evacuate upon being alerted of a fire. This means some transient consideration of failure probability is warranted, with tentative studies presented elsewhere [36] which warrant revisiting and deeper consideration.

The exact values arrived at herein in terms of fire resistance recommendations are linked to the statistical parameters underpinning EN 1991-1-2, as presented in the Natural Fire Safety Concept Valorisation Project. These are adopted on the basis of them underpinning normative harmonised standards; nevertheless, it is likely that they warrant review and changes to these values would have an impact on the figures presented in this paper.

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