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Safety factors: can they be inherently captured in modelling assumptions? A short scoping study

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Introduction

When considering a building design from a performance-based perspective, it is common for fire engineers to carry out an available safe escape time (ASET) vs. required safe escape time (RSET) analysis. For a given situation to be demonstrated to achieve an adequate level of fire safety, then it is often expressed in the form:

$$\mathrm{ASET} \geq \gamma(\mathrm{RSET})\text{; or alternatively} \qquad (1)$$

$$\frac{\mathrm{ASET}}{\gamma} \geq \mathrm{RSET} \qquad (2)$$

where γ represents some form of safety factor. The safety factor should not be confused with the safety margin, which is equal to the ASET less the RSET.

As discussed by Notarianni and Parry [1], safety factors can either be implicit or explicit. Implicit safety factors may take the form of conservative assumptions and input parameters, or in the definition of ‘reasonable worst-case’ fire scenarios. In contrast, explicit safety factors are multipliers applied either to input parameters or to the final outcome criteria, where the latter approach is indicated as γ in Eqn. (1) and (2). Typically, the purpose of a safety factor is to counter uncertainties within the steps of a calculation or simulation [2], where these uncertainties can relate to input parameters and their interaction, the selected calculation methodology, potential unknowns in the design, the ability of the model to reflect reality, etc. The magnitude of the safety factor will also be a function of the residual risk that is deemed adequate, with the residual risk representing the remaining risk quantity after the impact of any risk controls has been considered. It would therefore be expected that a lesser residual risk will correlate with a larger safety factor for the same inputs, models, etc. However, the safety factor is often determined by the engineers’ subjective judgement [3] or guided by the collective experience of the profession [4], in the same way that a ‘reasonable worst-case’ scenario may be defined. The selection of a safety factor may therefore appear somewhat arbitrary, with recommended values ranging from 1 up to 4 [5] depending on the application, jurisdiction and the judgement of the author(s) or committee(s) making the original recommendation. In the absence of a full quantitative risk assessment (QRA), and without explicit safety targets and a clear definition of what defines an adequate residual risk, it may be hypothesised that one of three approaches could be taken with respect to safety factors in deterministic fire engineering analyses:

- **Approach 1:** The engineer attempts to define a fire scenario which represents a more ‘typical’, ‘average’ or ‘characteristic’ situation (or a ‘reasonable’ upper bound of such a situation) and then subsequently applies an arbitrarily defined but ‘high’ explicit safety factor to capture the potential range of uncertainty.
- **Approach 2:** The engineer implicitly embeds the safety factor in their selection of distributed / stochastic variables, i.e. through the selection of appropriately high or low percentile inputs, and adopts a ‘low’ safety factor or omits the safety factor altogether.
- **Approach 3:** The engineer combines both approaches by adopting high / low percentile inputs as well as applying a ‘high’ safety factor, i.e. a combination of both implicit and explicit safety factors.

While the last option is the most ‘conservative’ approach, it may be argued that it is unreasonable from a design perspective and will result in a process that is effectively the ‘double counting’ of safety factors. Related to this point, the International Fire Engineering Guidelines [6] states that safety factors should only be applied at the end of a calculation and not throughout as it could lead to an ‘over conservative’ outcome.The increase in the demonstrated safety level will usually correspond to an increase in project cost, where beyond a certain threshold this increase will be disproportionate to the safety benefits and thus could represent a potential misallocation of resources (i.e. a net dis-benefit to society) [7]. In some cases, the ‘double counting’ of safety factors may result in a design target which is impractical, bordering on unattainable, resulting in a residual risk far beyond what might be considered 'as low as is reasonably practicable' (ALARP).

The true resolution to this question is complex, requiring explicit safety targets for fire safety design to be defined, which is well beyond the scope of this article and has been discussed in detail by others [4], [8]. Nevertheless, in the absence of these explicit safety targets, it is worth considering the impact of the above three approaches on the demonstrated level of safety of a reference case. The article therefore details an illustrative ASET assessment for a simple, exemplar building enclosure, determining the ASET from both a deterministic and probabilistic perspective. By generating a continuous output distribution of possible ASET values for a given building situation, the three deterministic approaches specified above are compared to examine where they sit on what is intended to be a full spectrum of possible ASET outcomes. However, the authors acknowledge that the probabilistic approach does not eliminate all uncertainty and a lesser degree of uncertainty will remain within the selected distribution functions, the adopted modelling methodology, model uncertainties, etc.

While the article focusses exclusively on the ASET, it is important to note that the same debate over uncertainty and safety factors is applicable to the RSET, with PD 7974-6:2019 [2] stating that "to allow for uncertainties within each step of calculations application of a safety factor ought to be considered".

Exemplar building enclosure and fire safety provisions

The exemplar building considers a single storey floorplate of an office. The office enclosure is 50 m long by 30 m wide by 2.8 m high. The enclosure incorporates 75 m^2 of glazing (5% of the total floor area), with 20 individual windows which are each 1.5 m high by 2.5 m wide (the sill of each window is positioned 1.0 m from floor level). The building is afforded an ordinary hazard group 3 (OH3) sprinkler system designed to BS EN 12845:2015 [9]. Sprinklers are spaced at 4 m apart with 'quick' response pendent heads, achieving an assumed response time index (RTI) of 50 $m^{½}s^{½}$, a conductivity factor (C factor) of 0.8 $m^{½}s^{½}$ and a specified activation temperature of 68 °C [10] (assuming a typical 20 °C ambient temperature). A sprinkler offset of 50 mm (relative to the ceiling) has been adopted, based on previous model calibration studies carried out by Hopkin and Spearpoint [11]. When in operation, the sprinklers are assumed to achieve a water spray density of 5 mm/min [9].

The wall and ceiling surfaces are assumed to be lined with 15 mm thick gypsum plasterboard with surface properties from Hopkin et al. [12] while the slab is 100 mm thick concrete with properties from BS EN 1992-1-2:2004 [13].

Modelling methodology

To determine the ASET output distribution, fire and smoke modelling has been carried out using the B-RISK [14] zone modelling software, version 2020.03. The enclosure dimensions and simulated heat release rates (HRRs, discussed later) sit within the recommended bounds of TR17 [15], suggesting that a zone model is an appropriate assessment tool for the given fire and enclosure size. The fire has been simulated with an undisturbed axisymmetric plume.

The ASET is considered to be the point in time when the smoke layer descends below 2 m from floor level and the visibility is shown to be less than 10 m [2] for light reflective signage. Due to the large volume of the enclosure, the onset of untenable conditions from visibility is shown in the simulations to occur prior to that of downwards heat radiation (from the upper layer temperature) and convective heat exposure.

The modelling considers both the likelihood that a sprinkler successfully 'controls' a fire, where the HRR is capped upon the activation of the first sprinkler head, as well as the likelihood of suppression, where the HRR decays following sprinkler activation. For suppression, B-RISK adopts the decay model of Evans [16] for unshielded furniture fires.

The possibility of window breakage has been incorporated into the simulations using the glass fracture model within B-RISK, which is based on the work of Parry et al. [17]. However, it has been observed within the simulation outputs that, given both the size of the enclosure and the inclusion of sprinklers, window fracture does not occur in the majority of cases and never occurs prior to the onset of untenable conditions (the ASET). A low-level vent area has been incorporated into the geometry as a 1.5 m^2 opening (1.5 m wide by 1.0 m high), estimated from construction leakage for walls, floors and windows using data from BS EN 12101-6:2005 [18].

Two deterministic modelling 'approaches' have been adopted, alongside a series of probabilistic simulations. Approach 1 adopts 'average' input parameters derived from distribution functions in the literature and Approach 2 adopts what are considered by the authors to be 'reasonable worst-case' high / low percentiles (and broadly representative of a more 'standard' ASET approach). A third approach, which has been discussed in the introduction, is inherently captured by Approach 2, where the safety factors are post-processed and are discussed further in the results section.

For the generation of the probabilistic output distribution, the Monte Carlo method has been applied for 8,000 iterations. PD 7974-7:2019 [19] outlines a calculation method to determine an adequate number of iterations, recommending a coefficient of variation (V) below 0.05 for a given percentile. Adopting a limit of $V \leq 0.05$ indicates that the 95th percentile of the distribution could be reasonably interrogated.

Input parameter assumptions

Table 1 provides a series of input parameters for fire and sprinkler properties. Shown in Table 1 are representative parameters for 'Approach 1' and 'Approach 2', defined previously, as well as the probabilistic distribution functions for these parameters.

Approach 1 generally adopts the mean, modal or median values, derived from the specified distribution functions. Approach 2 represents high / low percentiles based on the judgement of the authors (relative to the distribution functions shown) and is considered broadly representative of input parameters which may be adopted by fire engineers in the UK, although invariably there will be some debate and disagreement in places. In some instances, lower percentiles have been adopted as they represent a less favourable input in the context of the analyses, such as where a lower heat release rate per unit area (HRRPUA) for a given HRR would result in a greater fire area and thus a greater estimation of perimeter entrainment [20].

All distribution functions are informed by the referenced literature or guidance-based calculations, except for the elevation of the fuel bed from floor level, which has been arbitrarily selected (with no known literature available to the authors). For Approach 1, an elevation of 0.5 m has been selected in line with the recommendations of the New Zealand verification method C/VM2 [21].

Where multiple resources are known for the distribution functions, the authors have attempted to select the more 'conservative' option. For example, the fire growth rate has been selected from the work of Nilsson et al. [22] when, in contrast, recommended distributions by Hopkin et al. [23] and Holborn [24] would estimate substantially slower fire growth rates. There is frequent debate in fire and smoke modelling around the selected soot yield, with a design soot yield of 0.07 kg/kg adopted herein for Approach 2, while 0.1 kg/kg is often quoted in industry. It is important to note that a 0.1 kg/kg yield is inherently captured in the soot yield distribution function derived from Robbins and Wade [25], [26], representing a 97th percentile.

The deterministic approaches assume that the sprinklers successfully control the fire, and therefore the maximum fire area and HRR has been specified in Table 1 at the time of sprinkler activation, where these values have been obtained from the simulations. For the probabilistic model, the initial inputs for the maximum fire area and HRR are specified assuming an absence of sprinkler involvement, with the performance of sprinklers being dependent on the discrete probabilities (i.e. likelihood of operation and extinguishment). The distribution function for the maximum HRR has been estimated using a combination of the HRRPUA and maximum fire area.

The distribution function for the radial distance has been determined using the principles given by Fraser-Mitchell and Williams [27], by applying the Pythagorean theorem for an equidistant maximum sprinkler spacing of 4 m specified previously.

For the purposes of this scoping study, certain input parameters have remained fixed throughout for reasons of brevity. These parameters include the sprinkler RTI and C factor, discussed previously. Fixed values of 20 MJ/kg and 0.35 [21] has also been used for the effective heat of combustion and radiative fraction, respectively. The simulation time for each Monte Carlo iteration has been capped at 3600 s (60 min).

Table 1. Fire and sprinkler input parameters.

Parameter	**Approach 1** ***'Average'***	**Approach 2** **[percentile]** ***'High / low percentiles'***	**Distribution function**	**Refs.**
Fire				
Duration of incipient stage [s]	101	0 [0th]	Normal mean = 101, std dev = 26.9	[28]
Fire growth rate [kW/s^2]	0.011	0.0117 [73rd]	Lognormal mean = 0.011, std dev = 0.017	[22], [29]
Soot yield [kg/kg]	0.027	0.07 [95th]	Lognormal mean = 0.027, std dev = 0.03	[25], [26]
Maximum fire area [m^2]	1.1*	2.2*	Lognormal mean = 9.3, std dev = 38.1	[24], [30]
HRRPUA [kW/m^2]	400	255 [21st]	Uniform min = 150, max = 650	[31]
Maximum HRR [kW]	440*	570*	Lognormal mean = 3770, std dev = 14,520	[-]
Elevation of fuel bed [m]	0.5	0 [0th]	Normal mean = 0.5, std dev = 0.6	[-]
Sprinklers				
Radial distance [m]	1.95	2.8 [100th]	Triangular min = 0, max = 2.8, mode = 1.95	[-]
Sprinkler-controlled [-]	Yes	Yes	Discrete p = 0.91	[19]
Suppressed [-]	Yes	No	Discrete p = 0.69	[32]

* Determined at the time the fire becomes sprinkler-controlled, i.e. when the sprinkler first actuates. Percentile therefore not stated.

Results

Figure 1 presents the complementary cumulative distribution function (CCDF) of the ASET, as determined by the B-RISK probabilistic zone modelling. Also marked on the CCDF of Figure 1 is the outcome of different deterministic approaches with explicit safety factors of 1.5, 2 and 4.

It can be observed for this specific exemplar that Approach 1, with no inclusion of an explicit safety factor, achieves an ASET of 36.4 min, with an 84% likelihood of a lower ASET. Approach 2, with an implicit safety factor, produces an ASET of 9.9 min (9% likelihood of a lower ASET). Approach 1 therefore results in an ASET which is approximately 3.7 times greater than Approach 2 when an explicit safety factor is not included. This would indicate that, for this exemplar, a safety factor in the region of 3.5 to 4 would need to be applied to Approach 1 to achieve an equivalent level of demonstrated safety to that of Approach 2.

Approach 3 takes the ASET as estimated from Approach 2, with its implicit safety factor, and applies an additional explicit safety factor. It is shown that if an explicit safety factor greater than 1.5 is applied, then this generates an ASET which is lower than the estimated range of possible outcomes, i.e. the residual risk associated with the design would be zero.

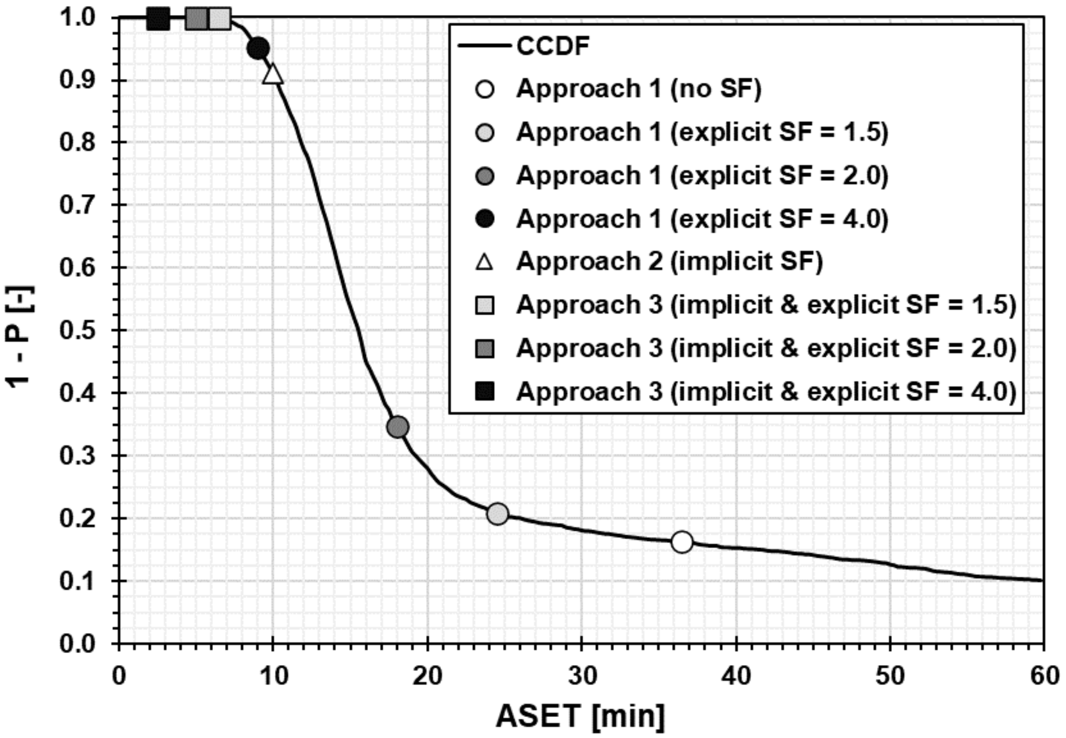

Figure 1. CCDF for the ASET and different safety factor (SF) approaches.

Discussion and conclusions

The article presents the probabilistic modelling of a single, exemplar office building enclosure. The aim is to illustratively compare different methods in which safety factors can be incorporated into fire engineering assessments and the indicative implications for the achieved safety level.

There is an initial indication that the adoption of informed but 'conservative' inputs, i.e. implicit safety factors, will likely produce an ASET which sits towards the lower bound of possible outcomes (only a 9% likelihood of a lower ASET, in this case), where it may be argued that this outcome is sufficiently representative of a 'reasonable worst-case' scenario. In contrast, adopting 'typical' mean, modal or median values from distribution functions is shown to require the application of a safety factor in the range of 3.5 to 4 to achieve a similar level of demonstrated safety. The study also appears to indicate, for the specific case evaluated, that applying a safety factor to a scenario which already has inherently conservative inputs (implicit safety factors) can result in an ASET which is lower than the range of possible outcomes, signifying zero residual risk and a potentially unrealistic safety target. Some engineers may contend that this is a reasonable approach to take as, particularly in fire engineering design, 'more conservative' is often be equated with 'better'. However, the aim of fire engineering building design is not to achieve absolute safety and attribute a residual risk of zero to building occupants, but instead to achieve an 'adequate level' of safety. Engineers are ethically obliged to maximise societal welfare under the constraint of finite resources. This principle is bound in wider health and safety law, where the common ALARP concept states that further investment in safety measures are not required where the costs are out of proportion with the benefits. Further, many aspects of fire engineering design guidance operate on an adequate tolerance of failure, for example where structural fire resistance ratings provided in BS 9999:2017 [33] for given ventilation conditions are calibrated on the basis of a 20% failure likelihood for an 18 m tall office building exemplar [34], in the event of a structurally significant fire.

It is important to acknowledge that there will always be a degree of uncertainty in the selected inputs, distribution functions, applicability of the methodology, modelling tool, building design, etc. There will also be uncertainty relating to the interaction of different parameters, such as where a slower growth rate and lower soot yield could result in a slower smoke detection time (and thus a greater RSET). However, engineers must make a judgement based on the best information available to them at the time. When undertaking deterministic analyses without known safety targets, it appears that this judgement may be better placed in attempting to select informed but conservative input parameters to capture scenario uncertainty than through the post-processing application of arbitrary safety factors.

This paper only outlines a brief scoping study for a single exemplar office enclosure, focussing on the ASET. The authors intend to undertake further work in relation to both explicit safety targets and what this means for ASET-RSET analyses, as well as potentially considering a variety of different building designs using probabilistic fire and smoke / evacuation modelling similar to that illustrated in this article.

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