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Cadena, J.E., McLaggan, M. orcid.org/0000-0002-4173-5615, Osorio, A.F. et al. (2 more authors) (2022) Maximum allowable damage approach to fire safety performance quantification. Fire Safety Journal, 128. 103537. ISSN 0379-7112

https://doi.org/10.1016/j.firesaf.2022.103537

Maximum Allowable Damage approach to fire safety performance quantification

Jaime E. Cadena[a*], Martyn McLaggan[b], Andres F. Osorio[c], Jose L. Torero[d], David Lange[e]

[a]The University of Queensland, Crn Staff House rd, St Lucia, QLD, Australia, je.cadena@uq.edu.au

[b]The University of Sheffield, Sheffield S1 3JD, United Kingdom, m.s.mclaggan@sheffield.ac.uk

[c]The University of Queensland, Crn Staff House rd, St Lucia, QLD, Australia, a.osorio@uq.edu.au

[d]University College London, Gower Street, London, UK, j.torero@ucl.ac.uk

[e]The University of Queensland, Crn Staff House rd, St Lucia, QLD, Australia, d.lange@uq.edu.au

*Corresponding author, je.cadena@uq.edu.au

Keywords: fire performance quantification, fire risk assessment, risk acceptance, probabilistic risk assessments

Abstract:

Risk assessments are used to inform decision-making in hazardous systems. The process involves highly technical steps such as quantifying uncertainty and it is typically carried out by subject matter experts with a robust engineering background. The process also involves value-loaded steps such selecting the risk acceptance criteria for evaluating the risks. In the built environment, risk assessments support performance-based design and of late, these have been increasingly framed as the preferred option to quantify and demonstrate adequate fire safety performance. This argument is supported by the assumption that risk is an adequate proxy for fire safety goals. The present work puts forward a counterargument, stating that fire safety performance should be mainly defined as a function of fire consequences, avoiding the use of fire risk assessments as a proxy to fire safety goals. An alternative fire risk assessment methodology is introduced based on the concept of maximum allowable damage, which is exemplified in a combustible façade residential building case-study. The methodology presented here aims at building upon the knowledge and tools of fire safety engineering to obtain more trustworthy risk assessments and therefore attain a safer built environment.

1 Introduction

The application of Fire Safety engineering (FSE) to the development of performance-based fire safety design has emerged, in the last four decades, as an alternative for building and infrastructure designers to move away from compliance based on adherence to rule-based (prescriptive) construction codes towards compliance based on evidenced performance [1]. Performance-based assessments can be typically done employing deterministic or probabilistic methods [2]. In FSE, as in other engineering disciplines dealing with complex problems, deterministic methods focusing on phenomenological modelling have been found to be lacking in: precision, certainty, robustness and completeness [3]. Thus, the limitations of deterministic methods have encouraged the use of probabilistic assessments. Responding to this, performance-based guidelines for FSE identify probabilistic risk assessments (PRAs, also known as probabilistic safety assessments – PSAs or quantitative risk assessments - QRAs) as a possible tool that can be used to demonstrate acceptable performance. Watson [4] provides a comprehensive analysis of what probability represents in the context of a PRA, based on the different accepted theories of probability. None of those theories support defining probability as an indisputable source of truth. Instead, Watson concludes that under the limitations imposed by the existing theories of probability, PRAs' output should be handled not as proof of safety for compliance (using a pre-determined risk threshold), but as one element of evidence that can inform relevant stakeholders in order to make a decision, e.g. choosing a design alternative. Therefore, PRAs can be used to identify hazard scenarios, to produce risk metrics for specific failure modes and to estimate consequences. These variables will then serve to inform decision making.

The performance of infrastructure in the event of a fire depends on building design and variables associated to its purpose and use such as fuel load. Performance is also dependent on the fire safety features implemented during the design and build. Therefore, the response of infrastructure strongly depends on all these elements. Failure modes triggered by fire effects and the associated reliability data of fire safety measures are extremely difficult to capture as they depend on periodic inspection, maintenance and testing. For fire safety engineering design, reliance on these ongoing processes after handover is fraught with complexity. As concluded by Hackitt [5] and Shergold-Weir [6] when reviewing fire safety in the building sectors in the UK and in Australia, respectively, these activities are often not ensured by current FSE design approaches or regulatory frameworks. Thus, the information extracted from a PRA has to be caveated by all these issues and interpreted in a careful and bespoke manner. Nevertheless, a common approach to overcome the challenges of implementing a PRA is to adopt a mechanistic and highly structured approach, a sort of recipe. Such a mechanistic use of PRA's to demonstrate compliance, rather than to inform all relative stakeholders [7], could therefore unintentionally direct FSE practitioners to misuse this tool. This would perpetuate the issues identified by Hackitt [5] and Shergold-Weir [6].

Whether deterministic or probabilistic, risk assessments are typically undertaken as a positivist endeavor, implying that 1) problems are tractable and 2) a 'true' underlying value of risk exists. Due to the inherent limitations of all models, subjectivity and biases are unavoidably embedded in risk assessments, just as value judgments are prompted by their results when reviewed by decision-makers. Whether a 'true' value exists or not, it is not feasible to determine, starting with the fundamental issue of what 'risk' means. In the context of FSE, biases and subjective judgments play a key role in defining architectural and structural features of a building as well as the fire protection features incorporated, i.e. they influence the future fire safety performance. Such an influence cannot be eliminated but should be considered and managed through the risk assessment process in order to propend towards a safer built environment. This poses two problems: defining what we mean when we talk about 'risk' and defining whether the risk assessment will be approached within a positivist or a constructivist framework. Solberg and Njå [8] make it clear that risk is a concept that allows us to choose from a myriad of possibilities that can be realized depending on our choices, but it does not exist on its own and require interpretation, i.e. it is inherently subjective. In practical terms, each individual or organization needs to define how they judge and choose the possibilities associated to a range of choices, i.e. define what risk means to them. The authors believe that a reasonable starting point is understanding risk as a function of possibilities (scenarios), the uncertainty associated to them being realized (chance) and the effects these produce on something of value (consequences), underpinned by the available knowledge of those involved in assessing risk (assessor's knowledge); this is very much aligned with the definition put forward by Aven [9], which was originally proposed by Rosa [10]. The latter problem has been a part of the rich and complex discussions about the philosophy of science, which are beyond the scope of this manuscript. Defining the preferred framework to work is a task of the stakeholders, albeit informed by knowledgeable assessors, realizing that ultimately there is no 'right' framework. Taking a pragmatic perspective in the context of fire safety engineering, a positivist approach as previously mentioned is well suited for individuals and organizations dealing with well-defined problems that can be decomposed into simpler problems which can be addressed individually to then obtain an overall answer. This approach is meant to be free of subjective judgments and uses the scientific method as its bastion. However, reality is far from being free of subjectivity and value judgments, and the process of making judgments about choices and possible resulting futures (i.e. risk assessment) is not an exception even when the 'ideal' assessors are engaged (who is an ideal assessor?). Fire safety engineering cannot be free of value judgments as the choices it identifies and recommend following can have major consequences on all stakeholders, including building occupants and society more widely. Removing all value judgments from fire safety engineering would put the practice in a fictitious context where the consequences of a choice will not be fully understood. Therefore, the authors recognize that even when fire risk assessments are carried out from a strictly positivistic approach, their outcomes need to be interpreted through a constructivist lens. Doing this is also beyond the scope of this paper, yet some of the elements introduced in the methodology that will be proposed are tools to facilitate the necessary value judgments.

In considering the need to weigh in these value judgments and the inherent limitations associated to modelling fire behavior, an alternative fire risk assessment methodology is proposed in this manuscript. The methodology, namely the Maximum Allowable Damage (MAD), provides a framework to construct a representation of fire performance and judge whether it is acceptable or not. In doing so, MAD seeks to identify, and effectively communicate, the important subtleties of fire safety engineering assumptions and their potential impact on overall fire safety. Importantly, MAD was conceived as a consequence-driven risk assessment methodology which focusses on the inherent risk of a building as a means of drawing attention to the consequences of a fire as opposed to the likelihood.

In order to capture the subtleties of the assumptions underlying fire risk assessments, MAD introduces two key concepts Strength of Knowledge (SoK) and insensitivity. Strength of Knowledge (SoK), introduced by Khorsandi and Aven [11] in the context of risk assessments for Nordic oil & gas operations. SoK is used in MAD as a tool to identify robust assumptions that are likely to hold throughout a building's life cycle, as well as those that do not. The latter are of particular concern as they could lead to poor fire safety performances and endanger occupants and property. Is insensitivity, or the inverse of sensitivity, judges how easily the quantified fire safety performance changes in response to changes in a particular input. The combination of these two concepts provides a powerful tool to screen out assumptions and inputs that require further support through either research or more detailed consideration.

Section **Error! Reference source not found.** details how the subtleties of fire safety engineering might not easily be captured by PRA despite its robust methodology. These limitations are used as a basis to formulate a path forward for fire risk assessments (section **Error! Reference source not found.**). With this pathway in mind, MAD (section 4) is put forward as a potential methodology that focuses on understanding the damage potential of a fire and evaluating it against a consequence acceptance criterion. This novel approach is exemplified through a comprehensive implementation to a case-study with highly topical and challenging components, a high-rise residential building with a combustible façade (sections 5 and 6). Finally, the authors reflect on the limitations of the status quo for fire risk assessments and a set of conclusions (section 7).

2 Deterministic analyses

A deterministic analysis is one in which the same inputs will always produce the same outputs. It is characterized by using fixed quantities for the inputs, in lieu of ranges or probabilistic distributions which are to be sampled either in a structured or a random way. A deterministic approach requires selecting fixed values for variables and parameters which might have varying degree of supporting knowledge and represent different degrees of conservatism. Thus, the fixed variables can be boundaries within a range, conservative or characteristic values. These fixed values could be seen as a conservative sample from a probabilistic distribution, but they are explicit and can be challenged openly. This is not the case with inputs for probabilistic analyses using stochastic quantities. In the context of safety science, deterministic analyses are employed to gain detailed insight on the consequence component of risk [12]. This is consistent with the need to understand and manage consequences in FSE.

There are parameters and variables in the context of FSE for which the possible range of values is unknown. Such situation would trigger the need for developing further knowledge, for example through research. In cases where the ranges are known, it is a challenge to choose what value is conservative or onerous enough. However, a risk assessment is not concerned with selecting a 'correct' value, but with gaining useful insight. It is the process of understanding the system at hand, selecting conservative values (where needed) and iterating them as required that produces useful insight. This is exemplified later on in the case study (section 6), where feasible and onerous values are not necessary given an already unacceptable performance.

As discussed in detail by Paté-Cornell [13], deterministic analyses focused on consequences can provide adequate support, particularly when the range and probability distribution of key variables are unavailable, as is often the case in Fire Safety. Both in probabilistic and deterministic analyses, it should not be the point to run the analyses for its own sake, but to gain insight and this is only feasible by understanding the inputs and their values, as well as the underlying assumptions and the models used. Therefore, a deterministic risk assessment could help describe the possible upper limit for consequences in a particular risk.

Deterministic analyses are the basis for implementing an inherently safe design. Trevor Kletz proposed this concept for chemical process safety, having the minimization of the consequences as the main design driver. In inherently safety design, the specification of the design parameters and operating conditions are done as a function of the consequences, if the consequences are unacceptable the best solution might be removing the hazard from the process. Such an approach decreases the reliance on additional layers of protection and their timely and effective action. Gomez et al. [14] provide a simple example of this design philosophy for a simple pressurized vessel storing flammable gases.

Although inherently safer design is a recognized key element of the design process in hazardous industrial processes, it is conspicuous in its absence in fire safety design. In the absence of inherently safer design as a key driver of the design process, the inherent performance of a building (i.e. without safety measures beyond the bare-bones design) has significant potential to be unacceptable. Understanding fire safety performance as a function of the consequences can therefore help to identify features of a building which can lead to consequences in the event of a fire that are clearly unacceptable and require treatment. Scenarios can be identified and the potential consequences determined, enabling an estimation of what the Maximum Damage Potential for the building is. This Maximum Damage Potential can then be reduced through design decisions until an acceptable threshold is reached.

The output of implementing the inherently safer approach to FSE can give confidence that objectives such as life safety can be achieved. An approached based on frequency estimates might be use to argue compliance, nevertheless, will not necessarily achieve the objective. An inherently safer approach leads to understanding both the initial and residual damage potentials of the system, and then to introduce necessary design features or safety measures that enable an adequate performance. The need for such an approach is not unique to FSE, as Kirchsteiger [12] has presented, deterministic analyses can be used to complement PRA results in nuclear power plants, where *negligible likelihood does not offer adequate compensation for potentially catastrophic consequences*.

3 Probabilistic analyses

Producing trustworthy risk assessment results is typically represented by uncertainty measures or judgments. In engineering disciplines with a mature use of PRAs this is a challenge partly due to the complexity in characterizing random variables used as inputs, which relies on robust statistical data or the need for demanding sensitivity analysis, e.g. testing different probability distribution shapes and parameters. In FSE this challenge is very significant because of the complex nature of the fire phenomena and the impact of the many possible intervention strategies. The impact of all assumptions embedded in the available fire models and the limited statistical data represent a key challenge that will be discussed first in this section.

For a moment, assume that uncertainty margins can be appropriately established and communicated to key stakeholders. At that stage, the risk assessment is finished and its outputs can inform the selection of physical or administrative measures to prevent, control and mitigate fire risk. FSE has a long tradition of developing and improving physical measures that control and mitigate fires. This is self-evident from the contents and structure of building codes around the world. Linking the physical measures to the actual fire safety performance of the design is not self-evident. Although additional layers of protection would instinctively represent an added level of safety, this might not be the case if the fire effects, and the failures these can trigger, are not well understood. This is the second challenge that will be discussed.

3.1 Uncertainty

PRA-related literature from fields where it has been extensively used indicates that establishing and communicating the uncertainty involved in the assessment is a major challenge. No evidence exists to indicate this would be different in FSE. In contrast, the lack of predictive capacity [15] and accuracy [16] of PRAs when applied to fire safety problems has been previously recognized. Magnusson [17] first pointed this out in 1997 and called to apply PRAs from first principles, as data availability was a problem without a clear solution in sight. In a similar manner, in the context of hazardous facilities like nuclear power plants, warnings about poorly characterized uncertainty, the excessive complexity of acceptance criteria and the need to improve transparency in the PRA process have been noted decades ago [18].

The available statistical data for the reliability of fire safety measures like doors [19], smoke detectors [20] and sprinklers [21, 22] for the built environment is highly dependent on both the reporting quality and the conditions under which the data is captured; both of these factors are largely uncontrolled except by the assumption of compliance with the applicable construction code. Sprinkler reliability is extremely high as most frequently assumed in fire safety engineering practice, if the data is presented with sufficient detail represent real life performance. A sprinkler can fail to provide its intended function if: 1) it activates and fails to suppress the fire, 2) it activates but fails to control the fire, or 3) it does not activate. Most often than not sprinklers fail to activate as a result of human error, not because of failure of the equipment itself [23, 24]. This type of failures are then representative as they can impair the sprinkler system and render it absolutely ineffective. Ignoring any of the failure modes would result in a rate that will not reflect the reality of humans interacting with the system (occupants, property managers, contractors, etc.) Taking a failure rate based only on the first rate, as often publicized, would require introducing a significant assumption into an assessment like a PRA, i.e. a >99% probability when the chances of a successful activation can be 7 out of 10. An important reflection is that data recording has not significantly improved since the late 1990s, back when Magnusson [17] carried out initial PRAs in FSE, making his conclusion still current and valid: Data availability and data quality is a huge problem that may obscure the trust on the outputs of a PRA.

Quality and granularity of fire reliability data

Smith [25] describes a best practice to recording failures, which goes beyond failures on demand (as in the case of a sprinkler not working when a fire occurs) and require a detailed accounting of time between failures, associated causes, cost, repair length (if applicable). For safety reliability data used in chemical process, Smith [26] identifies different issues to be considered with existing reliability databases. Despite these data bases having been constructed over decades, they still deliver results that establish failure rates with an uncertainty range of two to three orders of magnitude. Existing fire datasets do not even follow this best practice [27]. Furthermore, fire data does not capture all failure data, but only that associated to a recorded fire further increasing the uncertainty range. It is therefore expected that these data sets will suffer from many of the issues identified by Smith.

Completeness of fire reliability data

Often, guidance documents for fire risk assessments mention the issues of lack of data [28] but seldom discuss the quality of data in existing databases or their sample size. In contrast, in other disciplines the relationship between quality of data and sample size has been discussed extensively, as exemplified in the reliability analysis of autonomous vehicles [29]. Such considerations have not been introduced to judge the appropriateness of data associated to fire safety. In principle, suppliers of safety measures could provide probabilities of failure of sufficient quality to enable their integration into a PRA, however, this is currently not the case. The approach by Klara [29] might give some insight into how to obtain the necessary observation.

Assume that an individual risk value of 1 fatality per 10 thousand years (1×10^{-4} fatalities/year) is taken to define adequate performance. A confidence level (ranging from 50% to 99%) is defined and an assumption made that a building based on this design will not experience a fire while observed. Then, the number of years required for observation of a single building can be estimated based on the binomial distribution and yield the results of Figure 1. For a confidence level of 95%, a single building would need to be observed for 30 thousand years, which makes no sense. An alternative would be observing a thousand buildings based on the same design for 30 years, which although feasible, raises the question of finding a thousand identical buildings. Because buildings have different locations, occupation, regulations, etc and all these variables affect fire safety, finding one thousand building with the same expected fire safety performance is not possible. This simple calculation is meant to show the real challenges of using probabilistic risk criteria in FSE without adequate data supporting it. The reality is that data to support a positivist perspective simply does not and cannot exist.

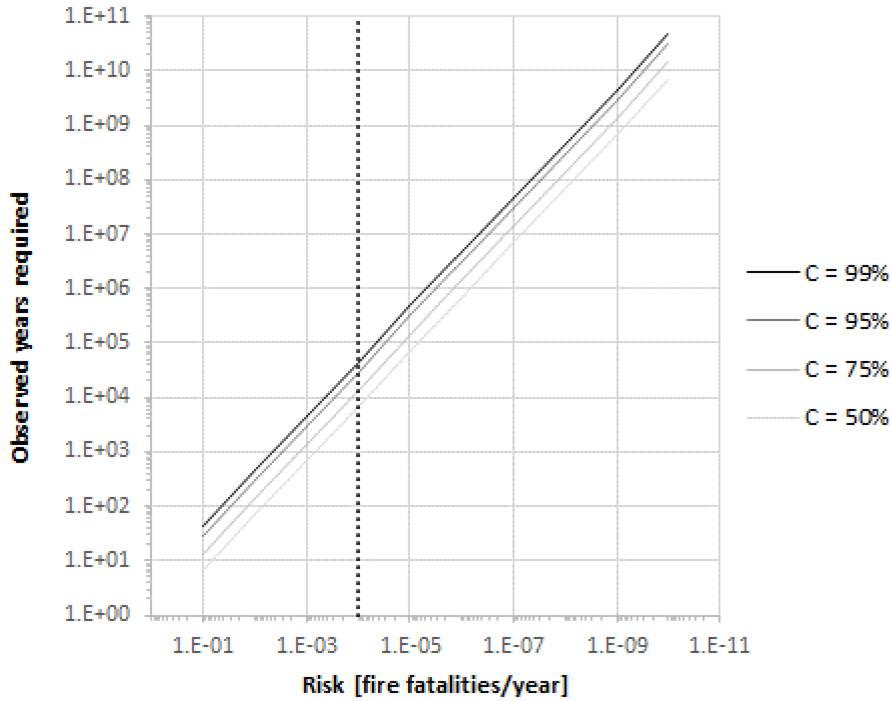


Figure 1. Number of years required for observation for different risk levels

3.2 Safety measures

Most FSE guidelines address fire as a low probability event, nevertheless, when referring to this low probability event, they are already referring to an event of significance. A non-significant fire is a high probability event that will occur somewhere within a building during its usable lifetime, and it is the fire safety design which prevents these from turning into significant fires. Therefore, within the design process of a building it must be assumed that a fire will occur and thus its probability is unity.

That assumption is the fundamental reason behind the fact that all buildings include some level of fire protection measures; and is consistent with prescriptive design. In prescriptive design, safety measures are introduced into a building to prevent a fire from becoming significant or to limit the potential for intolerable consequences of a fire to occur. The extent of these safety measures required is a function of the foreseeable size of the fire and/or the consequences should the fire safety strategy fail. They are never prescribed in response to the perceived frequency of a fire. PRAs are significantly driven by likelihood estimates and so are the safety measures selected to manage the risk measure they produce. This begs the question of how well these estimates convey the information linking failure modes and the consequences they can lead to; if this is poorly conveyed, selecting safety measures becomes a merely utilitarian exercise.

An example of a direct link between failure and consequence is concrete cover as a protection feature. Within a certain range of fire growth rates the concrete cover will remain in place and the probability of failure will be negligible, functioning as intended and yielding acceptable consequences. If the growth rate increases beyond a certain threshold, spalling may be expected and the concrete cover will no longer exist, resulting in the exposure of reinforcements. In this scenario, a different level of damage will be expected. A probability of unity can be assigned to spalling beyond that certain fire growth rate threshold. Using a detailed probability function is not granted given the complex nature of spalling and therefore a conservative step function can be used. The resulting consequences will have to be approximated because of modelling limitations; thus full exposure can be assumed once the growth rate threshold is reached. This and other approximations would have to be done in a rational and deterministic manner and most likely be very conservative.

In contrast, other elements of the fire safety strategy (see Figure 2), while having a specific function aimed at either preventing, controlling or mitigating the effects of a fire, are coupled to other safety features and can create multiple paths of consequence. When looking at each specific component it is important to understand the different manners in which it can affect the damage caused by fires. For example, detection will primarily address the effects on people by establishing the onset of the evacuation process while fireproofing of the structure limits the effect of heat on structural performance. Nevertheless, detection might be called to influence structural behaviour by enabling fire suppression, while fireproofing might support egress by providing a protected means of egress.

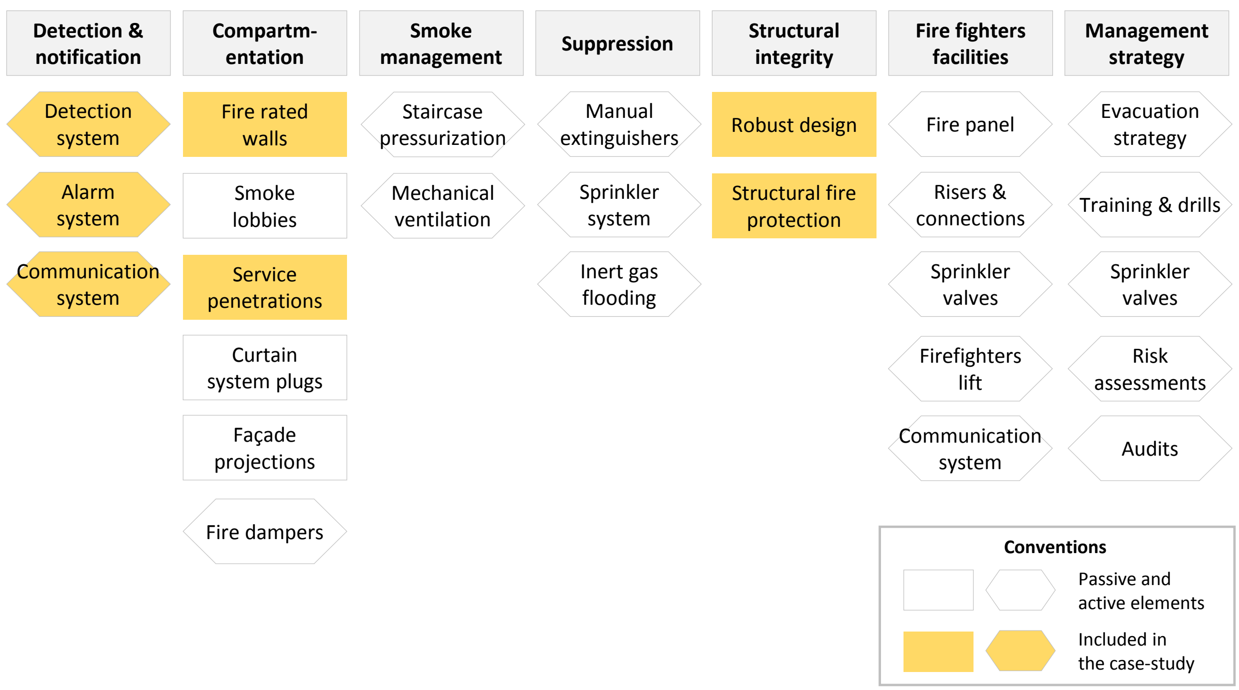


Figure 2. Typical safety features of a fire safety strategy. Highlighted elements correspond specifically to the risk assessment of the case study presented in section 4.

Reliability changes most significantly as a function of the manner in which the fire safety element reacts to the fire. Elements requiring a trigger to work are deemed *active*, while those that work without any triggering action are deemed *passive*. Reliability and availability of active safety elements cannot be ensured and there is evidence for their failure [30], which creates a very real 'potential for surprise' if they fail to provide the required function when needed. In contrast, passive elements have a much higher level of reliability but the effect of their failure on the consequences of a fire can be more significant. The collapse of WTC1 & 2 [31, 32] is an example where dislodged fire proofing was an event of negligible likelihood and which had an extreme effect on the consequences. This event was caused by a preceding event (aircraft impact) that was considered in the structural design of the building but the scenario of the impact effects was not accounted for in the design of the fire safety strategy. Reliability is therefore also a time dependant function that requires frequent reassessment to account for deterioration and new failure modes.

It could be argued that high consequence fires have low occurrence rates, therefore the focus should be on the reliability of safety measures. This seems to resonate with failures in the aviation industry. Downer [33] discusses the strict and independent failure rate required by authorities on components and the responsibility of manufacturers to demonstrate their products meet it, usually through redundant safety measures. Downer [34] draws attention to the use of redundancy as a way to demonstrate acceptance of technological risks and the problems it does not solve. The complexity of problems such as jet aircraft engine failure is such that testing of the engine cannot provide accurate reliability measures thus scenarios that could potentially alter the performance of the engine are also included in the reliability assessment. This is the case of the assessment of bird impact on the performance of an engine by means of an artificial chicken shot onto operating engines; defining the chicken and its impact parameters reflects the same issues mentioned earlier about scenario identification and the impossibility to exhaust them. Downer [34] indicates that acceptance has to address complexity, independence, unforeseen failure modes (as in the case of the Boing 737 MAX [35]) and human factors. Redundancy can be seen as the only way engineering can guarantee a particular result despite the possibility of it failing through unforeseen causes; this poses an important challenge that can be addressed through diversity of design [34]. Such an approach aims at designing redundancies in a way that they are not susceptible to common failure points by using creativity and innovative redundancies, in preference to simpler approaches such as doubling up a particular safety measure.

In FSE, justifying a building design based on the performance of a particular safety measure requires this system being available and reliable when needed, otherwise being backed up by an independent and diverse redundancy. With statistics not guaranteeing reliability and stakeholders pushing for cost reduction, diversity in design is rather an uncommon practice in FSE. Instead, it is not uncommon that performance is dependent on a single safety measure which despite reportedly high reliability is nevertheless subject to failure at a rate that cannot satisfy the required level of safety in a building. This is the case of sprinklers, which are commonly deemed as highly reliable and effective. As shown by Long et al. [36], data on sprinklers shows that in fires large enough to activate them, 1 out of 10 sprinkler systems fail to be effective. Those are significantly concerning odds if the whole adequacy of fire safety performance relies on this single safety measure. One of the key causes for sprinkler ineffectiveness reported by Long et al. [36] is improper maintenance; this is important, as poor maintenance for sprinklers might reflect poor maintenance overall and therefore reduce the odds of a successful redundancy or back up being in place.

4 Maximum Allowable Damage (MAD)

Apostolakis' [37] review of major PRA developments and criticism in the areas of nuclear power and space missions, concurs with many of the pitfalls described in section **Error! Reference source not found.**. Apostolakis also shows how a gradual implementation and evolution of PRAs provide a pathway to manage these pitfalls and turn them into useful outcomes. A robust risk management framework needs to underpin this evolutionary process, conceiving the risk assessment as a process to inform, rather than a mechanism to verify safety. FSE has a long way until scepticism is overcame on the use of PRA (Apostolakis refers to this as Phase 1) and it will not be overcome if the limitations and its potential benefits are not fully understood. This includes acknowledging that no risk assessment exercise compensates for a lack of a clear design philosophy, as well as recognizing that without a good hazard identification the remaining steps of the risk assessment become a futile exercise in number crushing.

The central premise of the methodology proposed here is that a building design has an associated maximum damage potential if a fire takes place. If this potential is characterized it can then be compared against the maximum damage that the stakeholders are prepared to accept, i.e. the maximum allowable damage or MAD. In order to characterize the maximum damage potential, it is reasonable to do it when the design is at early stages and includes few safety measures; in this manner the effect of added-on safety measures can be explicitly quantified. This is akin to the inherently safer design philosophy proposed decades ago by Kletz for the chemical process industries [38]. As in any risk assessment, the scenarios included in the analysis depend on the hazard identification techniques used such as logic (fault/event) trees. An important difference is that MAD acknowledges that fire scenarios are an output rather than an input, as some initial assumptions will evolve in the course of the assessment as partial results are obtained.

Since all engineering models (including risk assessments) are susceptible to unsupported or inadequate assumptions, MAD incorporates a simple feature to keep track of these. Assumptions can be embedded in inputs (e.g. assuming a determined notification time) or as modelling decisions (e.g. the smoke layer will behave as a uniform hot layer). By tracking each input and assumption and judging the evidence supporting them as well as their potential to change the results, an important layer of information is provided to the analysts, the peer reviewers and to the stakeholders. Such layer of information is typically missing even from the most sophisticated risk assessments, despite being typically hoped for in different guidelines [39].

The first outcome of MAD is a quantification of risk, measured as the gap between the maximum damage potential and the maximum allowed. This quantification is complemented by the second outcome, a layer of information regarding assumptions and their potential effect on the results. Effectively this drives the analysts conducting the assessment to continuously identify, judge and challenge their assumptions. Although this process does not guarantee all assumptions are captured or effectively managed, it does provide an explicit approach to judge the quality of a risk assessment. MAD's outcomes are meant to inform stakeholders on whether the damage potential could surpass the maximum acceptable damage, while explicitly accounting for the quality of the assumptions underpinning the assessment, i.e. the trustworthiness of the assessment.

An early version of MAD was previously introduced [40] in which the fire performance of a multi-occupancy office building is assessed. There, fire performance is described as a function of tenability for a given fire conditions and the outputs allow identifying safe operation ranges of spaces where fuel loads are variable and can lead to unacceptable performance (e.g. carpark). Such approach is consistent with Bjelland [7] and delivers both a performance assessment as well as an explicit reporting of the associated assumptions and limitations. The latter provides the basis to judge how reliable the consequence-based performance estimate is to support the decision-making process, i.e. assessment trustworthiness. This idea is aligned with the need for buildings to use the safety case scheme proposed by Hackitt [5], originally used in the chemical process safety field for major hazardous facilities who have to demonstrate that consequences of worst case scenarios are acceptable, whether using an absolute criteria or analysing the damage footprint. Such idea might be interpreted as an exaggerated conservative approach, but actual PRA guidance also include such considerations by setting cut-off thresholds for consequences [39, 41].

To discuss risk acceptance within MAD it is useful to discuss the generalized frequency-consequence diagram proposed by Coile et al. [42], where as a straight vertical line towards the upper end of the consequence axis is of notice. Such limit is found explicitly in some societal risk curves such as Hong Kong's [43] but it is not typically based on an explicit criteria for unacceptable consequences. The vertical limit indicates that tolerability of high consequence events is related to the magnitude of the consequences as opposed to the frequency of occurrence. In such instances, there is no benefit to considering the frequency and thus the only means to demonstrate tolerability is through mitigation of the consequences. This vertical limit in the F-N curve (where consequences are unacceptable regardless of likelihood) is where MAD is meant to be applied, as this boundary should be clearly defined and used as the ultimate acceptability criterion for evaluating fire risk and therefore the proposed design. Understanding whether the design can cross his threshold or not is the driver to bound the inherent risk of the design, and therefore should be done at very early design stages. Once a design is assessed and assuming its performance is acceptable, i.e. the maximum damage potential is below the maximum allowable damage, the remaining areas in an F-N curve can make use of typical QRA approaches to optimize the design as a function of both likelihood and consequences.

4.1 MAD process

The implementation of MAD consists of five steps (see Figure 3) with the main output being a performance assessment stating whether the system's performance is acceptable or not. The first step defines the safety objectives that typically include: 1) ensuring life safety of occupants, 2) reducing direct and indirect losses and 3) providing firefighters with a building that –when burning- will facilitate their operations, as this is their workplace. The Building Construction and Safety Code (NFPA 5000) [44] proposes having goals ("*nonspecific overall outcome to be achieved*" of qualitative nature) and objectives (a "*requirement that needs to be met to achieve a goal*"). In MAD, objectives reflect the desired outcome while also enable defining an acceptance threshold as a function of fire damage, e.g. no exposure of occupants to toxic concentrations.

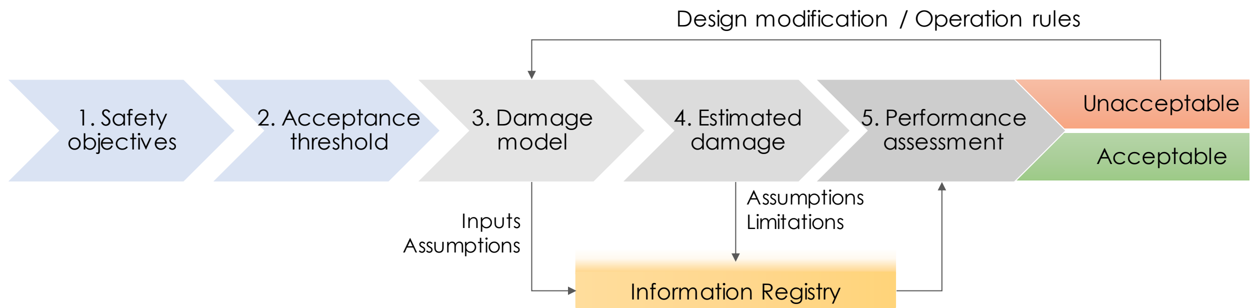


Figure 3. MAD methodology process

The second step is defining the *acceptance threshold*, which is closely related to the maximum consequence that the stakeholders are prepared to accept as described in the discussion of **Error! Reference source not found.**. Most PRA guidance assume that loss will result from the fire occurring, while in MAD the system performance is assessed to understand if the maximum damage potential is acceptable. An unacceptable result would call for design modifications or the reliance on additional safety measures, with the understanding that these can fail on demand and therefore requiring defining the responsibilities for their availability and reliability.

The third step requires constructing a model that reflects the available knowledge of how fire leads to damage in the system. Numerous existing tools can be employed for this purpose including causal diagrams, failure and event trees, failure mandalas [45] and systems thinking as suggested by Bjelland [7]. Deterministic methods can be regarded as simplistic, but they are only so if the abstract representation supporting them is simplistic as well. The damage model effectively reflects the relationships and phenomena taking place during a fire that the assessment will take into account, i.e. provides an initial bound to the scenarios and to the damage potential of a fire. Park et al. [46] exemplifies such complex relations between building and occupants characteristic and although all damage models are inherently imperfect, these are key to successfully achieving the objectives of a performance-based design [47]. In order to provide an adequate bounding to scenarios, the damage model construction must be led by a competent fire safety professional.

The fourth step uses engineering tools to quantify the damage model. In FSE there is a large range of tools to choose from, ranging from empirical correlations or simple tools as the compartment fire framework, all the way to computer fluid dynamics (CFD) and finite-element analysis (FEA) models. Each tool has underlying assumptions and parameters, which should also be incorporated in the information registry for trustworthiness considerations. Using the selected tools and inputs a set of scenarios or system conditions are selected and the damage is quantified.

The fifth and last step evaluates the maximum damage potential against the defined acceptance criteria. If the performance assessment is acceptable, the information registry provides insight on the actions required for the assumptions to remain valid during the lifecycle of the system. In the opposite case, trustworthiness enables identifying and prioritizing the aspects causing and thus understand how to modify the system to obtain a better performance. This approach is consistent with the *design for change* approach proposed by Bjelland [7] and with the holistic approach to fire safety advocated for by Hackitt [5].

MAD could be labelled 'too' conservative if understood as a typical deterministic assessment where inputs are as onerous as possible. This is not the case, as MAD provides a framework to understand the worst possible performance of the system as the first necessary basis for decision-making in Fire Safety

Engineering. Explicitly registering the quantities (and values), models and associated assumptions into the information registry constitutes an explicit log that allows iterating the damage model and improve the trustworthiness of the performance assessment. The registry enables practitioners to reflect upon the limits of their knowledge and the necessary degree of conservatism. As a result, MAD does not just provide a quantification, but a comprehensive insight on fire safety performance and the responsibilities associated to maintaining the conditions necessary for it to remain adequate.

4.2 Safety measures in MAD

The authors acknowledge the role of safety measures in assessing the performance of a building (see section 1). However, fire behaviour is a function of the active or failed safety measures. Assuming a safety measure will be in place and will be effective prescribes the conditions and departs from the intent of performance-based design and from the intended scenario discovery in PRAs.

To understand the performance of the building it is necessary to consider the effect of the active safety measures not being available (e.g. detection, notification, suppression, mechanical extraction). Assessing the building under this conditions allow identifying which of these systems are essential for an acceptable performance. In the case study it is clear that not having a detection system in place would yield an unacceptable performance regardless of the behaviour of any other variables, and therefore it must be ensured to work throughout the life-cycle of the building.

Other safety measures are assumed to fail ($p_{failure} = 1$) and are excluded from the damage model based on professional judgment and existing evidence, e.g. exclusion of suppression systems due to lack of applicable reliability data. Hence, the role of probabilities in MAD is to identify the assumptions required for an acceptable performance and the resulting responsibilities for these to remain valid. This avoids the objective –and temptation- of demonstrating negligible likelihoods. As discussed by Apostolakis [37], the purpose of a PRA is not finding the 'true' value of a risk index, but to reflect uncertainties and prioritize failure modes and scenarios that can inform resource allocation (including further research needs). This point is discussed by Aven [30] in a more pragmatic manner, claiming that PRAs should be restricted to understand the effect of variability in systems under available knowledge.

5 Context to the case study

A high-rise residential building with a layout and façade similar to the Grenfell tower has been selected for this case study. In the case study, the façade of the building was found to be non-compliant due to the flammable hazard it introduces. The aim of implementing MAD to this case study is to understand the damage potential of a fire and propose a remediation strategy for this non-compliant facade. Before introducing the case study itself, it seems necessary to provide context on the topic of façade fires and the large problem they represent across many jurisdictions around the globe.

Largely, the fire concerns associated with façade stems from their dramatic success in increasing building energy efficiency. Such effects is exemplified by the retrofitting of 44 existing buildings in Copenhagen [48] that led to a reduction of the buildings annual energy consumption of between 31% to 67%. Facade systems are significant and relevant solutions as 36% of global energy demand is associated to building construction and use [49].

However, the implications of using combustible materials in a façade are not addressed extensively in FSE. Existing studies use laboratory-scale flame spread to assess tenability in rooms over the fire of origin [50], while others qualitatively describe the complex behavior of the burning façade noting the effect that elements like sealants and tapes have on the overall behavior [51]. In 1990, Oleszkiewicz [52] described the complexities of evaluating flame spread in façade systems, claiming that a full-scale approach is the most reasonable and that escalation from laboratory-scale is not linear. Current design methods [53] and standardized large-scale testing [54] evaluate façades without taking into account key variables like wind loads, installation defects, complex geometries and other factors directly affecting flame spread. Studies exist on particular façade issues like the effect of the insulation layer thickness and [55] but do not provide an overall understanding or measurement of flammability at large-scale. Bonner and Rein [56] point out the usefulness of an index that reflects façade materials flammability, while also highlighting that this is not attainable under current testing protocols.

Considering recent fire events in Australia, Qatar, England, Scotland, China and United Arab Emirates [50, 57] that led to significant human, economic and legal consequences, these systems constitute a major challenge for the built environment, for FSE practitioners and for the FSE discipline itself. Consider residential buildings where combustible materials have been used in facades at a large scale. In Australia there are reports of expected 2000 affected buildings in New South Wales, while in Victoria about 800 privately owned (>400 deemed as 'high risk' [58]) and 400 government owned buildings have been identified [59, 60]. In England the situation is similar, where 155 high-rise residential and public buildings have already been remediated and more than 360 residential buildings remain to be treated (about half of these belong to the social housing sector) [61]. Noticeably, the Grenfell fire embodied the damage potential of a fire involving combustible cladding in a building with a single staircase, an intricate smoke extraction system and a stay-put evacuation strategy. Fu [62] discusses how a compliant building was stuck in time and was not updated to incorporate safety measures that could have helped providing a better performance during a fire. However, design decisions such as the staircase number or key components to compartmentation and redundancies are hard to update and typically will not be justified solely by an economic assessment.

6 Case study

The case study is set in a 20-storeys residential building comprised of a concrete frame and a single core containing the only staircase. Each residential level (levels 1 to 20) has four large and two small flats and a connection to the lift lobby area as described in Figure 4. In the lobby area of each level there is access to the elevators (not suitable for evacuation purposes) and to the emergency staircase, which is the sole evacuation path of the building. The building has an occupancy that can range between 494 people (normal occupancy) and 950 (maximum expected occupancy).

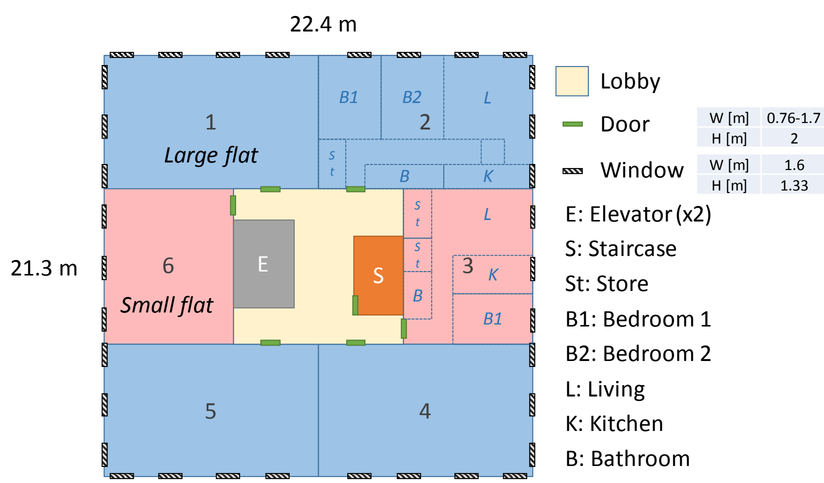


Figure 4. Floorplan for a typical residential level; numbers correspond to each flat

The existing façade system currently achieves a ten-fold reduction of the U-value of the building and significantly increases energy efficiency; at the time this was one of the main drivers for the design of the system. The materials chosen for the façade are Polyisocyanurate (PIR) for thermal insulation (100-160 mm thickness) and a 4 mm thick sandwich panel of aluminum layers with a 3 mm thick polyethylene (PE) core, as presented in Figure 5.

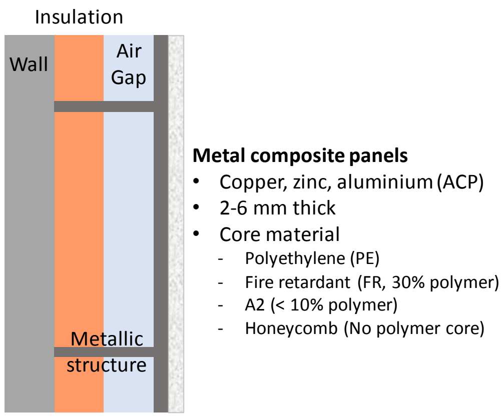


Figure 5. Schematic representation of façade system

6.1 Safety objective

One of the purposes of the building is to provide safe living quarters for the occupants, and installing the façade system introduces hazards that may jeopardize it. Given the combustible nature of the façade system materials (e.g. PE), there is a potential for an internal compartment fire spreading to the building's exterior and affecting the current evacuation plan and overall fire safety strategy. Therefore, the safety objective selected for the risk assessment is ensuring life safety of the occupants when a fire occurs. Structural integrity and fire-service intervention considerations are beyond the scope of this assessment.

6.2 Acceptance criterion

The stakeholders' acceptance criterion for life safety has been set in qualitative terms: with the exception of the flat of origin, the occupants will not be in contact with smoke or fire until evacuation is completed or the fire is fully extinguished. Other acceptance criteria could be envisioned but this one was chosen for clarity, simplicity and because it meets the intent of life safety of almost all building codes. This implies that occupants will have enough time to evacuate before being in contact with smoke or fire. The damage quantification then calls to estimate the available safe egress time (ASET) and the required safe egress time (RSET). ASET refers to the time that occupants have before the conditions in the building are untenable, while RSET refers to the actual time that they need to egress. When the ratio of ASET to RSET is greater than 1 the performance is unacceptable as occupants will be exposed to untenable conditions.

6.3 Damage model

ASET/RSET is made of quantities that reflect the damage potential. Defining each quantity is a complex problem on its own and the approach has recognized limitations [63]. Bjelland [7] discusses the relevance of this ratio in FSE as well as highlighting that currently there is no standard way of modelling it. Modelling the damage require proposing a model including the involved phenomena and the associated variables. The elements of the fire safety strategy considered for this particular case study are those highlighted in Figure 2.

The proposed damage model results in the flow diagram presented in Figure 6, which provides an understanding of how ASET and RSET are estimated for each location within the building. The assumptions and limitations associated to this damage model are established in the model and are identified with the reference marker A#, where # refers to the number of assumptions, e.g. A7. These are collated in Table 7. The impact of these assumptions on the fire safety strategy are discussed in section 6.6.

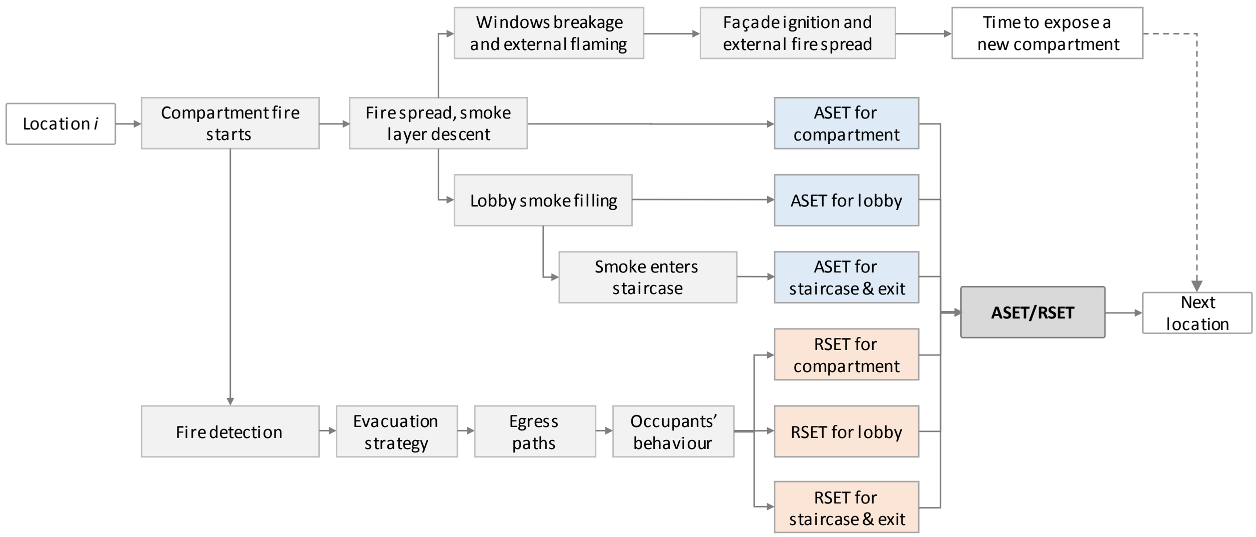


Figure 6. Damage model for the case study

ASET describes the time to untenable conditions defined by the smoke layer height (2 meters; A0). Tenability is assessed for (i) the compartment where the fire starts (location *i*), (ii) the contiguous lobby and (iii) staircase. Tenability is a function of several variables, including fire growth, compartmentation and safety barriers. Being consistent with the acceptance threshold (section 6.2), tenability is defined based on the time occupants have before being in contact with the smoke.

Given the significant uncertainty associated to defining the fire growth due to fuel load and distribution variability, fire growth is assumed to behave as an alpha t-squared fire (A1). As fuel load is unknown and impossible to fully control during the building operation, an onerous condition is selected. First, the fuel selected is polyurethane foam, typical of residential upholstery. Second, the area covered by the fuel is the total area of the compartment selected for the fire to start. Third, the fuel density is fixed at 26 kg/m^2, which is typical for a residential setting [57].

Compartmentation is the physical ability to stop smoke and fire spread, which can be broken due to lack of physical barriers or their failure due to occupants' behavior or material properties. Based on the previous and following the MAD rationale, compartment doors are assumed open, as well as fire safety doors leading to the emergency staircases (A2). Compartmentation is also relevant for the involvement of the façade. Window breakage is defined by the difference between the temperature of the smoke layer and that of the window in the unexposed side. Keski-Rahkonen [64] suggests that breakage is possible with differences larger than 100 K. A conservative breakage criterion of 80°C on the exposed side is selected, given that the smoke layer covers the windows fully (A3).

Broken windows enable external flaming, as the compartment is ventilation controlled (opening factors for the living room, bedrooms and kitchen range between 19.5 $m^{-½}$ and 23.8 $m^{-½}$). External flaming is assumed to begin immediately after window breakage (A4), given that the criteria for flashover is achieved (heat flux of 20 kW/m^2 on the floor of the compartment).

External flaming will lead to an impinging heat flux on the façade, which if above a critical heat flux will cause the ignition of the combustible materials present in the facade. This critical heat flux is set at 18 kW/m2, taking into account the particular materials of the proposed façade [57]. The delay between flame impingement and ignition given a heat flux higher than the critical one is assumed to be of zero seconds (A5).

Given that the façade has ignited, the damage model assumes that only upwards propagation will occur and that the flame spread rate will be similar to those recorded in real events (A6), e.g. 4 m/min [57].

No wind effect is considered (A7), besides the consideration of using real fire spread rates (A6). Although wind can significantly increase damage by helping flame spread horizontally, current knowledge limits the possibility of modelling its potential contribution to vertical and horizontal flame spread.

As flame spreads up the façade, re-entry is expected to occur once the spread reaches the next set of windows and cause their failure. Experimental setups of ACM cladding [65] resulting in a temperature range of 296-915˚C above the window sill (2.5 meters) and a temperature of 526˚C without flame spread barriers (most similar to this case study). Based on A3 and the previous experimental results, it is assumed that the time delay between the flames reaching the windows and the fire re-entry is zero seconds (A8).

RSET is a function of the detection time, notification time, pre-movement time, the time required by the occupants to reach a safe place and the evacuation strategy, i.e. evacuation order. Detection is modelled based on smoke obscuration, with a criterion of 24 %/m (A9). Notification is assumed to occur in 30 seconds after detection (A10), while pre-movement time can vary largely (A10). Modelling occupants' behavior is done assuming no erratic/panic behavior and a homogenous demography for the occupants (A11). The evacuation strategy is staged (A12), with the initial stage (level where fire originates and levels above and below) evacuating first, followed by the upper and lower stages (see Figure 7).

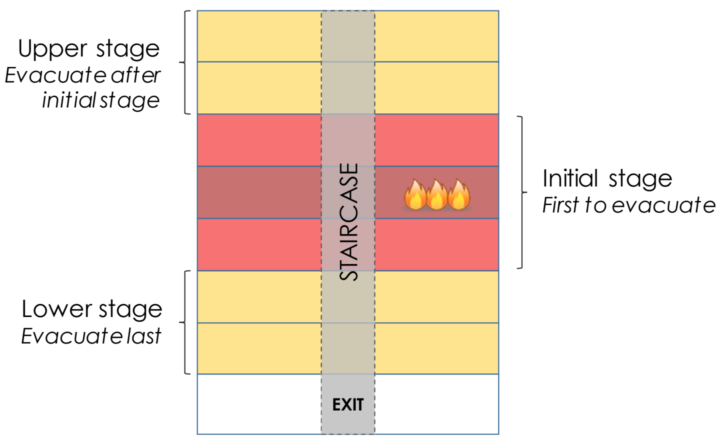


Figure 7. Staged evacuation scheme

The above allows estimating ASET and RSET for location i, as well as for contiguous lobbies and staircase sections. If the initial compartment fire triggers external flame spread, the model restarts at locations $i + 1$. This enables estimating ASET/RSET for the whole building and assess its overall performance. The quantification of this model requires inputs and engineering tools that are described in detail in the next section.

6.4 Damage estimation

Some quantities that directly feed the damage model have been already defined, for example, the use of critical heat fluxes for façade ignition or its vertical flame spread rate. To quantify the whole model, the following set of tools are selected:

a. CFAST v7 [66] to model the compartment fire and model tenability
b. Abecassis-Empis [67] model to estimate heat flux from the fire to the façade
c. Smoke detector model embedded in CFAST v7 [66]
d. Hydraulic model for modelling the occupants evacuation [68, 69]

From the selected tools, *a* and *b* allow estimating the fire dynamics while *c* and *d* address the detection and evacuation. Assuming the detection will behave exactly as in CFAST is not realistic, as some very fast fire could yield detection times of 0 seconds. Given uncertainties associated to the detection model implemented in CFAST, a minimum detection time of 50 seconds has been established (A9). This value of 50 seconds corresponds to the maximum detection delay presented in the validation data for the detection model implemented in CFAST [57]. The façade ignition is modelled using the critical heat flux for the façade materials and comparing them with the heat flux generated from the fully developed fire using the Abecassis-Empis correlations. The latter yields an estimated heat flux of 66 kW/m^2 impinging on the bottom of the façade (closest distance to the window opening), which based on known critical heat flux [57] ensures ignition. The criteria used for ASET calculation, including smoke layer height, toxic species concentration, critical heat flux for the façade ignition and window breakage are presented in Table 2.

Table 1. Representative quantities associated to the ASET calculation

Quantity	**Value / Range**	**Units**	**Justification**
Heat release rate per unit area (HRRPUA)	400	kW/m^2	The reported value for PU foam tests [70] is within this range, associated to residential values [71]
Fuel load for all flats	650	MJ/m^2	Value associated to an expected fire load of 26 kg/m^2 and the ideal heat of combustion of PU foam of 25 MJ/kg, within the bounds presented by [71]
Fire growth rate	[**0.0029**, **0.1876**]	kW/s^2	Bounding limits on t-squared fire growth
Peak heat release rate	Variable	MW	This value is computed as the product of the HRRPUA and the total area of the compartment
Location of initial fire	Kitchen, Living room, Bedroom	-	These locations have direct contact with windows, yielding the shortest times for the external fire spread to begin
Door status	[**Open**, Closed]	-	Bounding limits on ventilation
Upwards fire spread rate	**4**	m/min	This value corresponds to the rate registered in the Grenfell tower fire [57]

Table 2. Tenability criteria for ASET calculation

Quantity	**Value / Range**	**Units**	**Justification**
Compartment and lobby tenability: Smoke layer height	2	m	At this height occupants can start inhaling the toxic gases of the hot gas layer [72]
Staircase tenability: HCN and CO concentration	7000, 150	ppm	Criteria based on Purser [72, 73]
Critical heat flux for façade ignition	18	kW/m^2	Criterion based on Torero [57]
Window breakage criteria: upper layer/external flames temperature	80	˚C	Typical commercial glass fails at around this temperature; furthermore uPVC (used in the window frame) loses 80% of its stiffness by this temperature value [57, 74]

RSET was calculated using the quantities for detection, notification, and displacement and queuing within the level. The time for displacement in the staircase and until the exit is estimated for each level. The associated values and ranges for the application of the hydraulic model are presented in Table 3, with the rest of the parameters of the queuing model taking values as reported in [68].

Table 3. Representative quantities associated to the RSET calculation

Representative quantity	**Value / Range**	**Units**	**Justification**
Occupants	26	People/level	This value represents the upper limit of occupation, equivalent to three occupants in each small flat and 5 occupants in the large ones
Detection criterion	24	%/m	NIST CFAST Technical guide [75]
Notification time	[**30**, 600]	s	This value is unknown and could be expected to be at least 30 seconds [68].
Pre-movement time	[**30**, 60]	s	Expected to be at least 30 seconds for the room of fire origin and 60 seconds for other rooms [68]
Horizontal distance	20.2	m	Maximum distance from a flat door to the staircase door
Vertical distance	3.61	m	Stairs path from floor to floor taking into account the steps; distance between floor is 3 m

Representative quantity	Value / Range	Units	Justification
Walking speed (horizontal, vertical)	1.4	m/s	This velocity is used as the basis of the estimation of the occupants speed within the hydraulic model [68] and is based on statistical information of occupants egress speed [69]
Occupants density in staircase	[1, **2**]	People/m^2	Purser [76] reports that a density of 2.1 people/m2 yields no movement in stairs

In total, 66 representative quantities were used as part of the damage estimation. In the context of a traditional quantitative or probabilistic risk assessment, these variables define a range of possible 'scenarios' which could yield different performances (see quantities in Table 1 and Table 3). In this particular application, these quantities are a direct result of the damage model proposed in section 6.3, and could have been different if it was constructed using an event tree analysis or other appropriate tool.

6.5 Performance assessment

Using the values presented in Table 1 and Table 3, a wide range of conditions or 'scenarios' are possible for which the performance is assessed. Some of the inputs to the damage estimation may paint an extremely conservative approach. However, major events experience demonstrate that all these 'conservative' conditions are feasible and unfortunately, recurrent. The performance assessment presented in this section focus on discrete scenarios aimed at identifying the upper limit of the damage potential, i.e. the maximum damage potential (MDP). Exploring alternative scenarios, e.g. effective fire doors, yields a more complete picture of the damage potential as exemplified by Cadena [40].

Maximum Damage Potential

In this case study the focus is first put on identifying the MDP and then exploring the damage potential through additional (presumably less conservative) scenarios. To identify the MDP the bold quantities highlighted in Table 1 and Table 3 are used to quantify the damage model presented in section 6.3, corresponding to an ultra-fast fire and a vertical flame spread rate of 4 m/min. The results for the flat of fire origin result in an ASET/RSET ratio of zero for a fire starting in the kitchen (ASET = 0 s, RSET = 80 s) and of 0.12 starting at the living room or at the bedroom (ASET = 10 s, RSET = 80 s). These results are independent of the level at which the fire starts. The overall performance of the building depends on the level on which the fire originates.

The results for the lobby and the staircase consider fire origin at level 1, 4, 10 and 15 and a fire starting at the kitchen (lowest ASET with 90 s) are presented in Figure 8. For fires starting at these levels the resulting evacuation time using the staged evacuation ranges between 64 and 67 minutes (~1 hour), with the longest times for fires closer to the top of the building. Although the variation is not large in the evacuation time, Figure 8 shows the significant impact on the ASET/RSET due to the involvement of the façade and the resulting fire reentry.

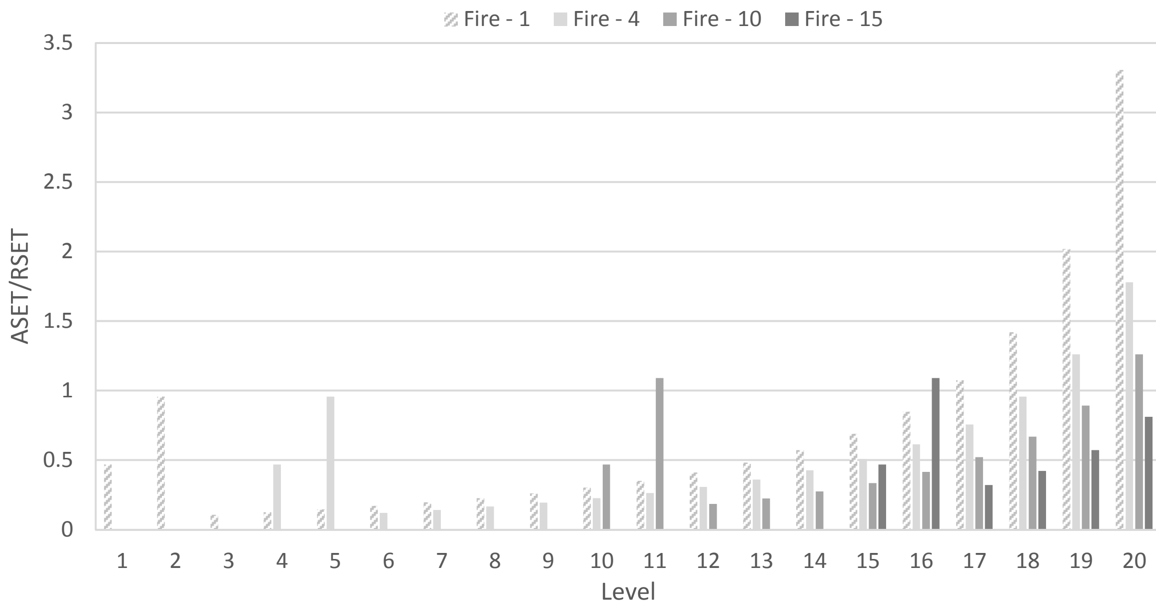


Figure 8. Maximum Damage Potential as a function of ASET/RSET for the lobby at each level – fire starting at 4th, 10th and 15th level

Damage potential – base scenario

The results of the previous section are based on the mean vertical flame spread registered in the Grenfell tower fire (4 m/min). Although variations were registered of up to 6 m/min, this rate is taken to represent the worst condition. An inherently safe approach for the remediation of the building is to ensure a maximum allowable flame spread as a result of the involvement of the façade, assuming no other variable can be modified.

The maximum allowable flame spread was obtained by iteration, modifying the results presented in Figure 8 until only the level of origin has an ASET/RSET<1. The results are presented in Figure 9 and indicate that a rate of 0.1 m/min should be ensured if the façade is involved in the fire in order to yield an acceptable result. Such a result can be ensured by using a non-combustible façade, as ensuring such a low rate would imply experimental and analysis uncertainties that cannot be managed [52].

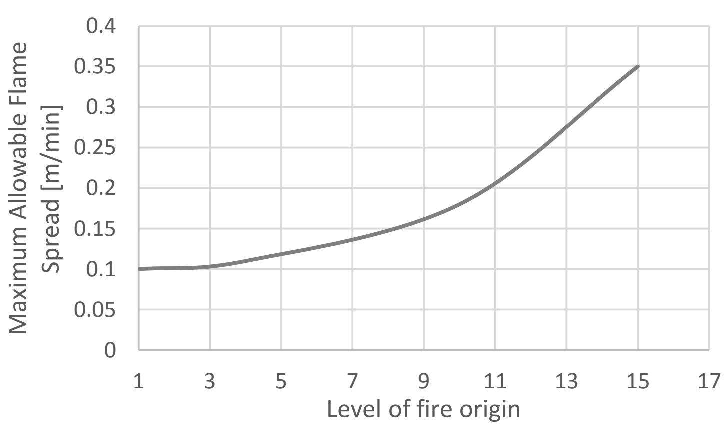


Figure 9. Maximum allowable upward flame spread

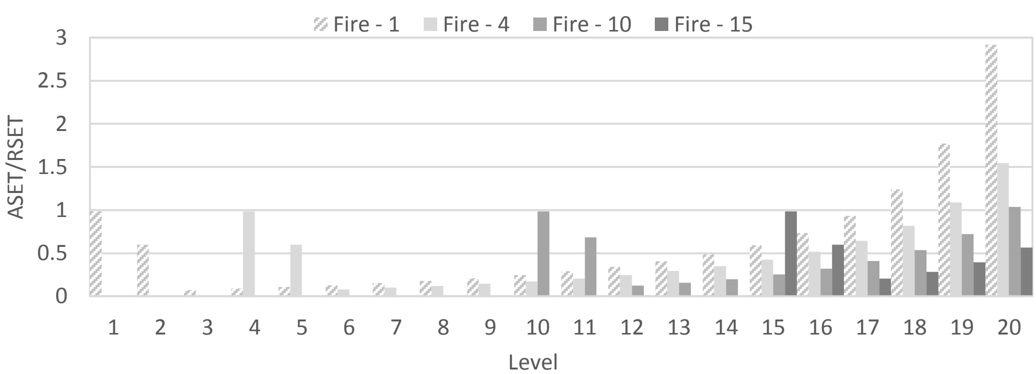
Damage potential – alternative scenarios

In order to better characterize the damage potential and to confirm the MDP presented in section 0, this section explores different scenario configurations based on the variables and values of Table 1 and Table 3. The performance for the flat where fire originates and the corresponding level is summarized in Table 4. Although slow growth fires result in an ASET>RSET for the rooms of origin, the ASET for the flat corridor is less than the RSET for the lobby and therefore in unacceptable performance. In the lobby, a slow growth fire performance is acceptable, while ultra-fast fires yield unacceptable performance (Table 4). Results indicate that even a slow growing fire provides a potential for unacceptable performance.

Table 4. ASET/RSET ratio for the flat and level of fire origin

Fire growth	Room of origin	ASET/RSET (flat)	ASET/RSET (level)
Slow	Kitchen	0.8	1.5
	Living	0.8	1.5
	Bedroom	0.8	1.6
Ultra-fast	Kitchen	0.2	0.6
	Living	0.2	0.6
	Bedroom	0.2	0.9

At the building level the scenarios evaluated consider effective compartmentation barriers (flat and staircase doors), which yield lobbies free of smoke. However, due to the vertical fire spread, flats above the flat of fire origin will be affected. Figure 10 presents the results for the performance at each level, displaying unacceptable performance for all scenarios except for the top levels (18th, 19th and 20th). Although these results seem worse than the MDP presented in section 0, in these scenarios the fire is contained at the level of origin and where it re-enters the building. Here, the ASET/RSET quantity fails to fully capture the performance of the building, despite providing insight on the evolution of fire spread through it.



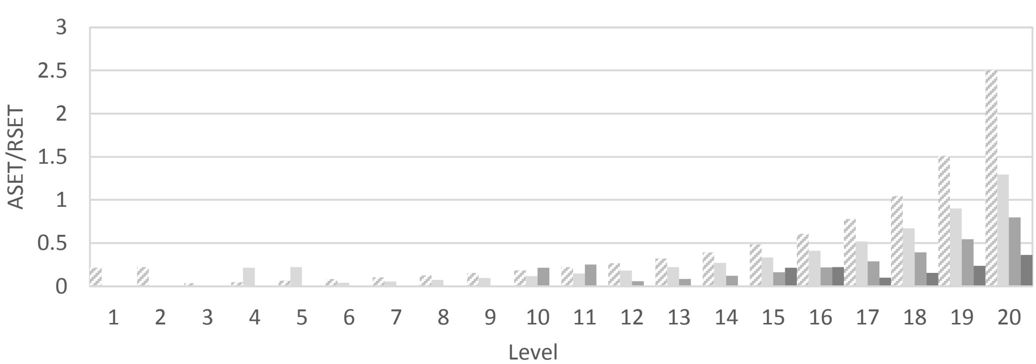


Figure 10. Damage as a function of ASET/RSET for the flats above the level of fire origin– fire starting at 4th, 10th and 15th level. Slow fire growth above, ultra-fast fire below.

6.6 Identifying remediation actions

A remediation strategy is required as the damage potential and the MDP indicate an unacceptable performance. The inherently safe option has been identified in section **Error! Reference source not found.** and to provide further alternatives the information registry is explored. The registry contains the variables and assumptions that affect performance and that can be used to formulate actions to improve it.

The information registry is meant as a basis for third party reviews and for incident investigation while addressing the issue of assessment credibility [77] or completeness uncertainty [39] in risk assessment. In the context of this case study this issue is referred to as *trustworthiness* and it is defined as a function of the available body of evidence (Strength of Knowledge or SoK) and the sensitivity of the damage to changes in inputs or assumptions (Sensitivity^{-1}). Qualitative criteria are defined for each of the trustworthiness components using a Low/Medium/High scale (Table 5). Judging trustworthiness of individual assumptions and input values allows prioritizing them based on their impact on performance, while identifying those requiring management actions. This approach adopts the ideas of Aven [11, 78-82] and addresses the issues of accountability in FSE identified by Hackitt [5] and Shergold-Weir [6].

Table 5. Trustworthiness criteria and number of entries

SoK	Criteria	Sensitivity^{-1}	Criteria
Low	Poor theoretical grounds, supporting references or low consensus between analysts	**Low**	Theoretical grounds for increased damage in case of changes leading to MAD breaches
Medium	Neither high nor low	**Medium**	Theoretical grounds for increased damage in case of changes
High	Recent references, strong and relevant theoretical grounds and agreement between analysts	**High**	Theoretical grounds indicate an increase in damage is not reasonable

The information registry contains 49 quantities employed in the damage estimation, with the distribution of SoK and Insensitivity presented in Table 6. The six quantities with low strength of knowledge pose the potential for the results of the assessment not to be trustworthy, while the 16 quantities with high output sensitivity could lead to different performances.

Table 6. Number of entries for each level of SoK and Insensitivity

SoK	No. of entries	Insensitivity	No. of entries
Low	6	**Low**	16
Medium	7	**Medium**	12
High	28	**High**	13

Each key assumption is associated to several of the quantities involved in the assessment. As each quantity has a SoK and Precision classification, this allows identifying the assumptions with associated low SoK and low Precision. These are the results with the lowest certainty and with the greatest impact on the outputs. This is presented in Table 7, highlighting those assumptions with a significant potential for improving or worsening the performance. This allows identifying the assumptions with the potential for a better performance (fire growth, compartmentation, ignition of façade and the fire re-entry criterion) and the those that could lead to worse outcomes (external flame spread; wind effect; notification and pre-movement times; and ordered evacuation).

In general, evacuation strategies can be optimized to improve the performance through the implementation of reliable and sophisticated notification systems through the building [83]. On the other hand, a worse performance could result from issues in the evacuation management (e.g. confusing orders, miscommunication) resulting in increased notification and pre-movement times, as well as in disorderly behavior from the occupants, e.g. oversaturation of staircase, increased que time. For the case study analyzed here there is a minimum margin for optimization of the strategy, which combined with the assumption of a calm and orderly evacuation (A11) do not justify exploring it as a remediation action.

Table 7. Key assumptions and trustworthiness

Key assumption		SoK	Sensitivity^{-1}	Discussion
A0	Tenability criteria	H	H	An alternative criterion such as smoke layer temperature [72] at 200˚C is verified using CFAST output, indicating that smoke layer height yields a more onerous result (Figure 11).
A1	Fire growth	H	L	Onerous fuel conditions were chosen assuming polyurethane as the fuel. This is consistent with fuel loads in residential settings [84]. An alternative fire model (B-Risk from BRANZ [85]) was used to verify the original simulations, showing consistency in temperatures within the compartment of origin and times for untenable conditions.
A2	Compartmentation	H	L	Past events reflect that loss of compartmentation is feasible. Unless specific evidence exist for considering compartmentation is maintained during the fire, this scenario is valid for assessing the performance.
A3	Window breakage	H	H	B-Risk model was used to estimate the temperature at which the glass breaks [86], yielding a time of 76 seconds, corresponding to an upper layer temperature of 75˚C (Figure 12).
A4	External flaming	H	M	Based on the simulation results, all configurations achieve flashover in the compartment of origin, which are ventilation-controlled fires. This justifies the assumption of external flaming. A delay on external flaming could be incorporated, but it would not reflect current knowledge nor represent an onerous scenario.
A5	Ignition of façade	M	M	An optimistic estimation for this complex phenomenon would result in increased ASET. Under current knowledge and available resources, such modelling would not be accurate nor reliable. A zero seconds' delay is recognized as an onerous but valid condition for the damage potential.
A6	External flame spread (upwards)	H	M	Despite the large variability of the upwards flame spread rate, the building of this case study is similar to the Grenfell tower, for which the rate of 4 m/min was the mean value during the fire [57].
A6	External flame spread (downwards)	L	L	Real fires have shown that downwards vertical spread is possible and actively contributes to fire spread and to increase fire damage. Modelling downward spread could lead to re-entry and to faster untenable conditions at the stairs, i.e. worse performance.
A7	Wind effect	L	M	Wind can influence external flame spread, reduce vertical flame spread and promote horizontal flame spread [67]. Current knowledge for assessing wind effects on external fire spread is limited, but its potential for a worse performance is recognized [87]. A theoretical model has been proposed by Bai et al. [88], although its applicability is limited to reduced scale setups with HRR < 18 kW.
A8	Fire re-entry criterion	L	M	Gandhi et al. [51] performed a façade resistance test using similar ACP configurations to the ones in the case study, resulting in a 67 seconds delay between window exposure and fire re-entry. Including such a delay once windows are exposed to flaming would yield a better performance, but ensuring it with current available evidence is not supported.
A9	Smoke detection criterion	H	H	The 24 %/m obscuration criterion is given by default in the CFAST detection model, however it corresponds to a reasonable setting based on the analysis by Schifiliti et al. [89].
A10	Notification and pre-movement times	L	L	These quantities depend on non-observable variables such as the state of mind of occupants. The assessment used the least onerous values and yielded an unacceptable performance; increasing these times would yield even worse performances.
A11	Ordered behaviour during evacuation	L	L	Assuming a homogenous demography (adults around 40 years old) is a simplification. Panic effects or physical difficulties of particular occupants could significantly increase the RSET and therefore yield worse performances.

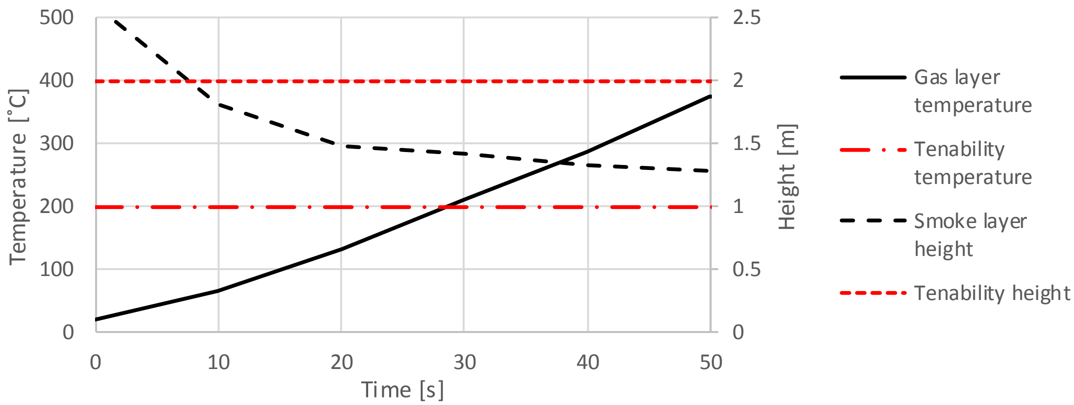


Figure 11. Comparison of tenability criteria for ultra-fast fire originating at the kitchen

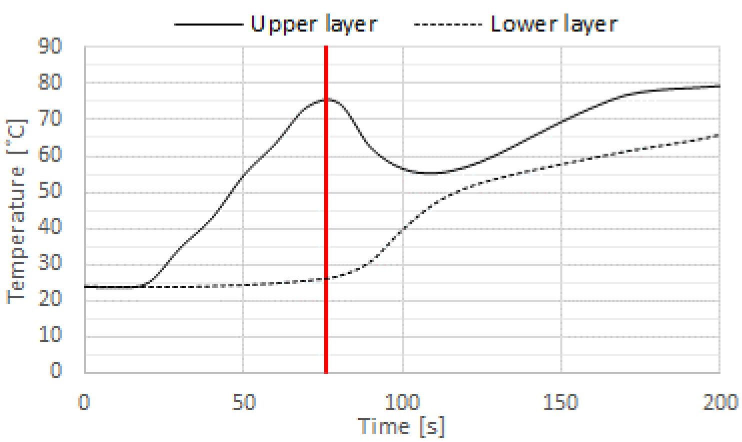


Figure 12. Time for window breakage using B-Risk model, plotted against the temperature of upper and lower layers in the kitchen compartment; red line denotes window breakage

The unacceptable performance of the existing façade system could be remediated through a series of actions associated to the key assumptions. These actions are presented in Table 8 and provide flexibility in the potential remediation actions to be defined by the stakeholders, considering that their cost-effectiveness largely varies. These actions are proposed on the basis that occupancy cannot be modified. Furthermore, the active elements of the fire safety strategy (detection, notification) need to function adequately during the lifecycle of the building as an inadequate management would not only invalidate the performance assessment but could also lead to disastrous consequences, e.g. failed evacuation due to lack of detection.

Table 8. Treatment options based on key assumptions

Key assumption		**Management actions**	**Description**
A1	Fire growth	Control: fire load management	Replacing combustible elements like carpets and combustible wall finishes could improve performance, limited to the common areas.
A2	Compartmentation	Control: redesign of door system	Alternative door design can lead to better performance. Fire-rated doors with a gap of 3 mm could enhance smoke containment [90], although self-closing mechanisms would be needed in addition [91]. However, failed compartmentation scenarios are not fully eliminated [19].
A5	Ignition of façade criterion	Prevention: Use less or non-combustible materials for the cladding	The flame spread rate can be iterated to find a maximum allowable flame spread, found at 0.1 m/min (see section **Error! Reference source not found.**).
A6	External flame spread	Mitigation: flame spread barriers	Giraldo et al. [92] studies the impact of flame spread barriers on timber facades, including building's geometry. The Lacrosse fire showed how

Key assumption		Management actions	Description
			an architectural decision prevented horizontal flame spread (under specific wind conditions) [93].
A8	Fire re-entry criterion	Control: Increase time for external flaming and fire re-entry	Nguyen et al. [87] suggests insulated and laminated glass performs better than regular glass despite its increased cost. This substitution would yield an increased time for breakage and re-entry.

6.7 Façade ignition and external flame spread

The performance assessment results can be deemed conservative but the proposed actions align with the intent of a performance-based design by providing flexibility in decision-making. This is achieved through the holistic approach of the MAD methodology. As fire research provides data and models to deal with some of the complex phenomena involved, the damage model employed can be updated and conservatism reduced while accuracy increased. If fire research does not develop substantively then the obtained information remains a valid base for decision-making without compromising the professional ethics of the engineers nor shutting down the stakeholder motivations.

Professional ethics require consideration of stakeholder motivations and never compromising the trustworthiness of technical studies. For example, a parameter such as the flame spread rate is critical in a fire risk assessment and it will have considerable influence on the outcome. In this case study, 4 m/min was used based on a series of full-scale real building fires and is independent of the materials used (A6). Refining this value by considering specific façade materials is desirable but must be done carefully to ensure that it is realistic and representative. Bench-scale flammability data from the Cladding Materials Library [94] quotes a rate of 0.1 m/min to be used only as part of correlations for flame spread theory. Applying this value directly would be tempting as it is a drastically lower flame spread rate and will thus often lead to an acceptable performance for a given building. However, a scaling analysis is required to be able to obtain a realistic value to apply to a full building, such as one by Chung and Drysdale [95].

Technical considerations which may appear unimportant can in reality have significant impact on the overall performance of a building. The consideration above of an alternative flame spread exemplifies this as using it would lead to a false safety sense and results which are not credible. The implications of this are relevant in Australia and worldwide where tens of thousands of buildings await remediation after their facades have been deemed non-compliant. The proposed methodology adds significant value to the technical information in these situations and helps potentially prevent incalculable losses.

7 Conclusions

This manuscript has put forward an alternative fire risk assessment methodology, which has an explicit focus on the consequences of an event. The methodology, MAD, aims at identifying the performance limits of a particular building design as a function of the resulting fire damage that can jeopardize one or more safety objectives such as ensuring life safety of occupants. MAD was developed on the basis of a design methodology that promotes inherent safety and does not attempt to disqualify PRAs or replace them, but to provide a robust risk assessment methodology that works as their precursor.

The proposed methodology was implemented in a non-compliant façade system for a residential high-rise building in order to identify a possible remediation strategy that can be used to reduce the consequences of a fire in the building. It is not an objective of this study to fully describe the physics and the complexities of a façade fire but to demonstrate the value of the methodology. Therefore, the analysis tools were purposely kept as simple as possible, discussing at the end the implications of assumptions and uncertainties on the remediation actions. The performance assessment relies on a series of assumptions, including a 'normal' occupation and an expected pre-movement time. These variables could take much more conservative values, as in the case of high occupancy during special dates or events, e.g. over holiday seasons. However, the performance results are unacceptable even under these optimistic values. Since the objective of the assessment is to provide a remediation strategy for the façade, modifying these variables would not yield an enhanced insight and are therefore not explored. Under a normal design process, the maximum damage potential would require exploring these more conservative conditions.

A valid question -as highlighted by the reviewers- is why would MAD improve the fire safety designs of buildings? The authors consider that MAD addresses the immaturity of QRAs in fire safety engineering, currently hampered by i) lack of availability of supporting data, ii) poor competence of many practitioners and iii) limited debate in the literature as to the utility and value of the QRA process in the built environment. The purpose of MAD is to understand the inherent risk in a building, understanding this is largely (if not solely) a function of the largest consequences attainable before introducing many of the typical fire protection systems, e.g. sprinklers.

MAD has a common element with PRA, namely its evidence gathering capacity [96], and capitalizes on delivering trustworthy information. Such information can support objective, proportional and coherent decision-making regarding the fire safety strategy of a building. As stated by Watson [4], these types of risk assessments (including PSA) should be understood as a part of an argument that supports safety, rather than as proof positive of safety. This makes it difficult to have a mechanistic approach to risk assessments, needed to foster the increasingly complex needs for developing the built environment.

It is clear FSE aims at designing a safer built environment. This paper has exposed that this is not guaranteed by imposing any particular risk assessment methodology. Instead, a safety built environment could be achieved if the existing limitations associated to risk assessments are acknowledged and a road map is set to overcome them; this will not be a short-term goal as the experience of more mature disciplines have shown. In the meantime, the authors consider that FSE should use alternative methodologies such as MAD to extract the most value of fire engineers' skills as well as the knowledge central to the practice. Gradually, this will enable a future in which more quantitative and even probabilistic risk assessments can done with a high degree of trustworthiness.

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