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The fire safety strategy

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ABSTRACT

The fire safety strategy has become a crucial component of modern fire safety engineering discourse. It forms a core part of the recommendations from Phase 2 of the Grenfell Tower Inquiry and has been referenced in the fire safety engineering literature and in recent reforms in many countries. However, it has never been formally defined. This creates a significant risk to the successful implementation of these recommendations. Through a review of past uses of the term, this paper explores its conceptual grounding, functional scope, regulatory considerations, and resulting implications for design. A formalized definition is introduced, and implications of this new definition on the fire safety engineering process and its implementation in existing regulatory environments is discussed. The definition is formulated from an understanding of optimum implementation of fire safety which has evolved over the past 50+ years and focusses on the narrative of how systems and features both define and deliver the required level of performance of a building in the event of a fire. The result reinforces the role of the fire safety engineer whilst integrating regulatory compliance into the design, offering a robust approach to fire safety engineering that can overcome many limitations associated with current practice.

1. Introduction

Engineers, regardless of discipline, are charged with the development of solutions to unique challenges which arise from some technical or social need. This is no different in fire safety engineering, in the practice of which the fire safety engineer is charged with developing the specifications of a solution which responds to the unique challenges associated with fire safety in a project [1].

In many jurisdictions, it is accepted that the outcome of the fire safety engineering design process is what is referred to as the fire safety strategy of a building [2]. This term can be found used frequently in recent literature. The Grenfell Tower Inquiry phase 2 report and the recent response of the United Kingdom (UK) government to this report both refer to a fire safety strategy. The phase 2 inquiry report in particular included at recommendation 10 [3]: "*That it be made a statutory requirement that a fire safety strategy produced by a registered fire engineer to be submitted with building control applications …*"; with the government's response being to accept this recommendation, stating that [4]: *"A fire safety strategy is already required with building control applications for the construction of and significant work to higher-risk buildings.*"; later going on to confirm that *"… a fire strategy should be part of the information submitted through the higher-risk building control regime to ensure fire risks are effectively managed throughout the building's life cycle."*

Elsewhere, in Australia for example, the recent Warren Centre project to professionalize fire safety engineering made frequent reference throughout and incorporated the fire safety strategy into recommendations around the future role of fire safety engineers [5]. This was

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adopted in the proposed competency framework that aligns fire safety engineers with the Engineers Australia stage 1 competency standard [6] and adapted to the Washington Accord stage 1 competencies [7].

However, and crucially, the term fire safety strategy has never been properly defined in the scientific or the technical literature. This is a significant risk not only to the implementation of the recommendations from the Grenfell Inquiry in the UK, but more broadly it represents a general risk to the practice of fire safety engineering.

The absence of an unambiguous definition introduces an unavoidable lack of clarity of expectations from design outcomes. On the basis that the fire safety strategy is the outcome of the design process then its definition must be clearly articulated. The reasons for this are multiple. Ambiguity in the intended meaning of the term fire safety strategy creates confusion as to the expected outputs of the fire safety engineering design process. Furthermore, it hinders meaningful design conversations, negatively affecting both design clarity and communication between stakeholders. A misalignment of expectations can lead to issues with stakeholder engagement and compromises the ability of the fire safety engineer to deliver an outcome that supports the vision of the architect or developer. Ineffective communication can also lead to technical misalignment on general approaches to engineering analysis. These can have a compounding effect leading to the introduction of regulatory and compliance risks because of misalignment between engineers, developers, architects, builders, and approval bodies, etc.

In this article we start with a discussion on past uses of the term, using these to identify requirements for a consistent definition that is intended to avoid ambiguity or misalignment (section 2). This is followed by a review of the recent evolution of the definition of a fire safety strategy and the proposal of a formalized definition of the term (section 3). Section 4 presents some practical considerations for the workflow associated with fire safety engineering including implementing the concepts presented here as the outcome of the design process in a performance-based regulatory environment (section 5). Reference is made in this paper to the regulatory environments in the UK and in Australia, however the intention is to use these only to illustrate the points being made in the development of a definition which is more broadly applicable in other countries.

As a point of ontological clarification, throughout this paper we will make implicit reference to a building as a system of systems, consistent with some of the literature cited herein. However, we will also refer to features of a building, being those physical characteristics of a building related to specific geometries, material selection, layout or ventilation characteristics which may influence in some way the evolution and spread of fire and smoke. We will also refer to attributes of a building, being the other non-physical properties of a building or the systems of which it is comprised which otherwise will impact on the ability to demonstrate fire safety. Thus, the building may be understood to be a system of systems which include the physical systems in place, the features of the building and the buildings attributes.

2. Implementation of fire safety

Fire safety engineering until the mid-1990s was practiced almost universally in environments dominated by prescriptive regulations. Prescriptive codes approach fire safety in a reductionist epistemology, meaning that they are structured around a decomposition of the elements of a building that contribute to the fire safety design of a building into individual specifications for each system that contributes to the overall performance of that building. The underlying assumption being that appropriate design of each and every component results in appropriate performance of the overall system.

In the beginning of the 1990s, Performance-based regulations began to be adopted in some jurisdictions. These Performance-based codes have largely followed the same structure as the Prescriptive codes that they replaced, with Performance Requirements for the same individual elements given. For example:

- In Australia separate Performance Requirements exist for load bearing elements, for fire spread, for protection of openings, fire isolated exits, etc. [8];
- and in England separate Performance Requirements exist for means of escape, internal fire spread, external fire spread, etc. [9] .[2]

These Performance Requirements can be met through the implementation of detailed specifications – in the case of the Building Code of Australia (National Construction Code) in the form of Deemed to Satisfy (DtS) provisions given in the code; in England, by so-called statutory guidance as specified in Approved Document B (ADB) [10]. Whilst there can be no doubt that in many instances current approaches to fire safety have delivered adequate outcomes these approaches also have many problems as highlighted by the Grenfell Tower Inquiry [3].

A fundamental problem with such a reductionist approach is that it is inconsistent with the epistemological stance, stressed repeatedly since the Summerland disaster in 1973 [11], the Stardust nightclub fire in 1981 [12], and in educational discourse since the 1980s [13] that successful treatment of fire safety can only be done having consideration for the holistic nature of the building to which it is applied, holism being the antithesis of reductionism.

There were in the past many practical benefits to this reductionist regulation and implementation of fire safety. Not least of which was the familiarity of the existing workforce with the regulatory approach that this new approach replaced, combined with the limited size of the workforce capable of adopting performance-based design (PBD). However, given the continued evidence from incidents which have led to, for example, public or other inquiries over the past 50+ years, some of which are cited above, an approach for implementation of fire safety on the basis of a reductionist approach (whether regulatory or analytical) is clearly far from optimal and is likely, in many instances, to fall far short of being able to deliver adequate outcomes in the event of a fire. It is here where the fire safety strategy appears as a suitable and holistic alternative.

An early reference to the fire safety strategy is made in a development study of a VA Hospital Building, published in 1972 [14]. Referring to specific elements of a hospital design which do not require separating walls to be taken to the underside of a soffit but rather to stop at false ceiling level, the study highlights that many other provisions which may assume separation to the soffit of the slab above are then disabled (for example compartment sizes, smoke detection and smoke management, egress strategy). The study goes on to state that "*in proposing what seems to be one simple deviation from conventional construction, an entire fire safety strategy becomes ambiguous in its application, forcing … authorities to evaluate … what amounts to a whole new strategy*." Whilst the use of the term is entirely consistent with the recommendations made and stance adopted by the inquiries and educational discourse cited earlier, key factors which are not adequately addressed are: (i) in what way the fire safety strategy becomes ambiguous, (ii) why this is the case, and (iii) what are the consequences of that for design as opposed to evaluation.

As another example of the use of the term, around about the time of the adoption of performance-based regulations in some countries, Meacham [15] wrote that "*performance-based design results in a comprehensive fire [protection] strategy in which all systems are integrated, rather than designed in isolation.*"

The term fire safety strategy can be found more commonly in recent literature, a full summary is outside of the scope of this paper, however a key and recurring theme in articles which use the term is that in very few instances is the term defined.

Given reference to the fire safety strategy as the output of the design

[2] These are variously called different things in different countries, for example they are referred to as Functional requirements in England, or Performance Requirements in Australia. For ease of reference, we will refer to them throughout this paper as Performance Requirements.

process, the position of the current work is that the fire safety strategy should be defined in such a way that it is bespoke for and can be instanced as a unique design output for any project in response to the unique design challenges of that project. Not all references to the term use it in such a way that it can be aligned with this position and there are examples which use the term from either a macroscale (in application to an entire building stock) or a microscale (in application to a specific building). Our position is that the fire safety strategy is an artefact which is to be developed in application to specific buildings. While discussing the strategies for delivering fire safety from a macroscale may be appropriate when considering for example regulatory change or impact, the description of this as a fire safety strategy adds to confusion about the meaning of the term.

The problem which is faced, therefore, is a persistent usage of the term which has evolved over the past 50+ years combined with an absence of a formal and broadly adopted technical definition. The remainder of this section will therefore focus on summarizing the evolving use of the term in this context. The objective is to present an understanding which has evolved to a point that it is possible to articulate a deliberative definition, in a way that optimizes future application of the term whilst drawing from and not excluding the validity of its past uses even if these present a suboptimal application. As such, the following sections present requirements that the definition and its implementation should fulfill. These requirements are structured around Conceptual Grounding, Functional Scope, Regulatory Considerations, and Data. These requirements are based on recurring themes identified in past use in the fire engineering literature.

2.1. Conceptual grounding

Requirement 1: The fire safety strategy needs to be goal(s)/objective (s) based.

- Goal oriented design is nothing new in fire safety engineering and was first proposed in 1972 as part of the Goal-Oriented Systems Approach (GSA) to fire safety [16,17], which was the origin of the Fire Safety Concepts Tree in NFPA550 [18]. In the GSA approach, systems level thinking was adopted and goals were set based on probabilities of loss of function of a building, for example mission-focused goals related to fire spread within a building. In its current form however the Fire Safety Concepts Tree serves primarily as a qualitative tool for exploration of alternative systems to achieve the stated goal.
- More recently, in 2002, design on the basis of safety goals was proposed as a means of considering during design the possibility of an event similar to September the 11th 2001 [19] over the course of a building's life. Importantly and as a key differentiator from earlier work, this concept is based on timescales associated with the achievement of certain goals which can be defined at the outset of the design process, and which are distinct from any regulatory Performance Requirements or other stakeholder-imposed Requirements for a project. Accordingly, in discussing goals base design in the remainder of this paper we refer specifically to goals based on timescales (which may include mission-focused goals). These timescales may include, for example, time for evacuation, t_e, the time until the structural integrity is compromised, t_s, and the time until conditions become untenable for building occupants, t_f.
- The premise is that the sequence of events that will occur in the event of a fire can be described in such a way that these timescales can be defined in narrative form. A schematic illustration of this implemented for a high rise building is shown in Fig. 1. The fire growth is depicted by the thick black line, increasing in size as it develops, with opportunities for controlling and suppressing fire by sprinklers in the compartment and then floor of origin, fire service intervention, compartment boundaries, smoke management systems, etc. The percentage of the building occupants evacuated is shown in the dashed line, within the example shown, based on an evacuation strategy which prioritizes the room of origin, then is apparently staged by floor of origin and then subsequent floors. The structure itself is shown in the dash-dot line. At all instances, the time scales are such that the time to evacuate a part of the building, for example $t_{e,compartment}$, is less than the time until fire induced untenable conditions in the same building part are attained, for example $t_{f,compartment}$; and the structure or compartmentation does not become compromised until evacuation is completed, i.e. $t_{e,building} < t_s$. Thus, the safety goals which the building can be expected to achieve can be defined in terms of time with the simple inequalities $t_{e,compartment} < t_{f,compartment}$, $t_{e,building} < t_s$, and $t_s \rightarrow \infty$ assuming that the structure should be designed to resist burnout of the fuel, including post decay and cooling.
- There are two significant benefits to this approach. Firstly, the relationship between those systems and features of the building that contribute to, for example, the evolution of tenability throughout and those that contribute to egress is clearly and mathematically connected by these goals. Secondly, the goals can be set in a way that they are entirely agnostic of a single event, but are specific to the building in question.

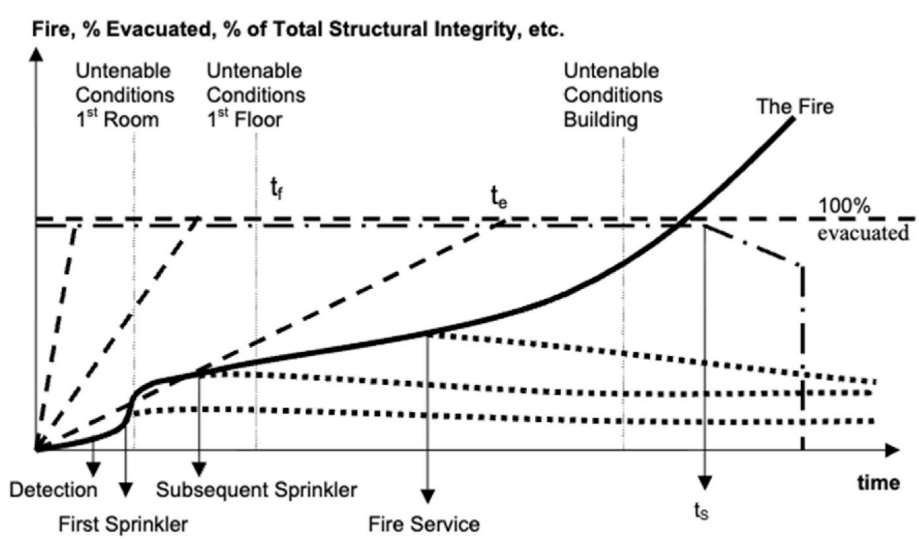

Fig. 1. Schematic of the sequence of events following the onset of a fire in a high rise building (redrawn from Ref. [19]).

Requirement 2: The definition of the fire safety strategy should address philosophical divergence in the historical use of the term.

- Early uses of the term fire safety strategy or fire strategy reflect important evolutionary steps in developing consistent approaches to fire safety engineering. Another early instance, from 1991, of a fire strategy in the scientific literature relates to the development of a fire protection strategy for an airport [20]. The underlying intention is to specify the internal layout of the terminal such that any resulting fire could never overcome the various fire safety provisions that were prescribed for the building. Importantly, this approach recognized that the fire (both in terms of the design fire scenario and its mathematical abstraction as a design fire) was an output from the design process, and not an input to it.
- A contrary approach, and one which is overwhelmingly adopted in the fire safety engineering design process today, is to base an analysis on assumed fires which are an input to the design process, where growth rate and fuel load are often predetermined, or are assumed on the basis of common approaches or collective experience (for example an αt^2 fire in an office building with a medium growth rate). The objective is to show through engineering analysis that the fire is unlikely to be able to overcome whatever countermeasures are in place within a building, and where this is not possible to increase the performance of these countermeasures or to otherwise modify the building.
- These different approaches have different underlying philosophies. In the case of the former then the philosophy is one of engineering the fire, whereas the latter is one of engineering the building. Neither of these in isolation are an optimum application of the body of knowledge of fire safety. Particularly, in the latter, the justification and defense of the design fire as an input to the process can be particularly difficult as the analysis done in this way may result in a positive decision to adopt a solution but it provides no real insight as to the margin of safety, i.e. how big a fire is needed for a buildings design to actually fail to achieve the Performance Requirements that are defined for it. Furthermore, by fixing the fire growth rate, it does not recognize the impact that design decisions might have on the fire growth rate.
- Philosophical divergence arises from these differing historical interpretations of fire within the design process—some treating fire as an input to be reacted to, rather than as an outcome shaped by design decisions.
- In a goal-oriented fire safety strategy, fire must be understood as an output: the result of deliberate choices in ventilation, fuel load, compartmentation, and other design features as well as the interaction of that fire with the various systems proposed. In this approach fire is not a diagnostic tool with which to evaluate building performance, but rather is a consequence of the design choices made. In other words, when implemented optimally, fire safety engineering enables the creation of systems and features that very deliberately deliver the required fire as well as the intended fire safety outcomes, rather than merely responding to a predefined design fire or scenario.

Requirement 3: The fire safety strategy (for implementation in the built environment) should fundamentally be structured around the response (e.g. egress strategy) and a description of system (e.g. building) performance as described in requirement 2.

- In most cases, the fire safety strategy will incorporate elements related to egress and building performance and will be written in such a way that it demonstrates that life safety objectives are achieved on the basis of egress and building performance. This is aligned with historical uses of the term and with work on, for example, tall building fire safety [21]. Despite this, it must be recognized that not all fire safety strategies will be implemented in the built environment and therefore other goals (for example related to environmental impact, property protection, or business continuity) may prevail and egress/building performance requirements may not be relevant for all developments. Nevertheless, in defining the term, for the built environment the incorporation of elements related to egress emphasizes the fire safety strategy as being a function of time and this will likely be no different for other possible goals.

Requirement 4: The strategy should combine numerous systems and features.

- The goals link in a very explicit way the different systems and features of the building that contribute to fire safety and fire development. Meacham [22] discusses the integration of systems and components to deliver a Performance-based design. Torero also emphasizes the fire safety strategy consisting of numerous components [23].
- This requirement for the fire safety design of a building to combine numerous systems and features also supports the definition of the fire safety strategy as a holistic concept—integrating all such elements that contribute to achieving the stated objectives. This holism is lateral (across design elements), rather than longitudinal (over time), as is becoming common in some guidance documents, e.g. Ref. [24], although as will be discussed both longitudinal and lateral holism may be appropriate.
- The layers of protection concept has been adopted by the fire safety community from the field of risk management [25,26], These layers will typically include prevention, detection, evacuation, compartmentation, suppression, and structural resistance – terms which may be taken to describe combinations of various systems and features in the building contributing together to achieve a stated function. Bonner et al. [27] identify the presence of what they call superlayers of protection, layers which act across multiple layers at once such as the fire brigades or building regulation.
- However, there is a potential weakness in the layers of protection concept applied to fire safety engineering. Each layer is an element to be activated sequentially if a preceding layer fails or is breached. However this does not fully capture the interaction between the different systems or features of a building and their roles in delivering an outcome in the event of a fire. Failure of one layer to achieve the required functions in the fire safety strategy cannot always be compensated by one of the other layers. For example, as part of the narrative first introduced above, compartment boundaries and sprinkler systems may achieve a similar outcome in terms of preventing or delaying the spread of fire and smoke from the compartment of origin and thus may be treated as redundancies to one another. However, the evacuation strategy serves an entirely different function in the narrative. In the event of failure of the compartmentation or sprinkler system, the evacuation strategy cannot contribute to achieving the same outcome and will in many instances simply be disabled by the failure of both suppression and compartmentation.
- Proper consideration of the holistic interaction between different systems and features as well as their place in the overall fire safety narrative will allow the identification of certain crucial attributes of the systems and features of the fire safety design of a building such as redundancies (for example multiple compartment boundaries), dependencies (for example dependency of an egress strategy on provisions that limit smoke or fire spread) or conflicts (for example conflicts between the egress strategy of a building and the operational requirements of fire fighters).

2.2. Functional scope

Requirement 5: The fire safety strategy is a function of time.

- Unlike other accidental loads (e.g., earthquakes, blasts), fire evolves over both space and time. This temporal evolution presents an opportunity to manage consequences dynamically [28] —an opportunity the fire safety strategy should reflect.
- This requirement in the functional scope of the fire safety strategy is closely related to the conceptual requirement to structure the fire safety strategy around the egress and building performance in the event of a fire.
- This requirement can be addressed through the narrative structure, also mentioned previously, the specific form of which is at the discretion of the fire safety engineer, which describes both the evolution of the fire over time as well as the occupant and system (e.g. the building) response to that fire.
- Achieving this requirement also enables the first requirement, the conceptual grounding of the strategy in safety goals/objectives for the building, to be achieved in a way that fully supports the holistic integration of the different elements of the building in contributing to the overall fire safety.

Requirement 6: the fire safety strategy should guide, control and define the evolution of the fire.

- Strongly related to the philosophical divergence which has been evident in the practice of fire safety engineering to date, the fire should be considered always to be an output from the fire safety strategy since it is the features of the building and the arrangement, composition and quantity of the fuel load that define the fire. This is the case for both design fire scenarios and design fires, where the design fire scenario is the narrative that describes how the fire develops in a building and the design fire the mathematical abstraction which allows the quantitative characterization of the fire.
- As an example, for the design fire scenario, the characteristics of the external wall and any penetrations in that will determine the possibility or otherwise for vertical flame spread; however the physical design of the building and the external wall itself will also contribute to the possibility of whether or not that external flame spread will be restricted, for example by spandrels or by discontinuities in any combustible materials. It is these features along with (i) knowledge about the possible fire development internal to a compartment and (ii) the possible external flaming from that compartment which allow the narrative description of a fire scenario to be written. It is the narrative that allows the fire safety engineer to be able to state clearly on what basis a specific fire can develop (or not).
- This requirement is consistent with other more recent work which references the fire safety strategy [6]. The fire safety strategy should therefore define the basis for how the features of a building influence the nature of a fire—through ventilation, fuel load, compartmentation, linings, material choice, topology, etc.

Requirement 7: The fire safety strategy should enable building and occupant response to fire and facilitate first responder intervention.

- Assuming these aspects are part of the strategy's goals - as they typically are - the strategy should encompass them. Other performance objectives, as noted elsewhere, may also be appropriate.

Requirement 8: The fire safety strategy should be integrated with the overall design of the building.

- Integration of fire safety with the design of a building has been discussed by several authors who adopt or develop a range of perspectives on this topic. For example, Park et al. [29] adopt a simple maturity-like scale combined with a network structure of building elements to explore the impact of different design decisions and management practices on fire safety. Alvarez [30] explores integration of fire safety measures with the building-occupant system, considering fire as a disruptive event to that systems performance. Bjelland et al. [30], incorporated fundamentals of systems theory, drawing insights from systems theory and moving towards socio-technical hierarchies, much of which resonates with the work of this paper – perhaps most significantly the idea that a reductionist approach to fire safety is not appropriate for buildings when viewed as complex systems or complex systems of systems [31].
- Building on and extending these concepts, this integration must be complete – that is to say, fire safety must not only be integrated into the building design, but that the building design must integrate fire safety. This is because in many instances the fire safety engineer holds a role which is not dissimilar to the architect in the design team. The fire safety engineer has the capacity to contribute to the principal design of a building, but to also impose additional Performance Requirements that most other members of the design team must incorporate in their specifications [6]. For example, the fire safety engineer will articulate specific Performance Requirements for smoke management systems in terms of extraction rates of operating temperatures which must be delivered to the HVAC engineer; or the fire safety engineer may have influence over the positive decision to reject a particular material over its incompatibility with a building that requires consideration of how a design fire scenario will evolve given a proposed geometry and ventilation characteristics. This represents an optimal implementation of fire safety and aligns with elements of the conceptual grounding described.

Requirement 9: the fire safety strategy should support collaboration and communication between stakeholders and facilitate the peer review process.

- While the fire safety strategy is not a communication tool, it should be communicated. The integration of fire safety with other disciplines in the design team necessitates that the strategy can communicate the requirements and the need for those requirements to other stakeholders.
- Peer review depends on understanding the intent behind proposed systems and features. As is necessary for communication with other stakeholders, the strategy should clearly articulate this intent in such a way that facilitates peer review.
- The fire safety strategy as a communication tool extends to the operation of the building through its lifetime, hence issues of required maintenance and management should also be included.
- Necessity of communication is also highlighted by others including, e.g. Ref. [31] and in standards and other practice documents, e.g. Refs. [32,33].

2.3. Regulatory considerations

Requirement 10: Preparation of the fire safety strategy must be reliant on professional competence and specialist knowledge.

- Recent discourse emphasizes the role of the professional in fire safety engineering and the importance of regulating the profession on the basis of knowledge, skills and experience. Given its societal importance, the development of the fire safety strategy should fall within the domain of and be the responsibility of the fire safety engineer—not of other design team members. Furthermore, delivering the fire safety strategy as appropriate to the problem context or specific building is the primary function of the fire safety engineering professional. This is consistent with the approach to provision of fire safety engineering which was recommended following the Summerland [10] and the Stardust fires [11], and which has been recommended following the Grenfell Tower fire [3].
- Engineering competencies are briefly described in the Australian Fire Engineering Guidelines (AFEG) [33]/International Fire Engineering Guidelines (IFEG) [34], and organizations such as the Society for Fire

Protection Engineering (SFPE) have produced and published engineering competency standards [35] that outline the expected technical knowledge that an individual should be able to demonstrate when seeking chartered membership of that association. Other competency frameworks exist in the literature which emphasize the design of the fire safety strategy as the core skill of the fire safety engineer, specifically those already noted in the introduction [6,7].

- The emphasis on this requirement means that fire safety engineering education and practice will need to re-adopt the aspirations and stance put forward by, for example, Rasbash in the 1980s [13]. Without this adoption of an educational focus on fire safety of the building as a systemic whole, it will not be possible for the profession to respond to, e.g., the recommendations of the Grenfell Tower Inquiry.

Requirement 11: The definition of the fire safety strategy should support plurality of approaches to fire safety engineering.

- The definition of the fire safety strategy should be analysis or evaluation method-agnostic, accommodating for example probabilistic and deterministic approaches as deemed appropriate by the fire safety engineer. It is the role of the fire safety engineer to take the lead in demonstrating that the proposed fire safety strategy meets the goals/objectives that it is intended to. Furthermore, the tooling choices, such as the use of computational fluid dynamics (CFD) or empirical correlations of smoke movement, are the prerogative of the fire safety engineer. This approach is necessary to avoid the overarching concept being constrained to one or a few specific types of projects and being unable to respond to changes in the built or indeed any other environment. For example, both probabilistic and deterministic approaches to fire safety engineering will inherently be constrained by a lack of data for new products, systems and materials or emerging hazards [36]. Thus, the utility in either a probabilistic or a deterministic approach is as part of the suite of tools available to the fire safety engineer to approach the evaluation of a range of problems. The choice of what approach to adopt must be a choice which is not limited by the definition of what is a fire safety strategy [37].

Requirement 12: The definition of the fire safety strategy should require the contribution of the fire safety engineer into the different stages in the life cycle of a project or a building.

- Similar to criteria around multiple layers of protection, the fire safety strategy could also be developed longitudinally over the entire design life of a building from concept through to completion and handover.
- In the academic literature, for example, Alvarez et al. [30] highlight the dynamic nature of the building-occupant system over its life span. The result of this dynamism is different to the concept of lateral holism discussed under conceptual grounding above and may be considered a longitudinal holism. This is already being adopted in some jurisdictions. For example, in New South Wales in Australia for some classes of buildings [38]. A fire safety strategy may also be extended longitudinally to incorporate aspects of building use, consistent with the Fire Safety Reforms in the UK in the mid 2000s [39] – the implementation of which may require adjustment to the strategy, but also possibly extending to include maintenance/renovation/demolition.

Requirement 13: The fire safety strategy should be an output which supports achievement of regulatory compliance (the fire safety strategy should therefore also demonstrate that the proposed solution meets the regulatory Performance Requirements).

- The strategy should align with various regulatory frameworks and should be instanced in such a way that it can be used to support demonstration of compliance with statutory requirements.

2.4. Data

Requirement 14: The fire safety strategy should be reliant on verifiable or justifiable inputs.

- Reinforcing the professional's role, the strategy should serve as a framework within which to justify the suitability of inputs used in analysis. The risks of adopting inputs to the fire safety engineering problem without positive deliberation as to their suitability are described in detail by Mohan et al. [40], who refers to this as the ‘assumptions trap’. More fundamentally, however, the fire safety strategy is an opportunity for the fire safety engineer to articulate on what basis the information that they are applying to a building is appropriate in application to that building. For example, in the adoption of a conservative assumption of ignition delay time equal to zero, the fire safety engineer can use the fire safety strategy to explore the reasons why this assumption might be conservative but also to provide the basis of why a less onerous assumption can be made. This in turn will facilitate peer review and stakeholder communication.

Requirement 15: The fire safety strategy should reflect the positive and deliberative adoption of inputs and assumptions throughout the process.

- While not excluding prescriptive solutions, the strategy should be an opportunity for the justification of the use of such provisions beyond their mere availability (e.g., classification-based provisions), i.e. through their deliberative and positive adoption [41].

3. A definition

A definition which incorporates all the requirements described in the previous section is:

> In the built environment, the fire safety strategy is the description of the ensemble of elements and attributes of a building which deliver fire safety and the narrative by which these elements work together to result in a satisfactory performance in fire of the building through the duration of the fire event. The fire safety strategy will provide a narrative of how this performance has been established and how it needs to be maintained through the lifetime of a building.

The elements of the fire safety strategy will serve to control or to guide the evolution of a fire inside of a building, the response of the building itself to a fire, the response of the building occupants to the fire whilst enabling the first responder intervention. Importantly, the strategy must characterize Performance Requirements on the basis of goals for the building such that it is possible to verify quantitatively that these requirements have been met; it must explicitly state the scientific, technical or engineering bases upon which the narrative relies; it must respond to the Performance Requirements of the regulatory environment; and it must comprise a narrative of how the systems and features work together which links this functioning with the goals and the Performance Requirements as stated. Finally, it must establish any management strategies that are necessary complements to the building performance as well as the mechanisms by which the desired performance needs to be maintained through the life of the building (e.g. maintenance).

3.1. Design process

As important as the definition, however, is the implementation of this concept, and the ability to implement it from a practical perspective. This is further discussed in this section drawing on the process of design from the field of Design Science Research (DSR) – specifically the Design Science Research Model [42]. The steps in the DSRM methodology may be defined as follows:

1. Identify the problem and motivate - specifically this entails the articulation of the nature of the problem which is to be solved and motivation of a description of the problem.
2. Define the objectives of the solution including a broad agreement as to what it is a solution is supposed to achieve, including goals in such a way that they describe what a better artefact, or solution to the problem, would accomplish; and against what criteria this performance should be evaluated.
3. Design and development of the proposed specifications of an artefact which addresses the problem and is intended to meet the objectives.
4. Demonstration of the performance of the proposed solution. Very often this will require either a prototype to be built, or for an abstract representation of a solution to be prepared. This abstraction could take the form of one or more numerical or other models designed to be used to demonstrate performance of the solution. These abstract models are then manipulated in such a way that the overall performance of the solution against a range of inputs can be demonstrated.
5. Evaluation of the performance of the solution against the objectives that were proposed in the second stage. This may be as simple as determining whether or not an objective is achieved, or it may be as complex as identifying to what extent an objective is achieved if multiple candidate artefacts are proposed.
6. Communication of the results of the process and the specifications of the artefact.

In the above, the problem to be solved in step 1 is the proposed development of a particular building, the objectives of the solution in step 2 are the fire safety goals which are to be achieved, the proposed solution, the artefact in step 3, is the fire safety strategy, incorporating all of the elements which are outlined above, the demonstration of the performance of the solution in step 4 is the manipulation of the strategy and its components through its abstraction to study its overall performance; the evaluation of the performance in step 5 is the verification that the specifications achieve the stated objectives.

There are two opportunities in this overall process whereby iteration can be performed. These are between steps 3 and 5, whereby if needed the design can be iterated to improve the performance and the subsequent evaluation against any performance criteria that were agreed. However, an additional iterative step may also be performed between steps 2 and 5, whereby if it is not possible to arrive at a solution which satisfactorily meets all of the Performance Requirements that were set then the Performance Requirements themselves can be iterated – or the overall problem can be reformulated. An example which may require rearticulation of the problem is a situation whereby it is not possible to satisfy sustainability and fire safety goals of a project whilst using a particular product which has desirable architectural qualities. In this case, two options may be to decide not to use the product (reformulating the architectural objectives) or to reformulate either the sustainability or fire safety objectives such that this product can be used.

3.2. Considerations for practice

Figure 2 illustrates the relationship between the Goals, the Narrative, and the Performance Requirements which form part of the fire safety strategy, the definition of which all forms a linear process. This process can be subject to rapid revision since it does not require detailed modelling or demonstration of the overall performance of the system. The benefit of rapid revision is the ability to conceptually trial several iterations or candidate fire safety strategies with other stakeholders of the design process, discussing the likely impact of delivering the desired outcomes on other members of the design team. At this stage the fire safety engineer having input to or working in collaboration with the principal design team will have significant input to the overall concept. Referring to the DSRM methodology, this will correspond with stages 1 to 3.

Slow iteration will occur when the project moves into detailed design and the evaluation of performance is done. This will correspond with stage 4 in the DSRM methodology. The fire safety engineer working in the role of analyst will have involvement at this stage, but their role will be limited to demonstrating the performance of the proposal (possibly including commenting on the feasibility of proposed solutions). Based on the detailed design, verification can and should occur in 3 stages, determining whether (i) the Performance Requirements have been met, (ii) the proposed narrative is supported by the overall design, and (iii) if the goals have been demonstrably achieved. An additional optimization step may also occur, ideally in the rapid revision phase considering cost-benefit analysis of proposed designs before these are finally selected

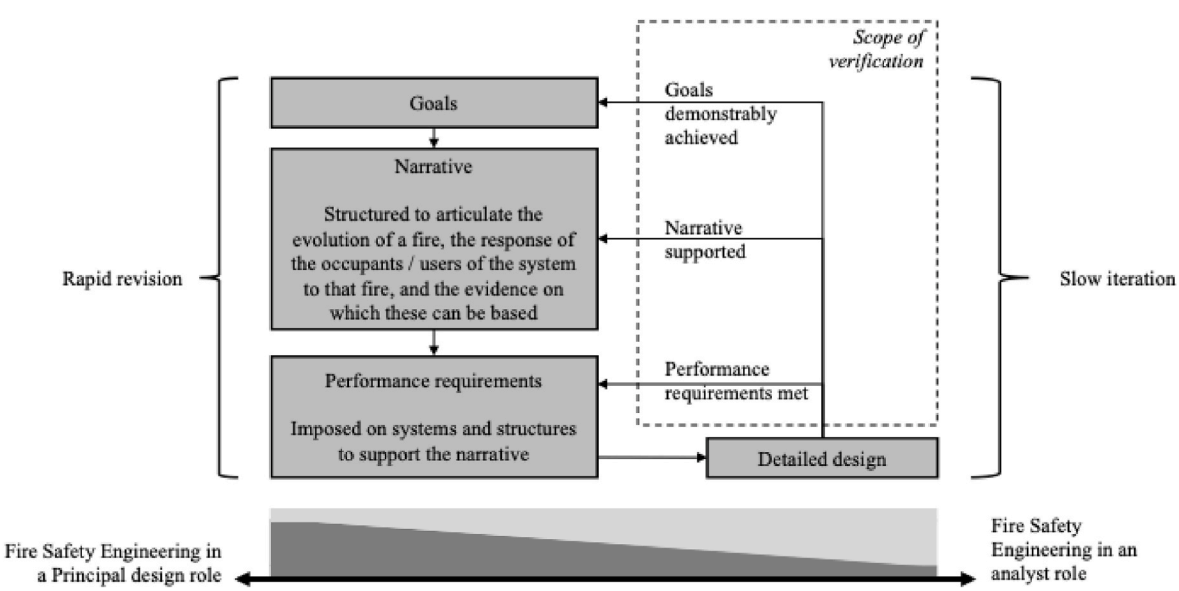

Fig. 2. The relationship between the fire safety strategy and an existing performance based regulatory environments.

from Refs. [43,44].

4. Considerations for adoption

The relationship between the fire safety strategy as we have defined it in the previous section and the regulatory structures in which it will be implemented is as crucial to its adoption as the requirements of the definition itself. The narrative component of the fire safety strategy is critical for the use of the concept in current regulatory environments. The reasons for this will be elucidated in this section.

Performance-based regulatory environments have a common hierarchical structure [45]. Elements of this hierarchy are combined in different environments, and some of the levels have different names in different regions or countries, however the general structure is consistent. The upper levels of this structure include at Level 1 the Goal, at Level 2 the Functional statement, and at Level 3 the Performance (Functional or Operative) requirements. The Goal states from a high-level perspective what is required in rather broad terms from a building. This Goal should not be confused with the goal of the fire safety strategy as described elsewhere in this article. This is because regulatory goals are typically policy-based and reflective of societies broader expectations of fire safety as opposed to building or project specific goals. The Functional statement describes (again at a high-level) how the goal should be achieved. The Performance requirement is intended to describe in more detail what the Goal and the Functional statement mean within a specific context.

These top three levels detail societal expectations as to what is to be achieved through meeting the regulations.

The lower levels in this hierarchy provide a structure for solution of the problem based on classification which either enables a specific set of prescriptive solutions, or on application of a performance-based solution to the individual Performance Requirements. A common and current process for implementation of fire safety in a building will rely on what is effectively an audit of the proposed design against the prescriptive solutions in the relevant classification. This audit can reveal departures from a part of the prescriptive solution as relevant for the classification of the building. These departures are then the subject of the development of performance solutions which meet the relevant Performance Objectives which have not otherwise been met. This reductionist practice falls far short of ensuring delivery of the fire safety outcomes that society expects. "Performance-based design" implemented in this way should therefore not necessarily be conflated with the development of a fire safety strategy, and certainly not explicitly. This is because any methodology which approaches the Performance Requirements individually is not synonymous with any concept that could be considered holistic (although it does not preclude it, it is misleading if directly associated with it).

However the fire safety engineer operating in a performance based regulatory environment consistent with this structure will be required to have confidence and to be able to demonstrate, when developing a fire safety strategy for a building, that the Performance Requirements have been met. To do this, the fire safety engineer will be required to determine the correct interpretation of the Performance Requirement. To illustrate this process, consider the example of the way building regulations may be applied with regards to external fire spread. The wording of the relevant Performance Requirement (C1P2 clauses 1 and 2) in the NCC of Australia [8] is:

> *A building must have elements which will, to the degree necessary, avoid the spread of fire* [via external walls] *appropriate to - (a) the function or use of the building; and (b) the fire load; and (c) the potential fire intensity; and (d) the fire hazard; and (e) the number of storeys in the building; and (f) its proximity to other property; and (g) any active fire safety systems installed in the building; and (h) the size of any fire compartment; and (i) intervention; and (j) other elements they* support; *and (k) the evacuation time.*

The basic limitation of the building classifications corresponding to high rise buildings is the interpretation of the term "appropriate to" when it concerns vertical flame spread, and most prescriptive provisions will limit fire spread by requiring non-combustibility of an external wall system or that the external wall is subject to some test and achieves a classification which enables its application in that environment (e.g. the BS8414 test series and classification according to BR135 or AS5113, etc.). Through the details of these tests (e.g. window detail/no window detail, return wing/no return wing, fuel source and definition of the fire, etc.) regulators adopting these tests in prescriptive provisions will have reached a consensus that the tests are demonstrations of a level of performance suitable to meet the relevant Performance Requirement when implemented as part of the prescriptive solution. Thus, the use of any of these tests in an engineering analysis is problematic since the Performance Requirement cannot be explicitly and quantitatively linked to the test outcome.

Through the narrative support for the fire safety strategy there are two possible ways of articulating the performance requirement above in such a way that it can be explicitly demonstrated that it has been met.

The first approach is to construct a narrative that considers, in the event of a fire involving the external wall, building occupants will be required to evacuate the building in a manner in which the egress routes do not become over populated (thus requiring phased evacuation), whilst being able to evacuate a floor before fire is able to re-renter the interior of the building. This narrative reveals the goal in this instance that $t_{e,compartment} < t_{f,compartment}$. This goal then allows articulation of the Performance Objective in the alternative form *That the avoidance of the spread of fire* via *external walls should be to a degree that ensures that the egress strategy can fully function despite some vertical fire spread, and that the extent of that vertical fire spread will be limited.*

The second option is to express the requirement in a definitive and restrictive form, based on a narrative that there will be no flame spread and thus the occupants will be able to stay in place. i.e. the definition of *appropriate* for a particular building is that the fire can never spread to any extent via the external walls ($t_{f,compartment} \rightarrow \infty$). What this means is either that the design and management must be such that fire can never re-enter a compartment either adjacent to or distant from the compartment where the fire originated via the openings. This can be achieved in many ways, for example, by either eliminating the possibility of flashover in the compartment of origin, or by guaranteeing that the external wall contains no combustible materials whatsoever and does not undergo mechanical deterioration to a level where the fire can breach any adjacent compartment, by encapsulating any combustible materials so that fire spread is completely avoided, etc. Every one of these solutions will have to be demonstrated and in every instance there will be advantages and disadvantages. Perhaps most significantly, this will result in significant impositions to the window layout of a building to ensure that window to window fire spread can be avoided, something which can reasonably be expected to occur in most instances and within a relatively short time frame [46].

Both approaches are valid, with the former being less restrictive than the latter and therefore offering a significantly wider spectrum of solutions. The level of restriction in the latter can vary, and the level of restriction will change the viability of the different solutions. The level of restriction will also affect the challenges in implementation and nature of the demonstration of performance, potentially rendering the demonstration of performance of certain solutions impossible or beyond the competency of the fire safety engineer.

5. Conclusions

The lack of a formal and widely adopted definition of the fire safety strategy is a significant risk. Recommendations following fire safety disasters over the past 50 years have all made reference to the need to consider fire safety as a systemic property within the context of a building, and yet current practice and regulation almost universally treats fire safety as a property which can be decomposed into the performance of individual elements. In this article we address this issue by reviewing the evolving use of the term over the past 50+ years and highlighting certain requirements that any definition of the term needs to meet to deliver the outcomes that society expects from fire safety engineering.

The result is a definition of the fire safety strategy which *is the description of the ensemble of elements, features and attributes of a building which deliver fire safety and the narrative by which these elements work together to result in a satisfactory performance in fire of the building through the duration of the fire event. The fire safety strategy will provide a narrative of how this performance has been established and how it needs to be maintained through the lifetime of a building.* This strategy must fulfill certain criteria, all detailed herein and including controlling or guiding the evolution of a fire inside of a building, the response of the building itself to a fire, and the response of the building occupants to the fire whilst enabling the first responder intervention.

The overall process of development is discussed at a very high level, using a generic design methodology for reference, and opportunities for integration as well as rapid design iteration are also highlighted. These can be done before the detailed design and verification stages to deliver a robust fire safety strategy.

Finally, the relationship between the fire safety strategy defined in this way and the regulatory environment is discussed. The process of developing a fire safety strategy incorporates the Performance Requirements of the relevant regulatory framework and characterizes these in response to safety goals which are defined at the outset of the development process, and which serve to connect the overall system performance. The resulting process actively integrates regulatory compliance as opposed to simply responding to the wording of regulation.

The outcomes of this work are particularly relevant for future development of the fire safety engineering profession, for education and for policy. Future work includes the development of case studies demonstrating the process of development and delivery of illustrative examples of fire safety strategies developed for buildings considering a range of contexts.

CRediT authorship contribution statement

David Lange: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **David Morrisset:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Ayyappa Thejus Mohan:** Writing – review & editing, Investigation. **Joshua Madden:** Writing – review & editing, Investigation. **Wenxuan Wu:** Writing – review & editing, Investigation. **Anwar Orabi:** Writing – review & editing, Conceptualization. **Ryan Hilditch:** Writing – review & editing, Conceptualization. **Felix Wiesner:** Writing – review & editing, Conceptualization. **Martyn S. Mclaggan:** Writing – review & editing, Conceptualization. **Vinny Gupta:** Writing – review & editing, Conceptualization. **Juan P. Hidalgo:** Writing – review & editing, Conceptualization. **Ian Pope:** Writing – review & editing, Conceptualization. **Michael Woodrow:** Writing – review & editing, Investigation, Conceptualization. **Jose L. Torero:** Writing – review & editing, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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