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Glenn Corbett *Editors*

Handbook of Cognitive and Autonomous Systems for Fire Resilient Infrastructures

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Preface

We continue to view buildings as gravity-defying structures designed to withstand the adversity of humans, nature, and time. One of the most extreme events a structure might undergo is fire. Unlike other traditional load actions (i.e., wind, seismic events, etc., which are primarily bound to a seasonal or geographical location/region), fire, on the other hand, can virtually break out anywhere and anytime. While fire has been noted as a critical issue over the past few years, research on this area continues to favor dated experimental and numerical approaches. To further complicate this matter, the fire design of structures still heavily relies on prescriptive solutions with little room for innovation or flexibility.

Unfortunately, the past few years have witnessed a drastic surge in both frequency and intensity of fire incidents, both of which are transforming our history—and, more specifically, our fire engineering history. The aftermath of these incidents is a continuous reminder of the serious flaws in our virtually unchanged, decades-old construction philosophy. It is equally concerning and troubling that structural engineers seem to converge on the notion that it is quite impractical, and perhaps unfeasible, to "truly" design fire-resistant structures. This motivates adopting a new look into this challenge, perhaps one that draws inspiration from the advent rise of automation and robotics. This is the primary motivation behind this handbook.

Through this lens, buildings (or structures) are not to be thought of as a series of passive and rigid arrangements of load-bearing members; but rather, we must appreciate the philosophically striking similarities between such buildings and robots. For example, buildings and robots are often subjected to external and/or internal forces. As such, they are designed with embedded structural systems capable of handling such effects to maintain structural integrity. Furthermore, both buildings and robots frequently operate in extreme environmental conditions under a continually complex combination of temperature, pressure, and stress. Nowadays, buildings are commonly being supplemented with sensory instruments, primarily to monitor their "health" as to give insights into deteriorating processes (i.e., corrosion), energy consumption, or into occupants' preferences (e.g., thermal comfort, etc.). Similarly, robots are also embedded with sensors to enable self-diagnostic interaction with surrounding environments and to deliver valuable information to human operators. One can see that there is more to buildings and robots than meets the eye.

The above discussion promotes the following question, what if buildings are designed to incorporate robotic features? What if buildings have cognitive and autonomous abilities? How can we realize such abilities?

With the onset of the fourth industrial revolution, advances in artificial intelligence (AI), internet-of-things (IoT), and robotics are expected to be heavily integrated into the construction industry. Unlike other works, this handbook is not interested in adopting robots as construction workers, nor as 3D printers, but rather seeks to integrate signature features from robots into skyscrapers and infrastructure with especial attention to disaster-induced collapse mitigation.

From this book's perspective, future buildings can be thought of as giant shape-shifting robots with cognitive and autonomous capabilities. The cognitive capability refers to a building's intelligence to understand its surroundings and interact with its occupants. For instance, a cognitive skyscraper will be able to identify the breakout of a disaster (i.e., multistory fire) while at the same time analyzing cascading events in real time using state-of-the-art AI. Such a skyscraper will also be able to pinpoint vulnerable regions or load-bearing components and foresee how damages arising from an extreme event can lead to unwarranted failure/collapse. This is equivalent to a robot assessing its own condition in the event of a mechanical arm impairment or loss. In this scenario, the robot will seek to first understand the impact of such loss, and then it will attempt to devise plausible solutions to overcome such damage.

However, "*knowing without action is useless*." Preliminary efforts have shown how a cognitive building is not only able to convey its predictions to occupants and first responders to facilitate evacuation but also be able to physically turn this information into actions (Naser 2019, 2020). In order to build up the "action" component, future skyscrapers can be supplemented with tentacle-like, and self-deployable (TL-SD) robotic load-bearing structural components. Such components are to be designed independently of the main structural system and hence can be integrated into building façade or compartment boundaries (see Fig. 1). The deployment of a TL-SD structural component can be activated once the cognitive component of the building detects excessive deformations or instability. The deployment of such a tentacle starts by unfolding and inflating a TL-SD structural component into a relatively stiff configuration through pressurized dynamic sliding and shape-memory hinges etc.—similar to those often used in octopus-inspired robots.

Thus, a building equipped with TL-SD structural components will have the capability to autonomously reconfigure its internal structure to divert the adverse effects of extreme events away from its occupants, as well as critical load-bearing members, and possibly towards outside the building; thereby preventing significant damage and collapse. Such events can include extreme temperatures in excess of 800–1000 °C, significant seismic vibration, blast, or impact. As a result, a cognitive and autonomous shape-shifting skyscraper can achieve higher levels of structural resilience (survivability) under extreme environments. This improved performance mitigates failure (collapse), thus allowing first responders to tackle the adverse effects of disasters.

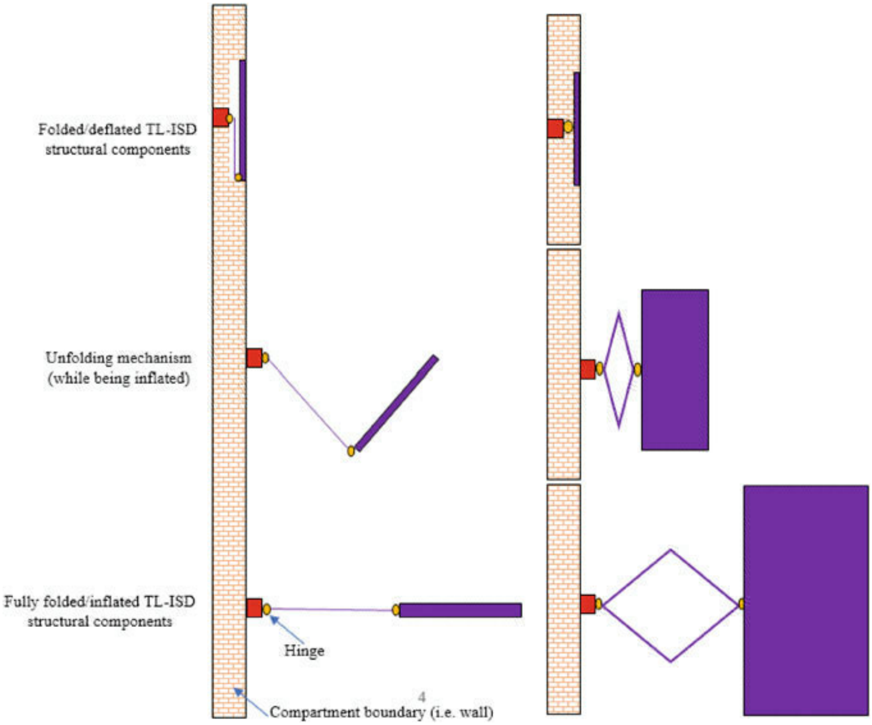

Fig. 1 Details of a TL-SD structural component

Despite the above optimistic look, one should note that the construction industry is notorious for its inertia and slow adoption of new technologies. Open discussions and collaborations are needed to enable a smooth transition from theory to design to implementation.

Notably, this forward-looking handbook addresses the critical issue of bringing buildings and emergency responders together, a rather novel approach to fire safety even in the twenty-first century. Incredibly, most building designs today do not consider the interaction between firefighters and the buildings they operate in. This handbook literally fills in this gap by providing cutting-edge research, providing design professionals with an understanding of the needs of firefighters and how that impacts building design.

This handbook homes findings from 13 chapters from leading experts on fire safety, engineering, and firefighting from around the world. These experts share state-of-the-art information with regard to various aspects of modernizing the future of safety, engineering, and firefighting. This handbook starts with Chap. 1 where Brian Meacham presents a look into *Sociotechnical Systems Framing for Performance-Based Design for Fire Safety* to lay the foundation for transforming our ways of tackling fire hazards. Then, enters Chap. 2 by Vytenis Babrauskas, to draw a picture for *A Twenty-First Century Approach to Fire Resistance* that stretches our comfort zone into a new frontier. In Chap. 3, Casey Grant showcases a roadmap to *Integrating Modern Technologies to Realize Fire-Resistant Infrastructures*. It is in this chapter that we start to tie automation concepts often seen in parallel fields to our fire domain. In Chap. 4, *Intelligent Science Empowers Building Fire Protection Technology Development*, Feng Luo goes on to showcase how existing fire protection technologies can tremendously improve by borrowing the concepts of IoT and AI.

LaMalva and Medina present us with a look into how the integration of automation will reshape our building codes and standards in Chap. 5, *Building Codes and the Fire Regulatory Context of Smart and Autonomous Infrastructure*. Then, in Chap. 6, Xinyan Huang and colleagues deliver *Perspectives of Using Artificial Intelligence in Building Fire Safety*, thereby delving into the depth of AI and its role in improving building fire safety. Chapters 7 and 8 are written in collaboration between Brian Lattimer and Jonathan Hodges. These two chapters specialize in *Intelligent Firefighting* and *The Role of Artificial Intelligence in Firefighting*—a key resource for our first responders in the new era of cognitive and autonomous structures. Charles Jennings' Chap. 9, *Implementing AI to Assist Situation Awareness: Organizational and Policy Challenges,* focuses specifically on the use of artificial intelligence to provide real-time situational awareness on changing conditions for emergency responders.

The last four chapters capture intricate details with regard to burning questions we continue to face. For example, in Chap. 10, Wojciech Kowalski and colleagues chart a *probabilistic-based reliability approach to overcoming fire hazards in structures*. Chapter 11 is titled *Autonomous Sensor-Driven Pressurization Systems: Novel Solutions and Future Trends*, where Wojciech Węgrzyński and Piotr Antosiewicz focus on autonomous solutions for smoke control in buildings to maintain smoke-free evacuation routes under fires. Ana Sausa revisits the classical standard fire testing from a new perspective—one that incorporates *Hybrid Fire Testing* to enable us to move from component-level testing to system-level fire testing in Chap. 12. Finally, in Chap. 13, Liming Jiang and colleagues give an approach for *Realistic Fire Resistance Evaluation in the Context of Autonomous Infrastructure*.

This handbook started with an idea that we shared during 2018–2019. Initially, we were hoping to complete this handbook by 2020. Little did we know that a pandemic was on the horizon. While the pandemic challenged our initial deadline, we could not have delivered this handbook without the hard work of our contributors. Our hats go to them. Finally, we would like to thank Springer for lending our contributors and us this platform to showcase a glimpse of what the future holds for our domain. A special thanks go to Paul Drougas, Kritheka Elango and R.Savita for believing in the message of this handbook, continued support, and for taking the lead on editing and formatting this handbook.

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Contents

Toward a Sociotechnical Systems Framing for Performance-Based Design for Fire Safety

1

Brian J. Meacham

1.1 Current Structure/Process for PBD of Fire Safety

This section reflects the author’s perception of the current structure and framing of performance-based design (PBD) for fire safety. It is suggested that PBD for fire safety emerged in the 1990s, [1–7] concurrent with the introduction of functional- and performance-based building regulations in several countries [1, 8–11]. The foundations of PBD for fire safety can be found in the following:

- Research into compartment fire dynamics of the 1950s–1970s [e.g., 12–18], which ultimately gave rise to important concepts such as defined stages of fire development, means to estimate compartment fire temperatures, fire growth rate, rate of heat release, and the like, which embody the fire safety science that underpins fire safety engineering [see, for example, 19].
- Concepts of reliability-based design [e.g., 20–24] and quantitative risk analysis and of risk-based and risk-informed design concepts [e.g., 25–31] which emerged in the 1960s and 1970s.
- The application of these concepts to fire design of structure in the 1970s and 1980s [e.g., 32–36].
- Systems constructs and design approaches introduced by pioneers of “fire systems approaches” in the 1970s and 1980s [e.g., 37–45]. Although different terminology is used, the “fire system” components introduced at this time, and still in use, include fire prevention, fire initiation, and development, means to control fire spread, means to control smoke spread, detection, suppression, structural stability, occupant protection, fire service operations.

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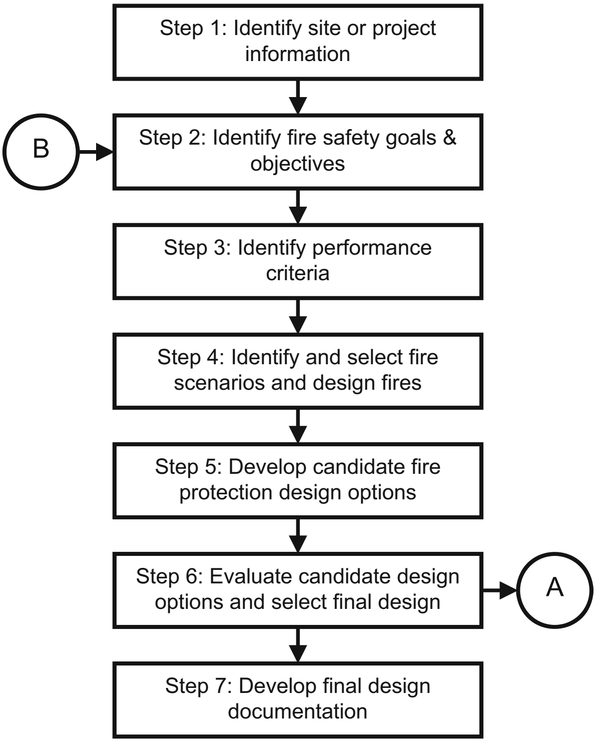

Fig. 1.1 Fundamental steps in the PBD for fire safety process (Source: author, adapted from [5])

- Introduction of computer modeling applications for fire in the 1970s and 1980s [e.g., 46–51].

By the late 1980s and through the 1990s, outcomes of fire safety science and engineering research, structural fire engineering research, the concept of fire systems components, and reliability- and risk-based design began to be integrated into structural fire performance design [32–36], fire safety engineering (FSE) frameworks [52–55], and ultimately into frameworks/process descriptions for PBD for fire safety [2, 4, 5, 8, 56, 57]. Although some differences exist between the various frameworks, they all follow the general structure and process flow as illustrated in Figs. 1.1 and 1.4 (adapted from [5]).

The starting point in the process is identifying the fire safety goals and objectives. These may be embodied in a regulation or may need to be developed for a specific facility, process, or system. When embodied in building regulation, the objectives may be referred to as functional statements, operative requirements, performance objectives, or simply objectives. These are often qualitative statements, which described the intended function of a system and/or the outcome that is desired. Examples include statements such as ‘the building and fire safety systems shall be designed to prevent the exposure of those occupants not intimate with first materials burning to untenable conditions during the time required for them to reach a place of safety outside of the building,' or 'the building and fire safety systems shall be designed to limit a fire which occurs in the building to the compartment of fire origin.'

It can be the case that in developing an actual design, the engineer needs to formulate "design objectives," which may still be qualitative, but which reflect a specific function or outcome that can readily be translated into engineering concepts. For example, in the case of the performance objective stated above, "the building and fire safety systems shall be designed to limit a fire which occurs in the building to the compartment of fire origin," there is no particular sense of how one might limit a fire to the compartment of fire origin. To narrow the focus, a fire safety engineer might therefore define a design objective, which will help meet the performance expectation, but can be readily quantified, such as "minimize the potential for flashover or traveling fire in any compartment in which a fire may occur." By expressing design objectives in such a way, metrics used to describe such phenomena, such as upper-level temperatures, or radiant heat flux at floor level, may be used as design criteria, as discussed below. Both performance objectives and design objectives should be formulated to adequately describe the expected outcomes (e.g., achievement of safety, avoidance of failure), and to the extent practicable, the associated timeframe, such that a decision regarding regulatory compliance and/or performance verification can be clearly made.

Once identified and agreed, performance (or design) criteria must then be identified and agreed. These are quantitative measures by which performance will be stated and designs will be evaluated. These too may be embodied in a regulation, a design standard or guideline, or may need to be developed for a specific component, facility or operational process. Performance (or design) criteria may be stated deterministically or probabilistically, will be related to the method of evaluation, and may be closely associated with specific analytical approaches or methods used for demonstration of compliance and/or verification of performance. It will often be the case that several performance and/or design criteria will be needed to adequately assess and verify the target performance expectations. Exemplar quantities that may be expressed as criteria include temperature, heat flux, species concentrations, visibility, probability of success or failure, and exceedance probability. When expressed deterministically, many criteria require some form of qualifier, such as location (e.g., temperature in the upper gas layer or temperature at 1.5 m above floor level; heat flux at floor level or at 1.5 m above floor level), time/duration (e.g., CO concentration of 1500 ppm for 10 min; heat flux level for 2.5 min), or both. When expressed probabilistically, there may be safety factors that reflect uncertainty or variability, or a time component (e.g., 95% likelihood within 10 min), or other. Criteria will be needed for each type or category of targets being considered by the analysis (e.g., people, contents, structural system components, nonstructural building system components, equipment or systems associated with the use of the building). As will be discussed later in the chapter, identifying and selecting appropriate criteria can be one of the most challenging parts of the performance-based design process.

The next step involves identifying fire scenarios of concern and developing quantified design fires that will be a fundamental basis of analysis. Many PBD frameworks for fire safety separate fire scenario and design fire development because they are approached in much different ways, using different data, tools, and methods. However, they are inextricably linked, a concept that some engineers sometime forget. A fire scenario is a description of a specific fire situation from ignition, through established burning, to maximum extent of growth and resulting decay [5]. There is an infinite number of event scenarios possible for any given building. However, if is generally possible to group the scenarios into smaller subsets of scenarios that can be used as part of the design process. These are called design fire scenarios. The range of design fire scenarios selected for consideration should reflect how likely it is that the event will occur, and if it does occur, how it is expected to impact the building or infrastructure.

In the current PBD for fire safety paradigm, there are many factors that one must consider when developing event scenarios and paring them down into design scenarios, including [5]:

- *Pre-fire situation*: building, compartment, conditions.
- *Ignition potential*: credible combinations of temperature, energy, time, and contact with fuel.
- *Initial fuels*: state, surface area to mass ratio, ignition temperature, rate of heat release.
- *Secondary fuels*: proximity to initial fuels, characteristics, amount, distribution.
- *Extension potential:* beyond compartment, structure, area (if exterior fire).
- *Target locations*: people, contents, structure, operational equipment.
- *Critical factors*: ventilation, environmental, operational, building use.
- *Occupant characteristics*: alert, asleep, ability, age, mental acuity, dependencies.
- *Available relevant data.*

Hazard and risk assessment tools are often the most appropriate mechanisms to help identify fire scenarios and clustering them into representative design fire scenarios.

Once a set of design fire scenarios has been developed, a set of corresponding design fires need to be developed. A design fire is an engineering description of a specific fire scenario or fire scenario cluster. Design fires are used to evaluate the candidate design options, much the same as design loads will be used in structural analysis and design to ensure that the strength of a structure is adequate [5]. Design fires may be characterized by such parameters as growth rate, heat release rate, species production and production rate, burning duration, and other such attributes that can be measured, calculated, and estimated. In its simplest form, a design fire may be reflected as a t^2 fire curve or temperature–time curve. A more complete design fire curve would include the realms or stages of fire development: pre-flaming, established burning, growth, peak and/or steady state, and decay. This is graphically represented in Fig. 1.2.

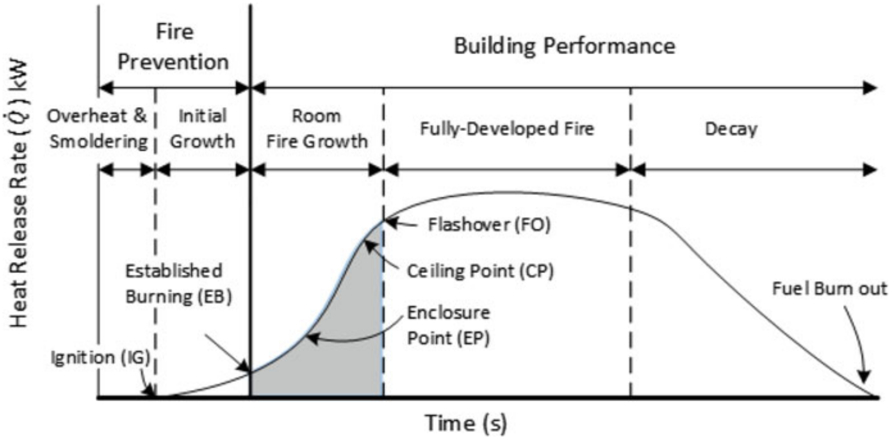

Fig. 1.2 Exemplar representation of realms (stages) of design fire (Source: author, adapted from [59])

In most cases, a design fire curve is actually a composite curve, representing an initial fuel package, and subsequently ignited fuel packages, until fuel has been exhausted, oxygen has been limited, or the fire has been suppressed.

In the current PBD for fire safety framework, design fires should be developed for every design fire scenario considered for a compartment, building, structure, or process. This particularly includes fires that may in some way pose challenges to the building or to fire suppression efforts, including concealed (e.g., in ceiling voids or wall cavities) or shielded fires (e.g., partially covered by a temporary or permanent building feature or content), readily combustible fuels with very fast growth rates and high heat release rates (e.g., flammable liquids, some plastics), areas in which large fuel loads are present (e.g., storage), and the like. Consideration should be given the types of fires that challenge the various fire design options, such as detection devices, sprinklers (where shielded and fast-growing fire can be a concern), large fuel loads (which can burn for long periods and present structural fire performance challenges), and deliberate fires (which may impact paths of fire egress and escape).

Only after the goals, objectives, criteria, scenarios and design fires have been identified and agreed should consideration of alternative fire safety design (mitigation) options be considered. This is particularly true for a full performance-based approach that begins with no specific fire protection measures embodied in the conceptual design. However, in some cases, code- or regulation-specified fire safety design may be suggested or required, with the performance-based process being applied to assess alternative approaches. In this situation, as well as in the case of the analysis and design of fire safety for an existing facility, the analysis should consider all features that are in place.

As noted above, a facility's holistic fire safety system is often comprised of several of the following system components: fire prevention means and measures;

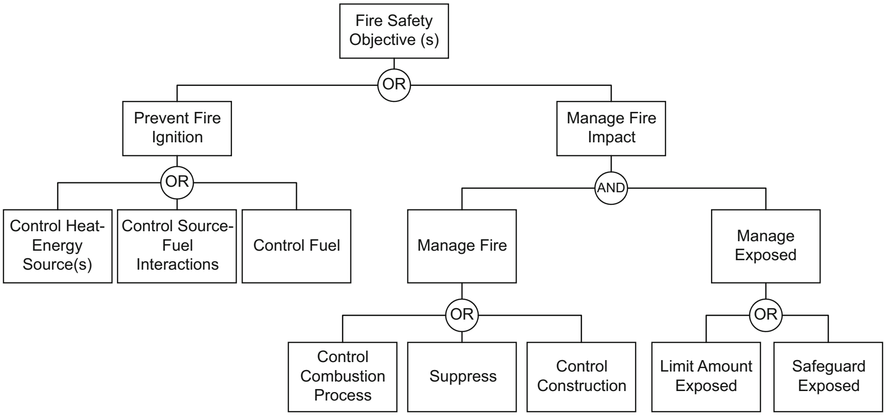

Fig. 1.3 Top Branches of the Fire Safety Concept Tree (Adapted from [60]. Reproduced with permission of NFPA from NFPA 550, *Guide to the Fire Safety Concepts Tree*, 2022 edition. Copyright © 2021, National Fire Protection Association. For a full copy of NFPA 550, www.nfpa.org

means to limit or control fire initiation and development; means to control the spread if fire and fire effluents; means to detect fire, notify occupants and the fire service, and means to suppress fire; means to assure structural stability; means to protect occupants during movement to a place of safety; and means to facilitate fire service operations. A particularly helpful tool to assist engineers in identifying options for consideration is the *Fire Safety Concepts Tree* embodied within NFPA 550 [60], which originally dates to 1985 [40] (Fig. 1.3).

Once an initial set of candidate design (mitigation) options has been identified, the next step is to evaluate their efficacy in achieving the agreed fire safety goals and objectives, as assessed against the agreed performance (design) criteria, when subjected to the set of design fires. This evaluation process is iterative, since there are likely several potential design options which will be technically feasible. The aim is to develop a set of technically credible options, and then apply benefit–cost analysis or other means to compare viable options and select a final design. This process is illustrated in Fig. 1.4 [5]).

There are three major components/considerations of the evaluation process—the analytical concept or framework for evaluation (e.g., the required safe egress time (RSET) must be significantly less than the available safe egress time (ASET) with an appropriate margin of safety)—the evaluation paradigm and level of complexity (e.g., expert judgment, comparative, deterministic, (risk) index, probabilistic, or some combination)—and the data, tools, and methods (e.g., risk assessment models, computational models) required for evaluation at the selected level of rigor. Within each component, due consideration and treatment of uncertainty, variability, and unknowns is required.

Consider the exemplar performance objective presented above, “the building and fire safety systems shall be designed to prevent the exposure of those occupants not intimate with first materials burning to untenable conditions during the time required

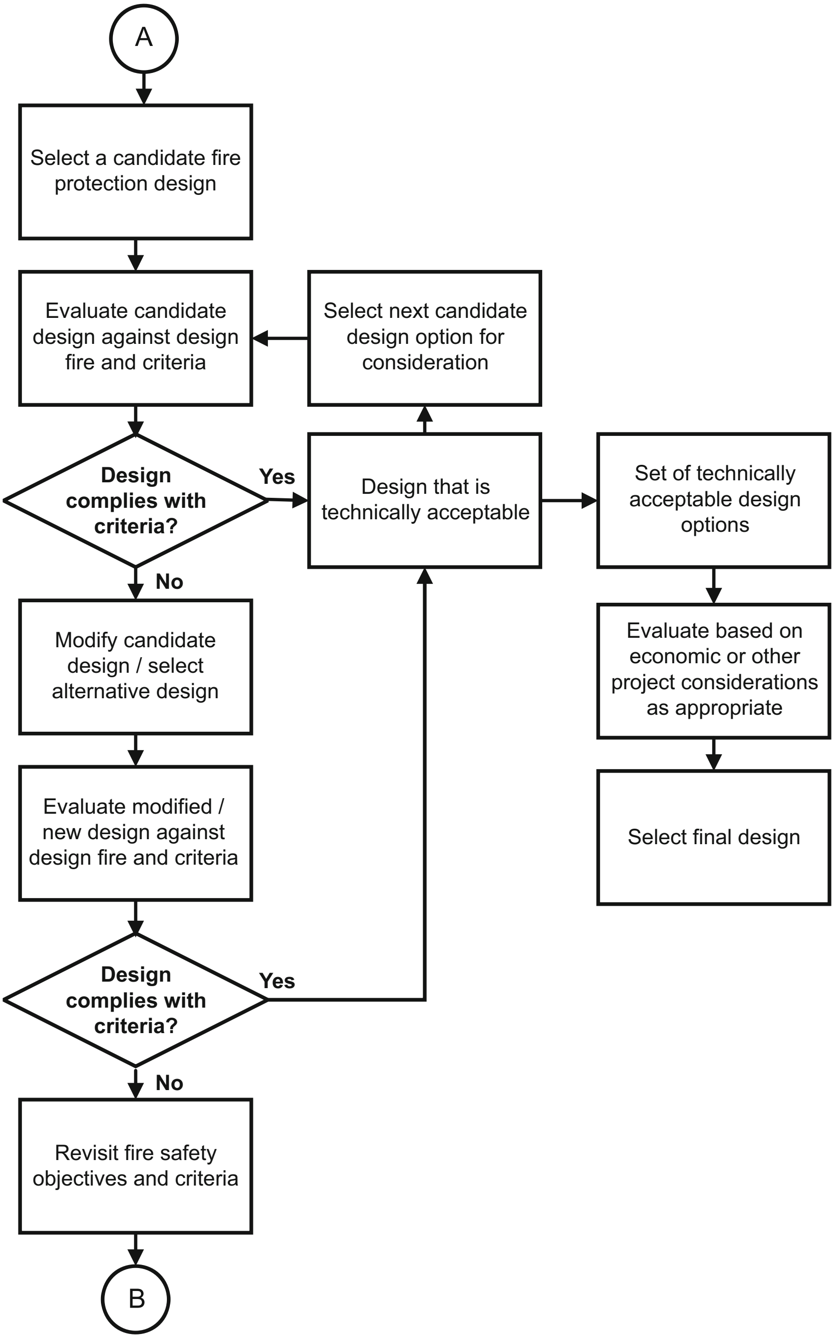

Fig. 1.4 Evaluation of potential fire safety design options (Source: author, adapted from [5])

for them to reach a place of safety outside of the building." In the current PBD for fire safety framework, an appropriate analytical concept/evaluation framework is that RSET (time to reach a place of safety) is significantly less than ASET (time to untenable conditions) with an appropriate margin of safety. How one conducts an ASET-RSET analysis can range from expert judgment to probabilistic or quantified risk analysis (PRA or QRA). The level of complexity varies widely between these approaches, as may confidence in the assessed outcome, especially as related to the level of recognition and treatment of uncertainty, variability and unknowns, which will be integrally related to availability and goodness of data and the appropriateness and appropriate application of specific tools and methods.

The above concepts and more are described in greater detail in any one of the several fire safety engineering or performance-based design for fire safety-related standards, guidelines (e.g., [61–68]), textbooks, and handbooks (e.g., [45, 58, 59, 68–73]) that are available. In addition, through the first two decades of the twenty-first Century, research has been conducted in each of the areas and more, with recommendations for enhancing PBD for fire safety frameworks, scenario analysis and design fire selection, risk-informed and risk-based approaches to FSE and structural design for fire, and more [74–97]. In addition, significant advancements have been made in the area of computational modeling of fire effects, structural response to fire, and occupant evacuation.

However, even with such advancements, the fundamental approach to PBD for fire safety has not changed significantly. This would not necessarily a bad thing—if the current approach is robust, one might argue few changes are needed. However, there are indications that this is not the case and that some concerns exist, even after some 30 years of experience. At present, the acceptance of PBD for fire safety remains challenging in many countries [e.g., 98–101], there has been what some have suggested as "backward" movement with the development of "prescribed performance" based approaches [e.g., 99, 102], and inadequate consideration of technological performance for facilitating consistent building fire performance throughout the building's life [e.g., 83, 88].

There are several potential reasons why such concerns persist [164].

First, fire safety engineering, and PBD for fire safety in particular, are in the adolescent stage of development [7]. Consider the following summary of observations made by Allin Cornell in 1981 on the maturation of a newly emerging engineering area [163].

> In its earliest stages, a new area is characterized by rather uncoordinated relationships between practice and research, between needs and solutions, and between the profession as a whole and those dedicated to the development of the area itself. The problems that have been addressed by researchers tend to reflect personal tastes, ease of formulation or solution, and simple chance. Those applications in practice that do exist tend to be 'local', small parts of larger problems isolated and resolved without reference to a broader framework, because the framework has not been constructed. The major attention is often given to certain minor problems that have been popularized only by the internal dynamics of the small research community itself.
>
> In contrast, at a mature, stable level of development of an area of engineering one customarily finds a smooth interaction between research and practice. A vocabulary has

> evolved, a general framework exists, and the capabilities and limitations of the area are widely appreciated. Virtually all practitioners have received exposure to the subject and are accustomed to recognizing the kinds of situations in which the method is applicable and even to articulating their problems in the language of the area. Most research is being conducted in response to obvious needs of practice.
>
> Clearly in between these two stages of growth there is room for the uneven levels of development that characterize adolescence. Stimulated by larger numbers of contributors, growth is very fast and in some problem areas is indeed beginning to follow rather than anticipate the needs of practice. New practice-generated problems for research are being identified not only by growing numbers of experienced researchers but also by the engineers in practice who have begun to appreciate which of their old problems the new area can help. These initial reactions from practice are often poorly articulated and often, unfortunately, too optimistic. Nonetheless one can see the establishment of certain consensus positions that determine both a framework and a viable set of solutions for at least some rather broadly defined problem areas. But the development and internal coordination of the area are still largely incomplete at this stage: some topics are virtually untouched, limits of effectiveness of the parts or the whole are not well understood, some applications are rather naively formulated, and some practical applications have begun to address a larger framework but not yet with the confidence or the wisdom of experience.

Given the current status of fire safety engineering, and especially performance-based design for fire safety, it can be argued that fire safety engineering is a healthy adolescent. Unfortunately, this has not changed since 1999, when it was observed that "research has begun better addressing the needs of practice, the essential elements of a framework and vocabulary have been developed, and many practitioners appreciate where and how the current methodologies can address their problems. However, the field remains largely uncoordinated, it lacks a comprehensive framework where the limits of effectiveness are well understood, and some applications are rather naively formulated." [7].

Second, much of performance-based design for fire safety currently focuses of safety to life of people, and control of human behavior is extremely challenging to assure [164]. Building occupants are highly variable and dynamically contribute to the fire hazards and risk, both in the probability of fire occurrence and in the magnitude of fire consequences, and it is not clear that assurance of life safety is feasible. Furthermore, consideration of "acceptable" levels of risk to life is a difficult construct for many actors in the building regulatory system, but "risk-free" environments are not possible. This confluence of a stochastic environment, in which the absence of risk is difficult for some stakeholders to agree with, remains a concern that must be addressed.

Third, following on from the above, even though fire is stochastic in nature, and therefore risk-informed and risk-based approaches to PBD for fire safety should be recognized as appropriate approaches, it can be difficult to gain acceptance of risk-informed and risk-based approaches to PBD for fire safety because it can be difficult to gain agreement on, and acceptance of, the fundamental premise that there is impossible to remove all risk (i.e., there is no absolute safety or 'zero risk' condition) [164]. Furthermore, even when it can be agreed that some level of risk exists, it can be difficult to gain agreement on how to express or quantify the tolerable levels of fire risk (and/or fire safety performance), especially when expressed in terms of risk to life. This is particularly difficult for the fire service, whose mission is to save people and property from the unwanted effects of fire. Ideally, they would like to reduce life safety risk to zero, but this is impractical. While they understand this, it can be difficult for such an admission to be made publicly, especially as a result may be that the public then questions whose life is unworthy of saving (which is not a particularly fair question).

Finally, performance-based design for fire safety has not adequately recognized and embodied sociotechnical system (STS) constructs [164]. Buildings, infrastructure, and many hazardous operations are complex sociotechnical systems (STS), with many complex interactions, not all of which are generally considered - or used - in fire safety analysis and mitigation, especially once the building, infrastructure or operations are in use. In addition, because fire is a rare event, and there are few "immediate" indicators of poor fire performance of buildings (i.e., they are tested only when there is a fire), fire performance is rarely tested, and feedback on performance into the sociotechnical system is limited and often incomplete. Complicating the situation further, in some parts of the world there is a lack of adequately educated and suitably qualified professionals across the spectrum, from analysis and design to approval and enforcement of designs, inadequate communication and information flows, and lack of feedback into the system on actual performance, all of which can contribute to a lack of confidence in analysis and design, the proper implementation of designs, and of actual performance in use (i.e., inadequate considerations of institutions and actors in STS context).

These are all sociotechnical system (STS) challenges—none can be solved solely through technology (e.g., computational modeling tools, building fire safety systems), institutions (e.g., regulations, certification), or actors (stakeholders)—but only with an integrated STS approach that recognizes and accounts for challenges and opportunities associated with each component. The following outlines concepts of STS and safety systems thinking, and how these approaches might be useful in advancing the discipline of fire safety engineering and the practice of performance-based design for fire safety. Excerpting and building on [164], the following describes how viewing the problem through a STS and safety system lens can result in a different approach to describing the fire safety objective(s), how they might be attained, and how performance might be assessed, which ultimately can lead to safer and better performing buildings.

1.2 Sociotechnical Systems (STS) Concept

The emergence of sociotechnical systems (STS) theory and concepts came from the study of the roles of social and technological components within organizations and the realization that they are integrally linked [103]. STS have been characterized as having three levels of focus: (1) primary work systems within an organization, (2) whole of organization systems, and (3) macrosocial systems, which include systems in communities and industrial sectors, and institutions operating at the overall level of society [104]. It has been argued that building regulatory systems are macrosocial systems, in which systems in communities, industrial sectors, and institutions operate at the societal level [105].

Many variations of STS theory have been advanced since 1993, largely driven by differing perspectives of the disciplines involved, e.g., business/organizational management, economics, psychology, sociology, design/technology/engineering, political science, and risk and safety management [105]. The characterization of infrastructure and buildings (i.e., the built environment) as STS came into focus with research into such areas as accident analysis, risk management, and system safety [106–108], building-hazard-regulation interactions [105, 109, 110], innovation in construction [111–114], and critical infrastructure interdependencies and vulnerabilities [115–119].

While most systems require interaction between technology, institutions, and actors, not all have the same level of interdependency. For example, Ottens et al. [117] characterize three types or categories of engineering systems: "(1) engineering systems that perform their function without either actors or social institutions performing a sub-function within the system [e.g., the landing gear of an airplane], (2) engineering systems in which actors perform sub-functions but social institutions play no role [e.g., an airplane], and (3) engineering systems that need both actors and some social/institutional infrastructure to be in place in order to perform their function [e.g., an airport]" (pp. 134–135), and conclude that "type 3" systems are STS. This is equivalent to Trist's macrosocial STS domain [105] (Fig. 1.5).

The "type 3" engineering or macrosocial systems, which rely on numerous actors and social/institutional infrastructure, have the added complexity of numerous actor involvement. Kroes et al. [118] note that: "At the sociotechnical level many stakeholders are involved that all have their own goals and visions, and normally none of these actors can impose their decisions on the other actors. For this reason, STSs cannot be designed, made, and controlled from some central point of view, as for instance a car. Instead, the STS is continuously being redesigned by many actors from within the system" (p. 813).

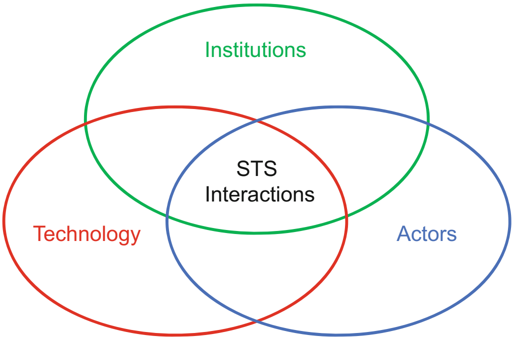

Fig. 1.5 Simplified representation of STS interactions [Source: author]

Arguably buildings, and the building regulatory process (including allowable design processes), are STS, as the system is continuously being redesigned by many actors from within the system [105]. As such, design of any building "system," including a buildings' fire safety system (the aggregate of all fire safety features), is a STS design challenge. If considered in this way, the design focus becomes controlling fire hazards and the safe operation of the STS—which is the building, system or infrastructure—throughout its intended life. Such a focus would result in a paradigm shift in thinking about PBD for fire safety.

1.3 Evaluating PB Design for Fire Through a STS Lens

Summarizing briefly the framing of buildings and building regulatory systems as STS [105, 110, 120, 164]:

- Buildings (complex buildings in particular) are macrosocial, or type 3 "systems of systems" that need both actors and some social/institutional infrastructure to be in place, and working integrally with technology, in order to deliver their intended performance. Buildings have multiple types and levels of technology which need to work together for the building to operate, such as heating, ventilation, and air-conditioning systems, façade/envelop design and construction, and sensor and control networks, or passive and active systems, sensors and controls for fire safety, and occupant evacuation. These technology systems are designed to work for the users—and rely on users to maintain them. The performance of these systems is regulated by and controlled via complex regulatory and private sector institutions, from building regulation to insurance. Ultimately, all components—actors, institutions, and technology—must work together holistically for the building (as a complex system-of-systems) to meet its societal and private sector objectives.
- Building regulatory systems are STS since they must consider the roles that institutions, stakeholders, and technology play in design, construction, and operation of buildings. This includes (a) the need to establish clear societal objectives for buildings, (b) how the technologies must work at each phase, and in total, in meeting the societal objectives, and (c) how to balance the myriad stakeholder input from those involved in the building design, construction, and operation phases of a building's lifespan. Failure to adequately consider any of these aspects, and their multiple components, can result in building regulatory system failure.

A model of building regulatory systems as STS [105], based on Petak's system model for building risk management and resiliency to earthquake hazards [109], is illustrated in Fig. 1.6.

With this as a base, a sociotechnical building regulatory system assessment model (STBRSAM) was created, with the aim being a tool with which building regulatory systems could be evaluated [110, 120]. A truncated representation of the STBRSAM is presented in Fig. 1.6, focusing on the system control component. The

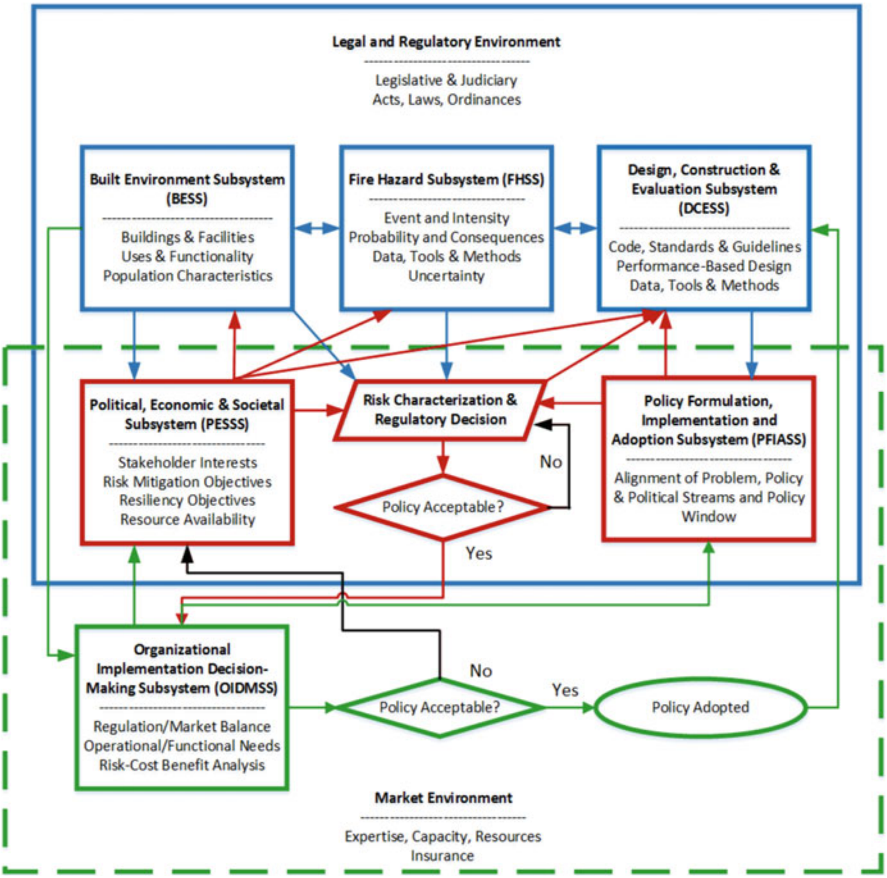

Fig. 1.6 Building regulatory system as STS [105]

STBRSAM is based on Rasmussen's Abstraction Hierarchy as applied to safety control [106, 107, 121, 122] and Leveson's System-Theoretic Accident Model and Processes (STAMP) construct for safety control [108, 123].

The safety management system, Leveson [108] argues, has two basic hierarchical control structures—one for system development and one for system operation—with interactions between them. An aircraft manufacturer might only have system development under its immediate control, but safety involves both development and operational use of the aircraft, and neither can be accomplished successfully in isolation: safety must be designed into the system, and safety during operation depends partly on the original design and partly on effective control over operations (the system control).

Underpinning Leveson's STAMP model is that system theory is a useful way to analyze accidents, particularly system accidents, and that in this conception of safety, "accidents occur when external disturbances, component failures, or dysfunctional interactions among system components are not adequately handled

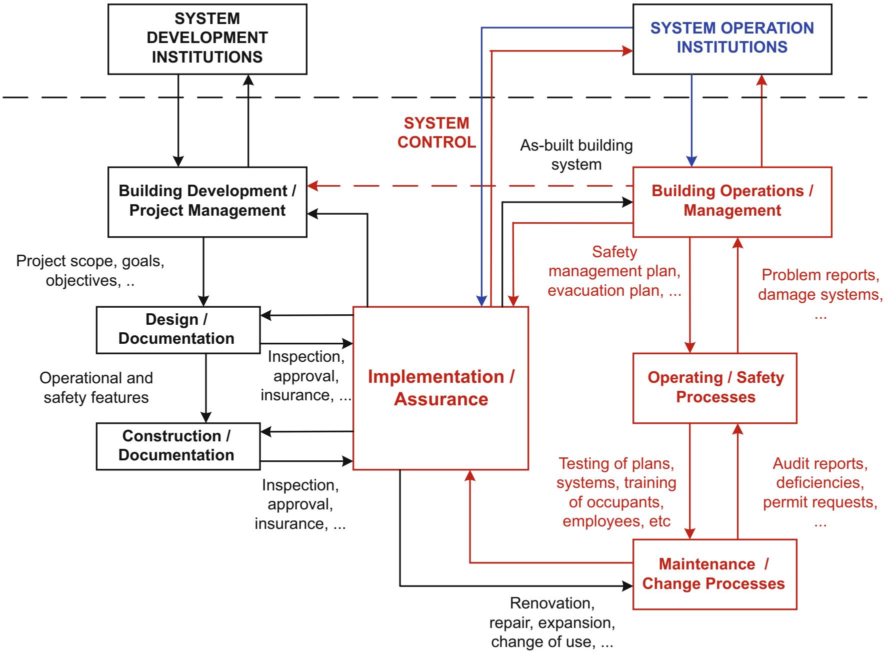

Fig. 1.7 System control component of STBRSAM (Source: author, adapted from [120])

by the control system, that is, they result from inadequate control or enforcement of safety-related constraints on the development, design, and operation of the system" [108]. In this paradigm, safety can be viewed as a control problem, and safety is managed by a control structure embedded in an adaptive socio-technical system, the goal of which is to enforce constraints on system development (including both the development process itself and the resulting system design) and on system operation that result in safe behavior. In this conception, understanding why an accident occurred requires determining why the control structure was ineffective, and preventing future accidents requires designing a control structure that will enforce the necessary constraints.

Bjelland et al. [84] introduce this type of systems thinking for fire safety design in the context of buildings as STS. Applying similar thinking, the STBRSAM framework [110, 120] was proposed as a tool to assess building regulatory systems for potential failure points. In Fig. 1.7, the "system development institutions" and "system operation institutions" reflect the legislation, regulations, standards and such which govern building design and operation; the technological components of the STS are the building and its fire safety systems; and the building fire safety system is controlled via the interactions of actors and systems within the "system control" framing. A main point behind the STBRSAM [110, 120] is that well-performing buildings depend on far more than just building regulations, which direct design requirements, and the fire and occupational health and safety regulations,