JFPE

Journal of Fire Protection Engineering
23(4) 249–276

DOI: 10.1177/1042391513484911
jfe.sagepub.com
SAGE

Twenty years of performance-based fire protection design: challenges faced and a look ahead

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Abstract
A review of two decades of worldwide experience using standards, codes and guidelines related to performance-based fire protection design for buildings has identified shortcomings in the interpretation, application and implementation of the performance-based design process, apparent inconsistency in the resulting levels of performance achieved and several opportunities to enhance the process. In a constantly evolving building environment, technical challenges have to be overcome because fire safety engineering still depends greatly on knowledge gained from scientific and engineering research across a broad range of disciplines (e.g., better understanding of the fire phenomena, the behavior and response of the building occupants/contents/structure to the fire, tools for engineering analysis and all the necessary data needed to support tool application). Political challenges also need to be considered as performance-based fire protection design requires the approval of the authority having jurisdiction and other involved stakeholders, at several of its different steps (design, construction, original usage, modifications of usage). The review presented here has been undertaken from an engineering perspective rather than a regulatory perspective. Two key outcomes of this engineering review are that several of the challenges that have been identified are strongly linked to the application of generic guidance to specific problems, which results in critical details being missed, and that some of the engineering issues are treated within a political context, while they should be addressed as purely technical issues.

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Keywords
Performance-based fire protection design, fire safety engineering, engineering process, literature review

Introduction

In recent decades, more and more building regulatory systems around the world have permitted or required a performance-based approach to fire protection design instead of requiring that code prescriptions be followed [1,2]. This option was interesting to the market because it was claimed to enable innovation, aesthetics and optimization of usable space, while maintaining an acceptable level of safety [3]. In addition, this option also added more emphasis on safety objectives other than ones related to life safety such as property protection, business continuity, environmental protection and historical preservation. From an engineering perspective, the performance-based fire protection design (PBFPD) framework is valuable as it integrates scientific knowledge into the design process so that fire protection engineers (FPEs) can do more than rely on code prescriptions that are usually implemented as a political response, after major accidents, by regulators and Authorities Having Jurisdiction (AHJs). Besides, using a variety of tools as a support, the analysis should bring more engineering rigor to the process. As Custer and Meacham have stated, "performance-based design (PBD) should result in a comprehensive fire protection strategy in which all systems are integrated, rather than designed in isolation" [4].

Basically, the current approach to PBFPD can be divided into the following three major steps (as reflected in guidance such as BSI [5], ISO [6], International Fire Engineering Guidelines (IFEG) [7] and SFPE [8]):

1. Stakeholders establish goals and objectives, which are then translated by FPEs into design objectives and performance criteria. FPEs, working with the client, architect and the design team, develop one or more packages of fire safety measures, often called "trial designs". Then, everyone agrees on design fire scenarios upon which trial designs are evaluated. This part of the process is documented in the Fire Engineering Brief (FEB);
2. The FPE evaluates the consequences of the selected design fire scenarios and compares their outcomes with the selected performance criteria. In order to do so, he/she uses appropriate tools to evaluate the development of the fire (fire effects tools), the evacuation of the building occupants and the response of the structure (and the building contents and systems) to the design fire scenarios;

3. From the list of trial designs that pass the performance criteria, the stakeholders decide which one to finally retain for the considered project and the FPE writes the related documentation in terms of specification, operation and maintenance of the fire protection measures.

The current approach relies on guidelines and standards that are rather generic, process-oriented documents that do not specify critical components such as performance (design) criteria, fire scenarios, quantified design fires and required means of design evaluation/verification. All of these decisions are left to the FPE working in concert with project-specific stakeholders, including other members of the design team. This has led to a wide variation in designs and levels of delivered performance. In 2007, examining the New-Zealand perspective, Wade et al. [9] identified that a "perceived deficiency in the [fire engineering practice was] the lack of clear guidance from the regulator for performance criteria and design fire characteristics and scenarios for use in PBD. This [meant it was] difficult to achieve a uniform approach and consistent safety level through the country".

Nonetheless, based on the large number of PBD projects that have been showcased in the literature over the past 20 years, it seems clear that this process has been accepted by AHJs and the other stakeholders involved in the project, that is to say, building owners, designers, reviewers, enforcers, insurers, contractors and the Fire Services. However, not as much has been learned as might have been from these projects since the level of detail in published summaries is sometimes light. Besides, full PBFPD reports are often client confidential, not all jurisdictions may make all design documentation available, and therefore few comparative reviews have been undertaken.

Reviews of performance-based codes (e.g., building codes in Australia, New Zealand, England and others), PBD processes (like the one elaborated in the SFPE PBD Guide [8]) and codes that allow a PBD option (e.g., NFPA 5000 [10]) can be found in the technical literature ([11,12]). Nevertheless, many of these reviews deal only with the global comprehension of the PBD process and possible ways to cope with generic technical issues and better interconnection between FPEs, "lawmakers and people making standards" [13]. In applying the FEB process, Schulz and Feeney [14] found shortcomings in the process, particularly when stakeholders are risk averse and unfamiliar with new design methods, which could lead to a higher (and more or less variable) extent of justification needed for the "selection of input parameters and relevant design scenarios". It should be noted that they also plead for incorporating flexibility as "design and preferences for different solutions change over the course of the project [...] which will invoke the need for specific discussion with various stakeholders (especially those involved in the regulatory approval)".

Also, while there is PBFPD in the USA, this country has not embraced performance-based building codes. In 2008, Tubbs and Okawa [11] examined why the

International Code Council (ICC) Performance Code (PC) has not been widely adopted since its first publication in 2001. They noted that one barrier to that adoption or to the adoption of the PBFPD option in the USA in general was related to the limitations in the use of computational tools and to data availability. Even though they recognized that advancements had been realized in computational fluid dynamics (CFD)-based fire effects models as well as with egress models, they noted that challenges still existed: ''all models of course have their limitations but if well documented and understood by the designer [, they] can be excellent design tools. The aspect that is most crucial to their use is the appropriate inputs. [...] This continues to be one of the largest barriers to wide spread implementation of performance based codes and design''. This barrier is related to the technical aspect of the application of PBFPD, notably linked to the use of tools (model limitation and validity) and data availability. Tubbs and Okawa also found a barrier related to the approval process: the ''uncertainty when applying the code in terms of qualifications and related process issues'' made the AHJ ''very wary of reviewing and approving PB [performance-based] designs especially those that are well beyond the basic code requirements''. In other terms, when accepting a PBFPD instead of a design meeting prescriptive requirements, the AHJ liability was extended further than when verifying that the code provisions have been followed, even if the AHJ could still rely on a peer reviewer.

Thus, 20 years of experience of using guidelines that are too generic in nature has resulted in considerable variability in the determination of the target building performance, in the analysis of performance against the target level in order to assess the acceptability of these designs and in the approval of these designs by the AHJs, even for like buildings under similar conditions. While it is acceptable that different design strategies can be used to deliver acceptable performance, the level of performance delivered should be more consistent within the risk/performance tolerance level of a jurisdiction. Because of the generic nature of current guidelines, the selection of acceptance criteria and design fire scenarios is more a 'collegial political' choice than an outcome of a real characterization and treatment of the fire risk in the building to an agreed level. Theoretically, this means that within the same community, three different engineering firms can develop three different designs for the same building project, each of which results in different levels of risk in terms of occupants, property and mission. Furthermore, simply by moving the building location to another community, the same designs could be accepted or rejected based solely on the perspectives of the different stakeholders involved. In this article, challenges related to the application of current performance-based analysis and design processes have been identified: political and technical issues appear during the design process, in which the FPE works with the design team to develop trial designs. Technical issues also appear during the analysis, in which the chosen trial designs are evaluated against the acceptance criteria (mainly issues on calculation methods and data appropriate to conduct the analysis used to justify the acceptability of the trial designs). To address these challenges and issues, a more robust framework is needed, with a clear and explicit process to help characterize the life safety risk, the property risk and the business risk, which will result in buildings with more equivalent levels of safety. A significant number of literature sources have been reviewed for this article to illustrate the key challenges facing PBFPD. This and other research by the same authors offer a new approach that is hoped will provide the basis for significant improvement of design outcomes and overall fire safety performance.

Technical and political challenges related to the use of PBFPD processes

Across the world, attempts have been made to address the aforementioned challenges, within the regulated structure of national codes and standards and using different approaches. Nevertheless, they all seemed to have failed in one way or another, in part because of the challenges posed by the applicability of generic approaches. The challenge of being too generic applies to the technical aspect of the engineering method, as well as the decision-making process embedded in the application of the approach itself, which is referred to here as the political aspect of the PBFPD process. As mentioned by Brannigan et al. [15] as early as 1996, "technological and policy issues raise fundamentally different kinds of questions:

– Technical decisions are those which deal with scientific or technological phenomenon that are the subject of well-defined scientific or technical decision processes.
– [Political or] Policy decisions are those which involve weighing of competing social, legal, cultural, technical and other judgmental factors in the regulatory process".

Technical challenges related to the use of PBFPD processes

Decades ago, when the PBFPD concept was introduced into national regulations, fire protection engineering was still in its "infancy stage" [2]. As a result, efforts were primarily undertaken to increase the global knowledge related to the consequences of a fire in a building. Some advances were also made in describing human behavior during the evacuation process [16,17], and fire loads were added to the more well-established formulas for the resistance of structures [18]. In addition, SFPE [19] indicated that research related to the use of PBFPD process had to be undertaken in order to address uncertainties in the following areas:

– Knowledge relating to the science and engineering being used, due to limitations in the amount of knowledge available for used in models,
– Human behavior, related to "unknowns with regard to the exact behavior of people",

– Risk perception, attitudes and values, as it is "difficult to capture all societal views when undertaking a project".

In order to address these uncertainties, research was undertaken regarding the technical aspect of the PBFPD process. For example, in 1997, Richardson et al. [20] already listed technologies required for PBFPD. Their list included extended examples of technologies to assess combustibility of construction materials, fire growth, smoke spread, fire resistance of compartmentation and structural assemblies, occupant evacuation and to lesser extent examples of technologies related to fire risk assessment and fire cost calculations. By looking at the technical literature, it can be seen as a plethora of elements that contribute to the reduction of uncertainties in the technical aspect of the PBD process. However, there are a lot of less-regulatory details that link the engineering analysis results of this technical aspect with the policy decision-making process or political aspect of the PBFPD process.

Political challenges related to the use of PBFPD processes

Since different levels of performance are achieved at different costs, political decisions of the PBFPD process can supersede technical decisions. As used here, political decisions refer to those made by stakeholders, which can include government (at all levels), clients and others. For example, in some situations, the cost of installing and maintaining a sprinkler system could exceed its perceived benefits in terms of the expected property remaining undamaged by a fire. This is an insurance approach that only considers property-related losses over some defined period of time (expected losses) versus capital expenditures and maintenance costs over the same period of time. For some stakeholders, the technical solution of 'install sprinklers,' which leads to a technically-acceptable fire safety design, may not be politically considered because of the way the benefit-cost ratio is determined. Charters and Ramachandran [21] illustrated this point with a PBFPD study that demonstrated business continuity and property protection benefits to an operator of bus garages in the UK if sprinkler systems were installed in these facilities. "However, the cost-benefit analysis and the operator's contingency plans meant that there was no cost-benefit or consequence case for installing sprinklers [in] the bus garage. As a result of the risk assessment, the operator did implement other forms of safeguard and fire precaution".

While the cost-benefit ratio approach is often applied for comparing two different technically viable fire protection options (e.g., sprinkler vs. fire rated barriers), even with the concerns noted above, it can be even more difficult to assess the relative costs and benefits of a technical fire protection measure as compared with a fire safety management measure (e.g., management of fire loads and ignition sources). In the case of nightclubs, managerial procedures that allow more people than the prescriptive limit, with the intent of providing a higher level of event staff during the more highly occupied time, has meant that some more viable technological solutions may not be considered. This has been seen where higher occupant loads have been permitted, but in conjunction with the use of fireworks and in an environment with flammable linings and no sprinkler protection. Such an approach has repeatedly led to fire disasters (Kiss nightclub, January 27, 2013 – Lame Horse Club, December 5, 2009 – Santika Pub, January 1, 2009 – Wuwang Club, September 21, 2008 – República Cromañón, December 30, 2004 – Station nightclub, February 20, 2003). It is conceivable that strict managerial procedures, including having appropriately trained staff with appropriate fire suppression equipment, might have prevented the elements that contributed to fire ignition and led to a very fast spreading fire and subsequent tragedies. Nevertheless, it is less certain how one would estimate the cost-benefit ratio of these managerial procedures as compared to the cost-benefit ratio of installing sprinklers. The implementation of managerial procedures in preventing the start or mitigating the consequences of a fire also raises the issue of their enforcement and their real efficiency or contribution in a benefit-cost analysis.

Detailed challenges of current PBFPD processes

From the time PBFPD processes were elaborated to their current applications in at least 15 countries, practitioners, code enforcers and researchers have shared their experience, in technical publications and during conferences. Discussions have been held on the advantages and drawbacks of applying and accepting PBFPD processes by identifying critical issues related not only to the use of a particular process but also to the definition of the steps of the process itself and to the interactions between the technical aspect and the political aspect of such processes. Before describing these issues in detail, consider the following examples of concerns, expressed across almost the last two decades.

In 1992, Grubits [22] suggested that a ‘‘performance building code must:

– Set out the process to be adopted,
– Provide the factors to be considered in design,
– Specify the performance levels to be attained,
– Adopt explicit safety margins,
– Specify what relevant data sources are acceptable’’.

Ten years later, Johnson [12] indicated that ‘‘many of [the challenges related to the use of PBFPD were] more in the policy, regulatory, approval and accreditation area, rather than in the science and technology field, although clearly traditional fire research is still needed, especially in the area on safety factors and uncertainty’’. He discussed some of the challenges, which concerned the Australian PBFPD process or the generic application of PBFPD:

– What should the extent be to which property protection be regulated on behalf of the building owners and insurers or on behalf of the community (which is also concerned by sustainability, job protection, environmental protection)?

– Fire fighter protection is addressed but application of performance criteria for building occupants does not seem to fit for these trained and better fit people. No guidance is given to get approved performance criteria for fire fighters.
– The concept of risk does not appear to be acknowledged by the regulators, which can lead the FPE to be legally exposed in case of a rare catastrophic event even though the building design seemed robust and appropriate to all the involved stakeholders. "It is essential that building codes and legislation recognize the balance of risk and cost. A key factor is the completion, validation and greater use of risk-cost models to 'measure' and agree to levels of risk and acknowledge this in our regulatory frameworks".
– Certification, accreditation and fees of people involved in PBFPD, as well as the independence of the peer reviewers and consistency of the approval process are still in discussion.
– Maintenance of the fire protection measures and change in the use of the building are linked to the issues of enforcement and approval of changes.
– Data "for input to [PBFPD] methods and models continues to be a limitation requiring conservative design".
– "The degree to which building codes are open and closed to internationally accepted standards, products and technologies is becoming a major challenge to international trade".

Johnson concluded that "these challenges need[ed] continuing research, debate and consultation across all sectors of this industry, and leadership both nationally and internationally. [...] In particular the need to improve administrative and regulatory processes [were] probably even more important than further development of the science and technology".

Also in 2002, Barber and Merkestein [23] explored the "issue of inconsistency in the approvals process and the reasons behind the difficulties in achieving a transparent design resolution, for PB fire engineering". They referred to Meacham [1] who had "recognized the need for peer review and a high degree of education for both [AHJs] and fire engineers". They also concluded that "a formal level of training, communication, forums and more education in performance based design and fire science for [AHJs] and fire engineers is required. [...] The fire engineering community as a whole (fire engineers and [AHJs]) should be working to achieve a globally recognized process of approvals".

More recently, in 2008, Johnson et al. [24] indicated that "in fire engineering for the built environment the process of hazard analysis, development of fire scenarios and choice of design fires for fire engineering calculations are the most problematic".

These examples show multiple challenges in the application of PBFPD processes, at a technical level and at a political level. The following paragraphs discuss the key challenges that have been identified in more detail.

Challenges when applying generic guidance to specific projects

Documents such as codes, standards, guides and guidelines related to PBFPD were written at a time when it was a priority to introduce the global concepts of the PBFPD process, to model all the phenomena and to determine and assess the influence of critical components of the PBFPD process. These documents were also written in order to be used for any type of project within the built environment. With this purpose in mind, they had to be generic in order to be assimilated by FPEs and used as widely as possible. After decades of application of such documents, it seems that their wide applicability has turned out to be a drawback for the following reason: the documents failed to be an effective tool in helping engineers thoroughly apply the PBFPD process for a particular project while delivering a level of consistent building performance in the market.

Characteristics that define a particular project and that need to be considered in the PBFPD process are presented in the aforementioned documents. Nevertheless, their influences within the overall analysis and verification of a particular fire protection design may only seem obvious to a trained FPE with years of experience related to well-defined building configurations. In other terms, the way parameters are introduced in the generic PBFPD processes can be confusing even for the FPE, leaving the FPE with the responsibility to decide which parameters are relevant and therefore need to be quantified in the PBFPD process.

For example, in the SFPE engineering guide to PBFPD [8], these parameters include building services and processes, operational characteristics, environmental factors, as well as occupant items. Information related to the building and its occupants is only introduced in Chapter 8 of ref. [8], as input data needed to characterize design fire scenarios. Although numerous building items are cited in this chapter, their uses within the PBFPD process are not explicitly indicated in the rest of the engineering guide.

A similar observation can be made for the International Fire Engineering Guidelines (IFEG) [7]. The principal building characteristics (1.2.3 of IFEG) are listed upfront because "in order to evaluate or design a building's fire safety system, it is important to understand the building's characteristics and its normal mode of functioning. The principal characteristics should be identified early in the FEB process in order to facilitate the decisions that need to be made and issues to be resolved". Nevertheless, the rest of this document does not explain the importance of these parameters in the overall process and how the FPEs should consider these parameters when applying the IFEG document to a specific project.

Challenges associated with the definition, use and quantification of performance/acceptance criteria

Custer and Meacham [4] defined performance criteria (also called acceptance criteria) as "metrics against which building materials, assemblies, systems, components, design factors and construction methods will be evaluated on their ability to meet specific performance requirements''. As early as 1997, they gathered the following performance criteria, which are presented in Table 1 with their references. The nature of the reference indicates the level of regulation (code, standard, guide and guideline).

Performance (or acceptance) criteria are measurements that assess whether goals (life safety, property protection, business continuity...) are attained. However, it is not always clear what criteria to select or why, as there are variations in representative criteria listed in different codes, standards and guidelines. In Table 1, for example, there are two criteria related to smoke interface height – one from Sweden of 1.6 + (0.1H) m, and one from the USA of 1.6 m for a period of 20 min. One has variable height and no time component. The other a fixed height and a fixed time. Which is 'right' under what circumstances, e.g., just the referenced environment or any situation? How is the engineer to choose?

Deterministic values of performance criteria have been published and some are embedded in regulations (such as Sweden, Japan and New Zealand). Even with these quantified performance criteria, there is a lack of guidance on how these generic values are to be applied.

Furthermore, these performance criteria are not really being used to assess the performance of the building to withstand the fire threat; rather, they indicate a technical perception of the potential damage to building occupants, contents and

Table 1. Performance criteria gathered in codes, standards and guides and guidelines. Reproduced with kind permission from the Society of Fire Protection Engineers [4].

Performance criterion	Reference	Date
The deflection of reinforced concrete structural members shall not exceed that permitted by ACI 318	The BOCA National Building Code, Building Officials and Code Administrators, International, County Club Hills, IL	1993
The level of fire gases shall not be lower than 1.6 + (0.1 H) m, where H is the height of the room	Swedish Board of Building, Housing and Planning, Building Regulations, Sweden	1994
Limiting conditions for tenability caused by heat radiation: less than 2.5 kW/m^2 can be tolerated for over 5 min; 2.5 kW/m^2 can be tolerated for 30 s; 10 kW/m^2 can be tolerated for 4 s	Fire Engineering Guidelines, Fire Code Reform Centre, Limited, Australia	1996
The smoke layer interface (shall be maintained) above the highest of either: the highest unprotected opening to an adjoining space or 6 ft above the floor level of exit access open to the atrium for a period of 20 min	The BOCA National Building Code, Building Officials and Code Administrators, International, County Club Hills, IL	1993

main structure. It is proposed that in the new approach developed in this and other articles, "performance criteria" should be called "fire effect criteria", as there is a subsequent layer of analysis needed in order to quantify the actual performance of the building. The level of building performance should be quantified by answering questions such as: how many casualties or injuries would be caused by each year of use of the building? For how many days a fire would cause business interruption? Regarding life safety objectives, the performance criteria seem to be implicitly associated with a "no injuries or casualties" performance of the building in case of a fire, at least for building occupants "not intimate with the initial fire development" [25]. Fire events produce effluents and heat that can cause these injuries and casualties, and FPEs are trained to assess the production of these effluents. Nevertheless, in case of a fire or emergency situation in a highly populated area (theater, stadium, nightclub...) people could become casualties, not because of toxic or thermal threat but because they stampede and get crushed at some point in the evacuation process. The latter phenomenon is never mentioned in the PBFPD-related documents that were reviewed but should be included when assessing life safety performance associated with fires in buildings. Without such a quantified performance criterion, how would FPEs reconstruct the Brooklyn theater fire which killed 278 people on December 5, 1876, the Iroquois theater fire (Chicago), which killed 602 people on December 30, 1903, or more recently the Uphaar Cinema fire (Delhi, India), which killed 59 people and seriously injured 103 people on June 13, 1997?

With respect to fire performance across all types of building structures, the "Eurocodes" [18] provide an interesting example of how the fire threat is considered, specifically for structures made of concrete, steel or timber. The main idea of these documents is to evaluate the action of a "structural design fire" as one more action on the structure, in addition to actions imposed by natural hazards such as earthquake, wind and snow. The definition and the evaluation of the consequences of the "structural design fire" only concern the structure of the building and not its occupants and contents. Nevertheless, Kruppa [26] indicated that the safety of people could be considered:

– During a fire evacuation by estimating if the time before collapse of the structure was less than the time to ensure the safety of people (which has to be estimated elsewhere) and
– After a fire, if the remaining deformation of the building components was less than the maximum allowed deformation assessed after the cooling phase.

After reviewing the pros and cons from the technical literature [27], it was decided that considering fire as an additional load was not the most useful for dealing with building occupant evacuation or protection of building contents, in spite of its usefulness for assessing structural component response in case of a fire. In conclusion, different fire characterizations may be needed to assess different outcomes, such as life safety, property protection and business continuity.

In addition, for life safety objectives, the fire effect criteria values should be a consensus of engineers, not only dealing with fire protection engineering but also toxicology and psychology. For a deterministic point of view, a single value per criterion could be defined for target types. For a probabilistic approach, a distribution should be given.

To summarize, as it is quantified in the current PBFPD processes, the performance criteria should be called "fire effect criteria". The terminology "performance criteria" should describe the actual level of performance achieved by the project under consideration, for each of its safety objectives agreed among its stakeholders. The fire effect criteria should be defined to compare the decreasing resistance of the ability of a target (building occupant, content or structure) to withstand a fire condition and the increasing fire stress on the target. Research to attain a consensus for fire effect criteria assessment between the different engineering disciplines should be done, not only for building occupants but also building contents relevant to the stakeholders (i.e. important piece of equipment, electronic cabinet used for process safety, priceless artifact), interruption to business, as well as environmental ecosystems potentially affected by the fire itself and the chemicals used for its extinguishment.

Challenges associated with the selection of design fire scenarios

SFPE [8] indicates that "in a deterministic analysis, one or more possible fire scenarios can be developed as design fire scenarios that are representative of potential worst credible fires in a particular building [...]. The central challenge in scenario selection is finding a manageable number of fire scenarios that are sufficiently diverse and representative". Unfortunately, this guide, or any other guide, guideline or regulation, does not provide the FPE and the involved stakeholders with detailed explanations of what the representativeness of potential worst credible fires in a particular building has to be:

– "Worst credible fires" seem to imply that fires developed to quite a large extent while remaining credible are the ones to be considered. This definition is too vague because the intensity of the fires necessary to have an effect on targets depends on the nature of the targets and on the relative position between the fire and the targets. The ICC Performance Code [28] gives different levels of "fire maximal tolerable damage" as a function of the importance of the building, but it does not provide a method to define scenarios leading to these different damage levels. It should be noted that focusing on high-intensity fires does not necessarily mean that less-intense fires are "covered" even if SFPE [8] also indicates that "finding a representative sample of scenarios ensures that if the design is safe for those scenarios, then it should be safe for all scenarios, except those specifically excluded as too unrealistically severe or too unlikely to be fair tests of the design". In the nuclear power production field, the OECD

Committee on the Safety of Nuclear Installations (CSNI) indicates that "not all large nuclear power plant fires are significant from a public safety point of view, nor are all safety significant fires large" [29]. As early as 1999, Brannigan [30] summarized concerns from himself and others regarding how design fire scenarios were selected and characterized; Hall from NFPA was cited regarding the modeling of fire scenarios with: "If only a few scenarios are modeled explicitly, then each one is implicitly required to be representative of a much larger and more varied collection of other scenarios. There may be no good evidence to support this". This cited remark is so important that it is still written, with no change, in the latest edition of the NFPA Fire Protection Handbook [31]. Brannigan also stated that the original meaning of a "scenario" used to "represent a technical description of the social expectation of safety" was redefined so "scenarios stopped including the entire hazard and became instead just a specified design fire". Building and occupant characteristics which defined the problem boundaries were then relegated to the background as input parameters of fire scenarios which became the focus of all the PBFPD process.
- The context related to "manageable number of fire scenarios" in ref. [8] is not defined, but Hall and Watts [31] link that phrase to the "computational burden" of assessing the consequences of these scenarios, as well as the "shakiness of the available data and a desire to minimize the number of different terms supported by expert judgments". This context then implicitly states that in a time-limited framework, such as the project consulting environment, scenarios would be excluded or "clustered" with other scenarios because of time and resources constraints.

NFPA 101 Life Safety Code [25] presents a list of design fire scenarios associated with the life safety of building occupants (not related to the fire origin) and the building regulations of New Zealand incorporate a list of scenarios (similar to the NFPA list). It should be noted that the scenarios of the NFPA list are qualified as "challenging" and are not necessarily the "credible worst case scenarios". Hall [32] explains that "excluding reliability issues, the conditions that make a scenario challenging tend to fall into two types:

- Conditions that lead to a more rapid onset of unacceptable outcomes (such as death) or a more rapid onset of fire conditions that are taken as proxies of unacceptable outcomes (such as incapacitation, flashover, or structural collapse);
- Conditions that line up with system limitations, which primarily means uncovered or shielded fire locations".

Concerning the second type of condition, fire protection systems have different *modus operandi*. It is assumed that when the PBFPD process is used to evaluate the benefits of changing one fire protection feature (usually a prescriptive requirement) for an alternative:

1. scenarios challenging both options should have to be elaborated, and
2. the overall analysis should not only have to be based on the damage ratio between the two options but also contain the evaluation of the likelihood of these scenarios and of the cost of installing and maintaining the different fire protection systems and their availability/reliability.

None of this is discussed in the current PBFPD processes that have been reviewed.

Attempts made by standards-making associations and regulatory bodies to better define quantified performance criteria and design fire scenarios reflect a positive step to increase coherence in the application of the PBFPD process. However, it appears that the intent and argument behind these quantification efforts have been somewhat lost in translation into the regulatory framework. This is because having regulations "prescribe" more detail on the specification of scenarios or on how to calculate scenario consequences does not necessarily guarantee that the stated scenarios and verification methods are applicable to the specific needs of a project. This could be better addressed if the regulatory documents forced engineers to explain *what* situations or conditions are analyzed by the scenarios, *why* and *how* they matter for a specific project and *why* and *how* the verification/calculation methods are appropriate in the circumstance. In doing so, better consistency can be achieved where the scenarios and verification methods are applicable, and better justification for variance can be developed where not (since the rationale for deviating would need to be elaborated).

Challenges when dealing with a priori lists of performance criteria and design fire scenarios

In the current PBFPD processes, the design fire scenarios and the criteria are selected and agreed upon among the involved stakeholders prior to any development of trial designs, without any estimation of the likelihood of the selected fire scenarios. Babrauskas [33] argued that "the fire scenarios and what happen[ed] to the building upon encountering a given scenario, [were] items for the designer to propose to the building official. The building official [could] then reject the proposal, but he [or she would] have no objective grounds for doing so". Related to this preoccupation and in order to have a more cohesive set of performance criteria and design fire scenarios across their jurisdictions, some national regulations decided to "prescribe" *a priori* lists of performance criteria and design fire scenarios. Current building regulation in New Zealand constitutes a typical example of that situation. It is conceded that in the short term, AHJs of New Zealand would be able to better judge applications based on a PBFPD process where scenarios are predefined but in the long term, difficulties are anticipated in applying these scenarios to very complex and unusual projects. Some difficulties are presented below.

As noted before, NFPA [34] introduced a list of 8 design fire scenarios, saying that "to provide a comprehensive design (i.e., to demonstrate how the fire safety system will respond to a variety of fires), more than one scenario should be considered. It is suggested that, at a minimum, the following three types of scenarios be considered: 1) High-frequency, low-consequences (typical) 2) Low-frequency, high consequence (high challenge) 3) Special problems scenario". The intent or the ideas behind some of the listed scenarios are presented in the NFPA 101 Handbook but not in the corresponding standard. The fact that this type of information is "lost" when editing the standard is deplored, as it is more important to tell a FPE what problem he/she needs to solve than how he/she needs to solve the problem.

Considering "severe" (or "high challenge") *a priori* lists of performance criteria and design fire scenarios may lead, in some cases, to the failure of all trial designs, even when the design involves as many or more fire protection measures than the prescriptive requirements. This was demonstrated by Lloydd [35] when she applied the 2005 version of Compliance Document C/AS1 of the New Zealand regulation to different building occupancy types.

Regarding performance criteria of the New Zealand regulation, in 2008, Lloydd [35] indicated: "there are two sets of criteria: a simple set of criteria, which if passed, no further analysis is required, and a more detailed set of criteria, for which a more detailed analysis is required. [...] The simple tenability criteria are based upon zero exposure of occupants to the negative effects of the fire. If occupants are kept away from all smoke and heat at all times, the building is considered to meet the requirements of the code, namely,

1. The clear layer height must remain at a minimum height of 2.5 m from floor level, and
2. The maximum upper layer temperature reached shall not exceed 200°C.

As can be quickly identified, rooms and spaces with ceilings lower than 2.5 m will not pass the simple criteria and more detailed analysis will always be required for these spaces. Also, the simple criteria may not be suitable for very large spaces where stratified layers may not form and a more detailed analysis of the conditions within the space may be required".

As explained by Lloyd above, the New Zealand regulation failed to provide any help concerning performance criteria to the FPEs when they are examining projects involving atrium spaces or complex geometries.

When dealing with a list of design fire scenarios, there are similar concerns: what to do when selecting the "loss of one exit" scenario when the building has a single main exit stair? Based only on the basic description of this scenario, it may imply to the AHJ that the building may require at least two exits, or the AHJ may agree with the other stakeholders to "ignore" that scenario as it is permitted in the PBFPD process. What is the meaning of this scenario when in the prescriptive regulation (e.g., US ICC International Building Code [36]), the second exit is only required for specific numbers of occupants and stories in the building, along with its main function (assembly, institutional...)? Besides, the scenario label itself is subject to interpretation. For a loss of exit, one could put the initial fire source in the stairwells, but also anywhere in the exit path. If the exits are designed according to requirements, does one still have to consider the scenario where one exit is blocked by fire?

As evident from activity in Japan, Sweden and New Zealand, many regulators want more specificity regarding the scenarios characteristics (i.e. fuel characteristics, evolution of the heat release rate with time, building characteristics, occupant characteristics...) because fire scenarios constitute the core of how the fire protection design is tested and verified, and ultimately judged to be acceptable by AHJs. The variability regarding design fire scenarios is still considered by many to be too large.

Even with a list of pre-defined scenarios, there are many parameters to evaluate in order to characterize each of the scenarios of any pre-defined list:

- The definition of the fire threat, including the location of the 1st burning item,
- The evolution with time of the heat release rate, the production of fire effluents and their spread within the built environment,
- The initial position of the building occupants (movable targets), the time required for these occupants to be aware of the fire condition, to realize the emergency situation and start to evacuate,
- The selection of the exit routes by the occupants and their travel speed.

This parametric characterization of design fire scenarios is not precise enough so the variability in interpretation of these scenarios increases not only among the different stakeholders but also FPEs. New Zealand regulators tried to implement these parameters, that is to say specify values for the different parameters of each scenario in a non-mandatory application guidance [35]. For example, the heat release rate evolution with time or "HRR curve" is specified as an "αt-square" curve. Nevertheless, no explanation is given on the selection by the regulators of the value of the α-parameter: is it a mean value based on the potential fire hazard of the combustible building contents? How does that value correspond with the actual situation of the considered project? How much could the actual building content configuration vary before another value of the α-parameter has to be considered by the regulators?

For tunnel ventilation design applications in 2007, Miclea et al. [37] gathered recommended minimum values of the heat release rate to consider, as follows: "the UN ECE recommendations suggested a minimum fire size of 30 MW. This is used in many countries such as Austria, Germany and Switzerland, whereas provisions of 50 MW can be found in the design standards of Germany and Britain". The authors also compared these values with the one reached in the Runehamar tunnel tests where fire from ordinary heavy goods vehicles could reach an intensity as high as 200 MW. This example illustrates the fact that quantified parameter values embedded in national or international recommended practices certainly decrease variability in the application of the PBFPD process, but they also need to be well documented with their applicability domain. Parameter values also need to change as fire research provides new data, new methodologies or new understanding of design problems.

In conclusion, attempts made by standard associations, and even regulatory bodies, to quantify performance criteria and design fire scenarios seemed a positive action in order to increase coherence in the PBFPD process applications. Nevertheless, intents and ideas behind developing such lists of fire scenarios are lost during their transcription into the regulatory framework. On the other hand, scenarios should be put forward in the context of explaining why the situations analyzed by the scenarios should matter, instead of having the regulations "prescribing" more and more details of the scenario specifications (and how the FPE has to calculate the scenario consequences). Applications already show some limitations and drawbacks of scenario over-specification.

Challenges when comparing levels of performance between an engineering solution and one based on prescriptive requirements

The acceptability of an engineering fire protection design can be determined by comparison with ones obtained using the corresponding regulatory requirements. In some projects, innovation is the main driver, as for example, the need to have beautiful, large, bright airports to accommodate the exponential increase of air traffic since the 1970s, as well as the use of airports to connect with nearby hotels and car renting or parking sites. The most recent airport terminals with their huge internally open structure of steel and glass (e.g. London Heathrow terminal 5, opened in 2008) are without comparison with their predecessors consisting of compartmented long corridors (e.g. old terminal building of London Luton airport). This example illustrates that comparing the fire safety options of these two types of airports would not make sense as their designs, which constitute their true nature, are too different.

What about new performance criteria such as sustainability? Performance of a building is not exclusively related to life safety, which along with health and amenity is just one of the primary objectives of most building codes (including no harm to adjacent building and safety of fire emergency responders as in the New Zealand regulation). Fire protection requirements are then mainly established according to the safety objective. The other stakeholders' goals and objectives, such as property protection, heritage preservation, would require specific regulations. Standards exist but they are not at the highest regulatory level [38], which focus "on performance-based evaluation as an important alternative to prescriptive codes" [39]).

Building codes authorize a trade-off between different fire protection requirements, usually when the building considered is fully equipped with sprinklers. For example, in offices, the ICC International Building Code states that the maximum common path of egress travel shall not be more than 75 ft (22.86 m) if the office building is not sprinklered and 100 ft (30.48 m) if the office building is fully sprinklered [36]. One wonders if these two fire protection options would always contribute to "equivalent solutions" for any possible fire scenarios in office buildings.

In conclusion, comparison of performance levels between an engineering design and a prescriptive one is not a trivial exercise, especially when the engineering design fulfills objectives other than life safety. Yet that is a common approach taken. On one hand, it is assumed that the rationale behind the quantification of the prescriptive requirements embedded in building codes is based on previous "good practices" and partial empirical evidence, notably when trade-offs are concerned. On the other hand, this rationale is not appropriate for a PBFPD process, and is not recommended without being made much more transparent (which is difficult, especially given the challenges presented above).

Challenges related to the determination of influential factors affecting the evaluation of trial designs

SFPE [8] lists factors affecting the evaluation of trial designs (cf. §10.2.1 of SFPE guide), but these factors are not clearly assessed nor always considered (sensitivity of subsystem output to design objectives, knowledge level [uncertainties], benefit versus cost [cost could be prohibitive and it may change the design objectives {cf. §10.1.5.4 of SFPE guide}], and absolute or comparative evaluation). IFEG [7] provides a list of input parameters and output parameters for each of the sub-systems these guidelines present: fire initiation, development and control, smoke development, spread and control, etc. Nevertheless, a hierarchy of the relative influence of all these parameters is not provided. For these parameters needed for the quantification of fire consequences, as well as other factors needed to perform a PBFPD process, no examined standards, guides and guidelines [5–8] establish a hierarchy for the influence of these factors. Additional factor influences, such as the "user effect" on tools, also have to be assessed [19]. Besides, in the consulting environment, such assessments are difficult due to time and resource constraints, thereby making the assessments less likely to be undertaken at an appropriate level. Likewise, evaluating trial designs is rendered complex because of multiple interconnected influences at a process level (influence in selecting scenarios, performing cost-benefit analysis), at a technical level (influence of the characteristics of the design fire scenarios) and at a political level (agreement on performance criteria).

Challenges when dealing with "idealized" design features and "real life" installed and running features

When applying the PBFPD "concept of optimization" in the design phase of a project, difficulties may arise in relation to design changes, changes during construction, and changes in use of the building throughout its life. In order to identify these difficulties, Stenstad and Bjørkmann [40] examined the interconnections between the different stakeholders involved in implementing PBFPD in the

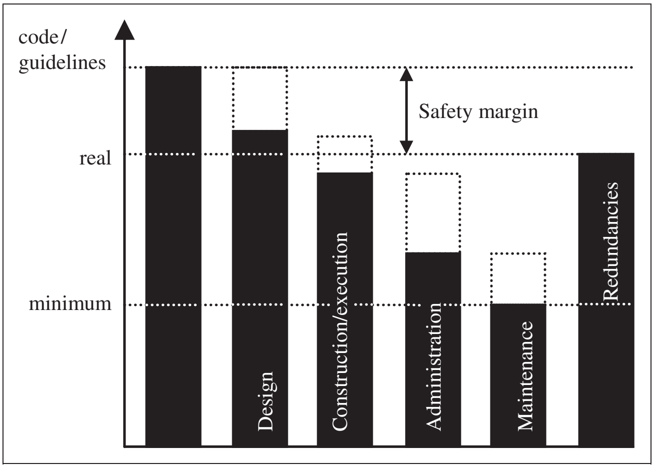

Figure 1. Level of fire safety and the reduction due to the different processes. Reproduced with kind permission from the Society of Fire Protection Engineers [40].

execution phase of a new project, which concern the "architect, the different engineering firms and contractors. Each company is responsible for a limited part of the building project related to their contract and will have no survey, nor responsibility for the project as a whole [...]. 'Minor' changes may be done without anyone questioning the consequences. In this way, prerequisites defined in the FSS [Fire Safety Strategy] report may be overlooked and not taken care of in a proper way". In practice, these interconnections and changes should be managed by an effective architect or project manager, but that does not always occur in relation to fire safety design. Looking at the problems related to the use of safety margins, they indicated that the "uncertainties to fire safety resulting from the design, execution, administration and maintenance of a building [were] most likely to reduce the level of safety from that stated by the building code. We [were] fortunate that our traditional buildings include[d] both materials and individual elements of construction that often [left] us with considerable redundancies. It [was] important to recognize this when we [tried] to identify the inherited or as called the political level of safety", as shown in Figure 1.

Even if most of the important decisions related to fire safety of a new project have to be made during the project conceptual design phase, documentation and maintenance protocols of the installed fire protection measures have to be transmitted to the actual users of the building as these users would be the ones who would have to deal with a real fire event. These protocols are not included in the evaluation of the trial design as they are elaborated after the final fire protection design has been accepted by the stakeholders. As illustrated by Stenstad and Bjørkmann [40] in Figure 1 above, due to constraints from the building usage in terms of administration and maintenance of the fire protection measures, such a design could be conceptually acceptable but at the end, not as compatible as expected with the actual usage of the building, with or without considering significant changes in the building management or use.

Challenges when estimating the consequences of design fire scenarios

While an integrated approach to building fire performance is the aim of current PBFPD processes, estimation of the consequences of design fire scenarios is not at all integrated. Until very recently, tools related to the estimation of the effects of a fire (fire effects tools) have been developed separately from the tools related to the estimation of the evacuation process and from the tools related to the estimation of the structural response in case of fire. This situation arose from the fact that these three components of the fire protection engineering calculations were so complex and different from one another that they required these separate developments, and the basic science and research developed at different times and different rates. Nevertheless, attempts to jointly calculate fire effects and egress are in development (such as FDS-EVAC co-developed by NIST and VTT).

Life safety objectives are often analyzed through two concepts: available safe egress time (ASET) and required safe egress time (RSET). The authors of this article assume that the corresponding analyses (fire effects, evacuation) are typically undertaken in isolation. As a result of this dichotomy in solving the ‘‘fire problem’’, it is not always clear:

– How factors such as fire and evacuation interactions are addressed (e.g., occupants opening and closing doors, which can change burning characteristics or counter flows of fire fighters and emergency responders and their actions on people and fire),
– Which parts of the process are most sensitive to changes from initial design assumptions,
– Where greatest sources of uncertainty and variability exist.

In other terms, challenges are related to the education and training of the FPE, who must not only be focused to estimate fire effects but also dedicated to assess evacuation of building occupants and structural response in case of a fire, as well as the interconnection of these three components.

An important consideration in evaluation of a fire safety design is to verify the appropriateness of tools to be used for a given application, as well as the user's ability to use such sophisticated research tools. Documents published by SFPE [41], ISO [42] or ASTM [43] provide generic guidance on the use or on the validation of computer models. In addition to the generic status of these guidelines and standards, it should be noted that the application of such published documents has to be reassessed with updated versions of the same models or with new models. One example concerns a fire detection computer model [44], for which the authors were unable to find any document to provide guidance on its interactions with fire effects, occupant evacuation and response of structural building elements.

As a consequence, challenges also exist with engineers selecting appropriate tools to be used for given applications, as well as the user's ability to use sophisticated research tools in design.

Challenges when adapting available literature values to use in models

In any engineering practice, injecting appropriate data into relevant analysis tools, such as equations or fire models, is as essential as using the appropriate tool in order to solve a given problem or verify a particular trial design. Care should be taken when selecting and using data from any source as:

– Data obtained from experiments performed decades ago do not necessarily represent current data as material properties and occupant characteristic distributions constantly evolve,
– Some data needed to use in tools are still missing so FPEs have to use their ''expert judgment'' to adapt the available experimental data to use with a chosen tool and
– Tools (models) also evolve with knowledge of the phenomena they represent. Experimental data are usually collected in order to supply validation points for a model. The data collection process is then elaborated in order to coincide with the model paradigm. In other words, the data may be model dependent; changing the model may disqualify a data validation set to be used in another model.

Current PBFPD processes emphasize the importance of using appropriate data with appropriate tools. As an example, Part 3 of IFEG ''provides a selection of data that may be used in applying [its] methodologies [gathered in its] Part 2 or other chosen methodologies. This does not preclude the use of other data that might be chosen by the fire engineer and that are acceptable to regulatory authorities or certifiers. Caution should be used in applying data because it may not be relevant as a result of:

– New methodologies
– New technologies
– New materials
– Varying regulatory requirements
– Cultural differences
– Construction practices''.

However, the current PBFPD processes fail to provide the necessary level of detail with which the FPEs and the different stakeholders, including peer reviewers, have to scrutinize the datasets used while performing any PBFPD process. Besides, data are often lacking for all required analyses and shortcuts are taken.

As a consequence, without validated repositories for input data, FPEs are forced to spend time and resources to look for appropriate data and demonstrate to the stakeholders that their chosen datasets can be used for the application they are analyzing. This statement is also valid for a researcher who usually starts his/her research by collecting data already found by prior researchers and relevant to his/her particular study.

Concerning the values of all the parameters needed in order to perform a calculation of the consequences of a fire, it should be noted that attempts were or are currently made to develop repositories of data collections usable by FPEs:

- Fire data were made available by the US National Institute of Standards and Technology (NIST), which created the Fire And Building Educational Resource Collection (FABERC) [45]. This database is no longer accessible via "faberc.org", but some experimental results from fires conducted by NIST still can be found at its website.
- The need for egress data collections was advocated by Fahy and Proulx [46]; Gwynne [47] with NIST support started to develop a web portal to support such a database, its structure being elaborated and ready for beta-testing.
- Standardized methods are in progress (i.e. NFPA 557 in the USA [48]) in order to collect basic data such as fire load and reliability of systems in a coherent and harmonized manner, which really permit the collection, use and comparison of data from different studies.

As long as the FPE community is not ready to consolidate such databases and standardize procedures to collect and apply data in order to provide appropriate data to use in any PBFPD process, FPEs and stakeholders will be required to spend unnecessary time and resources to find data and validate its use for each and every project. Or alternatively, assumptions may need to be so conservative that designs are not cost-effective to construct. Even with the most elaborate and sophisticated PBFPD process, using inappropriate data produces erroneous results that may lead to a building performance dramatically below its expected level of performance or in fact produces a design that is overly conservative.

Summary of the challenges related to the use of current PBFPD processes

A large number of articles in journals and conference proceedings that describe challenges and concerns regarding the use of PBFPD processes, published as early as the first drafts of these processes, and covering the last two decades, have been analyzed. It has been determined that 8 significant challenges still exist in the application of these processes in practice and that major changes are needed to address them:

1. Applying generic guidance to specific projects
2. Defining, using and quantifying the performance/acceptance criteria

3. Selecting design fire scenarios
4. Comparing the levels of performance between an engineering solution and one based on prescriptive requirements
5. Determining the most influential factors affecting the evaluation of trial designs
6. Dealing with "idealized" design fire protection measures and "real life" installed and running measures
7. Estimating the consequences of design fire scenarios
8. Adapting literature values, when available, to use in models.

Characteristics of a new paradigm

As summarized above, several challenges with current PBFPD processes have been identified. Even where found in the literature, successful applications of PBFPD processes show that addressing these challenges are currently costly in time and resources, in order to solve the engineering problem (technical level) and get an agreement among all the involved stakeholders (political level). Admittedly any feedback of the successful application of the current PBFPD processes would be worth analyzing. Nevertheless, this feedback is rare in overcoming the presented challenges and therefore reducing the uncertainties and concerns associated with all possible applications of these current processes. In addition, the current PBFPD processes are centered on the study of fire protection measures, which sometimes can lead to differences in the way these measures are designed and then used when the building is occupied. Furthermore, designers are not taking as full advantage of data and tools, for the types of applications being addressed, as they can or perhaps should.

In order to overcome these challenges, it is suggested that the solution is to: (1) re-center the PBFPD process on the subject of its application, that is to say the system formed by the building and its occupants, (2) create PBFPD processes that are specific to different types of occupancies and (3) provide a mechanism to help FPEs select the most appropriate tools and data for the types of applications they are considering. To address (1), by integrating the study of the fire protection measures as a component of the overall study of a building-occupant system, challenges with taking fire systems out of the context of building operations could be identified and then hopefully minimized. In addition, this shift in the paradigm, from the study of the fire protection measures to the whole building-occupant system not only allows the FPE to extract all the data required to perform the analysis but also to characterize the context for which the analysis is carried out, thus determining the overall performance of the system vis-à-vis the fire threat. Explanations related to this paradigm shift as well as the main characteristics of the new paradigm based on a building-occupant system will be published soon [27]. To address (2), by developing system-specific guidance, a much greater level of guidance can be provided, thus minimizing challenges in application and interpretation of data, use of tools and methods of evaluation to verify a trial design or package of fire protection measures chosen by the FPE and design team for a particular project. The authors strongly advocate for the establishment of system-specific guidance and process documents that would help FPEs with minimizing issues related to current generic guidance even if these future documents would not cover every individual building and project. A new risk-informed PBFPD process, based on this new system paradigm, has been developed, which separates the technical decisions to be elaborated by the FPE and the political decisions to be taken by the involved stakeholders. The risk-informed PBFPD process that would be able to overcome the challenges listed in this article is also expected to be presented soon [27,49]. To address (3), by creating 'test bed' environments, displayed on an Internet portal, FPEs and all other interested parties are expected to share their own knowledge on tool uses and therefore fill the need for guidelines to aid the selection of appropriate fire consequence analysis tools for specific fire protection engineering applications [50].

Conclusion

Challenges in applying current PBFPD processes arise from technical and political concerns. Challenges still exist regarding the definition/quantification of the strategic elements of any PBFPD process: the performance criteria (the current definition for which should be changed to "fire effect criteria"), design fire scenarios and use of tools to quantify the trial designs. Efforts have been made to consolidate databases gathering information related to buildings, fires and occupant behavior, but it is still necessary to make such databases available for the whole engineering community. Besides, validation and verification domains related to the tools still need to be defined according to the engineering problems these tools are used to solve. A new proposition has been elaborated in that matter [27]. Challenges related to the difference between the building design and its numerous alterations during its lifespan should be better considered in the examined PBFPD processes.

Funding

The authors would like to thank the US National Institute of Standards and Technology (NIST) for supporting the research on which this present paper is based, under grant 60NANB10D228.

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