

**AN INTEGRATED FRAMEWORK FOR THE
NEXT GENERATION OF RISK-INFORMED PERFORMANCE-BASED
DESIGN APPROACH USED IN FIRE SAFETY ENGINEERING**

by

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ABSTRACT

Review of 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, wide variation in the resulting levels of performance achieved by such designs, and several opportunities to enhance the process. While others have highlighted shortcomings in the past, as well as some ideas to enhance the process, it is proposed that a more fundamental change is needed.

First, the political and technical components of the process need to be clearly delineated to facilitate better analysis and decision-making within each component. Second, the process needs to be changed from one which focuses only on fire safety systems to one which views buildings, their occupants and their contents as integrated systems. In doing so, the activities associated with the normal operation of a building and how they might be impacted by the occurrence of a fire event become clearer, as do mitigation options which account for the behaviors and activities associated with normal use.

To support these changes, a new framework for a risk-informed performance-based process for fire protection design is proposed: one which is better integrated than current processes, that treats a fire event as a disruptive event of a larger and more complex "building-occupant" system, and that provides more specific guidance for engineering analysis with the aim to achieve more complete and consistent analysis.

This Ph.D. Dissertation outlines the challenges with the existing approaches, presents the "building-occupant" system paradigm, illustrates how viewing fire (or any other hazard) as a disruptive event within an holistic "building-occupant" system can benefit the overall performance of this system over its lifespan, and outlines a framework for a risk-informed performance-based process for fire protection design. Case studies are used to illustrate shortcomings in the existing processes and how the proposed process will address these. This Dissertation also includes a plan of action needed to establish guidelines to conduct each of the technical steps of the process and briefly introduces the future work about how this plan could be practically facilitated via a web-platform as a collaborative environment.

EXECUTIVE SUMMARY

Performance-based design (PBD) approaches are being developed for numerous engineering disciplines, including mechanical, structural, and fire protection engineering. Allowed nowadays in the building regulatory framework of more and more nations, the application of these approaches has made possible real innovative and aesthetically pleasing as well as safe, efficient and cost-effective building designs.

However, PBD approaches are still not as widely applied as some predicted two decades ago. In part, this is because the political and technical aspects of PBD have been intertwined. This creates challenges as approaches and solutions to political and technical challenges can be quite different.

The decision to apply PBD approaches instead of following the prescriptive requirements of building codes is a political choice agreed among the different building stakeholders, who may have different (if not competing) objectives related to the buildings performance. In addition, final selection of a design option is also a political decision, in this case of the client, which should be informed by engineering analysis but not made by the engineer. In the political sense, then, the application of current PBD approaches for fire remains limited, as:

- The building design team can be reluctant to use a PBD approach, as when compared to the strict application of the prescriptive code requirements, it can be quite costly in terms of time and resources while its outcome may be rejected by enforcement officials, leading to more delays, more spending and alterations of the initial design.
- The regulators and enforcement officials express various concerns with PBD, including:
 - Selection and use of performance criteria, which should be a policy decision, but is currently largely a technical decision made by the FPE, usually with agreement of project stakeholders, as they are not regulated.
 - The comparison of a building safety level established through application of a PBD approach with the one established by the prescriptive requirements.
 - The validation of the tools, data and methods used in the PBD approach.

On the technical aspect of fire protection engineering, it should be noted that while having a solid research base, this discipline has not yet reached a mature state. When academic programs started to be established in the 1970's, their main focus was to incorporate research results in the understanding of fire phenomena. Nowadays, they have added modules including risk concepts and human behavior. In spite of these abundant research results, the transfer of information from research into practice suffers from the inertia intrinsic to practitioners, policy makers and law enforcers when confronted with new engineering methods and concepts.

In the 2000's, the publishing of performance-based fire protection design (PBFPD) documents including guides and guidelines from fire protection engineering societies (e.g. Society of Fire Protection Engineers) or international committees (e.g. International Organization for Standardization or Inter-jurisdiction Regulatory Collaboration Committee) as well as codes and standards embodied in some national regulations (e.g. Sweden, New Zealand and Japan) appeared as a benefit but turned out to be a drawback to the dissemination of PBD approaches. For instance, the PBFPD processes currently included in codes, standards, guides and guidelines 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. With this purpose in mind, they had to be generic in order to be used as widely as possible. This generic attribute of all the PBFPD documents, initially looking for uniformity in the application of their respective PBFPD process, led to a diversity of results from fire protection engineers who, used to follow prescriptive requirements, might not fully understand how the generic concepts were to be applied to specific and innovative projects.

As an engineering discipline, fire protection engineering relies on the utilization of tools and models in order to quantify relevant parameters describing the fire phenomena themselves, occupant evacuation and structural response. Since property protection, business continuity, heritage preservation and environmental protection are objectives of potential interest for a building project stakeholder, fire protection engineers, if not directly assessing relevant parameters unique for taking into consideration these objectives, still needs to communicate with the corresponding experts and to incorporate their assessment into their own assessment. In other terms, fire protection engineering has expanded to become a real inter-disciplinary field, which means that not only fire protection engineers have to keep up to date with fundamental research in their main disciplines (e.g. fire dynamics, fire modeling) but they are required to constantly expand their knowledge to other disciplines, as well as being aware of innovations occurring in the built environment with new materials and new construction practices.

Engineering calculation methods are presented in only a few regulations, usually as recommended practice, but are limited to particular and isolated part of the whole engineering problem (e.g. temperature and velocity in an unobstructed and axisymmetric fire plume). Fortunately, along with the development of computer science, tools were developed to assess temperature profiles and smoke transport for simulated user-input fires, with more or less definition of the complexity of the building geometries (e.g. atrium space, multiple rooms and multiple floors) and specificities (e.g. mechanical ventilation). Evacuation tools, dealing with human behavior and structural response tools were also developed on their own. Unfortunately, all these tools provided with a more or less easy-to-implement graphic user interface, remain research tools with relatively limited validation domains, and their use in PBD application requires fire protection engineers to have a good understanding of the uses and limits of the tools, especially when they need to combine the different results from each tool for their global engineering analysis. User effects as well as the need to apply these tools for configurations they were not tested or designed for, raise skepticism and concerns from the authorities having jurisdiction when judging the validity of the PBD application process which is still largely dependent on the calculations performed with these tools.

Recognizing this wide range of expectations, concerns and challenges related to the use of current PBFPD processes, the research presented in this Ph.D. dissertation identifies a path forward for advancing performance-based fire protection design and the fire safety engineering profession, founded on three fundamental concepts:

1. Fire protection engineers need to make a paradigm shift from one in which fire is the center of the problem, to one in which building performance metrics are evaluated in the case of fire events. This paradigm shift is necessary because current PBFPD guidelines are so focused on *design* fire scenarios, to the extent that fire protection measures deemed appropriate at the time of design might not be the most appropriate when implemented in a building, that key aspects of resultant fire protection designs might be ignored or worse "rejected" by the occupants of the building when needed the most, since fire is not a daily concern of building occupants. Fires, as with earthquakes, floods or even terrorism, instead have to be seen as one of many potential 'acute' disruptive events that may occur during the 'chronic' lifespan of a building. In consequence, fire protection measures should be an integrated part of a "building-occupant" system formed by specific building types, the activities being undertaken in the buildings, and the building occupants in order to limit the effects of fire events on the overall performance of the system, which is the main concern of the system stakeholders.
2. To assess the effects of fire or any other disruptive event on the overall performance of the building-occupant system, and result in a mitigation strategy which considers the impact of the 'acute' event within the 'chronic' lifespan of a building, a system-specific, risk-informed performance-based process has been established. This process clearly separates the technical aspect related to the tasks engineers have to perform (acute impact analysis) from the political aspect which determines the normal (chronic) performance expectations of the system stakeholders, including the level of degradation in building performance that the stakeholders would accept in the case where disruptive events affect their system. As a consequence of this separation, the technical stage of the process becomes transparent, both for stakeholders who establish the performance targets (political decision) and for the engineers in charge of the evaluation of the disruptive effects on the system performance (technical analysis).
3. To facilitate the paradigm shift and successfully implement the new risk-informed, performance-based guidelines for use within the building-occupant systems framework, detailed guidelines are needed for a broad set of building-occupant systems. While development of such guidelines was outside of the scope of this Ph. D. research, since it requires the participation of many different actors, time and resources that are not compatible with a single Ph.D. program, a plan of action is proposed to facilitate creation of the guidelines for each of the technical steps of the risk-informed, performance-based process for specific "building-occupant" systems. As future work, a web-platform dedicated to facilitating and speeding up the execution of the plan, is being developed and will follow the publication of this Ph. D. dissertation.

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1. INTRODUCTION

1.1 *Context of the research*

Fire safety issues have to be considered for the built environment, as fire is one of the technological hazards of concern. Regulations regarding fire safety have been implemented for centuries, most often with new requirements developed mainly after disasters.

Fire safety regulations are typically implemented via "building codes" and "fire codes," which in turn rely on reference standards and guides for deeper technical aspects. For example, in the USA, a state might promulgate a building code based on the International Building Code [1], a model building code developed by the International Code Council. The IBC in turn requires the installation of sprinklers in particular types or classes of buildings. The technical specification of the sprinkler system design is referenced to a design and installation standard published by the National Fire Protection Association [2]. In the USA system, the requirements in the building code and reference standards are highly prescriptive.

The concept of performance-based design (PBD) for fire protection emerged in the 1970s in the USA in order to consider alternatives to the prescriptive design with the objective to obtain a built environment at least as safe as the one that would have been designed according to the regulation. This concept emerged in other countries, such as England and Australia in the 1980s and 1990s as fire safety engineering (FSE).

PBD has been used in cases where the involved stakeholders (mainly the building owner and the architects) wanted to design a building that was "outside of the box". Unique buildings such as skyscrapers, buildings with inner large open spaces (atria), complex built environments such as subway transit stations or airport terminals and even buildings inside buildings are the best candidates for the use of PBD, as prescriptive regulations have a difficult task to consider generic solutions to such particular buildings.

While national building codes are primarily concerned with the safety of the building occupants, with some variations to include the neighboring people and outside personnel operating during emergency situations, PDB solutions may also incorporate objectives that are not life-safety related such as business continuity, property protection, environment protection, and heritage preservation.

It should be noted that the engineering process of PBD is currently aimed at comparing the final engineering design with the one elaborated from the prescriptive regulation within a particular jurisdiction, as the final design would have an equivalent level of safety to that provided by the "prescriptive" solution. Because non life-safety objectives may not be fully addressed in local building codes, authorities having jurisdiction may accept the PBD solution that they judge acceptable while not adequate to fulfill objectives such as property

protection. In other terms, as authorities having jurisdiction are used to judging prescriptive solutions aimed at life safety objectives, the PBD solutions they deem acceptable may not address non life safety objectives that could be of a major concern for other building stakeholders.

Several countries around the world have integrated performance-based elements into their regulations at two fundamental levels:

- at a technical level, as fire protection engineering still requires significant research in order to describe and model all the different phenomena;
- at a political level, as PBD is part of a decision-making process involving stakeholders' risk acceptance, determined at a national level with regulations and at a local level when the authorities having jurisdiction judge the PBD report acceptable or not, based on their own risk acceptance/aversion level.

A building project implies the participation of different groups of stakeholders, including contractors, building owners and users, architects, mechanical engineers, fire protection engineers and the authority having jurisdiction which approves the construction and the use of the project. These groups are involved at different stages of the project and undertake different tasks and mandates. So, each of these groups defines the performance of the project according to their mandates that run for a limited time or expand to the overall lifespan of the building. The overall performance of a building depends on the interrelations between the different components of the building such as the architectural system, the climate system, and components used for emergency situations, many of these components are separately managed by specific engineers.

1.2 *Organization of the dissertation*

The dissertation is organized into seven chapters as follows:

Chapter 1 (this Introduction) provides some background and context to the Ph.D. research.

Chapter 2 presents the results of a review of two decades of worldwide experience using standards, codes and guidelines related to performance-based fire protection design for buildings, in terms of challenges and shortcomings resulting from the application of these documents. Two key outcomes of this review are that (1) several of the challenges which have been identified are strongly linked to the application of generic guidance to specific problems, which results in critical details being missed, and that (2) some of the engineering issues are treated within a political context, while they should be addressed as purely technical issues.

Chapter 2 served as the basis of a paper that was submitted to the *Journal of Fire Protection Engineering* (submitted 12 August 2012, with the manuscript number JFE-12-0035), which was under review when this dissertation was published.

Chapter 3 presents a new study paradigm organized around systems formed by specific building types, the activities being undertaken in the buildings, and the building occupants that I define as "building-occupant" systems. It focuses on how events such as fires or any other emergency situations can affect the overall performance of these systems. A system specific risk-informed performance-based process is established in order to assess the effect of a single or multiple disruptive effects of any type on the overall performance of the system.

Chapter 3 served as the basis of a paper that was submitted to the journal *Building and Environment* (submitted 29 November 2012, with the manuscript number BAE-D-12-01181) and was under review when this dissertation was published.

Chapter 4 presents the application of the aforementioned process to fires as they constitute one of the main disruptive events that can affect the overall performance of a "building-occupant" system. This chapter focuses on how a successful implementation of the corresponding new risk-informed PBFPD approach will require acceptance of the need for a paradigm shift from one in which fire is the center of the problem to one in which building performance metrics are evaluated in case of fire events. This chapter also details the different steps of the new PBFPD process and how this process differs from the current ones, notably in separating technical steps from political steps related to decision making and policy. Finally, this chapter presents how the process is practically applied to a project and it focuses on a proof of concept of the new PBFPD process.

Chapter 4 served as the basis of a paper that was submitted to *Fire Safety Journal* (submitted 3 December 2012, with the manuscript number FISJ-D-12-00256) and was under review when this dissertation was published.

Chapter 5 presents an iterative plan of action related to the establishment of the guidelines required to perform each of the technical steps of the process presented in the previous chapter for fire disruptive events. It provides elements of research currently available in the technical literature and how these elements could be incorporated into future guidelines. It also emphasizes on the importance of the involvement of the stakeholders for establishing the validation domain of models needed at each step of the PBFPD process.

Chapter 6 summarizes the main outcomes of this PhD research study.

Chapter 7 briefly introduces future work and how this plan could be practically facilitated via a web-platform as a collaborative environment.

A total of three appendices (A1 to A3) are provided at the end of this document as supplementary material.

Appendix A1 is a paper titled "Towards an Integrated Performance-Based Design Approach for Life Safety Across Different Building Use Groups" which was presented at the international conference "*Interflam 2010*". This paper stated the advantages and drawbacks of using fire incident databases and fire investigation reports as information for selecting and quantifying fire scenarios. It also indicated the relevance of other sources such as building and fire codes, agency- or occupancy- specific guidance. This paper also showed the limitations of generic methods used to treat this information and that established in current Performance-Based Fire Protection Design (PBFPD) guidelines, based on the differences between configurations found in assemblies, offices, hospitals and so forth, which make it difficult, if not impossible to develop detailed guidelines without dealing with the elements that make a building occupancy specific. It also replaced fires as one of the "perturbations" occurring in buildings, which specific types had specific "chronic" or everyday demands.

Appendix A2 is a paper titled "“Ready-to-Use” Building Layouts and Combustible Packages for 3-D Fire Simulations" which was presented at the *Fire and Evacuation Modeling Technical Conference 2011*. This paper first introduced the concept of 'test bed' studies related to the use of fire effects tools for given applications, with an emphasis on the fire Computational Fluid Dynamics model FDS (Fire Dynamics Simulator) developed by US National Institute of Standards and Technology. It also proposed to establish databases gathering together already constructed 3-D building layouts, fire and combustible packages containing information on heat release rates and fire effluent productions that fire protection engineers or researchers could easily use.

Appendix A3 is a paper titled "'Test bed' environment process for assessing the appropriateness of engineering tools to be used in performance-based design applications," published in the *Proceedings of the 9th International Conference on Performance-Based Codes and Fire Safety Design Methods*. This paper extended the concept of 'test bed' studies to all the engineering tools as it developed a new holistic approach for selecting tools to be used in performance-based fire protection design applications, at a technical level due to the complexity of the tools involved (fire effects tools, evacuation tools, structural response tools) and at a user level due to the facts that tools are used in a specific context, where input data may not be available as needed, analytical methods from already existing standards may be preferred to more sophisticated engineering methods based on their better acceptance by the authority having jurisdiction.

References

1. International Code Council (2012), International Building Code, 2012 edition, International Code Council
2. NFPA (2010), NFPA 13 "Standard for the Installation of Sprinkler Systems"

2. TWENTY YEARS OF PERFORMANCE-BASED FIRE PROTECTION DESIGN: CHALLENGES FACED AND A LOOK AHEAD

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 enabled 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 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, of code enforcers and Authorities Having Jurisdiction (AHJ). Besides, using a variety of tools as a support, the analysis should bring more engineering rigor and "furthermore, performance-based design 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 Performance-Based Fire Protection Design (PBFPD) can be divided into the following three major steps (as reflected in such guidance such as BSI [5], ISO [6], IFEG [7] and SFPE [8]):

- 1) Stakeholders establish goals and objectives, which are then translated by fire protection engineers into design objectives and performance criteria. Then, stakeholders agree on fire design scenarios upon which trial designs, elaborated by the FPEs, are evaluated. This part of the process is documented in the Fire Engineering Brief (FEB);
- 2) The FPE evaluates the consequences of the selected fire design 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 fire design scenarios;
- 3) The FPE elaborates 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 which are rather generic in nature, process-oriented documents, which 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. This has led to a wide variation in designs and levels of delivered performance. In 2007, examining the New-Zealand perspective, Wade *et al.* [11] 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 performance-based design. This [meant it was] difficult to achieve a uniform approach and consistent safety level through the country".

Nonetheless, based on the large number of performance-based design projects which 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. Examples of these projects include a unique hotel and Casino complex [12], a complex rental car facility integrated in an international airport [13], extension of an existing airport [14], and numerous high-rise buildings [15,16]. However, I have not learned as much as I might have from these since the level of detail in published summaries is sometimes light, full PBFDP reports are often client confidential, not all jurisdictions may make all design documentation available, and few comparative reviews have been undertaken.

Reviews of performance-based codes (e.g., building codes in Australia, New Zealand, England and others), performance-based design processes (like the one elaborated in the SFPE PBD Guide or actual PB design solution), and codes that allow a performance-based design option (e.g., NFPA 5000 [17]) can be found in the technical literature ([18,19]). Nevertheless, many 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" [20]. In applying the Fire Engineering Brief process, Schulz and Feeney [21] found shortcomings in the process, particularly when stakeholders are risk averse and unfamiliar with new design methods, which would lead to a higher (and more or less variable) amount of justifications 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)".

In the USA, there is no centralized mechanism for consolidating feedback regarding how the PBFDP process is handled from a regulatory perspective, so comparative reviews are lacking. There are several reasons for this:

- The building regulatory system in the USA is managed by the states – there is no federal government mandate and therefore no centralized systems for building regulation at the federal level.
- There is no standardized mandatory system for review and acceptance of PBFDP at a state or local level. Acceptance of PBFDP projects therefore varies widely across cities, counties and US states.
- AHJs may have considered that each PBFDP project was unique in terms of key fire engineering components (e.g., quantification of performance criteria, selection of fire design scenarios, implementation of fire protection measures), so no reason was seen for collecting and compiling the specifics of each project.

Also, while there is PBFDP in the USA, the USA has not embraced performance-based building codes. In 2008, Tubbs and Okawa [18] 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 general adoption of the PBFDP option in the USA in general, was related to 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 PBFDP, 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 designs especially those that are well beyond the basic code requirements". In other terms, when accepting a PBFDP instead of prescriptive requirements, the AHJ liability was extended further than when simply 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 application and in the acceptance of the PBFDP option. Because of the generic nature of the guidelines, the selection of acceptance criteria and fire designs is more a 'collegial political' choice than an outcome of a real characterization and treatment of the fire risk in the building. 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. To address these issues, FPEs need a more robust framework, 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.

2.1 *Technical and political challenges related to the use of PBFDP processes*

Across the world, attempts have been made to address this need, within the regulated structure of national codes and standards and using different approaches, but 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 in this dissertation as the political aspect of the PBFDP process. As mentioned by Brannigan *et al.* [22] 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".

The main technical and political challenges related to the use of PBFDP are presented as follows.

2.1.1 Technical challenges related to the use of PBFDP processes

Decades ago, when the PBFDP 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 [23,24], and fire loads were added to the more well established formulas for the resistance of structures [25]. In addition, SFPE [26] indicated that research related to the use of PBFDP 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 on 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 PBFDP process. However, it was not addressed in the definition of the PBFDP process itself, in particular in its political aspect, which links the engineering analysis results with the policy decision making process. For example, in 1997, Richardson *et al.* [27] already listed technologies required for PBFDP. 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, but there are a lot less regulatory details which interface the political aspect of PBD with the technical aspect.

2.1.2 Political challenges related to the use of PBFDP processes

Since different levels of performance are achieved at different costs, political decisions of the PBFDP 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 benefits in terms of the property remaining undamaged by a fire. For some stakeholders, this technical solution, which leads to a technically-acceptable fire safety design, may not be politically considered because of its cost. Charters and Ramachandran [28] 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 installing sprinkler systems 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 sprinkler [in] the bus garage. As a result of the risk assessment, the operator did implement other forms of safeguard and fire precaution".

In some cases, it is possible to compare the cost-benefit ratio of two different fire protection design options, particularly when they are both technically viable (sprinkler vs. fire rating barriers), but it can be quite difficult to assess the relative costs and benefits of a technical fire protection measure as compared with a managerial fire prevention measure (e.g. management of fire loads and ignition sources). In the case of nightclubs, managerial procedures such as allowing more people than the prescriptive limit in conjunction with the use of fireworks in an environment with flammable linings and ceiling have repeatedly led to fire disasters (Lame Horse Club, December 5, 2009 - Santika Pub, January 1, 2009 - Wuwang Club, September 21, 2008 – República Cromañón, December 30, 2004 - Station nightclub, 2003). One might ask what the costs of having strict managerial procedures which would have prevented the over capacity of the nightclubs and elements that led to a very fast spreading fire would have been as compared to the costs and the benefits of 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.

More detailed discussion of the analysis of the current PBFPD processes is presented as follows, in terms of challenges that these current processes have to overcome in order to ultimately establish guidelines that would be more complete to follow through for the fire protection engineer and easier to verify for the authorities having jurisdiction.

2.2 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. They discussed 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 [29] 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 [19] 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 community (which is concerned by sustainability, job protection, environmental protection) or on behalf of the building owners and insurers?
- Fire fighters 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 fire protection engineer 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 levels of risk and acknowledge this in our regulatory frameworks".
- Certification, accreditation and fees of people involved in the performance-based fire protection design, 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".

He 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 [30] also 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 AHJ's 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 AHJ's and fire engineers is required.[...] The fire engineering community as a whole (fire engineers and AHJ's) should be working to achieve a globally recognized process of approvals".

More recently, in 2008, Johnson et al. [31] 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 PBFDP processes, at a technical level and at a political level. The following paragraphs discuss the key challenges which have been identified in more detail.

2.2.1 Challenges when applying generic guidance to specific projects

To date, codes, standards, guides and guidelines related to PBFDP have been written in order to be used for any type of built environment and project. Paradoxically, this generic applicability has made the guidelines ineffective in helping engineers thoroughly apply the PBFDP process for a particular project. Parameters to be considered in the PBFDP process are presented, but even if their influences within the overall analysis may seem obvious to a trained FPE, they may not be for the stakeholders. In addition, the way parameters are introduced in the generic PBFDP processes can be confusing even for the FPE. For example, in the SFPE engineering guide to PBFDP [8], information related to the building and its occupants, needed for the analysis is only presented in its Chapter 8, as it should be considered for characterizing design fire scenarios. Numerous building items, including building services and processes, operational characteristics, environmental factors, as well as occupant items are cited in this chapter but their uses within the PBFDP process are not explicitly indicated in the rest of the engineering guide. Neither their metrics (for example, how is the "social affiliation" item supposed to be considered as a parameter of egress models?) nor influences on the overall analysis are indicated. It should be noted that this guide indicates in its Section 6.2.2 that "the process of developing quantifiable design objectives should focus on target(s)", but that focus is totally absent in the subsequent

chapters dealing with the development of design fire scenarios. By this, SFPE [8] defines targets are as "building, compartment, process, or occupant that is protected in order to meet a specific stakeholder objective".

A similar observation can be made with respect to 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". Dominant occupant characteristics are listed in the following section (1.2.4 of IFEG), as they "should be considered in identifying the design occupant groups for the building [...] explained in Section 1.2.12 of these Guidelines", which states that "if any occupant groups have characteristics which would influence the outcome of a fire scenario, they should be considered for identification as a design occupant group. In some cases, the design occupant group may consist of only one person". The IFEG provide an example of design occupant groups for hospitals: staff defines the detection time and the pre-movement time while movement times would be defined by the types of patients. In spite of this single detailed example, it is unfortunate that the Methodology Part of the IFEG does not go on while presenting methods to assess the evacuation process (chapter 2.8 of IFEG) and that the Data Part of the IFEG does not include any corresponding data on design occupant groups, or at least help the FPE by providing ways to access this data.

To summarize, PBFPD processes included in codes, standards, guides and guidelines 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. With this purpose in mind, they had to be generic in order to be used as widely as possible. After decades of application of these processes, it seems that this wide applicability turned to be a drawback leading to all the challenges presented as follows. For this reason, it appears that the next generation of guidelines will have to include more details and specificities of the considered types of projects, to which all the engineering process have to be refocused on.

2.2.2 Challenges associated with the definition, use and quantification of the 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). No change occurred between the editions of the references examined in Table 1 and the current official editions, if still in use. It should be noted that some thermal exposure criteria can also be found in standards and regulations used to determine the hazard distance to people exposure from a LNG fire, outside a built environment [32].

Acceptance criteria are derived from fire protection goals (life safety, property protection, business continuity...): they are highly dependent on the characteristics of the building occupants, contents and structure. When looking at the values collected in Table 1, these characteristics can be implicit: for example, the criteria associated with "level of fire gases" mix the person height (1.6 m component) with the height of the room (0.1 H). The criteria related to heat radiation effects on people seem derived from physiological studies and translate well the potential damage to building occupants while receiving radiative heat fluxes from a fire. What is more disturbing is that the last criterion in Table 1 can be found in Section 921.2 of the sixth edition of the Massachusetts State Building Code as the design criteria of a smoke control system. In consequence, since the performance criteria are a technical transcription of a political agreement, it seems interesting to find the rationale behind the selection and the quantification of the published performance criteria. Nevertheless, this task is out of the scope of the current dissertation.

Table 2-1. Performance criteria gathered in codes, standards and guides and guidelines [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 minutes; 2.5 kW/m ² can be tolerated for 30 seconds; 10 kW/m ² can be tolerated for 4 seconds	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 feet above the floor level of exit access open to the atrium for a period of 20 minutes	The BOCA National Building Code, Building Officials and Code Administrators, International, County Club Hills, IL	1993

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. Custer and Meacham [4] indicated that many countries using or developing performance-based codes have not included values for the performance criteria because, even if some performance criteria may be applicable to any design situation, the selection of performance criteria remains situation-dependent.

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 main structure. It is proposed that "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 year of use of the building? 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" [33]. Fire events produce effluents and heat that can cause these injuries and casualties, and FPEs are trained to assess these productions. Nevertheless, in case of a fire or emergency situation in a highly populated area (theater, stadium, nightclub...) people could result as casualties, not because of toxic or thermal threat but because they stampede and get crushed at some points on the evacuation process. As a recent example, a student was crushed to death, two others were in a critical condition and at least six (or eight) other people injured after a stampede at a nightclub in Northampton, UK. The club was overcrowded (1,300 capacity). It is not clear if a fire alarm went off when people were asked to leave the club to get into their buses [34]. This phenomenon should also be included when assessing life safety performance criteria associated with fires in buildings. When reviewing different PBFPD processes, a performance criterion associated with a crush effect in case of stampede for exits has not been found or mentioned: without such a quantified 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" [25] 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 fire design" as one more action on the structure, such as actions imposed by natural hazards such as earthquake, wind, and snow. The definition and the evaluation of the consequences of the "structural fire design" only concern the structure of the building and not its occupants and contents. Nevertheless, Kruppa [35] 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.

In 1997, using an analogous concept taken from the American Society of Civil Engineers, Lucht [36] proposed to introduce a simple state equation where the resistance or "strength" of the building was greater than the sums of the applied loads: a smoke load, heat load and carbon monoxide load were added with corresponding safety factors and then compared with the combined "resistance" of the fire protection systems and the exit system, pondered by their reliability factors. In 1999, Meacham [2] attempted to expand upon this concept, with a specific focus on evacuation analysis and associated uncertainties in the process. Concerning the definitions of the loads and resistances of the fire threat, Fitzgerald [37] had already established a list of technical differences between the building structural system and the "far more complex" building fire safety system, rendering unpractical the merging of the two concepts. In 2004, Bukowski [38] considered that "fire [was] an event like an earthquake or hurricane, but where these natural events [had] statistical distributions in time (magnitude and return frequency), fires [were] unique because nearly all fires start[ed] small and gr[e]w until they r[a]n out of fuel or air or [were] extinguished. Large fires [were] generally the results of many things going wrong simultaneously, and thus represent[ed] a string of conditional probabilities that [were] not well described in normal terms, One suggestion for how to develop design fire specifications specific to a building space to result in the same stress on the space ha[d] been proposed but this [did] not address the issue of return frequency".

After reviewing the pros and cons from the technical literature, I decided that this potential way to include fire as an additional load was not the most adequate to deal with building occupant evacuation or protection of building contents, in spite of its usefulness to assess structural component response in case of a fire. In conclusion, this example shows that it does not seem possible to mix methods of evaluations of performance criteria for different objectives. This implies that different objectives (life safety, property damage...) have to be assessed according to their corresponding level of performance.

In addition, for life safety objectives, I consider that the corresponding 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 fire effect 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 considered project, for each of its safety objectives agreed among its stakeholders. 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) as well as environmental ecosystems potentially affected by the fire itself and the chemicals used for its extinguishment.

2.2.3 Challenges associated with the selection of fire design 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 fire protection engineer and the involved stakeholders with detailed explanations on what the representativeness of potential worst credible fires in a particular building has to be:

- "Worst credible fires" seem to imply that fires having developed to quite a large extent while remaining credible are the ones to be considered. This denomination is too vague because the intensity of the fires necessary to have an effect on targets (building occupants, contents and structures) depends on the nature of the targets and on the relative position between the fire and the targets. The ICC Performance Code gives different levels of "fire maximal tolerable damage" as a function of the importance of the building [39] 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 necessary means that less intense fires are "covered" even if SFPE 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, in one of its own technical opinion papers, that "not all large nuclear power plant fires are significant from a public safety point of view, nor are all safety significant fires large" [40]. As early as 1999, Brannigan summarized concerns from himself and others regarding how design fire scenarios were selected and characterized; Dr 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" [41]. This cited remark is so important that it still written, with no change, in the latest edition of the NFPA Fire Protection Handbook [42]. 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 PBFDP process.
- The context related to the term "manageable" is not defined but Hall and Watts [42] link that term 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 [33] presents a list of design fire scenarios associated with the life safety of building occupants (not related to the fire origin) and a list of scenarios (similar to the NFPA one) is proposed to be integrated in the building regulations of New Zealand. It should be noted that the scenarios of the NFPA list are qualified as "challenging" and are not necessary the "credible worst case scenarios". Hall [43] 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 conditions, fire protection systems have different *modus operandi*. I assume that when the PBFDP process is used to evaluate the benefits of changing one fire protection feature (usually a prescriptive requirement) by an alternative, scenarios challenging both options should have to be elaborated, and the overall analysis would 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 options. None of this is discussed in the current PBFDP processes I reviewed.

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

In the current PBFDP processes, the fire design 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 [44] 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 sets 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. New Zealand building current regulation constitutes a typical example of that situation. I concede that in the short term, AHJs of New Zealand would be able to better judge applications based on a PBFDP process where scenarios are predefined but in the long term, I anticipate difficulties in applying these scenarios to very complex and unusual projects. Some difficulties are presented below.

As presented in the previous point, NFPA [45] introduced a list of 8 design fire scenarios as follows: "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. I deplore the fact that this type of information is "lost" when editing the standard as it is more important to tell a FPE what problem he/she needs to solve than how he/she has 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 considering as many or more fire protection features as the prescriptive requirements.

Regarding performance criteria of the New Zealand regulation, in 2008, Lloyd [46] indicated: "there are two sets of criteria: a simple set of criteria, 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 [:]

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".

When dealing with a list of design fire scenarios, I have similar comments: what to do when selecting the "loss of one exit" scenario when the building has a single main exit stairs? 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 PBFDP process. What is the meaning of this scenario when in the prescriptive regulation (e.g. US ICC International Building Code [47]), the second exit is only required for a 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 fire (i.e. untenable conditions) 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 loosed?

Regulators want more specificity regarding the scenarios characteristics (i.e. evolution of the heat release rate with time) because scenarios constitute the core of how the fire protection design is judged to be acceptable and the variability regarding their characteristics is too large.

Even with a list of pre-defined scenarios, there are so 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 are. This parametric characterization of fire design 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 [46]. For example, the heat release rate evolution with time or "HRR curve" is specified as an " α -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.* [48] gathered values of the 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 as high as 200 MW. This example illustrates the fact that quantified parameter values embedded in the regulations certainly decrease variability in the application of the PBFPD process but they also need to be well documented with their applicability domain.

In conclusion, attempts made by standard associations, and even regulatory bodies to define more quantification of 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 fire scenarios in such lists are lost in their transcription into the regulatory framework, while on the contrary they should be put forward in this context (to explain why the situations analyzed by the scenarios should matter), instead on having the regulations "prescribing" more and more details on the scenario specifications (on how the FPE has to calculate the scenario consequences). Applications already showed some limitations and drawbacks of this concept.

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

The acceptability of an engineering fire protection design can be made according to a comparative evaluation of this design with the ones elaborated using the corresponding regulatory requirements. In some projects where

innovation is the main driver, like for example, the need to have beautiful, large, bright airports to accommodate the exponential increase of air traffic since the 1970's, as well as the connective use of airports with nearby hotels and car renting or parking sites. Fig. 2-1 shows the "check in" hall of Terminal 4 Barajas airport in Madrid. Such wonderful airport aesthetics are without comparison with the airport ancestors provided with compartmented long corridors. 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.



(source: http://en.wikipedia.org/wiki/File:Barajas_terminal_4_panorama,_Madrid.jpg, in the public domain)

Fig. 2-1. Barajas terminal 4 panorama, Madrid

What about new performance criteria such as sustainability? Performance of a building is not exclusively related to life safety, which is the primary objective 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 this 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 regulatory highest levels [49], which "focuses on performance-based evaluation as an important alternative to prescriptive codes" [50]).

Building codes authorize trade-off between different fire protection requirements, usually when the considered building 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 feet (22 860 mm) if the office building is not sprinklered and 100 feet (30 480 mm) if the office building is fully sprinklered [47]. Scenarios to be used in estimating the engineering solutions would also be used for the deem-to-comply requirements. For the list of selected scenarios, there is no certainty that the quantified trade-offs inscribed in the regulation would pass the selected scenarios.

In conclusion, comparison of performance levels between an engineering design and a prescriptive one is not a trivial exercise. I assume that the rationale behind the quantification of the requirements embedded in building codes is based on previous "good practices", partial empirical evidence and not on system approach of the problem, especially when trade-offs are concerned. This rationale does not have a common background with the one used in the PBFDP processes, so I do not retain this form of comparison in the rest of this chapter.

2.2.6 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 [9] provide a list of input parameters and output parameters for each of the sub-systems these guidelines present: fire initiation and development and control, smoke development and spread and control, etc. Nevertheless, they do not provide a hierarchy on the relative influence of all these parameters. For these parameters needed for the quantification of the fire consequences, as well as other factors needed to perform a PBFPD process, no examined standards, guides and guidelines [7-10] established a hierarchy between the influences of these factors. Additional factor influences, such as the "user effect" on tools, also have to be assessed [26]. Besides, in the consulting environment, such assessments are difficult due to time and resources constraints. 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).

2.2.7 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 for futures changes. In 2004, Ryber *et al.* [51] identified related minefields and proposed possible tools to overcome these difficulties. Besides, Stenstad and Bjørkmann [52] examined the interconnections between the different stakeholders involved in implementing PBFPD in the 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 [Fire Safety Strategy] FSS report may be overlooked and not taken care in a proper way". Looking at the problematic 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 Fig. 2-2.

Even if most of the important decisions related to a new project fire safety have to be taken 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 aspects are not included in the evaluation of the trial design. A solution could

be conceptually acceptable but not compatible with the actual use of the building, with or without considering significant changes in the building management or use.

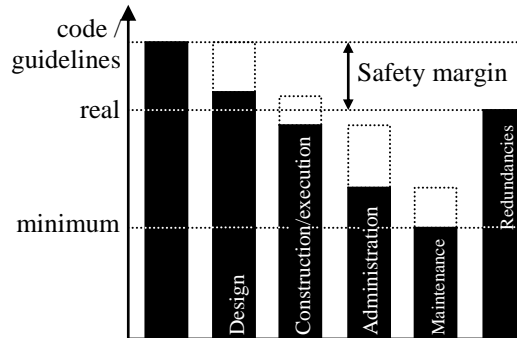


Fig. 2-2. Level of Fire Safety and the reduction due to the different processes [52]

2.2.8 Challenges when estimating the consequences of fire design scenarios

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 arises 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. 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: ASET (Available Safe Egress Time) and RSET (Required Safe Egress Time). In 2008, Averill *et al.* [53] assessed that priority had been given to the estimation of the ASET concept. I assume that their assessment relies on the fact that FPEs are more trained to deal with the estimation of fire effects than the estimation of the evacuation process; because egress modeling had been a concern for FPEs for decades, as soon as they tried to calculate the RSET. Indeed, in 1988, Kendik [54] stated that an early distinction was made between two egress model categories: movement models and behavior models and in 1999, Shields [55] presented a possible path to follow in order to develop human behavior knowledge as "hard science alone cannot solve the "fire problem"". This dichotomy in solving the "fire problem" can be seen, for examples, in the fact that there is still no or seldom feedback of the evacuation side to the fire side (i.e. building occupants closing doors while escaping) or evaluation of the counter flows of fire fighters and emergency responders and their actions on people and fire. Challenges are then related to the education of the FPE, who must not only be trained to estimate fire effects, but also evacuation of building occupants and structural response in case of a fire.

Besides, it is necessary to verify the appropriateness of tools to be used for a given the application, as well as the user's ability to use such sophisticated research tools. Documents published by SFPE [26,56] ISO [57] or ASTM [58,59,60,61] 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 documents has to be reassessed with updated versions of the same models and with new models. One example of applied document concerns a fire detection computer model [62]. It should be noted that I was not able to find any document which provides guidance on the interactions of model uses to assess fire effects, occupant evacuation and response of structural building elements.

2.2.9 Challenges when adapting literature values, when available, to use in models

As previously presented in this chapter, consensus of the fire protection engineering profession and the regulators should be found for the values of the "fire effect criteria" so that reports can be published regarding these criteria. Governmental institutes NIST [63] or INERIS [64], international societies such as SFPE [65] or ISO [66] should provide such reports, so national regulators and AHJ could reference the recognized values and, if necessary, adapt them for their own purposes. Current works in ISO TC92/SC3 are dedicated to the revision of an International Standard providing guidelines for the estimation of time to compromised tenability limits [67].

In any engineering practice, injecting appropriate data in tools is as essential as using the appropriate tool in order to solve a given problem. Care should be taken when selecting and using data from any source as:

- Data obtained from experiments performed decades ago does not necessary represent current data as material properties and people characteristic distributions constantly evolve,
- Some data needed to use tools is 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 is 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 on 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".

Nevertheless, 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.

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 was made available by the US National Institute of Standards and Technology (NIST), which created the Fire And Building Educational Resource Collection (FABERC) [68]. This database is no longer accessible via "faberc.org", but some experimental results from fires conducted by NIST still can be found at its own website.
- The need for egress data collections was advocated by Fahy and Proulx [69]; Gwynne [70] 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 [71]) in order to collect basic data such as fire load and reliability of systems in a coherent and harmonized manner, which really permit to collect, use and compare 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. Even with the most elaborate and sophisticated PBFPD process, using inappropriate data produces erroneous results which may lead to a building performance dramatically below its expected level of performance.

2.3 Summary of the challenges related to the use of current PBFDP processes

A large number of articles in journals and conference proceedings that describe challenges and concerns regarding the use of PBFDP 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 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

The PBFDP processes currently included in codes, standards, guides and guidelines were written at a time when it was a priority to introduce the global concepts of the PBFDP process, to model all the phenomena, and to determine and assess the influence of critical components of the PBFDP process. With this purpose in mind, they had to be generic in order to be used as widely as possible. After decades of application of these processes, it appears that this wide applicability has turned out to be a significant drawback, leading to a number of specific challenges as presented here and summarized below. For this reason, it is proposed that the next generation of guidelines will have to include more details and specificities of the considered types of projects, to which all the engineering process has to be refocused on.

2. Defining, using and quantifying the performance/acceptance criteria

As quantified in the current PBFDP processes, performance criteria should actually be called "fire effect criteria". The terminology "performance criteria" should describe the actual level of performance achieved by the considered project, for each of its objectives agreed among its stakeholders. Research to attain a consensus for 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) as well as environmental ecosystems potentially affected by the fire itself and the chemicals used for its extinguishment.

3. Selecting fire design scenarios

Attempts made by standard associations and regulatory bodies to define more quantification of performance criteria and design fire scenarios seemed a positive action in order to increase coherence in the PBFDP process applications. However, the intents and ideas behind developing fire scenarios, as ultimately reflected in such lists, are generally lost in their transcription into the regulatory framework. This is unfortunate because these intents and argument should be provided in context with the scenarios to explain why the situations analyzed by the scenarios should matter, instead on having the regulations "prescribing" more and more details on the scenario specifications or how the FPE has to calculate the scenario consequences.

4. Comparing the levels of performance between an engineering solution and the one based on prescriptive requirements

Comparison of performance levels between an engineering design and a prescriptive one is not a trivial exercise, yet that is a common approach taken. I assume that the rationale behind the quantification of the requirements embedded in building codes is based on previous "good practices", partial empirical evidence and not on system approach of the problem, especially when trade-offs are concerned. This rationale is not appropriate for a PBFDP process, and is not recommended without being made much more transparent (which is difficult, especially given (3) above).

5. Determining the most influential factors affecting the evaluation of trial designs

Current PBFDP processes list factors affecting the evaluation of trial designs, but these factors are not clearly assessed nor always adequately considered with respect to such attributes as sensitivity of subsystem output to design objectives, knowledge level (uncertainties), benefit versus cost (cost could be prohibitive and it may change the design objectives), or absolute versus comparative evaluation. There is no hierarchy between the influences of these factors. Additional factor influences, such as the "user effect" on tools, also have to be assessed. In the consulting environment, such assessments are difficult due to time and resources constraints, thereby making them less likely to be undertaken. 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), and lack of data, time and resources means that the evaluation required does not always get done at a level that it should.

6. Dealing with "idealized" design fire protection measures and "real life" installed and running measures

At present, most PBFDP processes consider "idealized" representations of future actual conditions, often times not accounting for how buildings are used and the state of systems over time. At the time of design, decisions may be made without all stakeholders being involved, and without the stakeholders understanding the implications for the future. Even if the fire protection "design" is the most important aspect of any building design project, things may change during construction that need to be documented and accounted for, and maintenance of systems and consideration of how the systems performance with respect to normal operation of the building becomes critical once the building is occupied. These aspects are not explicitly included in the evaluation of the trial design by current PBFDP processes. As a result, a "design" solution could be conceptually acceptable but incompatible with the actual use of the building, with or without considering significant changes in the building management or use.

7. Estimating the consequences of fire design scenarios

While an integrated approach to building fire performance is the target of current PBFPD processes, estimation of consequences is not at all integrated. Life safety objectives are often analyzed through two concepts: ASET and RSET. 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. Data are often lacking for all required analyses and shortcuts are taken. As a result, these analyses (fire effects, evacuation, structural fire performance) are typically undertaken in isolation. As a result, 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 which parts of the process are most sensitive to changes from initial design assumptions, or where greatest sources of uncertainty and variability exist. Challenges also exist with engineers selecting appropriate tools to be used for given the applications, as well as the user's ability to use sophisticated research tools in design.

8. Adapting literature values, when available, to use in models

In any engineering practice, use of appropriate data in analytical or computational tools is as essential as using the appropriate tool in order to solve a given problem. Care should be taken when selecting and using data from any source as:

- Data obtained from experiments performed decades ago does not necessarily represent current data as material properties and people characteristic distributions constantly evolve,
- Some data needed to use tools is still missing so FPEs have to use their "expert judgment" to adapt the available experimental data to use with a chosen tool, and
- Tools and models also evolve with knowledge of the phenomena they represent. Experimental data is 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 dependant; changing the model may disqualify a data validation set to be used in another model.

However, 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. 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.

2.4 *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 showed that addressing the 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). Because the current PBFPD processes are generic, it seems difficult to incorporate any feedback of the successful applications into these processes in order to overcome the presented challenges and therefore reduce the uncertainties and concerns associated with them. In addition, the current PBFPD processes are centered on the study of the fire protection measures, which sometimes can lead to differences on 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 its application subject, 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) to provide a mechanism to help FPEs select the most appropriate tools and data for the types of applications they are addressing. 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 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 to extract all the data required to perform the analysis but also to characterize the context for which the analysis is carried out and which determine 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 are detailed in the following chapter of this dissertation. 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. A new risk-informed PBFPD process, based on the system paradigm, has been elaborated, 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 chapter is presented in Chapter 4 of this dissertation. To address (3), by creating 'test bed' environments, displayed on an web-platform, 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 types of fire protection engineering applications [72].

2.5 Conclusion of this chapter

Challenges in applying current PBFPD processes arise from technical and political levels. Challenges still exist concerning the definition/quantification of the strategic elements of any PBFPD process: the performance criteria (which current denomination should be changed to "fire effect criteria"), design fire scenarios, use of tools to quantify the trial designs. Efforts are made to consolidate databases gathering information related to buildings, fires and occupant behaviors 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 [69]. 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.

References

3. Meacham, B.J. (1998), The evolution of Performance Based Codes and Fire Safety Design Methods. Report no. NIST GCR 98-761. Gaithersburg, MD: National Institute of Standards and Technology
4. Meacham, B.J. (1999), International Experience in the Development and Use of Performance-Based Fire Safety Design Methods: Evolution, Current Situation and Thoughts for the Future. *Fire Safety Science: proceedings of the Sixth International Symposium*, University of Poitiers, France, 5-9 July 1999. London: International Association for Fire Safety Science, 1999; pp. 59-76
5. Hadjisophocleous, G.V., Bénichou, N. and Tamin, A.S. (1998), "Literature review of performance-based codes and design environment", *Journal of Fire Protection Engineering*, Vol. 9, No. 1, pp. 12-40
6. Custer, R. and Meacham, B.J. (1997) Introduction to performance-based Fire Safety, Society of Fire Protection Engineers
7. (BSI) British Standard Institute (2001), Application of fire safety engineering principles to the design of buildings. Code of practice – BSI 7971:2001
8. (ISO) International Organization for Standardization (1999), "Fire safety engineering -- Part 1: Application of fire performance concepts to design objectives," ISO/TR 13387-1:1999
9. IFEG (2005) International Fire Engineering Guidelines, Australian Building Codes Board, Department of Building and Housing (New Zealand), International Code Council (USA), and National Research Council (Canada), 2005 edition
10. SFPE (2007), SFPE Engineering Guide to Performance-Based Fire Protection, Society of Fire Protection Engineers
11. Wade, C., Beaver, P., Fleishmann, C., Lester, J., Lloyd, D., Moule, A., Saunders, N. and Thorby, P. (2007), "Developing Fire Performance Criteria for New Zealand's Performance Based Building Code", presented at the Fire Safety Engineering International Seminar, 26 and 27 April 2007 in Paris, France, available at: http://www.branz.co.nz/cms_show_download.php?id=f8f5f396ba47ccae10e62e5c335d917d4d9301c0 (checked 2012.06.06)
12. Evans, D.H. (1998), "Luxor Hotel and Casino: An Application of Performance-Based Fire Safety Design Methods," Proceedings of the Pacific Rim Conference and 2nd International Conference on Performance-Based Codes and Fire Safety Design Methods, International Code Council/SFPE, pp. 477-494
13. Suarez, A. (2007), "Performance Based Design for the Miami Inter-modal Center -Consolidated Rental Car Facility," APICI Conference: Performance-Based Design for Buildings, Industry and Transport, (presentation available at: http://www.alamys.org/documentos/apici_2007/download/Miercoles/5_grupo_m/Alfredo%20Suarez/PBD%20Suarez%20-%20BM%20FINAL.pdf, checked 2011, 12, 12)

14. Morgan, H.P., Williams, C., Harrison, R., Shipp, M.P. and De Smedt, J.C. (1995), "Hot Smoke Ventilation Test at Brussels Airport," Proceedings of the International Conference on Fire Research and Engineering, Orlando, Florida, USA, September 1995, pp.495–551
15. Chow, W. K. (2005), "Building Fire Safety in the Far East," Architectural Science Review, vol. 48, issue 4, pp. 285-294
16. Quiter, J. R. (1996), "Application of Performance Based Concepts at the Stratosphere Tower, Las Vegas, Nevada". Fire Risk and Hazard Assessment Symposium. Research and Practice: Bridging the Gap. Proceedings. National Fire Protection Research Foundation. June 26-28, 1996, San Francisco, CA, pp. 118-126
17. NFPA 5000 (2012), Building Construction and Safety Code, 2012 edition, National Fire Protection Association
18. Tubbs, B. and Okawa, R. (2008), "Performance Codes and Design in the US, an International Code Council (ICC) Perspective," Proceedings of the 7th International Conference on Performance-Based Codes and Fire Safety Design Methods, Society of Fire Protection Engineers, pp. 59-65
19. Johnson, P. (2002), "Performance Based Fire Safety Regulation & Building Design – The Challenges in the 21st Century," Proceedings of the 4th International Conference on Performance-Based Codes and Fire safety Design Methods, Society of Fire Protection Engineers, pp. 3-13
20. Takeichi, N., Matsumoto, K. and Wataru, G. (2008), "Review Japanese performance-based code- Recommendation by Research committee on Building legislation in AIJ," Proceedings of the 7th International Conference on Performance-Based Codes and Fire Safety Design Methods, Society of Fire Protection Engineers, pp. 25-33
21. Schulz, J. and Feeney, M. (2008), "The Fire Engineering Brief Process in Performance Based Fire Engineering – Is it Working?," Proceedings of the 7th International Conference on Performance-Based Codes and Fire Safety Design Methods, Society of Fire Protection Engineers, pp. 35-46
22. Brannigan, V. Smidts, C and Kilpatrick, A. (1996), "Regulatory Requirements for Performance Based Codes Using Mathematical Risk Assessment," Proceedings of *Interflam '96*. Interscience Communications Ltd, London, pp.621-630
23. Bryan, J.L. (2002), "Behavioral Response to Fire and Smoke." in The 3rd SFPE Handbook of Fire Protection Engineering, edited by P.J. DiNunno. Quincy, MA: National Fire Protection Association, pp. 3-315 – 3-341
24. SFPE (2003), Engineering guide: Human behavior in Fire, Society of Fire Protection Engineers, June 2003
25. (CEN) European Committee for Standardisation (1990), EN 1990: Basis of Structural design
26. SFPE (2004), SFPE Code Official's Guide to Performance-Based Design Review, Society of Fire Protection Engineers – International Code Council, June 2003
27. Richardson, J.K, Yung, D., Loughheed, G.D. and Hadjisophocleous, G.V. (1997) "The Technologies Required for Performance-Based Fire Safety Design," Proceedings of the 1996 International Conference on Performance-Based Codes and Fire Safety Design Methods, 24-26 September 1996, Ottawa, Ontario, Canada, Society of Fire Protection Engineers, pp. 191-201
28. Charters, D. and Ramachandran, G. (2011), Acceptance Criteria, Chapter 4 of Quantitative Risk Assessment in Fire Safety, Spon Press, p.193
29. Grubits, S. (1992), "Fire Safety Engineering Research in Australia," Proceedings of the International Fire Safety Engineering Conference, Commonwealth Scientific and Industrial Organisation, Sydney, Australia
30. Barber, D. and Van Merkestein, R. (2002), "Can the approval of Performance Based Solutions Be Improved?," Proceedings of the 4th International Conference on Performance-Based Codes and Fire safety Design Methods, Society of Fire Protection Engineers, pp. 143-154
31. Johnson, P., Gildersleeve, C. and Williams, P. (2008), "Road Tunnel Fire Safety – Approach to Fire Scenarios," Proceedings of the 7th International Conference on Performance-Based Codes and Fire safety Design Methods, Society of Fire Protection Engineers, pp. 251-262
32. Raj, P. K. (2008), "A Review of the Criteria for People Exposure to Radiant Heat Flux From Fires," Journal of Hazardous Materials 159, pp. 61-71
33. NFPA (2009a), NFPA 101 Life Safety Code® 2009 edition, National Fire Protection Association
34. The Sun (2011), "Woman crushed to death in nightclub stampede - Eyewitness says there was rush to exits," available at <http://www.thesun.co.uk/sol/homepage/news/3881282/Woman-crushed-to-death-in-nightclub-stampede.html> (checked 2011, 10, 23)

35. Kruppa, J. (1997), "Performance-Based Code in Fire Resistance: a First Attempt by Eurocodes," Proceedings of the 1996 International Conference on Performance-Based Codes and Fire Safety Design Methods, 24-26 September 1996, Ottawa, Ontario, Canada, Society of Fire Protection Engineers, pp. 217-228
36. Lucht, D.A. (1997), "Public Policy and Performance-Based Engineering," Proceedings of the 1996 International Conference on Performance-Based Codes and Fire Safety Design Methods, 24-26 September 1996, Ottawa, Ontario, Canada, Society of Fire Protection Engineers, pp. 65-87
37. Fitzgerald, R.W. (1996), "Thoughts on Building Codes, Design Standards, and Performance Evaluations for Firesafety," Proceedings of the 1996 International Conference on Performance-Based Codes and Fire Safety Design Methods, 24-26 September 1996, Ottawa, Ontario, Canada, Society of Fire Protection Engineers, pp. 127-137
38. Bukowski, R.W. (2004), "Building Regulatory Systems in a Post-September 11 World," Proceedings of the 5th International Conference on Performance-Based Codes and Fire Safety Design Methods, 6-8 October 2004, Society of Fire Protection Engineers, pp. 15-25
39. (ICC) International Code Council (2009), International Code Council Performance Code for Building and Facilities
40. (NEA) Nuclear Energy Agency (2002) CSNI Technical Opinion Papers (No. 1: Fire Probabilistic Safety Assessment for Nuclear Power Plants; No. 2: Seismic Probabilistic Safety Assessment for Nuclear Facilities), Nuclear Energy Agency – Organisation for Economic Co-operation and Development (available at: <http://www.oecd-nea.org/nsd/reports/nea3948-fire-seismic.pdf>) (last checked; 2011-10-25)
41. Brannigan, V. (2000), "Fire Scenarios or Scenario Fires? Can Fire Safety Science Provide the Critical Inputs for Performance Based Fire Safety Analyses?," Fire Safety Science: Proceedings of the Sixth International Symposium, International Association for Fire Safety Science, pp. 207–218
42. Hall, J.R. Jr and Watts, J. Jr (2008), Fire Risk Analysis, Volume 1, Section 3, Chapter 8 of the 20th edition of the Fire Protection Handbook, NFPA
43. Hall, J.R. Jr (2011), "Defining the Challenge: Selecting Fire Scenarios for Fire Protection System Design and Evaluation," Proceedings of SUPDET 2011: Suppression, Detection and Signaling Research and Applications - a Technical Working Conference, March 22-25, 2011, available at <http://www.nfpa.org/assets/files//PDF/Proceedings/SUPDET11HallAbstract.pdf>(checked 2011, 10, 25)
44. Babrauskas, V. (1998), "Ensuring the Public's Right to Adequate Fire Safety under Performance-Based Building Codes," Proceedings of the Pacific Rim Conference and 2nd International Conference on Performance-Based Codes and Fire Safety Design Methods, International Code Council/SFPE, pp. 239-247
45. NFPA (2009), NFPA 101 Life Safety Code[®] Handbook, eleventh edition, edited by R. Coté and G. E. Harrington, National Fire Protection Association, pp.667-669
46. Lloyd, D. (2008), Evaluation of the Conceptual Framework for Performance Based Fire Engineering Design in New Zealand, Fire Engineering Thesis, Department of Civil Engineering, University of Canterbury
47. International Code Council (2012), International Building Code, 2012 edition, International Code Council
48. Miclea, P.C., Chow, W.K., Shen-Wen, C., Junmei, L., Kashef, A.H and Kang, K. (2007), "International Tunnel Fire-Safety Design Practices," ASHRAE Journal, August 2007, pp. 50-60
49. NFPA (2010), NFPA 914 standard "Code for Fire Protection in Historic Structures"
50. Watts, J. M. (2001), "Fire Protection Performance Evaluation for Historic Buildings," Journal of Fire Protection Engineering, Vol. 11 - November 2001, Society of Fire Protection Engineers, pp. 197-208
51. Ryber, M., Kylefors, M., Nählinder, J. and Nystedt, F. (2004), "The Minefields of Performance-Based Fire Safety Design," Proceedings of the 5th International Conference on Performance-Based Codes and Fire Safety Design Methods, 6-8 October 2004, Society of Fire Protection Engineers, pp. 36-41
52. Stenstad, V. and Bjørkman, W.R. (2004), "A Systematic Approach to Fire Safety Design," Proceedings of the 5th International Conference on Performance-Based Codes and Fire Safety Design Methods, 6-8 October 2004, Society of Fire Protection Engineers, pp. 67-78
53. Averill, J., Reneke, P. and Peacock, R.D. (2008), "Required Safe Egress Time: Data and Modeling," Proceedings of the 7th International Conference on Performance-Based and Fire Safety Design Methods (April 16 –18, 2008), Society of Fire Protection Engineers (available at <http://fire.nist.gov/bfrlpubs/fire08/PDF/f08011.pdf>) (checked 2011, 10, 25)

54. Kendik, E. (1988), "Means of Escape – 1988 How Close Are we to Modelling Egress from Buildings in Fire?," Proceedings of Interflam'88, 4th International Fire Conference, pp. 156-163
55. Shield, T.J. (1999), "The Science of Human Behaviour: Past Research Endeavours, Current Developments and Fashioning a Research Agenda," Fire Safety Science: Proceedings of the Sixth International Symposium, International Association for Fire Safety Science, pp. 95-114
56. SFPE (2011), SFPE Engineering Guide – Guidelines for Substantiating a Fire Model for a Given Application, SFPE G.06.2011, Society of Fire Protection Engineers
57. (ISO) International Organization for Standardization (2008), "Fire safety engineering -- Assessment, verification and validation of calculation methods," ISO 16730:2008
58. (ASTM) American Society for Testing and Materials (2007a) E1591-07: Standard Guide for Obtaining Data for Deterministic Fire Models, ASTM
59. (ASTM) American Society for Testing and Materials (2007b) E1895-07 Standard Guide for Determining Uses and Limitations of Deterministic Fire Models (**Withdrawn in 2011, no replacement**), ASTM
60. (ASTM) American Society for Testing and Materials (2007c) E1472-07 Standard Guide for Documenting Computer Software for Fire Models (**Withdrawn in 2011, no replacement**), ASTM
61. (ASTM) American Society for Testing and Materials (2011) E1355-11: Standard Guide for Evaluating the Predictive Capability of Deterministic Fire Models, ASTM
62. SFPE (2002), Engineering guide: Evaluation of the Computer Model DETACT-QS
63. Kuligowski, E. (2009), "Compilation of Data on the Sub lethal Effects of Fire Effluent," NIST Technical Note 1644, National Institute of Standards and Technology
64. (INERIS) Institut National de l'Environnement Industriel et des Risques (2011) Fiches de données toxicologiques et environnementales, available at: <http://www.ineris.fr/substances/fr/page/21> (175 hazardous substances are listed at 2012/12/10)
65. SFPE (2000), Engineering guide: predicting 1st and 2nd degree skin burns from thermal radiation, Society of Fire Protection Engineers, March 2000
66. (ISO) International Organization for Standardization (2011), "Guidelines for assessing the fire threat to people," ISO 19706:2011
67. (ISO) International Organization for Standardization (2011), "Life-threatening components of fire — Guidelines for the estimation of time to compromised tenability in fires," ISO/DIS 13571, revision of first edition ISO 13571:2007
68. Woycheese, J.P., Raghavan, V., Kim, M. and Geller, F. (2006), Online Access to and Data analysis Tools for Experiments in Building and Fire Science. Final Report, National Institute of Standards and Technology (NIST GCR 06-894)
69. Fahy, R.F. and Proulx, G. (2001) Toward Creating a database on delay times to start evacuation and walking speeds for use in evacuation modeling, Report NRCC-44758, National Research Council Canada (available at:<http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc44758/nrcc44758.pdf>, checked 2011/11/28)
70. Gwynne, S.M.V. (2011), "Improving the Collection and Use of Human Egress Data," Fire Technology – Online First
71. NFPA (2012), NFPA 557: Standard for Determination of Fire Loads for Use in Structural Fire Protection Design, Proposed Standard Next Edition: 2012, National Fire Protection Association
72. Alvarez, A. and Meacham, B.J. (2012), 'Test bed' environment process for assessing the appropriateness of engineering tools to be used in performance-based design applications, Proceedings of the 9th International Conference on Performance-Based Codes and Fire Safety Design Methods, 20-22 June 2012, Hong Kong

3. USING A SYSTEMS APPROACH TO ASSESS HOW DISRUPTIVE EVENTS AFFECT BUILDING OVERALL PERFORMANCE

The main drivers for performance-based design (PBD) are demands from users for better building use performance, in conjunction with a change in legislation allowing a broader use of the PBD option instead of prescriptive requirements. Within a PBD framework, the demand of the "end users" of the building become priorities [1] so that PBD provides a more "client" oriented process [2] than the one used when following building code regulations.

Performance-based design (PBD) applies to all the components of a building project related to, among others, acoustics, aesthetics, operability, sustainability, and safety. Then, it involves numerous actors including, on one hand, the building users who should define the level of performance of the building and on the other hand, the building industry which should create optimal solutions in order to achieve this level of performance within a regulatory framework established by policy makers.

Because of the complexity of the engineering thinking related to these building components, PBD guidance has been segmented such that each engineering discipline has to consider separately how clients' objectives connected with each of the building components should be achieved. This statement is not only valid for building components dedicated to the normal use of the building (e.g. mechanical components including heating, ventilation, and air conditioning (HVAC) and plumbing) but it also concerns building components installed to address disruptive events, such as fires or earthquakes. In other words, some PBD guidance has thus far been elaborated to treat fire safety objectives exclusively [3] while other guidance only addressed earthquakes [4] as these hazards are very specific and the engineers quantifying these hazardous situations have specialized expertise.

However, in practice, the building end users are not really interested in the performances of different building components as they wish to experience, on a daily basis, the performance of the building as a whole [5]. As such, the design team individual entities; rather members dealing with the multitude of building components have then to co-operate in order to achieve this seamless daily performance [6].

The research presented in this chapter originated from a review of decades of worldwide experience of the performance-based option for fire protection design, which identified shortcomings in the interpretation, application and implementation of performance-based fire protection design (PBFPD) processes. This review is presented in the previous chapter of this dissertation. I found that the application of these processes, which the aim of is centered on the design of fire protection measures, and not building performance, may lead to the possibility that these measures, deemed appropriate at the building design stage, might be ignored or worse

"rejected" by the building end users when needed the most, since fire is not a daily concern of these users. I realize that this can be generalized to any disruptive event and mitigation strategies.

This chapter presents the outcomes of my research related to the treatment of disruptive events on the overall performance of a building project, using fire as an example:

- first, I define a system formed by specific building types and their associated occupants, so as to characterize the nature of disruptive events and their effects on the overall performance of that system;
- second, I establish a risk informed performance-based design process which would be applicable to any disruptive event and include a step evaluating the integration of the protection measures into the considered system.

3.1 Definition of the daily performance of a "building-occupant" system and its decrease during a disruptive event

Primary stakeholders in a building project, including the building owner and the potential users, generally define building performance objectives in terms of the everyday uses of the building. For a hospital, this performance is related to the type of treatments offered, the number of patients who can be treated, the types of equipment and services needed to treat patients, and so forth. For a school, performance is related to delivering education to the target student population, the number of registered students, the numbers and qualification of teachers or faculty required to deliver education, etc. For a museum, it is related to the exhibits and holdings, number of exhibition attendees who can be accommodated, security of the holdings, etc. Unfortunately, the owners and operators of these buildings do not always think about events which can disrupt this daily use. This has an impact not only during use, but with respect to decisions made at the design stage.

Disruptive events can be of different natures [7], such as:

- supplier business disruption leading to operational vulnerabilities,
- fires, earthquakes, severe weather, accidents or terrorism leading to hazard vulnerabilities,
- currency exchange fluctuations leading to financial vulnerabilities,
- new foreign competitors leading to strategic vulnerabilities.

Such disruptive events can significantly impact the operation of a building and the mission it supports. If the building owner and other key actors are unprepared, the disruptive event can have catastrophic effects on continued operations [8]. Because of my experience, I will be focusing, for this chapter, on fires as an example of a class of disruptive events, as well as an example on how my paradigm of study, centered around a "building occupant" system differs from the one considered in the current PBFPD processes, centered around the fire protection measures themselves.

3.1.1 Introduction of the "building-occupant" system paradigm

In many countries, buildings are classified in terms of the general class of use, such as places of assembly, business occupancies, residential, and so forth. However, these general descriptions lack the complexity to describe the interaction of the building users in the context of the building. To address this, I looked to identify a more appropriate "building-occupant" system. In order to define the system formed by specific building types and their associated occupants, which I call "building-occupant" systems, I first looked at building code classifications. To frame this discussion, I focus on healthcare occupancies. I also focus on the situation in the USA.

An obvious way to categorize the different existing "building-occupant" systems is to follow the classification established in building regulations. For example, in the USA, Chapter 3 of the International Building Code (IBC) established by the International Code Council (ICC) provides 10 different groups [9]. The purpose of the building (or part of the building) determines the group of the building (or part of the building). "Sections 303 through 312 of the ICC IBC identify the occupancy characteristics of each of the 10 groups. In some of these sections, specific group classifications having requirements in common are collectively organized such that one term applies to all". For example, Groups I-1, I-2, I-3, and I-4 are individual groups for Institutional-type buildings. The general term "Group I", however, includes each of these individual groups. Prescriptive requirements are defined for each of these groups, with specific requirements when applicable: for example, Section 403 adds requirements if the building qualifies as a "high-rise" building; Section 404 adds requirements related to the presence of an atrium in the building; Section 407 adds provisions for occupancies in Group I-2.

By reviewing the occupancy group classification of the ICC IBC, I determined that this classification is too coarse to take into consideration all the specificities of different "building-occupant" systems. For Institutional Group I-2 defined according to the ICC IBC classification, detoxification facilities, nursing homes, hospitals, and mental hospitals do need the same requirements. In all these facilities, populations are vulnerable, unable to evacuate without assistance but they are very different and the building systems are also very different, as shown in Fig. 3-1. A classification, such as the one established in ICC IBC, is a "good" start but still necessitates going in a deeper taxonomy level to clearly define a proper "building-occupant" system.

Related to this point, Lataille [10] indicated that "prescriptive codes apply to facilities with widely varying characteristics. For example, the same prescriptive codes apply to an office building whether it has one or several stories, small or large building footprint, or low or high combustible loading. Different provisions in these codes might apply to different buildings, so the prescriptive protective scheme can vary from building to building". This statement issued for prescriptive requirements can be extended to the PBFDP processes.



a) Child care facility, source: <http://www.flickr.com/photos/shaggypaul/351385178/>, free to share and remix with the attribution of the work to "Shaggy Paul"



b) Hospital, source: <http://www.flickr.com/photos/usnavy/5913202904/sizes/o/in/photostream/>, free to share and remix with the attribution of the work to Official U.S. Navy Imagery



a) Nursing home, source: <http://www.flickr.com/photos/13384589@N00/2780553606/>, free to share and remix with the attribution of the work to by "Robinsan"

Fig. 3-1. Examples of facilities under the ICC IBC Institutional class (I2)

Performance-based building codes present an opportunity to go beyond ‘simple’ classifications and consider more specific "building-occupant" system features. However, this requires the stakeholders and design team to focus more effort on describing the system as part of the PBFDP process. The structure of some PB building codes helps facilitate this. For example, one distinction of the ICC Performance Code (ICC PC) approach [11] from the IBC and from many other performance building codes is its classification of the building in terms of performance groups (Section 302.1 of ICC PC): "the objective of the assignment of use and occupancy classification is to identify the primary uses of buildings and facilities, and portions of buildings and facilities, and to identify risk factors associated with these uses, in order to facilitate design and construction in accordance with other provisions of this code". This classification is useful to demonstrate that the PBFDP process has to take into consideration the importance of the building for societal expectations in respect of the level of safety.

As the ICC PC is one of the building codes developed by ICC, the building uses are to be taken from the prescriptive "Uses and Occupancy Classification" chapter of the ICC IBC. Nevertheless, the ICC PC performance group classification goes beyond the IBC classification in considering the building "importance" to the community, which allows for making a distinction between different buildings inside a same IBC occupancy classification. For example, a hospital that is intended to remain functional after an earthquake or other hazard event, to care for those who may be injured in the event, can be designated as having a higher level of performance than other healthcare facilities in the same geographical area. As such, a higher level of performance and resiliency during and after a hazard event is warranted.

Looking at other systems, I found the classification by the US Bureau of Census [12] more useful than the ones defined in building codes in defining more precisely the "building-occupant" systems. In this taxonomy a distinction is made between child day care (with the code 624410), general hospitals (with the code 622110), Psychiatric and Substance Abuse Hospitals (with the code 62221) and nursing care facilities (with the code 62311). In addition to providing a better "building-occupant" system descriptor, a benefit of using this taxonomy is that the Bureau of Census periodically collects information concerning each of its categorical areas, which can be helpful in the performance assessment.

Based on this taxonomy, I defined a "building-occupant" system as a system defined by a structure (i.e. building) inside which occupants are primarily engaged in a specific activity. This activity is quantified (e.g. activity number carried out by day or week) and then the performance of the system is estimated by the level of this activity.

Occupants are defined as persons who are physically inside the system, independently of the duration of their stay. Building components are defined in my paradigm as physical portions of the system which can include, for example, spaces dedicated to a particular occupant activity of the system or in support of that activity (e.g. HVAC system).

If I examine a hospital, I can see that there are different building areas which can be identified according to the functions they provide, such as reception areas, emergency rooms, examination rooms, operating rooms, patient rooms and intensive care units. I call any such area which can be grouped by function as a "functional" zone, as they are created to fulfill the functions related to the daily objectives of the facility. In addition, there are utility systems and areas which provide support functions, such as power, heating, ventilation and air-conditioning (HVAC), throughout the facility. These utility systems can be located in "utility" zones (mechanical rooms, electrical rooms, cafeteria...) or throughout the building (such as the HVAC system). When designating zones, care should be taken to define them based on the "building-occupant" system characteristics of importance. It is also important to identify direct and indirect relationships.

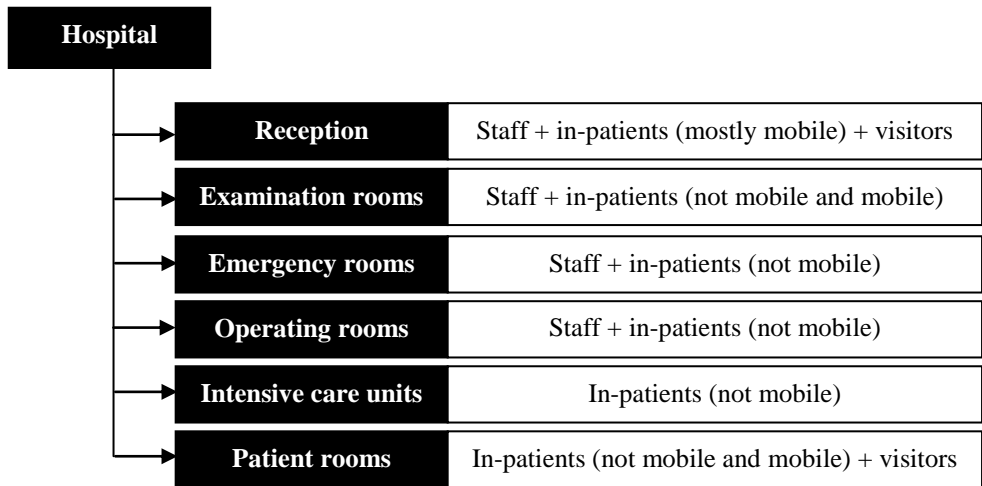


Fig. 3-2. People description according different functional zones of a hospital

For example, Fig. 3-2. illustrates the required level of detail for different functional zones of a hospital, describing the types of population in each of the zones. For example, people located in the reception area are future in-patients, visitors and staff and almost all of them are mobile and conscious. This is important as they would require no or little assistance in case of a hazardous disruptive event such as a fire. In-patients located in emergency rooms or in operating rooms are undergoing surgery and are connected to life-supporting machines. This is important as extracting them during a fire would require following procedures and requiring time that may not be compatible with a rapidly growing fire [13]. In addition, while a utility zone supporting a reception area may be important to facilitate the comfort of the occupants, a utility zone supporting an operating room functional zone is essential. If a fire occurs in the utility zone supporting a reception area the impact in the reception area could be limited to an ‘inconvenient’ loss of power or lighting. If a fire occurs in the utility zone supporting the operating room, the impact could be life-threatening.

To summarize, characteristics of occupants within specific locations of a building, as well as the intended function of spaces in a building and contents in those spaces which are essential to achieving the required function needs to be clearly understood, identified and categorized. This constitutes essential information required by the Fire Protection Engineer (FPE) in order to address stakeholder objectives for "building-occupant" systems when elaborating a fire safety strategy. However, no current PBFPD process directs an FPE to examine a building at such a level of detail, explains the reasons why such a level of detail is important, or provides guidance how to approach the assessment. In large part this is because current PBFPD processes are focused too much on the fire event itself instead of being target-oriented, focusing on the objectives of concern within the specified functional zones or a well-defined "building-occupant" system.

3.1.2 Characterization of the effects of a disruptive event on the performance of a "building-occupant" system

To show the importance of considering the building to be analyzed as being part of a system network, let us describe the events that started with a small fire in a manufacturing plant in USA and ended up with a US\$2.34 billion loss for one of the plant clients. This example is taken from Sheffi's book "The Resilient Enterprise" [7].

On March 17, 2000, lightning struck the industrial plant of Philips NV, located in Albuquerque, New Mexico, USA. As a consequence a small fire started within the facility but was extinguished by sprinklers and staff in less than 10 minutes. There were no injuries and the fire fighters arrived at the plant just to record a minor blaze. From a fire protection engineering design perspective this could be considered a success, with systems operating as intended. However, due to ensuing activities, the damage to the plant contents and disruption to the plant activity was tremendous.

So why was the disruption so significant? First, the plant was engaged in manufacturing of semiconductor chips for some 30 clients, including the mobile phones companies Nokia and Ericsson, whose orders accounted for 40 percent of the Albuquerque plant's production. Indeed, a semiconductor manufacturing facility such as this cannot tolerate any dirt or particulate in normal activities, in any of its clean rooms, much less soot in case of a fire. Not only did the fire destroy the chip batches in the furnace (with an equivalent of thousands of mobile phone production) but also smoke, soot and the tramping of staff and fire fighters from the fire scene (in the mix of dirt and water) contaminated chips at every stage of the production, increasing that loss to millions of mobile phone chips. The losses for Philips did not stop at the ones related to property damage. Removing the dirt from the clean rooms implied that the production would be back up after one week. This was the Philips estimation right after the fire, but two weeks later, Philips staff realized that the disruption caused by the fire would take weeks before production could restart. When two of the main clients of Philips, Nokia and Ericsson received the call from Philips on March 20, 2000, they each dealt differently with this situation, which ended up with two very different business outcomes.

As soon as it received the call, Nokia started to work closely with Philips and other of its providers so to maintain its own production of mobile phones and satisfy its customers in a period of time when demand for this type of product was booming worldwide. Ericsson's reaction was different: they treated the fire incident at the Philips plant as a "technical matter" which would result as a chip production disruption of one week only, which is something that could easily be taken care of. Unfortunately for Ericsson, the disruption lasted longer and by the time it realized the size of the disruption, it was too late and Ericsson failed to deliver mobile phones to its customers.

As a result of the small fire that occurred in 2000 at the Philips Albuquerque plant, Philips's chip sale loss, estimated to a US\$40 million, was almost covered by a 39 million Euro settlement with its insurance company; this loss only accounted for 0.6 percent of the US\$ 6.8 billion semiconductor global benefits of Philips for 2000.

Having failed to deliver its new generation of mobile phones, Ericsson reported losses between US\$430 and US\$570 million in the first disruption-affected quarter, due to a lack of parts, that is to say more than ten times Philips' losses. In addition to the fire disruption effects, incorrect product mix and marketing problems are to be blamed for Ericsson's US\$2.34 billion losses in the mobile phone division by the end of 2000. This situation led to a Sony-Ericsson merging for designing, producing and marketing mobile phones, in April 2001. In addition to its competitor economic situation, Nokia's fire disruption treatment helped to increase its percentage of the mobile phone market.

Fig. 3-3. illustrates the profile of a disruption of the system, adapted from [7] for a fire disruption, based on the aforementioned Philips fire. Prior to the fire, the plant is performing at a certain level, i.e. it is manufacturing (x) chips for its clients. The disruptive event occurs (fire on March 17, 2000) and the performance of the plant decreases, leading to a full impact of a completely stopped production. In this case, the performance of the plant went down to zero for weeks. The full impact was the sum of the direct consequence of the fire (damage to the furnace and smoke spread) and of the indirect consequence of the fire fighting operations (staff and fire fighters walking all around the plant and contaminating all the remaining furnaces). The recovery time was not the expected one week but several weeks. A long term impact was observed, as Nokia engineers sent to the Philips plant in the recovery phase ended up with increasing the pre-event production rate.

For the authority having jurisdiction (AHJ) approving the use of the plant, the life safety objective was not compromised. Related to fire safety, the plant could have been "code compliant" or designed to perform as well as a building provided with regulatory requirements. With regard to property protection objectives, the fire did not lead to severe damage of the production line in itself, but it contaminated all the production (with the involuntary help of the staff and fire fighters). It should be noted that Philips adopted a risk transfer towards insurance companies and hardly "suffered" from the disruptive event. On the long term, even if its premium may be more expensive, the subsequent boost of production may have compensated for the monetary loss. However, not all entities that suffer such as disruption are so lucky [8].

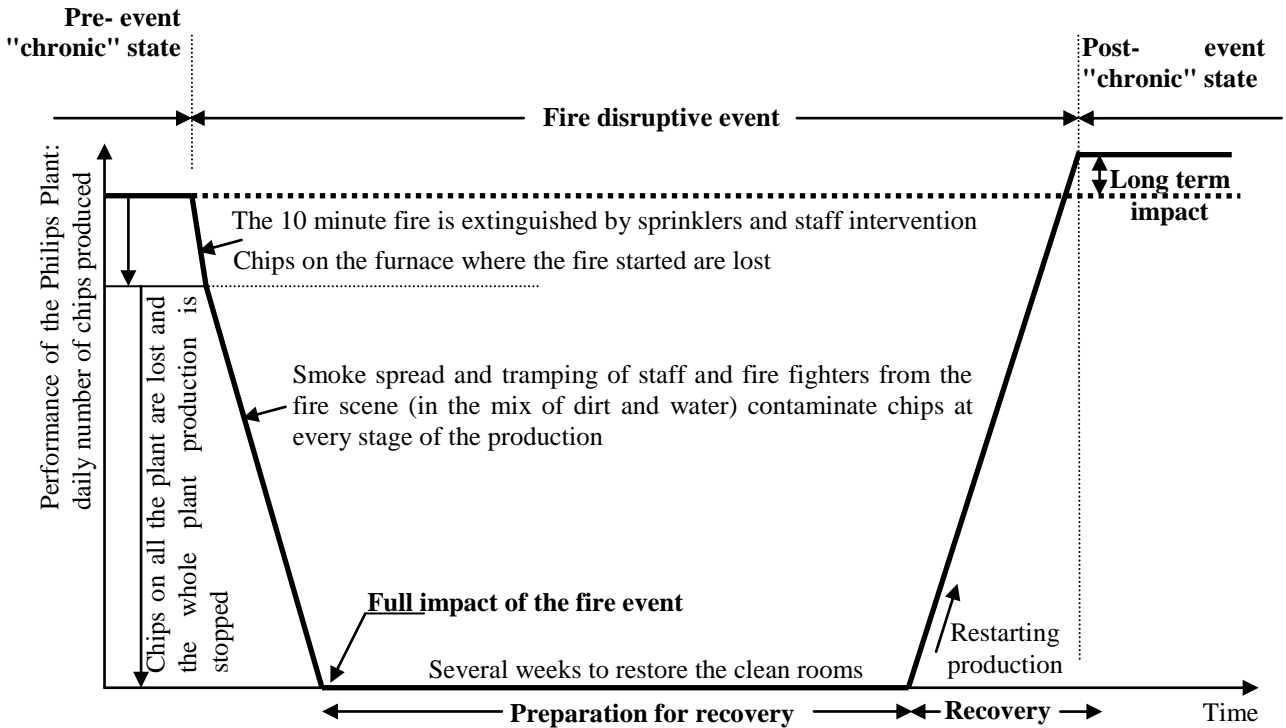


Fig. 3-3. "Disruptive event" profile of the Philips Plant fire (Albuquerque, New Mexico, USA), March 17, 2000, adapted from [7]

In the "building-occupant" system paradigm, fire is one of many disruptive events that may (or may not) occur during the lifespan of a building. In current performance-based fire protection design (PBFDP) guidelines, the design for fire is focused on the fire scenario only: from the fire ignition to the fire extinguishment. This runs the risk of ignoring how the normal operations of the building will influence human actions and systems when a disruptive event occurs.

So, I consider the system formed by the building and its occupants, and analyze the fire as a "disruptive event" or perturbation of the "building-occupant" system. Independently of providing safety to its occupants in case of emergencies, a building is designed, operated and maintained to perform objectives that correspond to the everyday uses of a building, objectives that I qualify as "chronic". Objectives associated with emergency situations related to disaster events, including natural hazards, technological hazards and terrorism, that may occur or not during the life span of the building are then qualified as "acute".

3.1.3 Key-concepts of "building-occupant" systems

In order to summarize my "building-occupant" system paradigm, I have several key concepts:

- Functional zones: spaces which are directly linked to the performance of the system (e.g. in hospitals, visiting areas where patients are checked in, patient rooms where patients are being prepared for surgery, operating rooms, intensive care units and patient rooms where patients recover before checking out);
- Utility zones: spaces which indirectly contribute to the performance of the system, often providing support to the "functional zones" (e.g. storage rooms, electrical rooms, mechanical rooms);
- Targets: key elements whose performance is of concern within systems (the actors or users of the functional zones). For example, targets can be building occupants (patients including their visiting families and friends and staff in hospitals, pupils and teachers in schools) or building contents (important piece of equipment required to contribute to the performance of the system such as a newly developed micro-chip in high tech industry or a priceless artifact in a museum);
- Chronic states of the system: which represent the situations of the system while it is operating as designed or after each modification of its design (e.g. normal use of the system).
- Chronic objectives: objectives the system is designed or subsequently modified, to attain during its chronic states;
- Disruptive events: every possible event (technological events, natural events, socio-economical events) having an effect on the performance of the system. A disruptive event lasts between two chronic states of the systems.
- Acute objectives: objectives the system is designed or subsequently modified, to attain during disruptive events;
- Event effects: damaging effects of a disruptive event on a target. These can be 'direct effects' or 'indirect effect.' With respect to fire as a disruptive event, "direct effects" reflect fire-induced damage upon targets, such as heat, toxic, corrosive, irritant effects. "Indirect effects" reflect loss of building components which are vital for the targets to perform in the system. For example, a fire can through 'direct fire effects' such as heat directly damage power cables to a life supporting equipment, which then has an indirect effect on the safety of people connected to this equipment.

3.2 Identifying and avoiding competing objectives within a "building-occupant" system

Generally speaking, a "building-occupant" system is designed by architects to perform according to "chronic" objectives. From a societal point of view, a "chronic" objective for hospitals is to cure sick or injured patients, and for schools to educate people. However, there are also have societal goals to safeguard the most vulnerable populations. Because society does not want patients or pupils to suffer from a potential fire that can occur in the respective buildings they use, a life safety objective is added to the performance of these buildings, and any other type of building or built environment for that matter. While life safety from fire is the focus of most fire protection engineering analyses, fire protection measures are only one component of the "building-occupant" system, and in some cases competing objectives may exist.

3.2.1 Fire safety objective competing with "chronic" objectives established at a design stage

When looking for the goals and objectives that are relevant for the different stakeholders involved in a project, a FPE also has to verify that the safety objectives related to the fire risk in the system are not competing with all the other stakeholders' objectives. Let's see how this point is already considered in the current PBFPD processes.

For example, the International Fire Engineering Guidelines (IFEG) [14] indicate that "in addition [to general regulatory objectives], the client may have various non-fire related objectives for the building design that impact on the fire safety of the building. For example, the client may require:

- Increased security
- Extensive natural lighting
- An open plan layout
- The use of new materials
- Measure to improve energy efficiency and sustainability
- Flexibility for future uses
- Low life-cycle cost".

Unfortunately, the IFEG do not provide any guidance on how to consider these additional objectives, which can be competing with the ones related to fire safety. As a result, there is currently no guidance for managing competing objectives in current PBFPD processes during the design stage. If the FPE happens to identify and address such issues through discussion with stakeholders, it is more by experience or chance than by direction.

3.2.2 Fire safety objectives competing with "chronic" objectives established after the design stage

Building stakeholders may decide to establish additional "chronic" objectives, a long time after the design phase, when the building is actually operating. For example, as a result of the 11 September 2001 events, increased security at airports multiplied check points that may impede safe egress capabilities in the case of an emergency. It should be noted that increased security has now become a "chronic" condition, not only for that type of transportation but also in major crowd gathering configurations and events. It should be noted that adding more security check points concentrate people in certain areas, people that are managed to follow predefined and controlled paths. This configuration induces a competition between the security crowd management and the needs for efficient and safe accessible escape routes in the case of an emergency, fire or other disrupting event. Not only does this security driven "chronic" condition compete with the conditions employed for dealing with emergency situations, but it also competes with a previous "chronic" objective of the architectural design to have uncongested pedestrian movement in the airport, as well as the aesthetic goal to have passengers walking in a quiet, spacious environment (compare Fig. 3-4. which visually translates the ideal vision of the designer with Fig. 3-5. which illustrated the real situations of airports).



a) Barcelona Airport Terminal 1

source: http://www.flickr.com/photos/francesc_2000/4583309008/, free to share and remix with the attribution of the work to Francesc_2000



b) Hong Kong Airport Terminal 2

source: <http://www.flickr.com/photos/gkpics/953052759/>, free to share and remix with the attribution of the work to jgmarcelino

Fig. 3-4. Examples of airport architectural designs



a) source: <http://www.public-domain-image.com/full-image/people-public-domain-images-pictures/crowd-public-domain-images-pictures/airport-security-lines.jpg-copyright-friendly-image.html>, in the public domain, Author: Kitt Hodsdon



b) Palma de Mallorca Airport
source: <http://www.flickr.com/photos/kalleboo/3536493996/>, free to share and remix with the attribution of the work to Karl Baron

Fig. 3-5. Examples of impacts of the security "chronic" condition in airports

The only way to address such concerns is to build into the PBFDP process a mechanism for not only looking at expected normal operations (chronic use) but for triggering reassessment if certain operational schemes are modified by the building in use. While PBFDP processes like that from SFPE tries to address this by having the FPE identify bounding conditions and to develop an Operations Manual, it is not clear from my review that these mechanisms are being utilized as intended (cf. previous chapter of this dissertation).

3.2.3 Fire safety objectives competing with "chronic" objectives evolving over very long period of time

As another example, consider how the design of hospitals 30 years ago assumed one set of chronic objectives, for which specific measures were designed to address fire events, and how internal changes to the hospitals may negate the benefit of those fire protection measures. Starting in the 1850's, based on Florence Nightingales' "Notes on Hospital", hospital wards were designed as large, open, well-lit facilities so that nurses could supervise a lot of patients [15]. As illustrated in Fig. 3-6(a), the "chronic" objective at that time was nurse and staff efficiency. Later, patient privacy and comfort became the primary concerns and the "Nightingale" ward design was replaced by a series of patient rooms (Fig. 3-6(b)) [16].

Looking at these two configurations from a fire safety point of view, the following comments can be made: in an open patient ward, staff is present and can detect a fire (or any agitated patient) as soon as possible and may extinguish the fire before it spreads away from the 1st burning item. In case the fire is not detected and controlled that quickly, smoke and fire may spread fast and evacuation of all ward patients becomes vital. In the private patient room configuration, fire detection would rely on automatic detection rather than detection by staff who are only briefly present in each patient room. An automatic suppression system could also prevent the patients in the room from being injured and a door closing upon fire detection could limit smoke and fire spread outside of the room of fire origin. This example clearly illustrates that the design of the system is highly

dependent of its "chronic" objectives, which design has a strong impact on how the fire protection measures should be designed, installed and maintained as a whole as these measures both include managerial and technical measures, prevention and protection measures. More detailed "chronic" objectives related to hospitals can be found in [17].

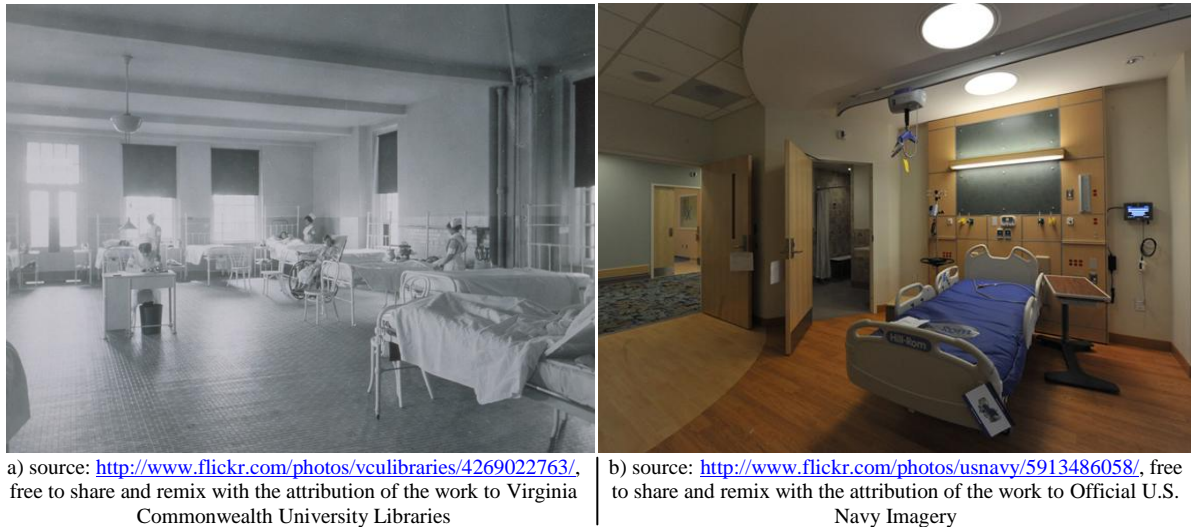


Fig. 3-6. Examples of a) well lit facility ("Nightingale" ward), b) private patient room in a hospital

3.2.4 Fire safety objectives competing with "chronic" objectives evolving over short or long periods of time

A "building-occupant" system is dynamically defined with time. A convention center is a typical example of such a system characteristic: the structure of the building remains the same in the lifespan of the building but the interior configuration constantly changes as a function of the exhibitions proposed by the convention center. From a FPE perspective, nature, amount and location of fire loads are very different for a comic convention, boat show, sport event, etc. Distributions of attendee characteristics (e.g. age, gender) are also relevant and should therefore be gathered and their consequences considered in the fire risk evaluation analyzed by the FPE.

Looking at turnover rates of building materials and their impact on the environment, Wærp and Holthe [18] notably conducted surveys and interviews of property managers and architects in Norway. The following paragraph is extracted from their paper:

“The architects were asked which materials that are often replaced in buildings. This is dependent on type of building and year of construction of the building. In office building interior materials is often changed e.g. flooring materials, ceilings, interior walls and lightening are all changed within 5-15 years. Buildings that are refurbished today are from 1970-80. Solutions and materials are in general poor. There are necessary to change ventilation. After 25 years you are left with façade (when quality is good), stairway and load bearing structure. In building from about 1900 more components are kept: e.g. doors, windows, ceilings, facades and often original interior materials. New buildings from today will probably

have better quality than in the 1970-80, but there will probably be frequently change in surface materials”.

This information illustrates the fact that even if a building remains an office building during its whole lifespan, the nature and the amount of material (including combustible materials) as well as the exit pathways (interior separation may change or completely disappear with "open space" configurations) have to be reassessed periodically to verify that the performance of the system regarding fire safety has not decrease.

It should be noted that building occupant demographics also evolve over long period of times, which may have a significant impact on emergency situations. For example, fire evacuation parameters such as walking speed and crowd density, established from experiments in the late 1980's, should take into consideration population obesity increase. Global ageing population should also be considered [19].

The "building-occupant" system can be stable over its life (i.e. a shopping mall would remain a shopping mall) but the nature of the individual shops inside may vary in time. Fluctuations can also be seen in the characteristics of this system concerning the population number and repartitions during the day (food court being more populated around meal times) and days of the week. Transitory combustibles can be located in the common areas (outside the mall shops) for more or less extensive periods of time (e.g. Christmas decorations in Fig. 3-7). It is necessary to consider of all these fluctuations when assessing fire protection system performance (e.g., sprinkler efficiency and combustible control, for this shopping mall example).



Fig. 3-7. Christmas tree located close to exit routes and main entrance of a shopping mall

The "building-occupant" system also "reacts" when new components are introduced inside. Introduction of new components, used for "chronic" objectives, may have an influence on the fire risk, because of their own hazardous properties. This situation is reviewed by the FPEs when analyzing fire hazards, and it is even quickly integrated into standards and good practices when the introduction of the hazardous components is anticipated. Following are two examples:

- In health care facilities, alcohol-based hand-rub solutions have been found to be more effective for standard hand washing or hand antisepsis by health care workers than soap or antimicrobial soaps. Placing dispensers of alcohol-based solutions in corridors and suites of rooms is expected to decrease the estimated more than 88,000 patient deaths attributed to US hospital-acquired infections [20]. It should be noted that there is an estimated single annual death in hospital or hospice facility [21]. In other terms, numerous combustible liquid sources were added to reach a new "chronic" state, in order to decrease the risk for hospital patients to suffer from nosocomial diseases. This change in the "chronic" state of the system has been already analyzed by the National Fire Protection Association (NFPA) which integrated it into their Life Safety Code, NFPA 101 [22]. The point is that if analysis of a new hazardous material introduced in the system is carried out by the FPE, analysis of a new fire protection measure into the "building-occupant" system also needs to be carried out, especially if this measure is a managerial one. This is illustrated by the second example below.
- Also in the health care facilities, O'Connor [23] indicated that for these facilities which established smoke-free environment / no smoking policies, it was observed that visitors were giving smoking materials to patients and residents without the health care staff's knowledge and that this system adaptation was found to explain why this type of ignition source was not decreasing in the corresponding fire statistics.

3.2.5 Impact of "chronic" objectives in performing the risk analysis related to disruptive events

Knowledge of the "chronic" objectives is also important when estimating how long building occupants delay their evacuation after an alarm starts. In case of a fire, the estimation of this "pre-movement" time is related to several factors, and particularly to two called "commitment" and "focus". In Fig. 3-8, people seem quite focus on playing slot machines, inside a Japanese game center. The row of slot machines is itself designed to maximize occupancy time by a single person whom is provided with a chair, has repetitive actions to perform in a very focused vision range, with people in the near proximity, which make it very easy to lose track of time and difficult to be aware of anything happening in the surroundings. People are committed to go on playing as long as they have still money to feed the machines. The "chronic" objective of these games centers (as well as of western casinos), related to a high degree of focus and commitment, leads to an increase of the "pre-movement" time, and therefore competes with the life safety objectives to have all these people evacuate as soon as possible in case of emergency.



(source: <http://www.flickr.com/photos/davidooms/2964039286/>, free to share and remix with the attribution of the work to David Ooms)

Fig. 3-8. Example of commitment in a Japanese game center

It should be noted that in case of an emergency many building users have a strong tendency to try to leave via the route that they entered by rather than using the nearest exit [24]. Displays in department stores and shopping malls are designed to make the potential buyer go from one stand or shop to another: the position of the displays, always changing, can also have some influence on the movement time as people need to find their way out. Estimation of egress paths would be much different when considering design floor layout empty of the movable booths and the real layouts during Sales periods (Fig. 3-9). Besides, lots of additional "Sale" signs may also make it more difficult to locate Exit signs. In consequence, during Sales periods, the use of exits other than the one people used to enter the department store might be lower than in regular store usage.



(source: http://fr.wikipedia.org/wiki/Fichier:Ambiance_de_solde.jpg, put into public domain by Wikimedia Commons User Medjai)

Fig. 3-9. Example of a French department store display during sales

3.3 Theoretical treatment of disruptive events affecting the performance of "building-occupant" systems

3.3.1 Fire is one disruptive event among others which may be "covered" by a contingency plan

For some types of building occupancies, a contingency plan is elaborated to ensure the safety of the building occupants and minimize the recovery period in the event of an emergency (fire, power or communications blackout, tornado, hurricane, flood, earthquake, civil disturbance, etc.). These plans mainly concerns installations of Performance Group IV, according to the ICC PC classification [11]: such as hospitals or designated earthquake, hurricane and other emergency shelters. They describe the actions of the building personnel to be performed for different scenarios. For example, the contingency plan of a hospital may contain information related to a fire or the loss of HVAC system by a fire. Examination of these contingency plans is needed to verify that the emergency actions are coherent with the ones elaborated by a PBFPPD process.

3.3.2 PBFPPD processes must examine the actions and events of the recovery phase following a fire

The actions required in the recovery phase need specific documentation to insure that the system components related not only to fire safety but all other components used by the system, are back in full operational mode. This specific need is illustrated by the fires that successively occurred in a New Orleans warehouse (Louisiana, USA), on March 21, 1996. Based on the information collected in the NFPA investigation report [25], the un-compartmented warehouse contained a combination of high racks (equipped with in-rack sprinklers) and low racks (not all with in-rack sprinklers). A first arson type fire successively started in a low rack section unprotected by in-rack sprinklers, was detected by staff who unsuccessfully tried to extinguish it, activated one over-head sprinkler which action did not extinguish nor control the fire, and eventually was declared out by the fire fighters, about 5 hours after they arrived on site. At that point, "once fire control had been achieved, all of the sprinkler systems in the facility were manually shut down by closing the individual OS&Y valves on the risers", as a result of the opening of numerous sprinkler heads throughout the warehouse, causing extensive water damage. Without evaluating the damage to the electrical system caused by water, the electric service of the building was restored, starting the second fire, in a high rack storage area, by ignition of combustible materials with arcing of damage wiring in this area. "As soon as the second fire was discovered, facility personnel began opening the OS&Y valves on the ceiling and in-rack sprinkler systems. However, because these systems were impaired during the initial stages of the second fire, they were overwhelmed". This time, the fire destroyed all the contents of the warehouse and collapsed the structure. The second fire was declared out several days after the fire fighters arrived a second time on site.

This fire event illustrates the importance of the actions to be performed and the needed documentation (as procedures or check-lists) in the recovery period, after the fire is extinguished. These actions not only concerned the impaired fire protection system but also one utility system to the warehouse, i.e. electricity. The authors of

the investigation report [25] advocated for a utility restoration in a "planned and coordinated manner, and only after a complete survey of the damage has been taken" so "that everyone involved with the overhaul and restoration operations be aware of what actions are being taken by the different agencies and services involved". Nevertheless, they "were unable to identify any reference in an NFPA standard, code, or recommended practice that addressed the issue of restoration of utilities and how it should be handled following an emergency".

After reviewing current PBFDP processes, I found them quite focused on the fire development itself, from ignition to extinguishment so that they ignore the recovery phase, which is essential to consider for the system as demonstrated by the New Orleans warehouse consecutive fires.

3.3.3 Specific interconnections may exist between different types of targets or between a target and a building component, so a fire can have a direct or an indirect impact on targets

In some systems, building occupants and building systems may have strong interconnections: in a hospital, people can be connected to life supporting machines, so fires impacting these machines (directly or indirectly) can affect the life safety of the people connected to them. Indirect effects of a fire on such patients could result from a fire damaging the distribution of electricity in the building, as well as the backup of this utility.

Also in a hospital, a HVAC/filtration system provides air quality and control of microbe and odor migration between the different functional zones of the hospital. Scott [13] studied a smoldering fire that happened in a storage room in a hospital in New Zealand, in 2008. Smoke generated by this fire traveled via a HVAC duct from the storage room to an operating room. This situation can be qualified as a direct impact of the fire, because the fire effluents directly affect the safety of the patient and of the medical staff (even if the room where the fire was located was not the same room where the targets were located). Keeping the same configuration, the HVAC/filtration system provides microbe migration control by maintaining a pressure differential between different functional zones: this ΔP assures that microbes are not going from the examination room towards the operating rooms where people are more vulnerable to this threat. A fire damaging the HVAC system ability to maintain this ΔP would compromise the safety of the patients most vulnerable to infections. Thus, this last example also illustrates the indirect effects of a fire on targets.

In healthcare facilities, the main safety targets are the patients. Losing a building component from a fire may affect patients. In other terms, the safety of the patient may depend on the safety of a building component. The opposite configuration also exists in some building occupancies. The most emblematic example of this configuration is the nuclear power plant, where staff may be in relative danger in case of a fire but have to remain within the plant in order to maintain the nuclear core within a safety range.

3.4 Practical treatment of disruptive events affecting the performance of "building-occupant" systems

Within my "building-occupant" system paradigm, I established a risk-informed performance-based process which could be applied to quantify the effects of any type of disruptive events affecting the overall performance of a specific system.

At the initial step of the process illustrated in Fig. 3-10, the stakeholders of a considered "building-occupant" system clearly indicate the nature and the characteristics of the system in terms of "chronic" objectives. This step is essential as it specifies the parameters of the "building-occupant" system to be examined in terms of building components, occupants and functional/support zones used by the system in order to achieve the "chronic" objectives.

This initial step is also a "political" step of the risk-informed performance-based process as the system stakeholders need to come to an agreement on the system main goals and decide whether the system will possess specific building attributes such as an atrium or a high rise configuration.

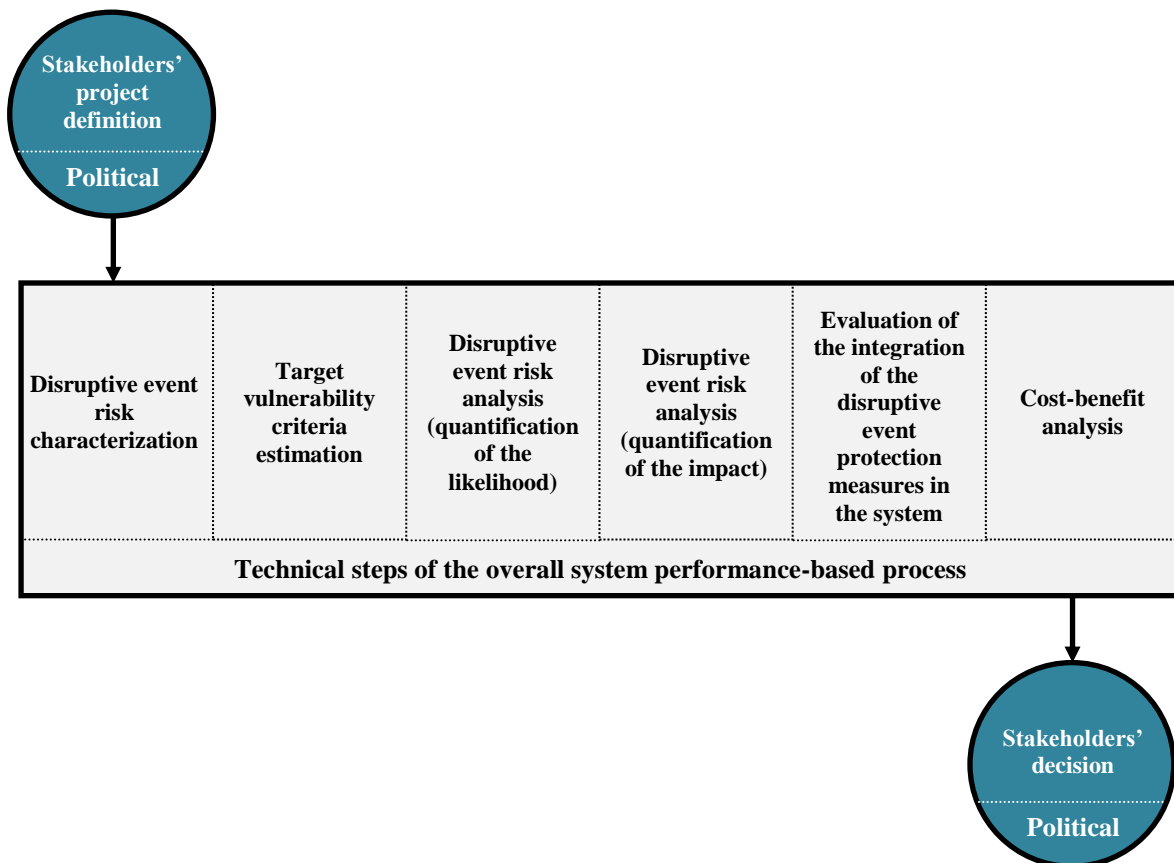


Fig. 3-10. Political and technical steps of the system specific risk-informed performance-based process

All the information gathered by the stakeholders is then transmitted to the engineer in charge of evaluating the impact of a certain type of disruptive event on the overall performance of the system: FPEs to deal with fires, structural engineers for earthquakes, etc. Since the system targets are the components which contribute to the overall performance of the "building-occupant" system, it is imperative that the stakeholders list in this step of the process all the system targets so that the engineer take them into consideration while performing the technical steps of the process.

At this point, the corresponding engineer carries out the "technical" part of the process, which mainly consists of a target oriented risk analysis, by performing the steps as follows:

- selecting risk acceptance metrics that are representative of the considered system in relation to the stakeholders' listed targets during the chronic use of the building. The aim of the "risk characterization" step is to correlate the likelihood of the disruptive events which occur during chronic operation with vulnerability criteria for each of the listed target (e.g. assessing how often the disruptive event causes injuries or casualties when the target is the building occupant, based on statistics and past events) - Step 1;
- quantifying the vulnerability criteria for each target in case of the disruptive event (e.g. evaluating the mechanisms by which the disruptive event can have direct and indirect effects on each listed target while taking into consideration the capacity/incapacity of the target to absorb the damage from the disruptive event and still be functional/loses its functionality) - Step 2;
- carrying out a risk analysis of the effects of the disruptive event on the overall performance of the system, via the characterization of both the likelihood - Step 3 and the impact - Step 4 of the disruptive event on each of the listed targets;
- evaluating the integration of the protection measures against the disruptive event, analyzed in the risk analysis, so to verify that these measures, once installed, would not be ignored or misused by the system end users - Step 5;
- performing a cost-benefit analysis of the protection measures against the disruptive event, analyzed in the risk analysis - Step 6.

At the end of the technical steps of the performance-based process, the engineer dealing with a certain type of disruptive event will transmit three important documents (or three components of a consolidated document) back to the system stakeholders:

- one document containing the results of the disruptive event risk analysis (from technical Step 3 and Step 4) including a risk matrix or risk curves and explaining how the engineer's proposed protection measures reduce the risk of the disruptive event affecting the performance of the studied system,

- one document describing the possible interactions of the protection measures designed by the engineer against the disruptive event and the other components of the studied system,
- one document estimating the costs and the benefits to install and maintain the proposed protection measures.

Based on the results of the technical steps of the system performance-based process, the stakeholders finally decide on the set of protection measures they want to be installed in the system, knowing how well these protections would help the system to mitigate the impact of the disruptive events on the performance of the "building-occupant" system in its chronic state, how well these protections would be integrated in the system and how much they would cost to install and maintain.

In case the performance-based process is simultaneously conducted on several disruptive events, the different engineers involved in proposing protection measures against their respective disruptive events have to generate a common additional document since it is important to verify that all their additional protection measures are not counterproductive (Fig. 3-11). It should be noted that the initial political step is identical for the stakeholders as they only need to provide once, in their own terms, the specifics of their "building-occupant" system. The "translation", in terms of solving the right problem for each disruptive event, is made by the corresponding engineer in the technical step related to risk characterization.

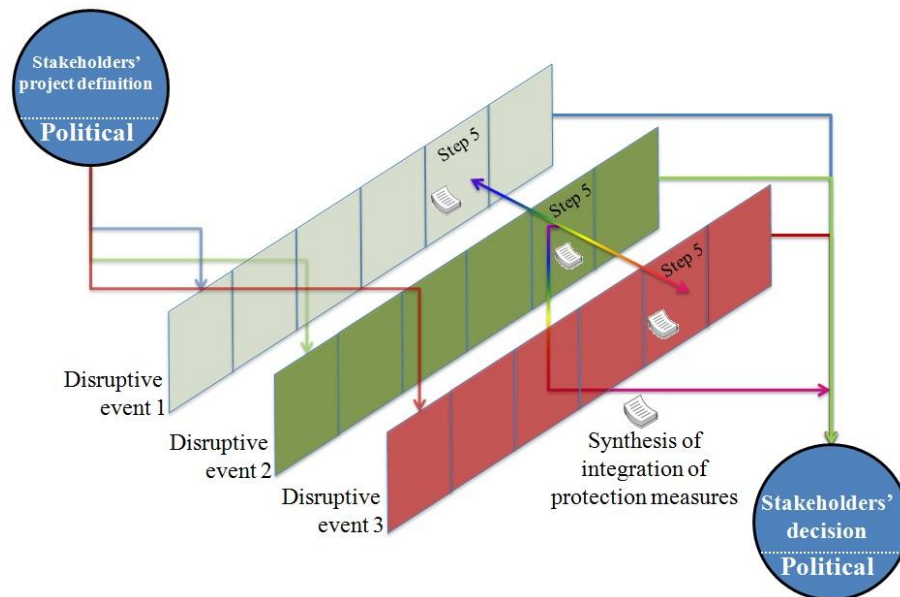


Fig. 3-11. Practical treatment of multiple disruptive events

3.5 *Conclusions of this chapter*

Designing a building project is a complex enterprise involving project stakeholders who are the main drivers of the project concept and professional groups who are the main drivers of the actual realization of the project. In addition to this complexity, differences arise between the building project at its design phase and when the building is actually exploited by its end users.

The performance of a building depends on the interrelations between the different components of the building which are separately designed by specific engineers, having their own objectives to fulfill, so the final integration of all the building components may not be optimal. When these components concern disruptive events, i.e. events affecting the daily performance of the building such as fires, it was found that the end users might misuse or ignore the protection measures against the disruptive events, because these measures were not integrated well enough by the end users.

This chapter presented the outcomes of research carried out in order to:

- define a paradigm of study organized around systems formed by specific building types and their associated occupants so to clearly determine how hazardous disruptive events such as fires affect these system daily performance,
- introduce a corresponding system specific risk-informed performance-based design process, which could take into consideration the complexity of such systems and their evolution during disruptive events.

References

1. Zalejska-Jonsson A. Evaluation of low-energy and conventional residential buildings from occupants' perspective. *Building and Environment* 58 (2012) 135-144
2. International Council for Research and Innovation in Buildings and Construction. Performance Criteria of Buildings for Health and Comfort. Report CIB number 292, prepared by ISIAZ-CIB Task Group TG 42. 2004
3. SFPE Engineering guide to Performance-Based Fire Protection - Second Edition, 2007
4. SEAOC, Performance-Based Seismic Engineering of Buildings, Volume I, Structural Engineers Association of California, April 3, 1995
5. Ornstein SW *et al.* Performance evaluation of a psychiatric facility in Sao Paulo. *Facilities* 27, 3/4 (2008) 152-167
6. Spekkink D. Performance Based Design of Buildings - PeBBu Domain 3 - Final Domain Report - Performance Based Building Network (PeBBu) October 2005 (available at: http://www.pebbu.nl/resources/allreports/downloads/07_D3_FinalReport.pdf, checked 10/31/2012)
7. Sheffi Y. *The Resilient Enterprise*, Massachusetts Institute of Technology Press. 2005

8. Knight RF and Pretty DJ. The Impact of Catastrophes on Shareholder Value, The Oxford Executive Research Briefings. Templeton College, University of Oxford, England
9. International Code Council (ICC) International Building Code, 2012
10. Lataille JI. Factors in Performance-Based Design of Facility Fire Protection. Fire Protection Engineering, 2nd quarter 2008, Society of Fire Protection Engineers, 2008 (available at: <http://magazine.sfpe.org/fire-protection-design/factors-performance-based-design-facility-fire-protection>, checked 10/31/2012)
11. International Code Council (ICC) Performance Code, 2012
12. US Department of Commerce, Bureau of Census, North American Industry Classification System (NAICS) Definitions. 2007 (available at: http://www.census.gov/eos/www/naics/2007NAICS/2007_Definition_File.pdf, checked 10/31/2012)
13. Scott D. Fire in an operating Theatre – What really Happened? – A Case Study of a Fire in a Private Hospital in Hamilton, New Zealand. Proceedings of the 4th International Symposium on Human Behaviour in Fire 2009, pp. 313-322
14. (ABCB) Australian Building Codes Board. International Fire Engineering Guidelines, 2005 edition
15. Richardson R. Florence Nightingale and hospital design. King's College, London. 2010 (available at: <http://www.kingscollections.org/exhibitions/specialcollections/nightingale-and-hospital-design/florence-nightingale-and-hospital-design>, checked 10/31/2012)
16. Tolley M. Institutional Buildings, the Built Environment – Public Spaces. 2011 (available at: <http://martintolley.com/environment/BuiltEnv2EnvPsy6.html>, checked 10/31/2012)
17. Alvarez A. and Meacham B.J., Towards an Integrated Performance-Based Design Approach for Life Safety Across Different Building Use Groups, in: Proceedings of the 12th International Interflam Conference, Nottingham, UK, 2010
18. Wærp S. and Holthe K. Turnover Rate and Environmental Load for Building Materials – Checkpoints in Design Process. CIB14251, SINTEF. 2009 (available at: <http://www.sintef.info/upload/Byggforsk/Bibliotek/Publikasjonsdatabasen/CIB14251.pdf>, checked 10/31/2012)
19. Spearpoint M and MacLennan HA. The effect of an ageing and less fit population on the ability of people to egress buildings. Safety Science, vol. 50, issue 8, 1675-1684, October 2012
20. (NFPA) National Fire Protection Association. NFPA 101 Life Safety Code® Handbook, eleventh edition, edited by R. Coté and G. E. Harrington, NFPA, pp.667-669. 2009
21. Flynn J.D. Structure Fires in Medical, Mental Health, and Substance Abuse Facilities, February 2009, National Fire Protection Association. 2009
22. (NFPA) National Fire Protection Association. NFPA 101 Life Safety Code® 2009 edition, NFPA. 2009
23. O'Connor D.J. Health care occupancies, chapter 15, section 20 of the 20th edition of the Fire Protection Handbook, National Fire Protection Association, 2008
24. Kobes M. et al. Way finding during fire evacuation; an analysis of unannounced fire drills in a hotel at night. Building and Environment 45 (2010) 537-548
25. Comeau E. and Puchovsky M. NFPA Fire investigation report, Warehouse fire, New Orleans, Louisiana, March 21, 1996, National Fire Protection Association. 1996

4. A FRAMEWORK FOR RISK-INFORMED PERFORMANCE-BASED FIRE PROTECTION DESIGN FOR THE BUILT ENVIRONMENT

Twenty years of experience with performance-based fire protection design (PBFDP) was reviewed and I determined that shortcomings and challenges still need to be addressed in order to expand the application of PBFDP processes as an option to the prescriptive requirements imposed by building regulations (cf. Chapter 2 of this dissertation). Existing guidance related to these processes has been found to be too generic, meaning that fire protection engineers (FPEs) are required to significantly expand upon the information provided by this guidance when applying it to their specific projects resulting in wide variation in practice. Furthermore, the application of these processes requires the agreement by all of the involved stakeholders regarding key elements of these processes, such as the definition of the performance criteria and the selection of the fire design scenarios against which the trial designs would be evaluated: issues upon which stakeholders have to expertise.

Given these findings, I conducted research aimed to ultimately lead to the establishment of more specific guidance for PBFDP, which provides more specific technical guidance and which incorporates a new process separating the ‘political’ decisions taken by the stakeholders from the ‘technical’ analysis to be performed by the FPEs.

One important initial finding of my research was that the generic characteristics of the current PBFDP processes could be attenuated when establishing guidance for specific building use groups and for specific objectives (e.g. life safety, business continuity, heritage preservation) [1].

In addition, my research indicated that current PBFDP processes are, on one hand too fire focused, and on the other hand too centered on the design of fire protection measures, leading to the possibility that fire protection measures deemed appropriate at the time of design might not be the most appropriate when implemented in a building, as key aspects of the fire protection design might be ignored or worse "rejected" by the occupants of the building when needed the most, since fire is not a daily concern [1].

A risk informed performance-based design process was then established in order to assess the overall performance of systems formed by specific building types and their associated occupants in case of disruptive events, such as fire, natural hazards, and economic crisis, affecting these systems (cf. Chapter 3 of this dissertation).

This chapter presents the application of this system specific risk-informed performance-based design process for the treatment of fire events, and how it differs from the current PBFDP processes, notably by providing a level of detail that is lacking in current PBFDP processes and by clearly separating the political steps from the technical ones, leaving the FPEs with a straightforward independent technical part.

I estimate that a successful implementation of the new system performance-based design process for the treatment of fire events will require acceptance, by the FPE community and the involved stakeholders, of the need for a paradigm shift from one in which fire is the center of the problem to one in which building performance metrics are evaluated in the case of fire events.

4.1 Challenges of the current PBFPD processes: the need to be more specific

It was found that there are complications with respect to application of the current PBFPD approaches from a regulatory perspective. While existing PBFPD approaches focus on fire and fire systems, they are very generic in how they do so, not specifying what scenarios to consider, how to characterize design fire, for which occupant attributes, and so forth. To a certain extent, such flexibility was targeted due to (a) the wide range of building considerations for which the PBFPD approach might be used, and (b) because specifics of design fires and acceptance criteria can be considered public policy decisions, not engineering decisions, as they help define tolerable levels of performance or risk. While such flexibility works well for engineers, it did not sit well with regulatory officials, since there was no clear way to determine 'good' designs. As a result, wide variation existed in developed designs, and in order to lessen the variation, some countries have now moved to 'prescribe' certain performance factors, such as scenarios, fires and criteria. While this is in some ways helpful, it also misses aspects of importance that need to be addressed. However, it helps highlight the need to separate 'political' decisions from 'technical' ones.

There are many more challenges for fire protection engineers created by the current PBFPD processes being too generic, which have been identified and detailed in Chapter 2 of this dissertation. For the purpose of this chapter, they can be characterized as:

1. Applying generic guidance to specific projects, often times lacking the detail necessary for comprehensive analyses, which may result in important fire performance concerns being missed.
2. Defining, using and quantifying the performance/acceptance criteria, which should be determined by policy makers and decision makers (AHJs), not by the FPEs.
3. Selecting fire design scenarios to test fire protection systems rather than to test building fire safety performance.
4. Comparing the levels of performance between an engineering solution and the one based on prescriptive requirements without have a good basis of comparison.
5. Having insufficient guidance to determine the most influential factors affecting the evaluation of trial designs.
6. Assuming "idealized" performance of fire protection measures (i.e., condition at time of design, omitting users) as compared with "real life" performance of installed measures over time, as impacted by occupant, and as otherwise impacted,

7. Estimating the consequences of fire design scenarios on building performance without having the whole performance picture adequately defined.
8. Resorting to adapting literature values, when available, to use in models, rather than being forced to demonstrate the values are appropriate and/or utilize appropriate values.

As intimated in (2) above, there has to be a clear understanding of both technical and political issues, as several decisions in the PBFPD process are dependent on policy makers and decision makers (e.g., performance criteria and design fire scenarios have to be agreed upon by the considered stakeholders before the fire protection engineer can really start the technical part of the process). As such, it would be extremely beneficial for the PBFPD process to clearly delineate 'political' (joint) decisions from 'technical' ones, making the engineering tasks more straightforward to address.

4.2 Shifting the paradigm: studying how a global system formed by a building and its occupants reacts when a fire can occur

While the "fire protection systems" approach makes sense in retrospect, given the somewhat uncoordinated development of the PBFPD idea, process, tools for analysis, data and so forth, it meant that fire in the context of overall building performance has not necessarily been analyzed sufficiently. When I investigated building fire protection designs that were developed using this approach, I found that FPEs only consider the characteristics of a building and of its occupants only into the PBFPD process as parameters of the fire design scenarios and in the development and evaluation of fire protection measures. This consideration taking place during the design phase of a building project led to a "disconnect" between the fire protection components and the context of the building in use: FPEs expected that the fire protection measures would be correctly designed and maintained so they would operate as intended, as an independent component of the system formed by the building and its occupants. Unfortunately, this was found not to be the case. In numerous instances, investigation reports of fire events reflected how the interaction between the building, fire and occupants influence each other during events. For example, a warehouse which suffered small damage after a first fire controlled by an automatic sprinkler system was completely destroyed by a second fire some hours later as the sprinkler system was shut off due to some water damage caused by the opening of numerous sprinkler heads throughout the warehouse [2].

The photographs below (Fig. 4-1) were taken in a conference center. One fire exit sign is practically hidden behind the black signage. Even if delegates find the fire exit sign, they would probably use the double door to a conference room (that they probably use to go during the conference), instead of getting through the fire exit door located at the right end of the corridor, almost hidden by the blue panel.



a) view from a corridor of a conference center



b) Fire exit door in the corridor side, mostly hidden by the blue panel and "competing" with the usual delegate path to go through the double door to a conference room

Fig. 4-1. Fire exit way finding problematic in a conference center

These illustrative examples made us consider that the study of the fire protection measures (technical systems and managerial procedures) could not be done without considering the system they are installed in. Indeed, on one hand, these measures involve the building occupants (during the evacuation process) for whom fire is a "disruptive" event during the otherwise normal building use. On the other hand, they are not completely independent from the other building parts as they deal with a lot of common space (e.g., rooms delimited by doors, corridors, atrium).

As a result, I needed to define a global system in which fire protection measures would be one component, among many, and then verify how shifting the paradigm of study to this system would prevent the fire protection component from being ignored (conference center example) or even worse rejected (warehouse example) by the occupants of the building when a fire occurs.

In addition, it should be noted that researchers have only recently started to incorporate building interior design in their models due to the complexity of simulating these details, as well as the needed time and resources to run the corresponding simulations. For example, Stern-Gottfried and Rein [3] looked at how building interior design influences fire spread in large, open-plan compartments while Oven and Cakici [4] examined how this building

interior design influences the evacuation process during emergencies, as obstacles increase travel distances and create bottlenecks. Thus, fire researchers also realize the effects of the building use on the fire and the fire evacuation process and are developing tools to assess these effects. Back on the engineering side, by shifting the paradigm, I estimate that FPEs will incorporate the results of the fundamental fire research more easily and more quickly into their safety analyses.

4.3 Application of the system performance-based process to fire disruptive events: Creating a new PBFPD process

One challenge previously identified in this dissertation concerns the relationship between the technical aspect and the political aspect of the current PBFPD processes. By shifting the current fire centered paradigm associated with these processes to a paradigm centered on the study of a "building-occupant" system, the performance of the system can be assessed when this system is affected by any kind of disruptive events (technological hazard, natural hazard, economical hazard...) as presented in Chapter 3 of this dissertation.

In my "building-occupant" system paradigm, I defined several key concepts in the previous chapter. These concepts are summarized as follows:

"Targets" are the system agents responsible for the system daily performance (building occupants and components). During normal every day conditions or "*chronic states of the system*", they are located in "*functional zones*" where they carry out their activities associated with "*chronic objectives*", established in accordance with the system scope and performance. "*Utility zones*" include system support components such as electricity, HVAC and plumbing. "*Disruptive events*", such as fires, have to be considered between two consecutive "*chronic states*". In order to mitigate the "*event effects*" on the system performance, "*acute objectives*" have to be set up so to take into consideration "direct effects" and "indirect effects" with which the disruptive events can possibly damage the targets.

Detailed information about the "building-occupant" system paradigm and the system performance-based process are presented in the previous chapter of this dissertation. The application of this process to a fire disruptive event is presented in Fig. 4-2. Each step of the process will be explained in the subsequent parts of this chapter.

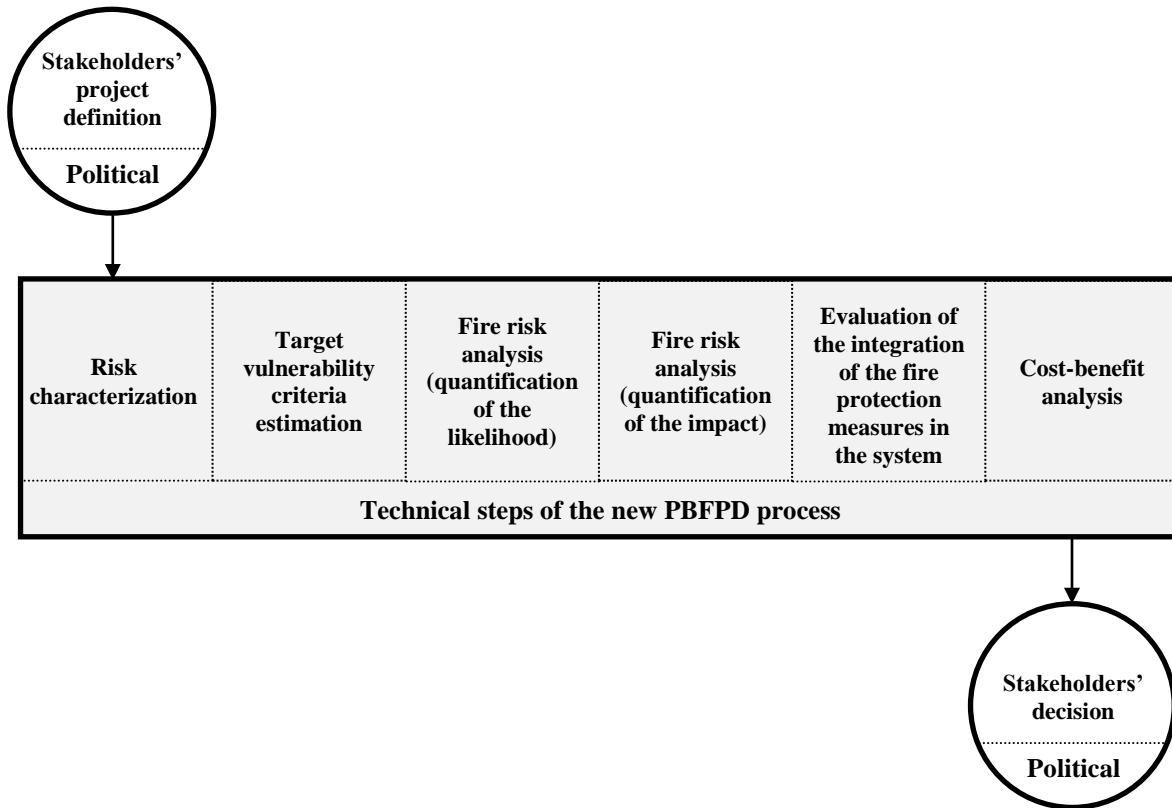


Fig. 4-2. Application of the system performance-based process to a fire disruptive event

The following section shows how the system performance-based process is applied in the case of the disruptive events being fires and how different this new PBFPD process is from the current ones.

4.3.1 The new PBFPD process is a target oriented process within the "building-occupant" system paradigm

The new process separates the political aspect from the technical one, concentrating the political aspect at the very start and the very end of the PBFPD process, leaving the technical aspect clearly within the realm of the FPE. Again, the political process includes regulated issues as well as stakeholder decisions. The principle of this separation is illustrated in Fig. 4-2.

- At the start of the PBFPD process, the stakeholders define the project and present all of the characteristics of the "building-occupant" system to be examined: building parameters, occupant parameters and functional/support zones used every day by the system. The stakeholders still have to agree on the main goals and objectives related to the considered "building-occupant" system and precisely what specific building attributes are of concern (e.g., atrium, high rise configuration...). These are considered political aspects of the problem, as decisions are required by others than the FPE alone. Once decided, all of this

information is transmitted to the FPE who starts the technical aspect of the PBFPD process by selecting risk acceptance metrics that corresponds to the considered project;

- After performing the technical steps of the PBFPD process, the fire protection engineer will give three important documents back to the stakeholders:
 - one document containing the results of the fire risk analysis (from Step 3 and Step 4) including a risk matrix or fire risk curves and how the selected fire protection measures reduce the fire risk for the studied system,
 - one document describing the possible interactions of the fire protection measures and the other components of the considered "building-occupant" system,
 - one document estimating the costs and the benefits of installing and maintain the proposed fire protection measures.
- based on the three documents provided by the FPEs, the stakeholders have all the information they need to take their decision regarding the fire protection measures they want in the studied "building-occupant" system, knowing how the overall performance of the system would be affected by fire events. This again is a "political" issue, as I consider that it is only the responsibility of the stakeholders to select the fire protection measures they will have installed in their systems in association with the loss of system performance that they ultimately accept for their system in the case of fire events.

It should be noted that some feedback is possible between the first technical task of the PBFPD process (risk characterization) and the stakeholders' description of the system, as at the beginning of a completely new project all the design features may not be available or finally set up, so changes that would influence the PBFPD may occur at that stage, implying some information feedback between the stakeholders and the FPE. Feedback is also considered concerning the risk characterization in the case the stakeholders have an idea of the level of risk they agree to accept. If it is so, this information is also gathered by the FPE as it will help him/her to design acceptable trial designs. More concerning this feedback process is presented in section 4.4 of this chapter.

It should be understood that the new PBFPD process is applied to specific "building-occupant" systems and not in a generic way which could be applied to every kind of project. In consequence, the guidelines that the FPEs use for a specific project are established for the type of "building-occupant" system the considered project is categorized into. This means that in order to apply the technical steps of the new PBFPD process (Fig. 4-3), specific guidelines for each of its six steps have to be written for specific and well defined "building-occupant" systems.

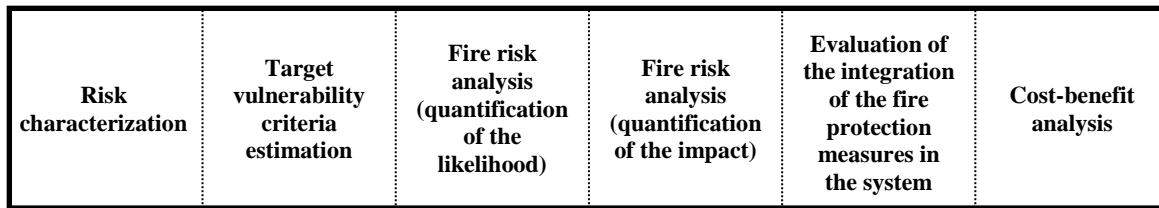


Fig. 4-3. Steps to be performed in the technical aspect of the proposed PBFPD process

Risk characterization is about translating the fire safety engineering problem from a stakeholders' perspective to a FPE perspective and to verify that the FPE has considered all the targets and define risk metrics relevant to the different targets of the studied system. In the "building-occupant" system paradigm, the problems FPEs have to solve are related to the characterization of the impact (in terms of occurrence and intensity) the targets are affected with, in case of fire events.

Then, for each considered targets, the FPE has to quantify how these targets are affected by direct and indirect effects of fire events, events involving a fire and defined between two "chronic" states of the system.

Fire risk analysis has then to be conducted in order to characterize the likelihood and the consequences of fire events on the targets. The FPE work is then to propose fire protection measures in order to minimize the occurrence of the damaging fires and mitigate the impact of these fire events on the system performance (i.e. the consequences of the fires events affecting system targets).

The next step of the technical process is then to evaluate how the fire protection measures analyzed in the fire risk analysis would be integrated into the studied system, in other terms, if they are going to be compatible with the components which are used on an everyday basis so they are not counter-productive and therefore ignored or worse rejected by the system. This step goes beyond the documentation on how the fire protection measures are designed, installed and maintained in the current PBFPD processes.

The last step of the technical process is for the FPE to perform a cost benefit analysis of the fire protection measures established during the fire risk analysis.

4.3.2 Comparison with the current PBFPD processes

When examining the portion of the PBFPD process established for example by the Society of Fire Protection Engineers [5] presented in Fig. 4-4, one can realize that the influence of the stakeholders remains important all along the process, while establishing the design brief, that is to say even before the fire protection engineer looks for solution with defining and evaluating trial designs.

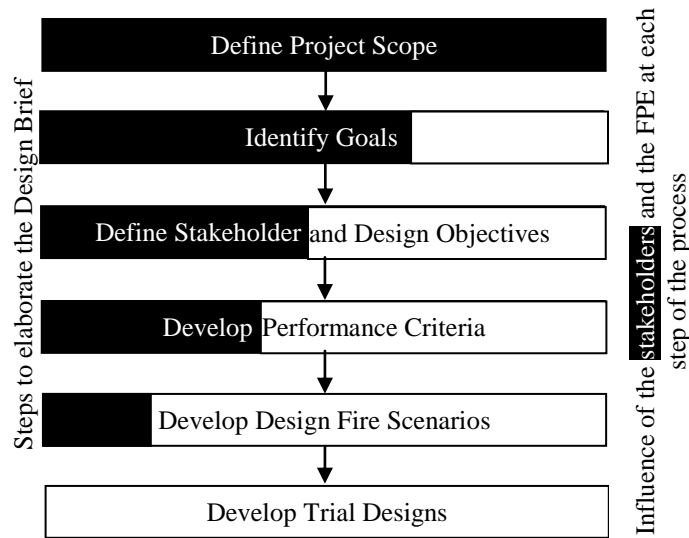


Fig. 4-4. Relative influence of the stakeholders and the fire protection engineer in the different steps of the elaboration of the design brief according to SFPE guide [5]

In conclusion, I estimate that the new PBFPD process allows a clear separation between the political aspect and the technical aspect of the process, which will bring the benefits for:

- the stakeholders who will only define the context of their considered system, in terms of their expected performance for the system to withstand fire events, and who will consider at the end of the process the different options proposed by the FPE based on a fire risk analysis, the evaluation of the integration of the fire protection measures into the system and their associated costs and benefits,
- the fire protection engineer who, after getting all the characteristics of the problem to solve, will conduct an independent straightforward engineering analysis and propose his solutions for the stakeholders to finally decide.

At the end of the new PBFPD process, a political decision is taken by the stakeholders based upon a technical analysis by the FPE, including results from a fire risk analysis describing how often and deep fire events would degrade the overall performance of the system, a document showing how the selected fire protection measures would be integrated into the system and a corresponding cost-benefit analysis of these measures.

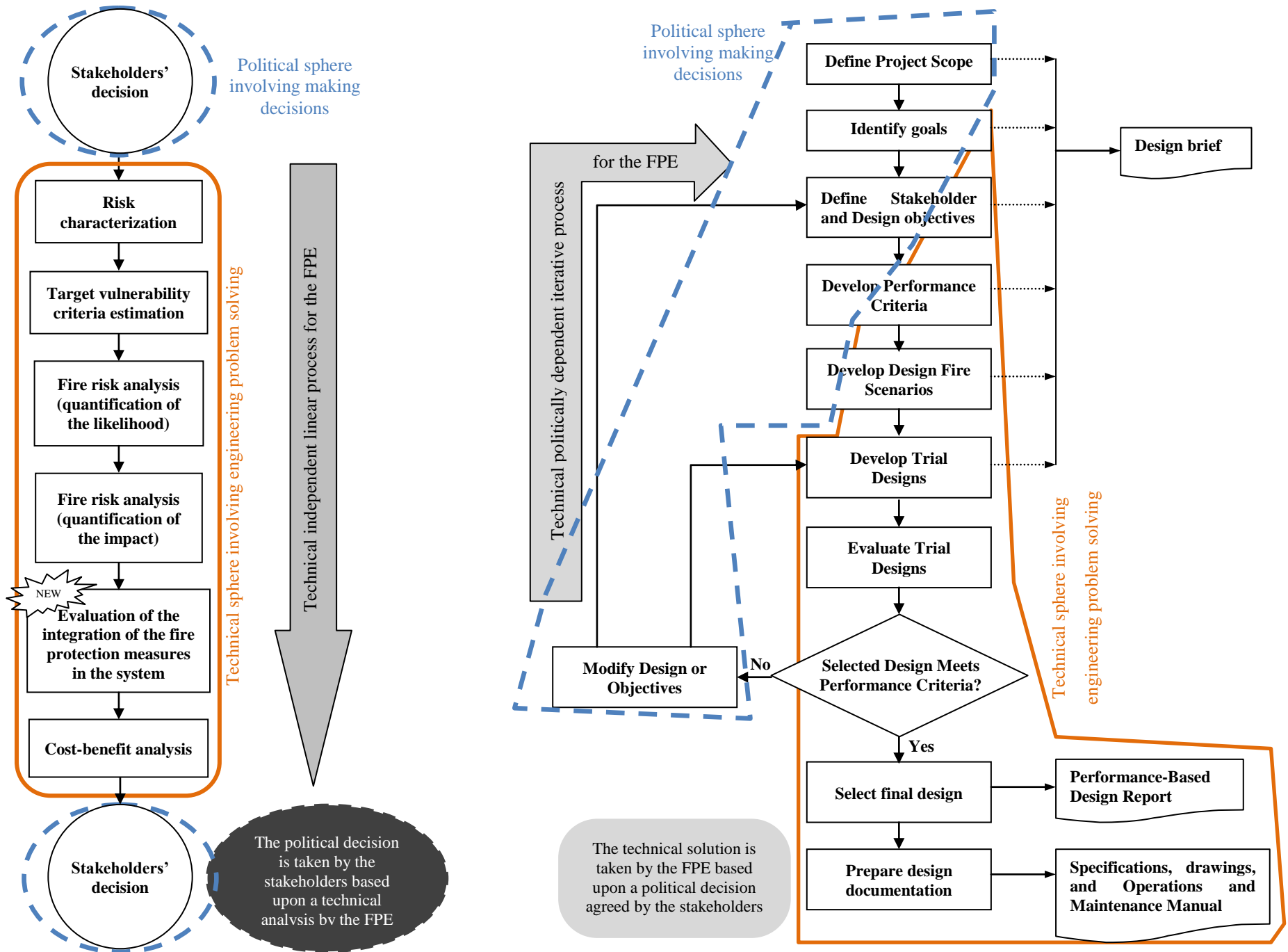


Fig. 4-5. Comparison between the new PBFPD process and the PBFPD process established by SFPE [5]

As a consequence of shifting the paradigm from one which is centered on the fire and the fire protection measures to one which describes in details the "building-occupant" system and evaluates its performance, a new PBFPD process has been developed and the main differences between this new process and the current ones are illustrated in Fig. 4-5. The main difference can be summarized by the end products of these two different processes:

4.4 Proof of concept of the New PBFPD process: closing "Iteration Zero" (verification of the usability of the process)

Now that I have shifted the paradigm from the study of the fire event itself (as in the current PBFPD process) to the study of the effects of fire as a disrupting event of a "building-occupant" system and developed a new PBFPD process to accommodate this new paradigm, this section presents the proof of concept for this process. This proof of concept constitutes "Iteration Zero" of a longer-term goal for the profession: establishment of detailed guidelines for each step of the process for all types of systems declared relevant to stakeholders.

Based on Fig. 4-2, the new PBFPD process is used as follows:

The different stakeholders define the characteristics of the project under consideration or review. Context about the use of the "building-occupant" system is detailed in order to assess the importance of this system inside a system network. Targets are defined by the stakeholders, as well as functional zones and other relevant information on how the system performs on a daily basis (interconnections between functional zones, utility systems, relations between building occupants and building systems...). Eventual contingency plans are given to the FPE. Metrics related to the goals and objectives agreed among the involved stakeholders are then defined in order to assess the proper parameters or targets of the system's performance.

At this stage of the PBFPD process, stakeholders may or may not have a preconceived estimation of their required levels of performance for the considered system. If not, the performance metrics characterizing each of their goals and objectives are used by the FPE to conduct the technical part of the PBFPD process. Fire risk curves or matrices are used to translate into the PBFPD process, the performance of the system to withstand fire threats, according to how often and how damaging these threats are. This is schematically illustrated in Fig. 4-6.

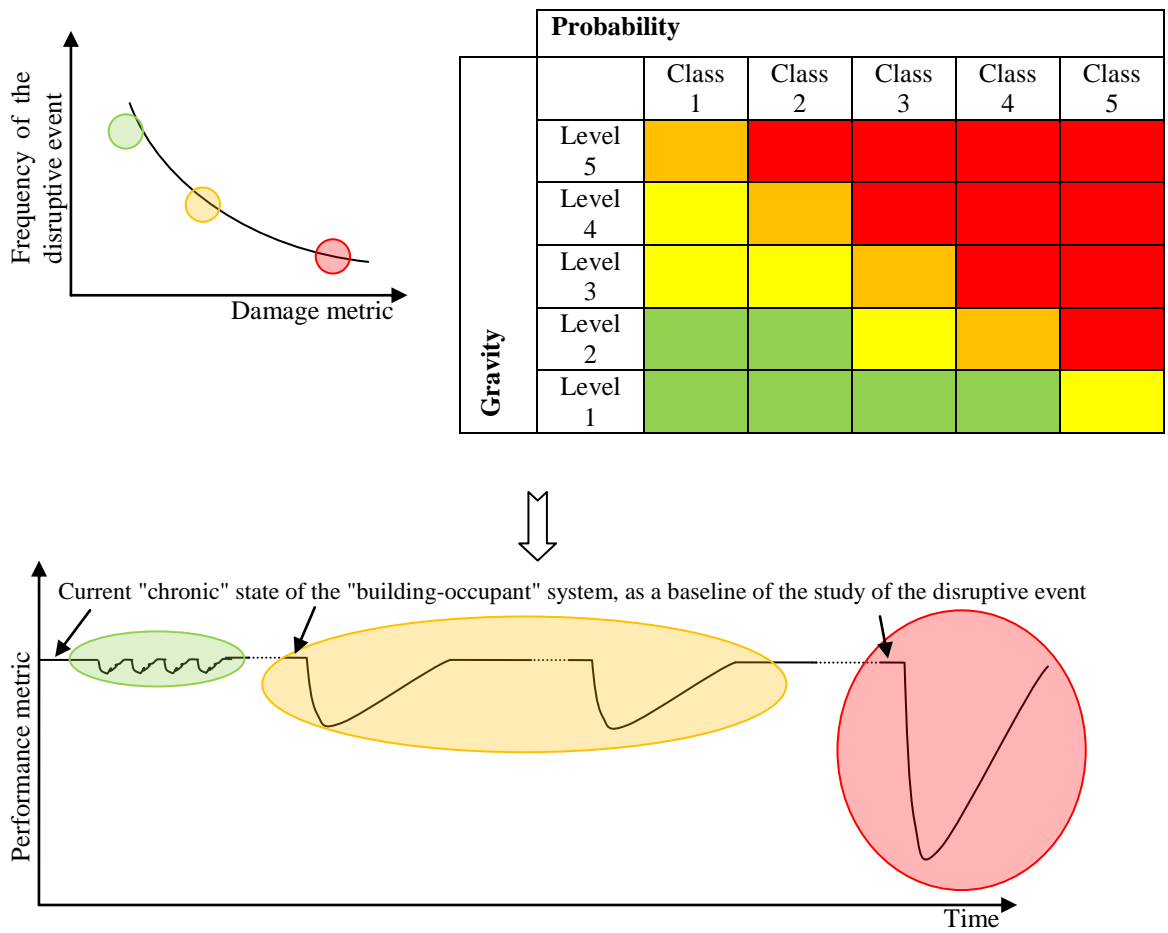


Fig. 4-6. Translation of fire risk characterization in the "building-occupant" system paradigm

Since the information related to the fire risk characterization is directly presented as fluctuations of the performance of the system, this information can be given back to the stakeholders who can then decide to clearly state their performance criteria, as illustrated, as an example, in Fig. 4-7. In this example, for a "frequent" disruptive event, the stakeholders allow the performance of the system to be less than the one defined in the risk characterization: in other terms, they allow more property loss or a longer recovery time, depending on the vulnerability metric. For a "less frequent" disruptive event, the stakeholders allow the performance of the system to decrease as the one defined in the risk characterization. For a "rare" disruptive event, the stakeholders do not allow the performance of the system to be less than the one defined in the risk characterization. Based on their performance requirements, a new fire risk curve can be constructed and fire disruptive events will then be assessed by their locations, in terms of (probability-consequences), relative to this new fire risk curve.

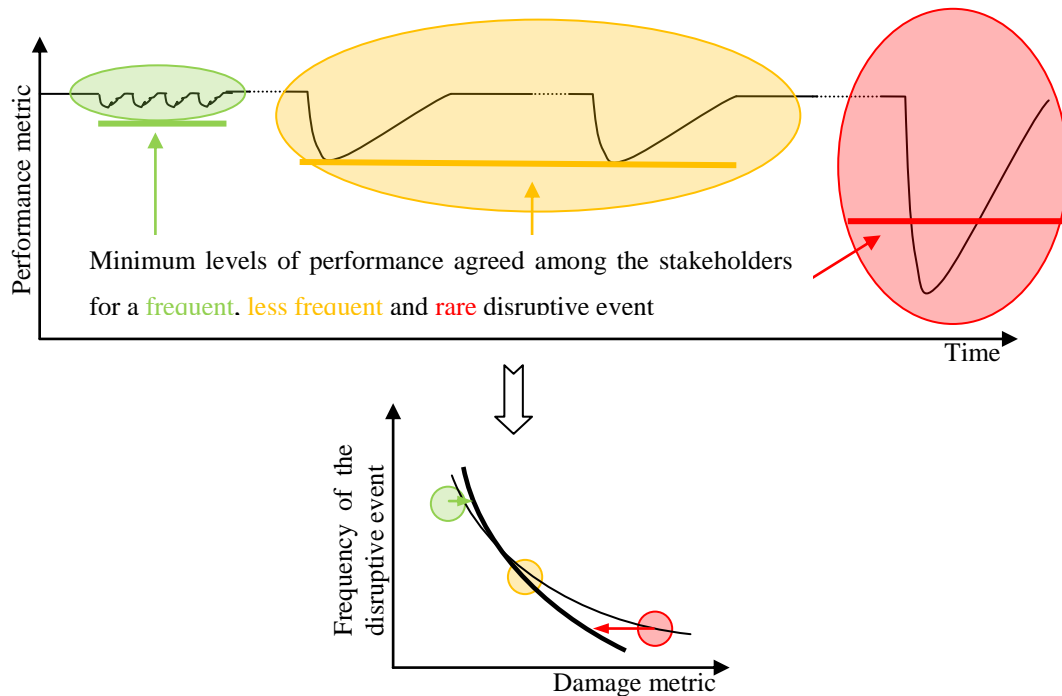


Fig. 4-7. Translation of the performance requirements of the "building-occupant" system as fire risk characterization

Targets vulnerability metrics are then gathered by the FPE, based on the targets' natures and characteristics.

Based on the description/information gathered about the system (functional zones, location and characteristics of targets...), the FPE performs the fire risk analysis. Event trees are used with zones containing targets and most probable fire ignition locations as initiation points of these trees. In conjunction, fault trees are used with "affected target" as final/top point, in order to capture the indirect threats to the considered targets. The aim of this PBFPD process step is for the FPE to cover fire events that are relevant to the performance of the system, that is to say the fire events that could affect the stakeholders' targets and to define fire protection measures or safety barriers to prevent these scenarios from occurring, with a frequency estimated on fire ignition frequencies and reliability of the considered fire protection measures. At the end of this process step, the benefits of the safety barriers, in terms of decreases of fire frequencies and consequences can be gathered in a synthetic form, as illustrated in Fig. 4-8.

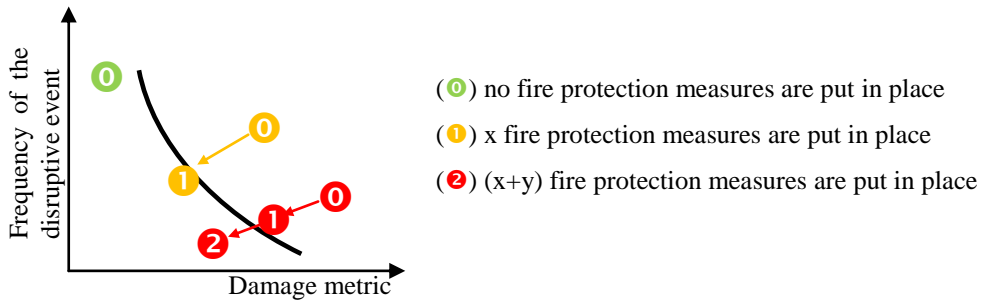


Fig. 4-8. Schematic representation of the risk reduction of scenarios of disruptive events

The next step of the proposed PBFDP process is performed to be sure that the inclusion of fire protection measures does not affect the performance of the other system components dedicated to achieve "chronic" objectives or other safety objectives. Not only is it verified that inclusion is not counterproductive for the daily performance of the system, in short term and in long term, but also that the safety barriers are maintained properly.

The final step of the technical part of the proposed PBFDP process is related to the cost-benefits of the fire protection measures.

At that point, the FPE delivers three important pieces of information to the stakeholders:

- The schematic representation of the risk reduction of scenarios with the different sets of fire safety barriers, as illustrated in Fig. 4-8, with a description of barriers and more details on the most "valuable" barriers, that is to say the ones which lower the fire risk the most,
- The means of verification that the fire safety barriers are not counterproductive for the level of performance of the analyzed system,
- The costs of the installation and maintenance of the different sets of fire safety barriers.

Based on that information, the stakeholders finally decide what fire protection measures to add as components of their system.

4.5 Closing "Iteration Zero" (demonstration of the ability to overcome the challenges encountered by the use of the current PBFPD processes)

Challenges that FPEs, code regulators and authorities having jurisdictions are facing when applying the current PBFPD processes are briefly listed in section 4.1 of this chapter and presented in detail in Chapter 2 of this dissertation. The following paragraphs are dedicated to demonstrate how the proposed PBFPD process overcomes these challenges.

The main challenge related to the application of generic guidelines has been addressed with the proposed elaboration of detailed guidelines designed for specific "building-occupant" systems and with the organization of "target oriented" risk analyses. Also, the challenge related to the intricacy of the technical and political aspects of the current PBFPD processes is overcome as presented in Fig. 4-2, and detailed in Section 4.3.2 of this chapter.

The following demonstration aims to illustrate, with real fire events or constructed ones, that the proposed PBFPD process is more suitable to deal with the specificities of a "building-occupant" system than the current ones and therefore it points out where the FPE really needs to focus his/her analysis, what information is needed, for what step of the process and why this information matters. This demonstration is organized according to the different steps of the proposed process. Each example is presented in three parts: the concern, how existing approaches fall short, and how my approach addresses the concern.

4.5.1 Risk acceptance characterization

Business continuity is often a FP goal but business recovery is not only dependant on the building that is analyzed but also on the network of buildings and industry it belongs to (cf. Chapter 3 of this dissertation), so establishing parameters of the performance of the analyzed building requires the FPE to look at not only how it operates by itself but also at how a disruptive event such a fire can decrease the performance level of the network. A "building-occupant" system is a dynamic one as its owner and users can constantly change during its life span, affecting how the system is used for, how it is managed and what level of performance is associated with it.

A generic PBFPD process is not as adaptable as a process which has been designed to take these changes into consideration as the analysis of the system is at the core of such an oriented process. The information related to the system is gathered at the start of the process, because the level of performance is a function of all these information, and the quantification of this level of performance is the "only" real engineering problem the FPE has to solve. Besides, the same information is needed across all the steps of the proposed process. In the current PBFPD processes, information and data are gathered more for the sake of running models than for

characterizing what the engineering problem is about. In other terms, the current PBFPD processes were elaborated by FPEs for FPEs, incorporating thought processes they were trained to have, which explained why the systems analysis they borrowed in the 1970's quickly focused only on fire protection components. This independent state of mind still results nowadays in frictions mainly between the FPE and the architect / building owner.

Since the proposed process is integrated into a global system analysis, I assume that its application would tend to attenuate these frictions, not only in the design phase but each time the building users modify the characteristics of the analyzed system. Thus, the proposed process will also manage the dynamic changes of the system as fire disruptive events are characterized with taking into consideration the current "chronic" state of the system, as illustrated in Fig. 4-6.

4.5.2 Target vulnerability criteria estimation

As discussed in Chapter 2 of this dissertation, the terminology "performance criteria" defined in the current PBFPD processes does not apply to the quantification of the overall performance of a "building-occupant" system, but it rather corresponds to target conditions when affected by the direct effects of a fire. For example, SFPE [5] indicates that "performance criteria generally take the form of damage indicators. It is not necessary that the means of preventing at this stage [i.e. when defining them], but a complete understanding of the acceptable limits of damage and injury must be well understood. If the engineer develops the performance criteria, the damage indicators utilized should come from technical documents and their selection should be thoroughly explained and documented for stakeholders". SFPE also indicates that "performance criteria might include temperature of materials, gas temperatures, smoke concentration or obscuration levels, carboxyhemoglobin (COHb) levels, and radiant flux levels".

In my "building-occupant" system paradigm described in details in Chapter 3 of this dissertation, these "performance criteria" are indeed related to the effects of a fire on a target but they only integrate the fire negative input on the targets. In other terms, they do not quantify how the target itself will respond to these fire effects (e.g. submitted to the same smoke environment, a bedridden patient after surgery would be endangered before a hospital staff member and before a fire fighter). My "target vulnerability criteria" integrate this response, as my process is dedicated to the variations of performance of the targets in the case of a fire event, not only during the fire itself until these targets recover and reach again a "chronic" state.

Let us consider people as targets. I found out that life safety criteria currently focus on direct fire effects. However, there are other issues. For life safety, the following criteria are not considered in current PBFPD processes: criteria related to stampede (e.g. Brooklyn theater fire on December 5, 1876, Iroquois theater (Chicago) fire on December 30, 1903, and the much more recent Uphaar Cinema fire, in India on June 13, 1997) or indirect damage (when people are connected to life supporting machines). Several criteria are absolute

values, with no notion of duration attached to it. When assessing the evacuation process, transitory states are not taken into consideration in the current approaches, as they do not detail the steps to perform a dynamic analysis of both the Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET). Loss of visibility may be transitory, in space (near the fire origin) or in time (until an eventual smoke management unit starts).

Because the proposed PBFPD process is target oriented, this specific step will include the most exhaustive and appropriate list of target vulnerability criteria required to perform the subsequent risk analysis. This is why the initial political step of my process is crucial as the stakeholders establish the list of targets (people, building content, etc) and describe how the activities of these targets contribute to the overall performance of the system.

4.5.3 Fire risk analysis (quantification of the likelihood)

It is intended that shifting the paradigm will also allow a more comprehensive and coherent definition of the performance of the "building-occupant" system among the stakeholders and the fire protection engineers. As a result, FPEs have to consider the fire problem inside this paradigm where the actors contributing to the performance of a system (building occupants and building components) have then to be the subject of a fire risk analysis as defined "targets" since fires affecting directly or indirectly these targets would diminish the overall performance of the system, which is the main concern of the stakeholders. It should be noted that "functional zones" and "utility zones" are concepts that are more accessible and understandable to the stakeholders than "fire zones" and "smoke compartments" that are centered about fire scenarios which are not a daily preoccupation of the building occupants. In order to fully grasp the impact of fire events and the benefits of implementing the system with fire protection measures, the FPEs need to communicate to the stakeholders with concepts that they are familiar with and verify that the FPE concepts integrate well with the stakeholders' ones.

As an example, Fig. 4-9. illustrates the differences of concepts between the "functional zones" in the "building-occupant" paradigm and the smoke compartments used by FPEs. In a), three functional zones have been established according to the system characteristics. Each functional zone contributes to the daily performance of the system. Without knowing this information, a FPE could design two different smoke compartments (in b)) according to the current PBFPD processes, resulting in affecting two or three functional zones in case of a fire spreading in Smoke Compartment 1 (SC1) or Smoke Compartment 2 (SC2) respectively (in c)). In terms of fire damage area, the consequences could concern up to the half of the system (in b). Nevertheless, in terms of performance for the system, up to three functional zones may be affected, potentially bringing the daily performance of the system to a zero. Shifting to the "building-occupant" system paradigm will allow the FPEs to better understand how the system operates in a daily basis and therefore establish fire protection measures to mitigate the effects of fire events on this daily performance, which is what the stakeholders are concerned about.

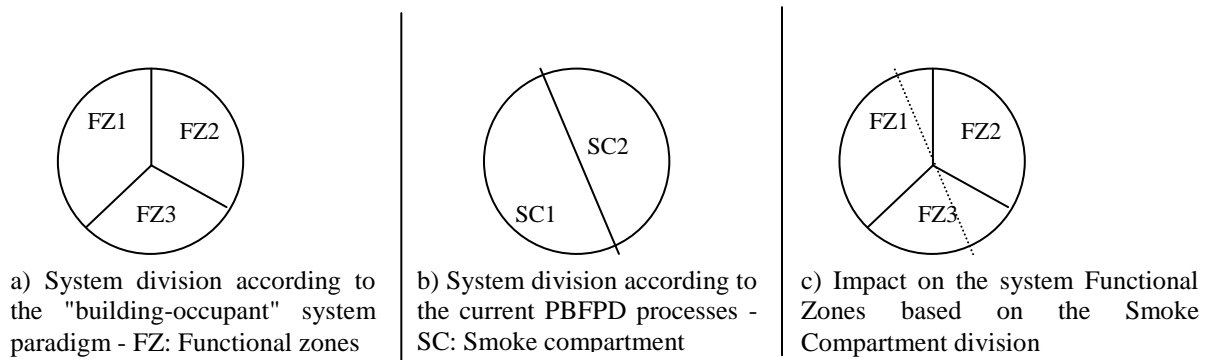


Fig. 4-9. Concept differences between the FPE current paradigm and the "building-occupant" system paradigm

As indicated above, targets are components of the system that contribute to the performance of the system. These targets can be affected by direct and indirect effects of a fire event. As an example, Fig. 4-10. illustrates the impact of the indirect effects of a fire on the overall system performance, focusing on how this indirect effect is not taken into consideration in the current PBFPD processes. Because shifting to the "building-occupant" system paradigm clearly shows the FPEs connections between utility zones and functional zones, the FPEs would be able to evaluate the indirect impact of a fire in an utility zone upon the overall performance of the system.

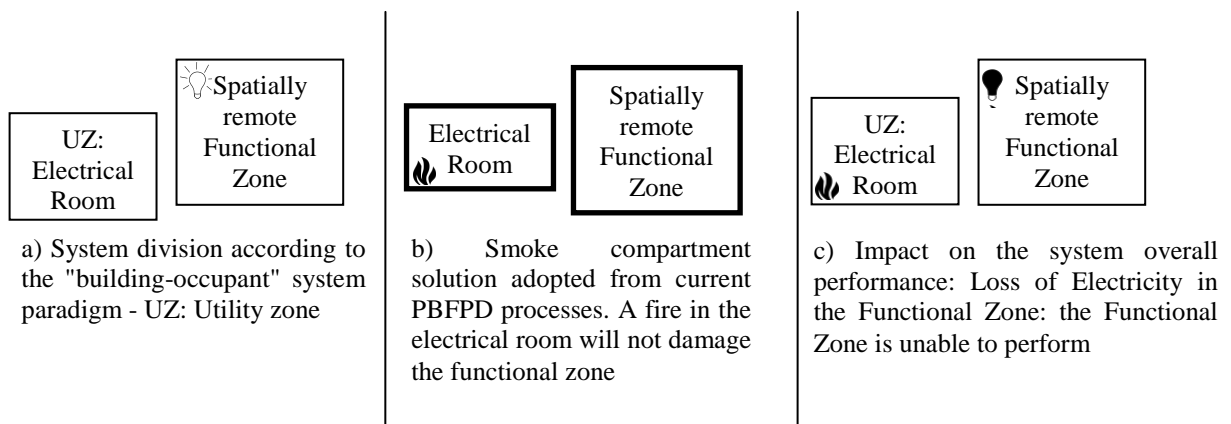


Fig. 4-10. Indirect effects of a fire upon the overall "building-occupant" system performance

The current PBFPD processes, being focused on the fire scenario, generally address fire "direct effects"; but are not describing how the "fire indirect effects" have to be analyzed and minimized. The new PBFPD process, being target-oriented, utilizes a fire risk analysis centered around the study of how often and how badly fire events can affect directly and indirectly the targets which contribute to the performance of the system.

Since the performance of a system is affected by potential damaging effects to the system targets, FPEs need to take these specifics into consideration when elaborating their fire strategy. The stakeholders are the ones who define the system targets when they elaborate the overall objective of their systems. Thus, it is essential that the stakeholders transfer the information related to the system targets as soon as possible to the FPEs, who can then design specific fire protection measures in order to minimize the fire impact on these targets, so ultimately the performance of the system is the least affected by fire events. No current PBFPD process indicates to a FPE the need to examine such a level of details or explains the reasons why this level is important because such processes are still too focused on the fire scenario itself instead of being target-oriented.

Fire protection measure reliability is not considered in the current PBFPD approaches based on a deterministic treatment of fire scenarios so that all the safety barriers are considered to be performing as designed. Exit signage is a typical example on how the efficiency of a fire protection feature varies from the design conceptual phase to the reality of the use in the system (Fig. 4-1).

In the proposed PBFPD process, target oriented scenarios are established with event trees and fault trees in order to determine all of the possible paths that can lead to a target being affected in the case of a fire disrupting the system. In the current PBFPD processes using a probabilistic approach, only event trees are considered as a technique to assess the likelihood of scenarios because these scenarios focus on the possible direct consequences of the fires themselves and how the fire protection measures would mitigate these consequences (e.g. appendix E titled "Risk Analysis" of the SFPE engineering 2.3 guide [5] or Section.2 of IFEG [6]). In some PBFPD processes, fault trees are also used but mainly to assess the conditions of fire ignition or the causes of failures of a fire protection measures. Still, they fail to assess indirect threat paths on targets.

Technical fire protection measures are always indicated in examples of event trees. Human actions are indicated as additional sources of fire detection (e.g. nurse detecting a fire in a patient ward) or fire suppression (e.g. staff using portable fire extinguishers and of course fire fighters controlling and extinguishing a fire). Besides, I assume that some of the human actions are also considered in fault trees related to fire ignition frequency (arson, poor maintenance of electric equipment, uncontrolled hot spot...). Nevertheless, I have not seen in event trees the impact of actions of humans leading to an aggravation of the consequences of fire scenarios. Maybe some of them are embedded in the fire parameters themselves, like an unauthorized use of fireworks, which is an important fire ignition source and which can potentially lead to a rapid fire spread. But what about "over capacitating of the system" as it was repeatedly observed in the aforementioned night club disasters? Indeed, this "human action" item is "controlled" by the regulation and needs enforcement but within the "building-occupant" system framework, it is clear that item has to be considered in the PBFPD process as it is a flagrant example on how a "chronic" objective of a night club owner related to profitability competes with fire safety objective. Less flagrant but worth noticing are similar incidences in department stores during sales or airports during holiday seasons or right after strikes.

Contrary to fire scenarios developed in the current PBFPD processes, the proposed process extend scenarios to take into consideration the period from fire extinguishment to the establishment of a new "chronic" state of the system, as explained in Chapter 3 of this dissertation.

4.5.4 Fire risk analysis (quantification of the impact)

4.5.4.1 *Quantification of impact vs. quantification of consequences*

As already indicated, fire scenario consequences are not limited to the extent of safe evacuation or direct fire damage, but they should include the effects of fighting the fire, including in term of monetary loss. Assessment of all impacts should be considered. For example, in open spaces, even if sprinkler heads locally activate, water tends to spread over a larger area than the area directly affected by the fire. As an example, at the Myrtle Beach Convention Center (USA), on October 12, 2011, a fire that started on a cherry picker lift in an exhibit hall activated sprinkler heads, which controlled the extent of fire spread. However, given the volume of smoke produced, a 2-hour effort by firefighters to remove the heavy smoke out of the exhibit hall was needed. Extensive damage to the machinery and water damage in the convention center were reported [7]. This example illustrates the concern that originates from the difference of perspective between the FPE who follows generic guidance to determine direct damages of the fire (e.g. sprinkler automatic system is adequate as the directly damaged area was small) and the building owner who is mainly interested in renting his convention center (e.g. water from sprinklers and smoke from the fire rendered useless a larger part of the convention center, which required cleaning before the overall damaged space was usable again). A more comprehensive and detailed example is presented in Chapter 3 of this dissertation, which clearly shows the dramatic aftermath of a cell phone company after a 10 minute fire.

The current PBFPD processes only deal with the direct consequences of a fire whereas the proposed process advocates for the quantification of fire impact of targets which contribute to the overall performance of a "building-occupant" system, evaluating direct and indirect fire effects as indicated in Section 4.5.2 and Section 4.5.3 of this chapter. Once again, the current PBFPD processes which are focused on fire scenarios, estimate direct fire effects between ignition and extinguishment, so they do not take into consideration the response of the different targets as well as the "recovery period" of the fire event.

As the proposed process is "target oriented", the FPE looks for this information which is essential for the study of the effects of fire events on the overall performance of a "building-occupant" system.

4.5.4.2 *Tools and data needed for the quantification of the impact of fire events*

Consequences on building occupants are often estimated via the (RSET / ASET) concept where RSET is the Required Safe Egress Time (i.e. time for building occupants to safely evacuate) and ASET is the Available Safe

Egress Time (i.e. time before untenable conditions appear). This concept is currently applied in too much of an independent manner: on the one hand, using fire effects models, the FPE estimates the time to reach untenable conditions. On the other hand, as a completely independent calculation, using egress models, the FPE estimates the time required for the building occupants to reach a place of safety. Emphasis is given on the "fire" estimation as FPEs are trained to do such estimations but uncertainties related to human behavior in fires are still nowadays quite significant to drive the validity of all the (RSET / ASET) estimation.

Not enough guidance on how human behavior affects the results of the evaluation of fire scenario consequences is contained in the current PBFPD guidelines and the current process framework advocates for more guidance, as well as a more dynamic integration of the two calculations (fire and evacuation) [8].

For this step, the proposed PBFPD process focuses FPEs on the "building-occupant" system, which requires integrated analysis to be conducted of the building-occupant-fire situation. In addition, the proposed process defines a framework for collaborative projects, called 'test bed' environments [9], developed to facilitate the determination of the most appropriate tools, data and methods for FPEs to apply in order to quantify fire impacts for specific "building-occupant" systems and for specific issues such as occupant evacuation, property protection or building structural response. In the future, guidance established during these projects in cooperation with stakeholders (including AHJs) would speed up the validation of the use of tools for their corresponding systems and issues, while decreasing the uncertainties due to the tool models, input data and tool user.

4.5.5 Integration of the fire protection measures into the "building-occupant" system

Since the current PBFPD processes consider the installation and the maintenance of fire protection measures after the stakeholders agree on them, the responsibility shifts from the designer (FPE) to the user (building owner and occupants) to maintain with time the operability and the efficiency of the fire protection measures.

The current process analyses the effects of integrating fire protection measures into the system in order to prevent these measures from being counterproductive or even "rejected" by the system. During the Pattaya Royal Resort hotel fire, June 11, 1997, emergency doors were locked by hotel operators to prevent customers from leaving without paying. This Code violation in conjunction with a lack of sprinkler system and no fire alarm heard by the survivors were the main causes of at least 78 casualties and at least 64 injured people. Also in Thailand, in 1993, a fire in a toy factory killed 188 people and police reported that factory supervisors had locked the exits to prevent workers from taking breaks [10]. Exits doors "locked in an effort to monitor employees and prevent theft" was also observed, among many other deficiencies in the Triangle Shirtwaist Fire that happened in a factory in New York, on March 25, 1911, (one century ago) killing 147 of the more than 500 employees [11].

Lack of code enforcement is also to blame partially in the fire that occurred in a chicken processing plant in Hamlet (North Carolina, USA) September 3, 1991, leading to 25 fatalities and 54 injured people. The plant had not been inspected during the 11-year operation of the plant, several doors leading to the outside were locked, and survivors indicated that there was no real organization in the plant's evacuation [12].

As an example of how some fire protection measures can be "rejected" by the system, Fig. 4-11. illustrates that competition between "chronic" objectives and fire safety ones does not go in favor of the latter one. The picture in Fig. 4-11. has been taken in an actual hotel, where a vestibule with two fire rating doors has been design to protect the single stairwell of the hotel from being invaded by smoke in case of a fire spreading in the corridor where the hotel rooms were located. The "chronic" objective is related to the ease of passage between the hotel rooms to the lobby via the stairwell. The objective clearly supersedes the objective to maintain an eventual smoke separation with the vestibule.

As mentioned in Section 4.2 of this chapter, current PBFPD processes consider fire protection measures as independent of the system in which they are installed. While these measures are required to be maintained according to design specifications, the current processes do not include a mechanism to verify how these measures would be perceived by the building occupant before and more dramatically when a fire occurs. In that perspective, FPEs design "independent" fire protection measures and they estimate that the system, in which these measures are installed and maintained according to their design, will conform to all these specifications (i.e. that the system will adapt by itself to these specifications).

This specific step of the proposed PBFPD process is aimed to avoid critical situations where the fire protection measures installed in a "building-occupant" system are ignored, or "rejected" by this system, potentially leading to a catastrophe in case of a fire occurring. The "chronic" use of the system needs to be addressed and as for the previous process steps, it relies on the stakeholders' input during the initial step of the process in terms of "competing objectives". For the example illustrated by Fig. 4-11, a FPE might suggest the use of a smoke vestibule as a smoke control feature, yet not thinking about how that system could be defeated by the daily use of the hotel patrons whose objective is to have an unobstructed path while carrying their luggage from their room to the lobby via the stairwell. In my approach, in the document related to this process step, the FPE would have to communicate to the hotel stakeholders how fire safety management would address this, and if not deemed reliable by the stakeholders according to their "chronic" objectives, propose another option.



Fig. 4-11. Blocked opened doors in a vestibule separating hotel room corridor from a stairwell in a hotel

4.5.6 Cost-Benefit analysis of the fire protection measures

Building owners usually want to spend an optimum of resources correlating the cost associated with fire protection measures and their benefits, according to the level of fire risk they are ready to accept (level evaluation that I consider as a political decision in this research).

In the current PBFPD processes, SFPE [5] indicates that "if several successful trial designs are available, cost could be one of the factors used to select which successful alternative is used". Effectiveness of the fire protection measures defined by their availability (capability of the measure to perform its fire safety function at a given time) and their reliability, is also one of these factors. Nevertheless, SFPE does not indicate how these different factors should be evaluated and presented to the different stakeholders for their judgment (i.e. how a more effective but more costly measure should be finally installed instead of a less effective but less expensive one).

The "Cost-Benefit analysis" Step is the last technical step of the proposed PBFPD process. This would not be suggested but required. Guidance would need to be developed, based on approaches outlined by Ramachandran [13], Watts and Chapman [14] or others. The Cost-Benefit analysis, in conjunction with Step 3, which assesses the reliability of fire protection measures, and Step 5, which evaluates how these measures are designed and maintained in order to be well integrated in the system, represents the package of information that the FPE needs to provide so that in the final step of the process, stakeholders are able to make an informed decision of the fire protection measures based on system options, reliability and cost factors and finally select the ones for their system.

4.6 *Conclusions for this chapter*

Research was undertaken as a response to the shortcomings and challenges related to the application of current performance-based fire protection design (PBFPD) processes. These difficulties were interpreted as a consequence of having generic guidelines for these processes which strongly rely on a political agreement between project stakeholders and the fire protection engineers. Besides, these generic guidelines seem too focused on fire scenarios so that fire protection measures deemed appropriate at the time of design might not be the most appropriate when implemented in a building, as key aspects of the fire protection design might be ignored or worse "rejected" by the occupants of the building when needed the most, since fire is not a daily concern.

As a consequence, it was estimated that a paradigm shift from one in which fire is the center of the problem to one in which building performance metrics are evaluated in the case of fire events, was necessary before implementing a new PBFPD process able to overcome all the current difficulties. A "building-occupant" system paradigm was then established along with a new risk-informed performance-based process focused on assessing the overall performance of the system in case of any type of event affecting its performance.

This chapter presented how this system performance-based process can be used for the treatment of fire events and how this new PBFPD process differs from the current ones. The new PBFPD process is system specific, so its associated guidelines cannot be generic as they are established by system categories.

Being focused on the system, a fire risk analysis is performed centered on the study of the actors of the system everyday performance and how fire protection measures can mitigate the effects of fire events on this everyday performance. Besides, the new PBFPD process contains a technical step dedicated on the evaluation of the integration into the system of the fire protection measures, selected after the fire risk analysis. A cost-benefit analysis finalizes the technical part of the process which has been performed independently and in a straightforward manner by fire protection engineers (FPEs). At the end of this technical part, FPEs have elaborated three documents detailing the results of the fire risk analysis, of the evaluation of the integration of the fire protection measures into the system and of the cost-benefit analysis. Based upon these documents, the stakeholders decide which fire protection measures they would have installed in their system. This process is then showing a complete separation between the "political" decision-making process and the "technical" resolution of the engineering fire problem,

As a proof of concept, it has been shown through text and examples how the new framework addressed the challenges with the existing approaches, operated within a more holistic "building-occupant" system paradigm, illustrated how viewing fire as a perturbation within the larger "building-occupant" system would increase fire safety performance over the life of a building, and deliver a higher level of building fire safety performance.

For the time being, no detailed guidance has been established for the new PBFPD process. Nevertheless, the following chapter of this dissertation will describe how the new PBFPD process is implemented. In other terms, Chapter 5 contains a possible plan of action needed to set up the basis for models and databases that would ultimately be part of system specific guidelines related to each of the technical steps of the process. Due to the facts that the technical steps of the process are connected in terms of input-output and that they will require the competencies of FPEs, stakeholders, policy makers, experts in fire science, human behavior, structural engineering, toxicology and economics, it is already anticipated that this plan of action to be iterative.

References

1. A. Alvarez, B.J. Meacham, Towards an Integrated Performance-Based Design Approach for Life Safety Across Different Building Use Groups, in: Proceedings of the 12th International Interflam Conference, Nottingham, UK, 2010
2. E. Comeau, M. Puchovsky, NFPA Fire investigation report, Warehouse fire, New Orleans, Louisiana, March 21, 1996, National Fire Protection Association, 1996
3. J. Stern-Gottfried, G. Rein, Travelling Fires for Structural Design-Part I: Literature Review, *Fire Saf. J.* 54 (2012) 74-85
4. V.A. Oven and N. Cakici, Modelling the evacuation of a high-rise office building in Istanbul, *Fire Saf. J.* 44 (2009) 1-15
5. SFPE, SFPE Engineering Guide to Performance-Based Fire Protection, 2nd edition, Society of Fire Protection Engineers, 2007
6. IFEG International Fire Engineering Guidelines, Australian Building Codes Board, Department of Building and Housing (New Zealand), International Code Council (USA), and National Research Council (Canada), 2005 edition
7. Firefighting News, Firefighters battle blaze at Myrtle Beach Convention Center, (available at: <http://www.firefightingnews.com/article-us.cfm?articleID=102260>, last checked 2012-09-20) 2011
8. V. Babrauskas, J.M. Fleming and B.D. Russel, RSET/ASET, a flawed concept for fire safety assessment, *Fire and Materials* 2010; 34:341-355
9. A. Alvarez and B.J. Meacham, 'Test bed' environment process for assessing the appropriateness of engineering tools to be used in performance-based design applications, Proceedings of the 9th International Conference on Performance-Based Codes and Fire Safety Design Methods, 20-22 June 2012, Hong Kong, 2012
10. The Independent, Hotel blamed as fire kills 78 at Thai beach resort, (available at: <http://www.independent.co.uk/news/world/hotel-blamed-as-fire-kills-78-at-thai-beach-resort-1250217.html>, checked 2012-09-20), 1997
11. J.S. Tubbs and B.J. Meacham, "Historic Events", chapter 2 of Egress Design Solutions – A Guide to Evacuation and Crowd Management Planning, John Wiley and sons, 2007
12. J. Yatts, Chicken Processing Plant Fires – Hamlet, North Carolina, and North Little Rock, Arkansas, Technical Report Series, United States Fire Administration, 1991
13. G. Ramachandran, Economics of Fire Protection, Routledge, New York, 1998
14. J.M. Watts Jr. and R.E. Chapman, in: P.J. DiNenno (Ed.), Engineering Economics, The SFPE Handbook of Fire Protection Engineering, fourth ed., National Fire Protection Association, Quincy, MA 02269, 2008 pp. 5/129–145.

5. ESTABLISHING A PLAN OF ACTION FOR THE DEVELOPMENT OF GUIDELINES IN SUPPORT OF THE FRAMEWORK FOR RISK-INFORMED PERFORMANCE-BASED FIRE PROTECTION DESIGN

In order to apply the new PBFPD process to a specific system, FPEs would base their work upon guidelines written for each of the technical steps of the process and established for specific types of systems, since it has been demonstrated, in the previous chapters of this dissertation, that generic guidelines are at the origin of challenges when applying them to specific projects.

These guidelines for the specific systems are not as yet written as the required research still has to be carried out. Nevertheless, a plan of action (Fig. 5-1) applicable to any disruptive event type, including fire, is proposed in order to:

- collect and compile information from research associated with each step of the process. This information primarily comes from technical literature where general advances in all of the corresponding fields (fire research, human behavior, material engineering...) are applied to specific systems. At this stage, input from stakeholders is essential as they have the best knowledge of the characteristics of their systems (in terms of target definitions and attributes, descriptions of functional zones and utility zones and how the system performs in a daily basis). Some important results found for a particular step can be used as input for research associated with a subsequent step of the PBFPD process.
- establish guidelines or standards associated with each step of the process. The aim of the performed research gathering together stakeholders, fire protection engineering and experts in different fields, is to produce specific guidelines for each step and specific "building-occupant" systems. It is intended that if generic standards, guides and guidelines are already published or in progress in relation to a process step, they would be integrated within the "building-occupant" paradigm. It is also conceived that specific system guidelines may have a common aspects or comparison between different systems may be looked at. For example, in order to avoid the multiplicity of databases, a global database regrouping common attributes defined across multiple "building-occupant" systems may be created and consolidated with specific data. Methods, models and tools developed in a generalized and consistent manner to quantify fire events will also be considered in the guidelines and standards, as the most appropriate of them would be used to describe fire events occurring in such and such systems and would be detailed in the corresponding guidelines.
- thus, by "climbing the research to application/regulatory ladder", the FPE at the top the "ladder" will use guidelines and standards established for specific "building-occupant" systems, along with databases containing information and data relevant to the matter being considered.

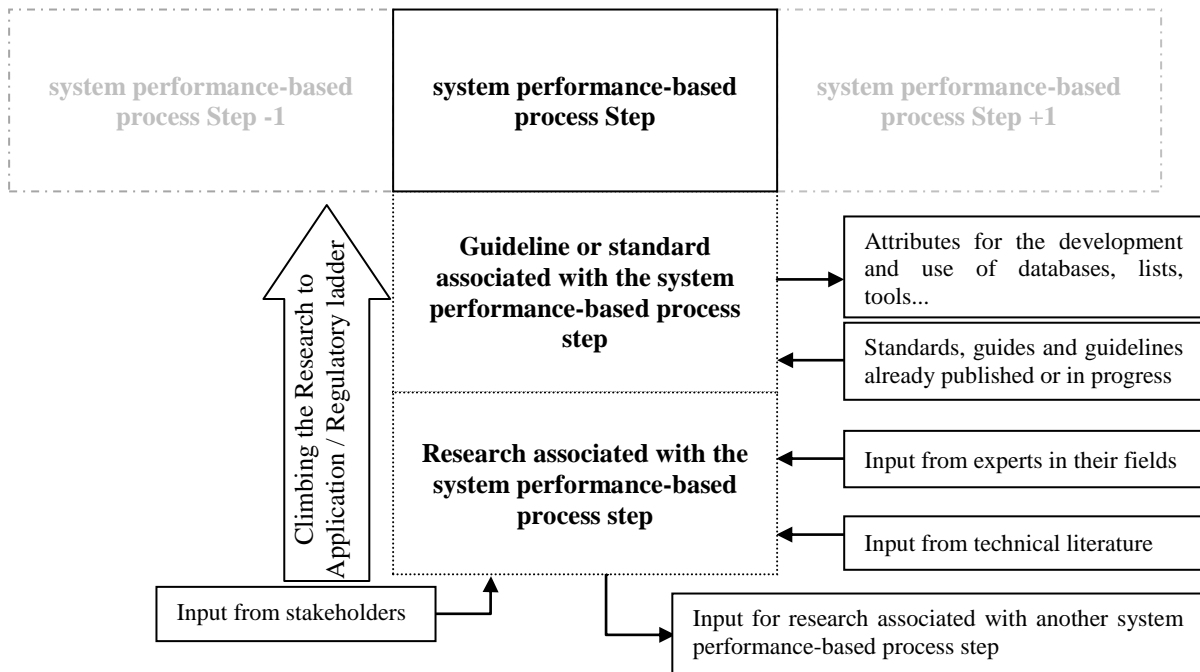


Fig. 5-1. Plan of action: "climbing the research to application/regulatory ladder"

This chapter proposes, for each technical step of the process, a plan of action including information that can already be extracted from past and current research. As well it outlines how I anticipate the future guidelines and standards related to the application of the new PBFDP process will be composed and structured. This plan of action, illustrated with Fig. 5-1, is planned to serve as the template of a decision-making process for the creation of the corresponding guidelines and standards for each step of the system performance-based process.

5.1 *The need for an iterative plan of action*

To perform, the PBFDP process presented in the previous section for a particular "building-occupant" system, FPEs need all the information related to the problem definition, that is to say the characteristics of the "building-occupant" system, including the nature of the different targets which determine the overall performance of the system. In order to perform the six different steps of the risk-informed PBFDP process, important information from the stakeholder has also to be collected, for each step of the process, as shown in Fig. 5-2.

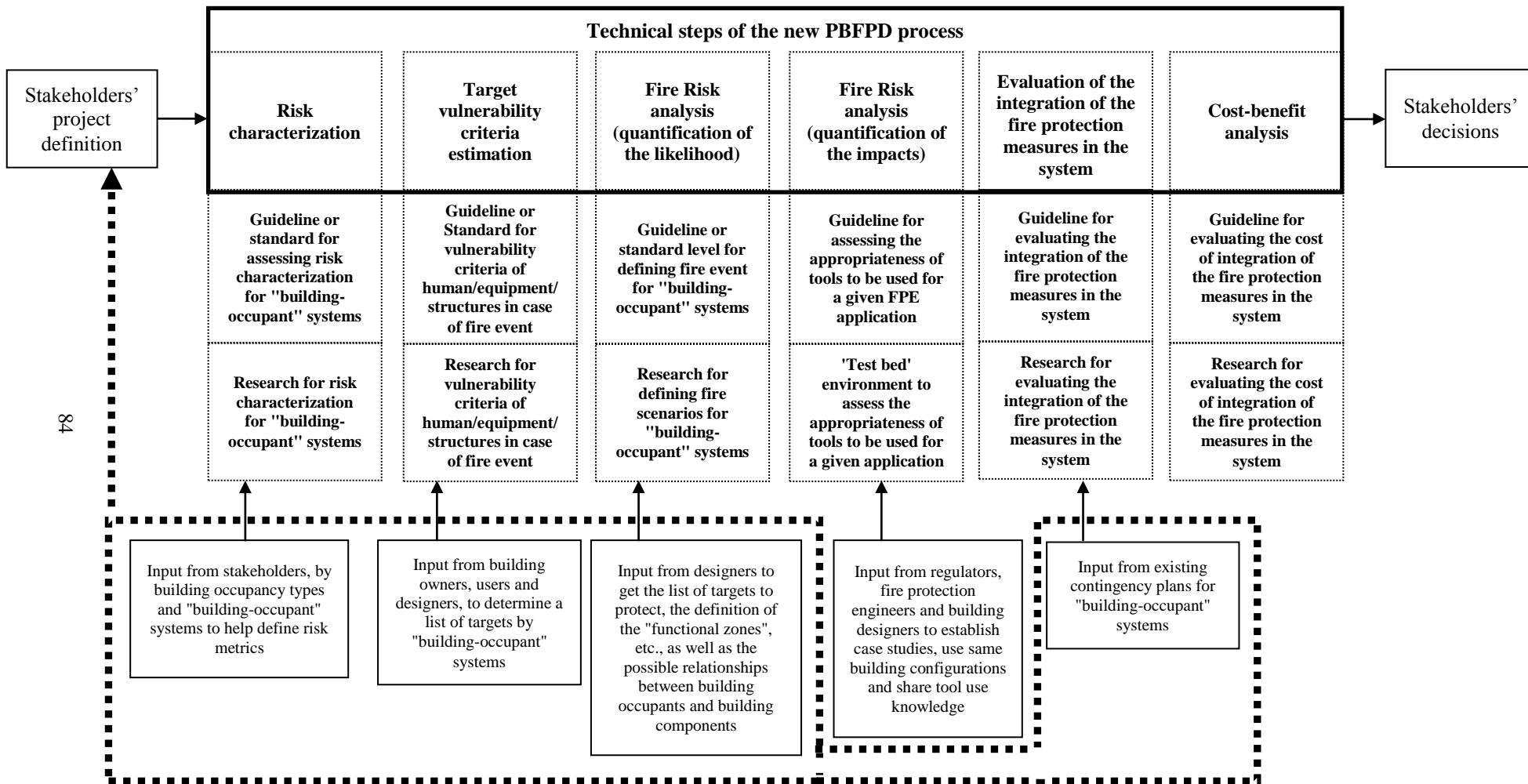


Fig. 5-2. Influence of stakeholders' input on the PBFPD process

Input from the stakeholders is necessary to apply the research to "building-occupant" systems of interest, to canalize this research to obtain the corresponding guidelines in the shortest times possible. For example, the application of decision-making processes similar to that presented in Fig. 5-1 demonstrate that it has been successful in overcoming technical and political obstacles in risk-informed performance-based design processes concerning hazardous facilities. These applications namely concern industrial plants in France [1] and nuclear power plants in the USA [2,3]. Bringing all the aforementioned participants together allowed in the French example the shift of the regulation from a prescriptive method related to the prevention of the worst case scenarios and land management to a probabilistic risk assessment of all the possible scenarios (fires, explosions and toxic releases) having consequences outside of a considered industrial plant. Dedicated groups were organized according to the type of activity and hazardous products (e.g. chlorine fabrication, LPG (Liquefied Petroleum Gas) storage facilities, oil refineries). The US example was dedicated to the effects of potential fires on the safety of the pieces of equipment which maintain the nuclear core in a safe state.

The French example concerned the safety of the population located outside the plant and the environmental impact of the industrial plant. The evaluation of the consequences of a fire in a populated building requires the evaluation of both the fire effects (temperature increase, production and spread of smoke and toxic effluents) and the evacuation process (when people need to evacuate the building to a safe place). This latter, complex but essential evaluation has not been considered in the two aforementioned studies so it is not possible to directly transfer their results to the built environment. It should be noted that communication between research groups dedicated to each step of the process would be necessary because of the interconnections between the research on a specific step as illustrated in Fig. 5-3. Thus, the process needs to be iterative since output from some research on specific steps is necessary input for research on other steps in the process.

Besides, the needed research is both generic and applied:

- it is generic regarding research concerning the tools used in any step which is currently producing more elaborated tools that can be used in the PBFDP process. Advances in fire protection engineering tools is, of course, my main concern when looking at tools which are used to quantify the effects of a fire, but I will also be looking at tools which can help and speed up the process when dealing with statistics, risk analysis, and cost benefit analysis.
- it is applied regarding research concerning the data which would serve as input data for the models and tools.

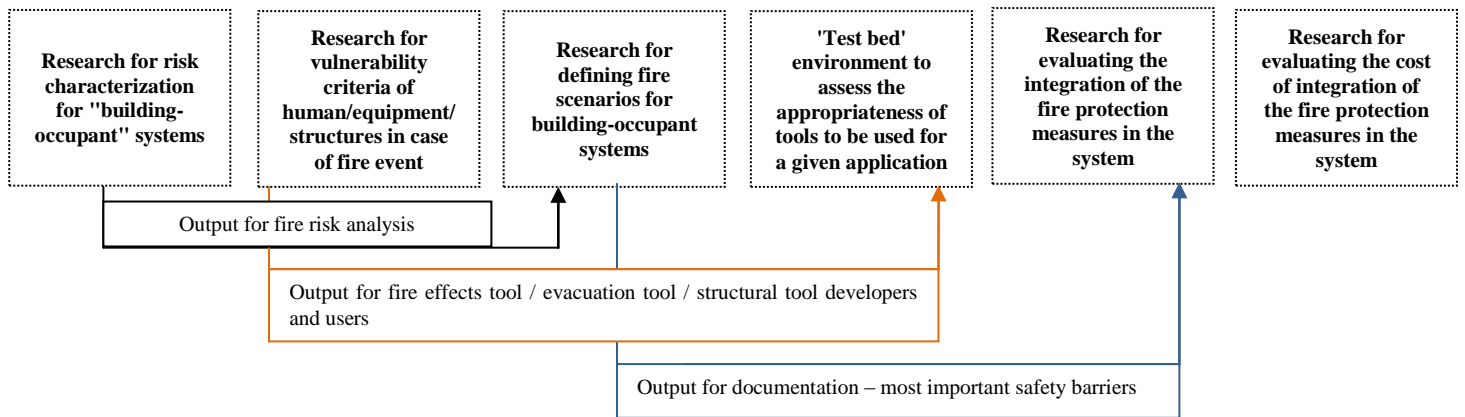


Fig. 5-3. Interconnections between the step researches of the proposed PBFDP process

Regarding the validation of tools, since each of the "building-occupant" system of interest constitutes a micro-domain of analysis and study, it will not be necessary to have the tools validated on a macro-scale (i.e. all their possible domains of application) but around each established micro-domain, and this is the case for all of the tools used in the different steps of the process. The same concept can be applied for data research: small groups of experts dedicated to the study of particular "building-occupant" systems can work a lot more efficiently than researchers looking to embrace all the possible data distribution for the whole building environment.

In consequence, because the generic problem is broken into manageable and well defined pieces, i.e. the "building-occupant" systems, the iterations needed to conduct the research and establish the guidelines would be much quicker than trying to solve the engineering problem in a generic way. Besides, since every system has its own characteristics, not only the aforementioned technical challenges would be solved more quickly, but also the risk characterization components of this process would be better accepted as risk mechanisms (risk control, risk aversion, etc.) are not perceived the same way by stakeholders dealing, for example, with hospitals, schools or high-rise office buildings.

At last, in the USA, the National Fire Protection Association organizes committees in order to establish standards related to requirements and recommendations related to fire protection of specific building types. For example, the technical correlating committee on health care facilities was created to write the NFPA 99 Standard for Health Care Facilities [4] and it gathered members from health care systems, academics, US departments, fire protection consulting companies and fire protection equipment manufacturers. Organizing similar groups or taking advantages of these committees would also benefit the development of the different guidelines of the risk-informed PBFDP process.

5.2 Importance of the involvement of the stakeholders for establishing validation domain of models needed at each step of the PBFPD process

In the past decades, models has been developed in a generic form because there was a tremendous need for fundamental research to describe and quantify all the different phenomena involved in a fire engineering evaluation, from the effects of the fire itself, to the building occupant process and the response of the building structure. Validation of these "research" models, as opposed to "engineering" models inscribed in codes and standards, has been and still remains a central question in the acceptance, by the authorities having jurisdiction, of engineering reports using the performance-based option of building codes [5]. Due to the complexity of the different types of aforementioned phenomena, scientists developed semi-empirical models based on a theoretical approach of the phenomenon completed by a "tuning" of these theoretical models with empiric correlations or factors. Thus, the contours of the validation domains of these semi-empirical models mainly correspond to the boundaries of the experimental tests that served to "tune" the models. It should be noted that setting up experiments for determining validation domains and thereafter increase them is a costly enterprise in terms of time and resources. Besides, as some empirical parameters are model dependant, experiments especially set up for assessing parameter values for one particular model may not be valuable or simply usable for increasing the validation domains of other models dealing with the same phenomenon as the other models may also have their own model dependant parameters which would have required different or additional specific experimental setting up.

Involvement of the project stakeholders is also crucial, not only for the execution of the political steps of the PBFPD process when this process will be applied to a particular project but also during all the process required to establish the corresponding step guidelines of the PBFPD process. This involvement is indeed essential because the stakeholders are the ones who know best the system they have designed and that they will ultimately use on a daily basis. The stakeholders know how the system behaves in a daily basis so they are able to describe, in details, the corresponding characteristic of the building components as well as the characteristics of the building occupants of the their system.

Benefits of having stakeholders participating at the research stage of each path include a better use of research as their data identifier input (i.e. targets' characteristics, risk metrics, functional zones, contingency plans...) would drive the need to obtain research data pertinent and if possible directly applicable all along the proposed PBFPD process. As a result of this participation at the research stage, the guidelines would contain if not all data values, processes that could lead to collect data while minimizing uncertainties and the use of engineering judgment.

5.3 Application of the plan of action to obtain the necessary guidelines to perform each step of the new PBFPD process

As illustrated in Fig. 5-2, six different technical steps are required to be performed by the fire protection engineer. This section briefly presents a possible way to elaborate these guidelines from research, past, present and future. Each guideline elaboration process is derived from the one presented for a risk-informed approach (Fig. 5-1), as each step requires the participation not only of FPEs and scientists, but also public officials and interested stakeholders.

5.3.1 Proposed path of action to quantify Step 1: risk characterization

5.3.1.1 Description of the risk characterization step and corresponding path of action

Risk characterization is the most important step of the process, as it defines and frames the engineering problem to be solved by the FPEs.

Within my "building-occupant" system paradigm described in detail in Chapter 3 of this dissertation, the system stakeholders define the main characteristics of their existing system or project, in the political initial step of the PBFPD process. They are concerned about the overall performance of their system, which is dependant of the "chronic objectives" associated with the system and they would like to know how this performance is affected in the case of fire events. The performance of the system is a function of the activity of the system "targets".

Since targets are defined as the actors of this performance, it is essential that the FPEs collect the list of these targets from the system stakeholders. The stakeholders' view of the fire problem is on the long term; in other terms fire events are disruptive events among many susceptible to occur during the lifespan of the system. The FPEs' view of the fire problem is focused on the fire disruptive events, how often they can occur and with which effects they have on the system targets.

The risk characterization step can be seen as the transfer of this problem, from the stakeholders' perspective to the fire protection engineer's perspective. Based on the stakeholders' list of system targets, FPEs have to define risk metrics which associate the frequency of the fire events with their effects on the system targets, as well as a quantification of these risk metrics.

I estimate that guidance related to current PBFPD processes focuses too early on the fire events for which safety goals and objectives are established upfront, leading to a potential disconnection between the stakeholders' overall concerns and the FPE specific fire-oriented analysis. The Risk characterization step is not only aimed at avoiding this disconnection at the start of the new PBFPD process (i.e. solving the wrong problem), but it is also useful at the

end of the process when the FPEs communicate their results to the stakeholders as they can easily "transfer back" these results into the stakeholders' perspective.

The corresponding path to quantify the risk characterization step of the PBFPD process is illustrated in Fig. 5-4, and detailed in the following paragraphs.

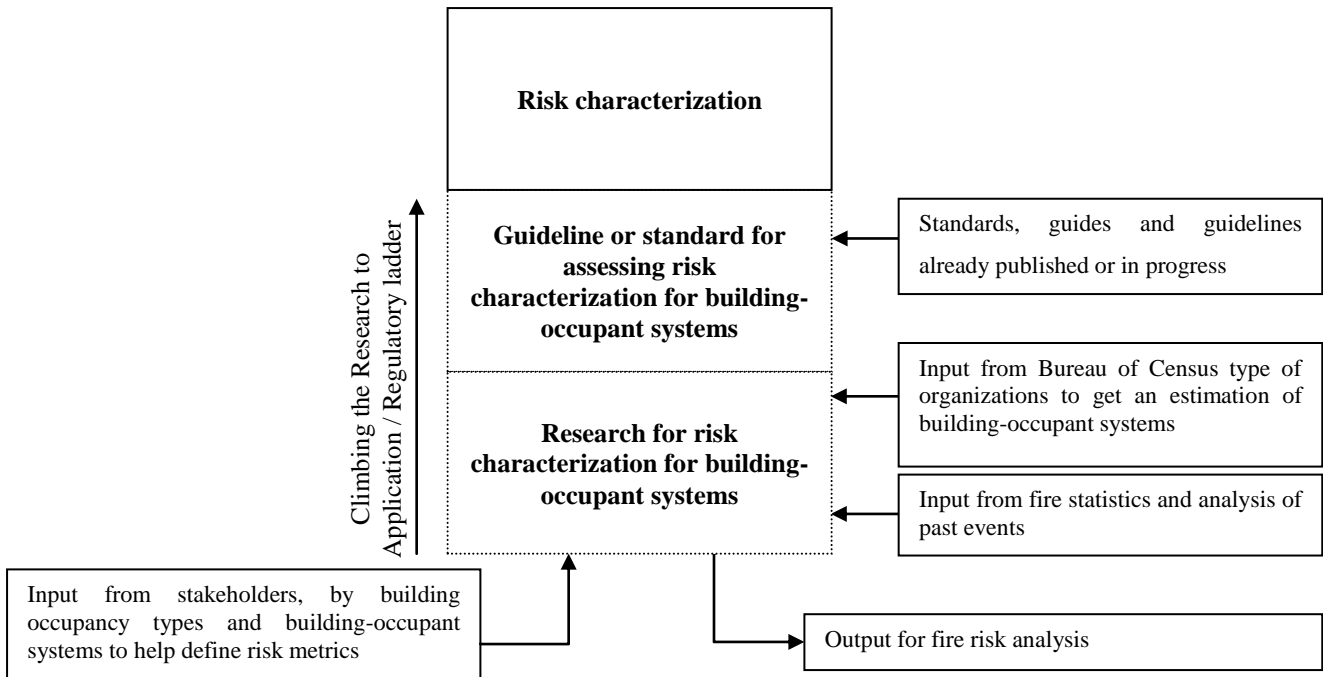


Fig. 5-4. Proposed path to risk acceptance characterization

5.3.1.2 Research to be carried out for "Risk characterization" Step

At a research level, stakeholders involved in similar "building-occupant" systems would help the fire protection engineer define the metrics that corresponds the closest to their own view on the performance of the systems.

Since these metrics are tied to the systems they represent, a possible formulation for these metrics is a fraction where the numerator deals with the fire events in a defined period of time and the denominator describes a relevant parameter of the system. Different objectives may be considered by the different stakeholders. All stakeholders are concerned by life safety so the metric numerator should include parameters dealing, for example, with annual deaths and injuries caused by fires affecting the considered systems; the denominator would include some information relevant to the activity of the occupant in the considered building. For property protection, the numerator of the corresponding metric could include parameters describing, for example, the amount of damage due to fires, including direct and indirect fire damage. For business interruption, the metric numerator could include the number of days lost in production due to fire events in similar industrial systems.

Within the presented process, I consider that risk characterization may be assessed on two different set of data:

- fire statistics, which provide fire frequencies and damage estimation,
- census data related to defined "building-occupant" systems, which provides information of the number of systems within the same category.

In the USA, the National Fire Protection Association [6] and the Fire Administration [7] periodically publish fire statistics. Special reports are also published by building occupancy types [8]. Alvarez and Meacham [9] give examples of US census database consultation, for different system categories.

Within the "building-occupant" system paradigm, stakeholders identify targets and risk identification is carried out to figure out how fires can affect the targets and lead to a change of the system performance. It should be noted that several authors already applied this way of looking at fire statistics and tried to determine which metrics were the most appropriate to represent fire risk and communicate concerning the policy levels of this risk for different systems.

Examples from the technical literature showed that data, even if not "complete and perfect" [8,10-13], can be associated and treated by system category. Thus, Kobayashi and Nozaki [14] looked at different Japanese sources, which classified non residential buildings in several categories. Table 5-1 presents their findings related to commercial buildings, as they defined four different classes based on floor area and number of stories. Fig. 5-5 presents the corresponding fire risk with an estimation of the damage area as a function of annual exceedance of probability.

Table 5-1. Calculations conditions for example risk curves [14]

Classification	Median floor area (m ²)	Median Number of Stories
Group "H"	36,597	10
Group "LL"	31,124	5
Group "LM"	11,239	4
Group "LS"	2,148	2

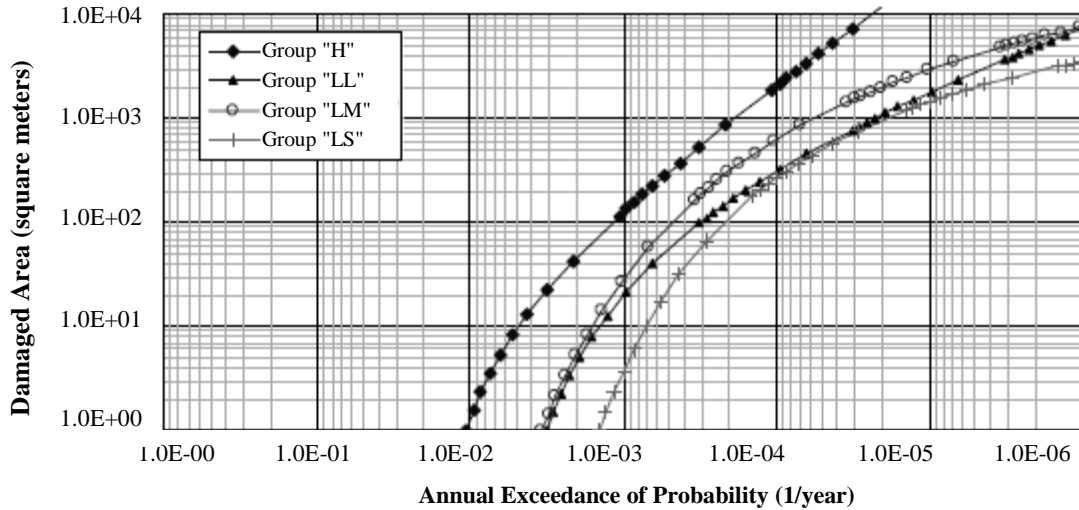


Fig. 5-5. Example of fire risk curves for commercial buildings [14]

Risk matrix or fire risk curves such as the one presented in Fig. 5-5. can be established for "building-occupant" systems, based on the corresponding fire statistics which describe the appropriate metric for each objective considered by the project stakeholders. For example, Tsujimoto [15] presented fire risks to Japanese occupants in residential buildings, hospitals and hotels from 1969 to 2000, as annual deaths per 10^5 users' year stays in each kind of place with the corresponding metrics:

- for residential buildings: $\frac{\text{annual deaths by residential fires}}{\text{population}}$
- for hospitals: $\frac{\text{annual deaths by hospital fires}}{(\text{total number of sickbeds in Japan}) \times (\text{annual used rate})}$
- for hotels: $\frac{\text{annual deaths by hotel fires}}{\text{annual total number of hotel guests}}$

Based on these metrics, he presented the death risk a person takes at one night in each place (Fig. 5-6).

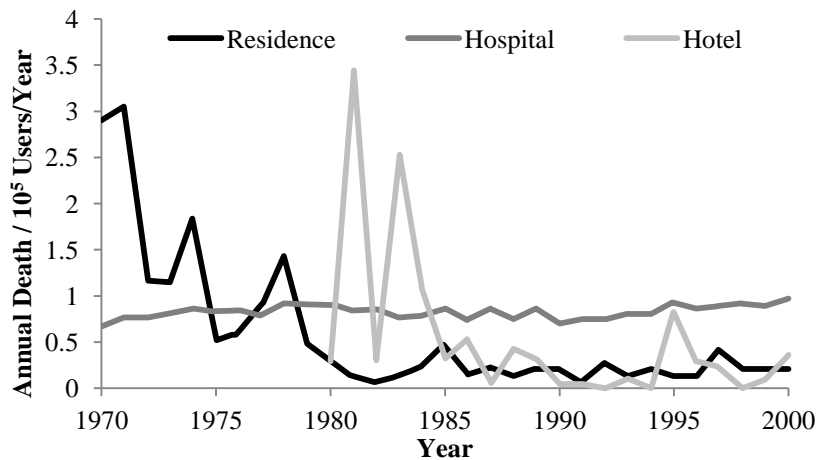


Fig. 5-6. Death risk trends in Japanese residential buildings, hospitals and hotels between 1969 and 2000 [15]

Particular care should be taken when aggregating buildings into a similar category. This situation is not only due to the evolution with time of building characteristics (e.g. open space office floors versus compartmented office floors) but also due to the evolution with time of building code prescriptive requirements regarding fire safety. For example, Tsujimoto [15] also looked at establishing a correlation between fatalities in hospitals and the number of beds with or without sprinklers (Fig. 5-7), mainly between 1960 and 2000. He listed the regulatory changes concerning the installation of sprinkler systems in Japanese hospitals during the same period (Table 5-2) and established a relation between fire death and the number of beds with and without sprinkler estimated by the change of fire code summarized in Table 5-2 and statistics about hospitals.

Table 5-2. Transition of Requirement for Sprinkler Installation of Hospital (Fire Code in Japan) [15]

1961.4	patients room over 4 th floor $\geq 1500 \text{ m}^2$
1967.7	4 th floor to 10 th floor floor area more than 100 m^2 over 11 th floor
1973.6	total floor area is over 6000 m^2 except one-story hospital over 11 th floor floor area more than 1000 m^2 which floor is underground or without window
1974.6	retroactive application to existing building
1988.4	total floor area is over 3000 m^2 except one-story hospital

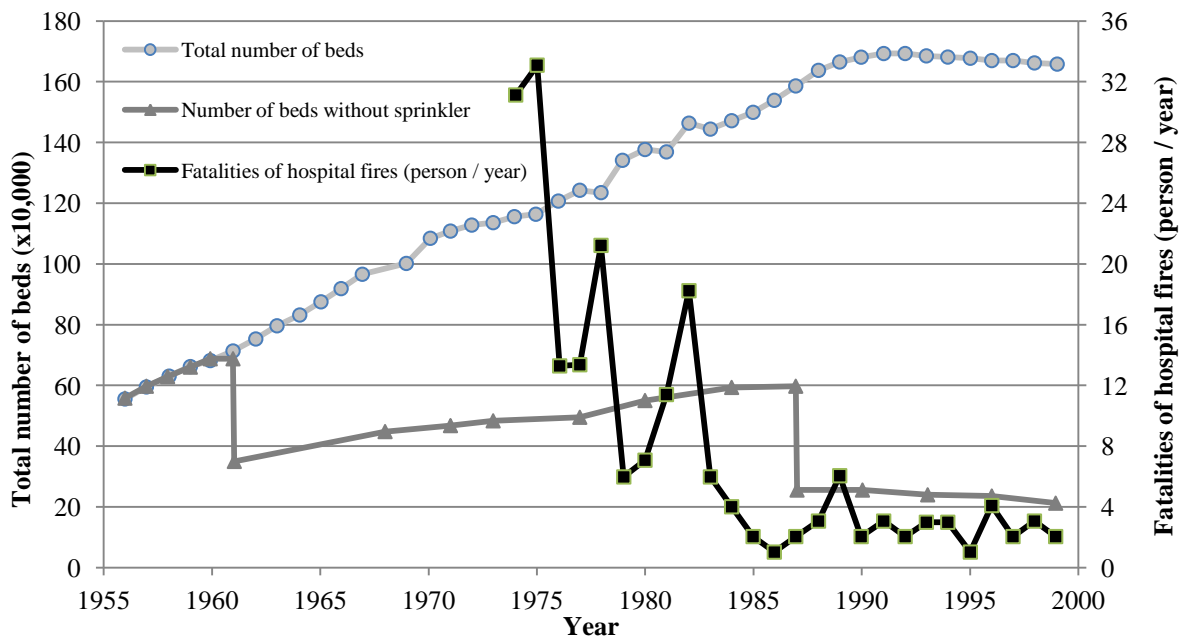


Fig. 5-7. Correlation between Fatalities in Hospital and Number of Beds [15]

It should be noted that some information output collected while performing research for the risk characterization Step (e.g. information related to the characterization of fires and of the considered systems) can be used as input for the next steps related to fire risk analysis (fire likelihood and fire consequence evaluation). For example, while assessing information about fire statistics and past fire events, elements of information related to scenarios, fire ignition, fire propagation in terms of frequency and intensity of damage should also be collected. Also, within the "building-occupant" system paradigm, characteristics of the different types of systems should also be collected so to have more information about the potential targets located inside the different parts of the systems.

The aforementioned examples collected in the technical literature appear to be almost applicable within the risk characterization step of the new PBFPD process. The methods followed by the different authors would also serve as a basis for the risk characterization guidelines and standards.

5.3.1.3 Establishing guidelines or standards for assessing risk characterization for "building-occupant" systems
Standards, guides and guidelines dedicated to fire risk assessment or containing elements dealing with risk assessment are already published or in progress [16,17]. Guidance provided by these documents is still generic but contains some useful elements to be adapted in the new "building-occupant" system paradigm.

A major concern regarding the use of data for assessing risk characterization for "building-occupant" systems comes from the different origins of the needed data. For example, in the USA, the classification of buildings is not the same when established by:

- the National Fire Protection Association, which deals with fire statistics and proposes fire protection standards,
- the International Code Council, which elaborates building codes,
- the architects, who design buildings according specific functions,
- the Bureau of Census, which codifies business buildings according their activities.

Due to the fact that each of the corresponding building classifications were elaborated according to specific objectives, it would be quite difficult to look for a homogenous taxonomy across so many fields. Nevertheless, within the "building-occupant" system paradigm, guidance is provided by system category. In consequence, it is imperative that the system be well defined for each PBFPD step guidance and especially for the first step, which is the one defining the engineering problem to be solved.

Guidelines or standards for assessing risk characterization for "building-occupant" systems shall clearly state the definition of the system concerned by these guidelines or standards.

Once the system is well defined, the guidelines or standards related to the new PBFPD process Step 1 would contain information related to well defined "building-occupant" systems, including the definition of the system targets and

their associated risk metrics for relevant objectives (life safety, property protection, business continuity...) as well as the quantification of these risk metrics, or at least a way to obtain this quantification, as again countries, regions and even cities may have been developing their own databases regarding fire safety and building/person census.

5.3.1.4 Using the guidelines for performing Step 1 in a PBFPD process

Once the guidelines related to Step 1 have been published for well defined "building-occupant" systems, the FPE can use its guidance for a project covered by the corresponding guideline as a means:

- To determine the targets which define the performance of the system according to the stakeholders, and
- To document how the fire risk associated with these targets is taken under consideration through the definition and possible quantification of appropriate risk metrics.

5.3.2 Proposed path to quantify Step 2: Target vulnerability criteria estimation

5.3.2.1 Description of the target vulnerability criteria estimation step and corresponding path of action

In Step 1 of the new PBFPD process, FPEs collected the targets which contribute to the system overall performance. Then, in Step 2, for each considered targets, FPEs have to quantify how these targets are affected by both direct and indirect effects of fire events, events involving a fire and defined between two "chronic" states of the system.

As the new engineering process is target oriented, it is essential to get the metrics allowing the estimation of the potential vulnerability of the targets. Vulnerability criteria metrics would have to include:

- Typical criteria related to fire impacts to humans (due to thermal threat, toxic threat and loss of visibility which impedes evacuation),
- Vulnerability criteria related to evacuation behaviors,
- Vulnerability criteria related to indirect fire threat to people,
- Vulnerability criteria related to safety equipment, building contents (e.g. for heritage preservation) and
- Vulnerability criteria related to the use of fire protection measures (sprinkler, fire fighting) on building contents and systems.

These vulnerability criteria have to be collected and the process by which the damage is assessed has to be a result of an agreement within the scientific community not only involving fire protection engineers but also:

- Toxicologists, psychologists, etc. when the targets are related to the life safety objective,

- Operators, electronics engineers, etc. when the targets are related to the business continuity objective,
- Structural engineers, etc. when the targets are related to the property protection objective.

The corresponding path to quantify the target vulnerability criteria estimation step of the PBFPD process is illustrated in Fig. 5-8, and detailed in the following paragraphs.

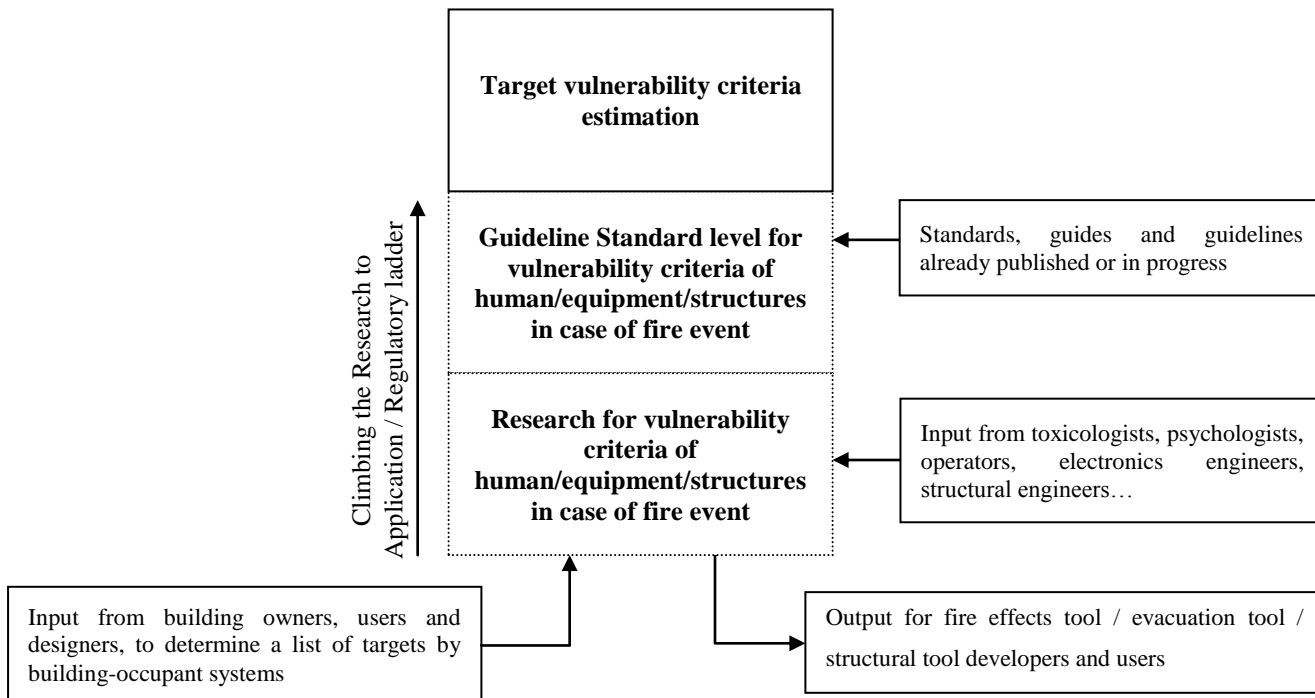


Fig. 5-8. Proposed path to target vulnerability criteria estimation

5.3.2.2 Research to be carried out for estimating vulnerability criteria

Methods of determining vulnerability criteria metrics as well as collecting and assessing collegially validated "technical" values to these criteria differ from the "performance criteria" presented in current PBFPD processes where they are prescribed by regulations or established via a political agreement among the project stakeholders. These prescribed values do not present the rationale behind them so it is quite difficult to validate their application to specific "building-occupant" systems (Cf. Chapter 2 of this dissertation).

Concerning the role of the stakeholders in that matter in the proposed PBFPD process, it should be noted that building owners and users are still actively consulted in this Step research as they are the most involved parties to determine the nature of the targets present in their "building-occupant" systems. Standards such as the one from ISO TC92 / SC3 [18] would contribute both the needed data and the worldwide consensus for human targets under fire

threat. The input from building designers is also required, from the research stage to the guideline/standard final stage, in order to define the users' domain of application. It should be noted that some output from this task research could be sent to fire effects tool / evacuation tool / structural tool developers and users in order for them to get the target vulnerability criteria metrics considered in the tools.

5.3.2.3 Establishing guidelines or standards for assessing vulnerability criteria of human/equipment/structures in case of fire events

As mentioned above, vulnerability criteria are engineering values, collected from experiments and models. Fires in structures generate heat, toxic and irritant products, lower visibility, damage the structure which can lead to falling objects over escaping building occupants and emergency responders. Building occupants are very different populations across the building occupancy spectrum [9] and they are also different from the emergency responders in terms of how they can withstand a fire event. Due to the complexity of these phenomena to take into consideration, it seems that the first tasks to perform to create guidelines or standards are:

- To look at defined "building-occupant" systems and collect the targets which are considered by the corresponding interested parties or stakeholders, in terms of nature (i.e. occupants, piece of equipments, contents, etc.) and distribution (e.g. percentage of population easily affected by fire effects due to health status);
- To analyze the possible ways of damaging these targets, during the fire event and in both short term and long term periods;
- To quantify these damages and the reaction of the different targets in terms of activity loss affecting the overall performance of the system.

5.3.2.4 Using the guidelines for performing Step 2 in a PBFPD process

While assessing the performance of a "building-occupant" system, the fire protection engineer will use the guidelines designed for Step 2 "target vulnerability criteria estimation" in order to determine the nature of the criteria (metrics determination) and to use validated values of these criteria that are relevant to the examined system (metrics evaluation).

5.3.3 Proposed path to quantify Step 3: Fire risk analysis (quantification of the likelihood)

5.3.3.1 Description of the fire risk analysis (quantification of the likelihood) step and corresponding path of action

In a deterministic approach, the current PBFPD processes do not specify detailed procedures on how to select fire design scenarios or they provide a list from where the FPE and the stakeholders can "pick up" and finally agree on the ones to use. Thus, the resulting fire design scenarios fell to consider the chronic use of a building, are focused on

the fire event instead of being target oriented and miss the importance of the recovery phase. In this step of the proposed PBFDP process, event trees are elaborated in order to describe quantitatively the different fire scenarios, not only characterizing the events between ignition and extinguishment, but also including the procedures to go back to a new "chronic" state of the "building-occupant" system. Fault trees are also established in order to characterize all the different scenarios leading to target damage, so as to capture the indirect threats to the targets. Fire risk models are used in this process step to help calculate the scenario likelihoods.

Because the fire safety analysis is target oriented, input from designers is required to define the targets to protect from fire threat, the definition of the "functional zones", support systems, etc., as well as the possible relationships between the building occupants and the systems (i.e. life supporting systems for patients in Intensive Care Units in hospitals). Quantification of the trees notably requires ignition frequencies defined by functional zones of interest as well as the reliability records of the fire prevention and protection measures, also called "safety barriers" in this process. Analysis of past events, including investigations of major events would be collected and made available in a database. Life safety being a common objective among all stakeholders, this analysis is aimed at providing in fine detail guidance so that when using the proposed PBFDP process, a FPE would use this guidance to demonstrate that a considered project would have the adequate barriers to prevent such life-threatening events from occurring with the lowest probability practically achievable. Once this database is detailed enough and this analysis is done for life-threatening events, regulators could set up this value (or class) of probability, which could become an upfront performance criteria at the start of the PBFDP process.

Besides, it is also expected that an output of this task research would be dedicated to implement building safety documentation, with at least the effects and the maintenance of the most important fire protection measures called "safety barriers".

The corresponding path relative to the PBFDP process step quantifying the impacts of fire events is illustrated in Fig. 5-9, and detailed in the following paragraphs.

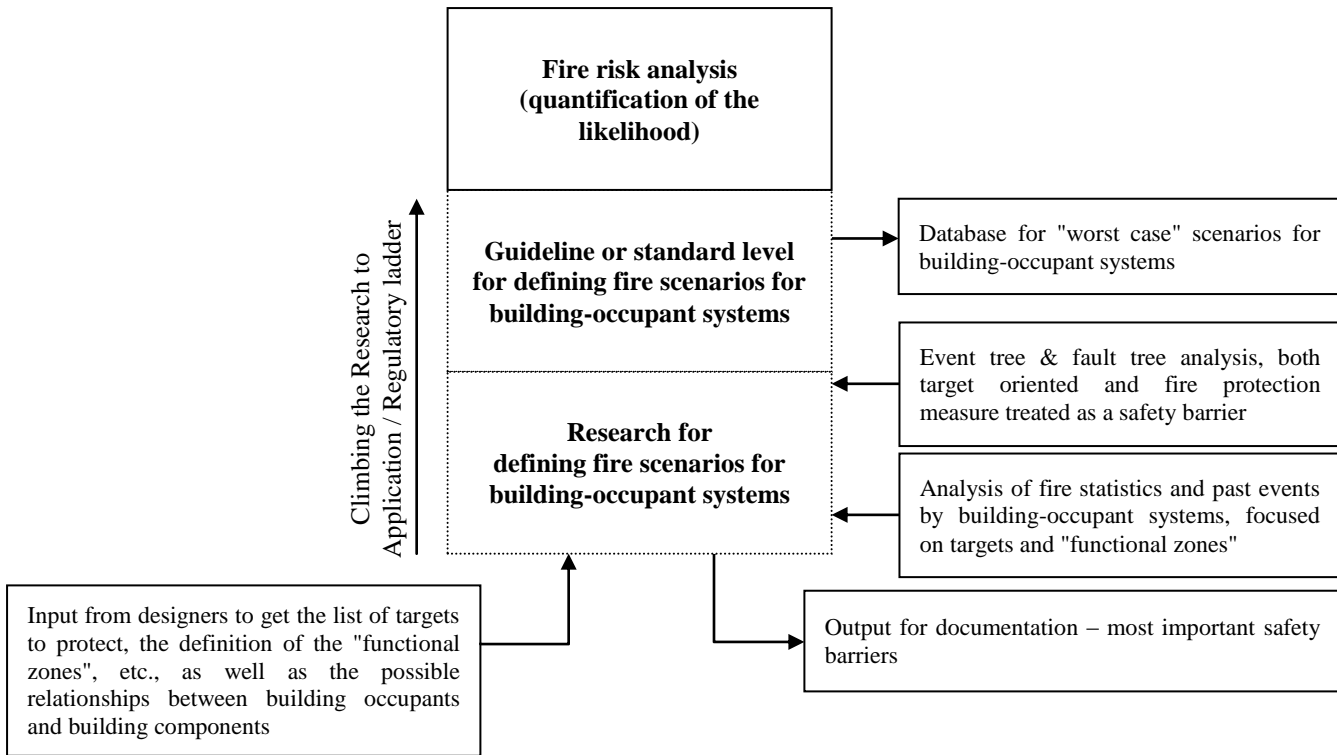


Fig. 5-9. Proposed path to the quantification of the likelihood of fire events

5.3.3.2 Research to be carried out for the process step related to the quantification of the likelihood of fire events

Table 5-3 below is an example of data presented in the NFPA reports of US fires in selected occupancies [8]. This data categorizes the number of casualties and injuries as well as the direct property damage for different extents of flame damage. A discrepancy appears between the fires that are related to the life safety objective as their maximum extent is the room of fire origin and the fires that are related to the property damage objective as the more the fire extents, the more damage it causes, which could indicate that the design fire scenarios for the life safety objective may not be the same for other business or property oriented objectives [9]. This information reinforces the fact that the fire risk analysis needs to be target oriented in order to determine the appropriate scenarios for each of the considered targets relevant to the different stakeholders.

Table 5-3. Structure Fires in Health Care Facilities, Excluding Nursing Homes by Extent of Flame Damage [8]

Extent of Flame Damage	Fires		Civilian Deaths		Civilian Injuries		Direct Property Damage (in Millions)	
	Count	Percentage	Count	Percentage	Count	Percentage	Count	Percentage
Confined or contained fire	560	18%	0	0%	8	9%	\$0.1	0%
Confined to object of origin	1,930	61%	0	0%	29	33%	\$3.8	18%
Confined to room of origin	510	16%	1	100%	44	51%	\$4.2	20%
Confined to floor of origin	60	2%	0	0%	1	1%	\$2.1	10%
Confined to building of origin	90	3%	0	0%	5	6%	\$10.3	49%
Extended beyond building of origin	10	0%	0	0%	0	0%	\$0.7	3%
Total	3,150	100%	1	100%	87	100%	\$21.3	100%

5.3.3.3 *Establishing guidelines or standards for assessing the quantification of the likelihood of fire events*

Step 3 guidelines will be established for specific "building-occupant" systems, and more precisely for the different targets considered by the stakeholders when defining the performance of the systems, as the risk analysis is target-oriented in this study paradigm. They will contain results from fault tree analysis, where the outcomes would be presented, not only with the evaluation of the fire scenario likelihoods, but also with the degree with which the different targets are affected by the fire scenarios. Scenario grouping or scenario clustering have been considered in the current PBFPD processes in order to have a manageable set of scenarios which could represent most of the possible fire scenarios which could occur in a considered project. Nevertheless, this grouping is still achieved project by project and it still requires the agreement of the different stakeholders.

Concerning industrial facilities, Barry [19] proposes different ways to group or cluster scenarios. The categories listed below have been adapted from industrial facilities to common buildings:

- by exposure category, considering categories such as localized exposure, moderate exposure (limited to a defined area) and major exposure (large effect zone). It should be noted that NFPA also provides fire statistics by exposure categories, as presented in Table 5-3 of this chapter,
- by contributing factor breakdown to the fire events, considering "failures" or "potential weak links such as human error", failures of fire protection technical measures (automatic detector, automatic fire suppression system...) or failures of fire protection managerial measures (locked egress doors...). This categorization could be valuable when assessing the most important fire protection measures for a considered "building-occupant" system,

- by hazard. In industrial plants, there are more issues than just the fire hazard to consider (explosion, release of toxic material). In common buildings, and in the present research, fire is the only hazard to be considered. This categorization could be used when different types of technological hazards are examined for "building-occupant" systems.

As within this "building-occupant" system paradigm, the risk analysis is target oriented, fault trees would also be considered in order to determinate not only the direct effects of fire events on targets but also the indirect effects of fire events (e.g., fires affecting life support system of a patient in an intensive care unit but not spreading in the vicinity of the patient).

A possible outcome for the guidelines to be established for assessing the quantification of the likelihood of fire scenarios would be the creation of databases for "worst case" scenarios for specific "building-occupant" systems, based on relevant investigation reports.

5.3.3.4 Using the guidelines for performing Step 3 in a PBFPD process

These guidelines are linked to a database of investigation reports on catastrophic fire events that happened in systems similar to the one examined by the fire protection engineer so the FPE can verify the examined system is provided with safety barriers which would prevent such catastrophic events from occurring in it. The fire protection engineer also uses the guidelines to select fire protection measure sets which are able to maintain the overall performance of the studied "building-occupant" system, as high as possible during fire events.

5.3.4 Proposed path to quantify Step 4: Fire risk analysis (quantification of the impacts)

5.3.4.1 Description of the fire risk analysis (quantification of the impacts) step and corresponding path of action

Current PBFPD processes include or reference calculation methods or tools that can be used to assess the consequences of the fire, with an emphasis on the estimation of the fire effects. Challenges related to the use of tools notably arise from the lack of validation of these tools, the "user effect" and the availability and estimation of the input data for all these tools. In this step of the proposed PBFPD process, fire effects tools, evacuation tools, structural response tools are used to estimate the consequences of fire scenarios for the considered targets. In spite of the tremendous amount of research and development related to the tools, they remain research tools and the results applied to fire engineering still nowadays require some engineering judgment. Use of engineering judgment will never go away. However, it is proposed that better guidance can be developed to help provide better uniformity in application and engineering analysis. To address this, it has been decided to create a 'test bed' environment in order to assess the appropriateness of engineering tools to be used for a given application. This environment, which implies the participation, not only of researchers who develop the tools, practitioners who apply them in an engineering environment, but also academia who can perform long term studies and stakeholders who are concerned by the validity of the tools to solve the engineering problems.

The corresponding path relative to the PBFDP process step quantifying the impacts of fire events is illustrated in Fig. 5-10, and detailed in the following paragraphs.

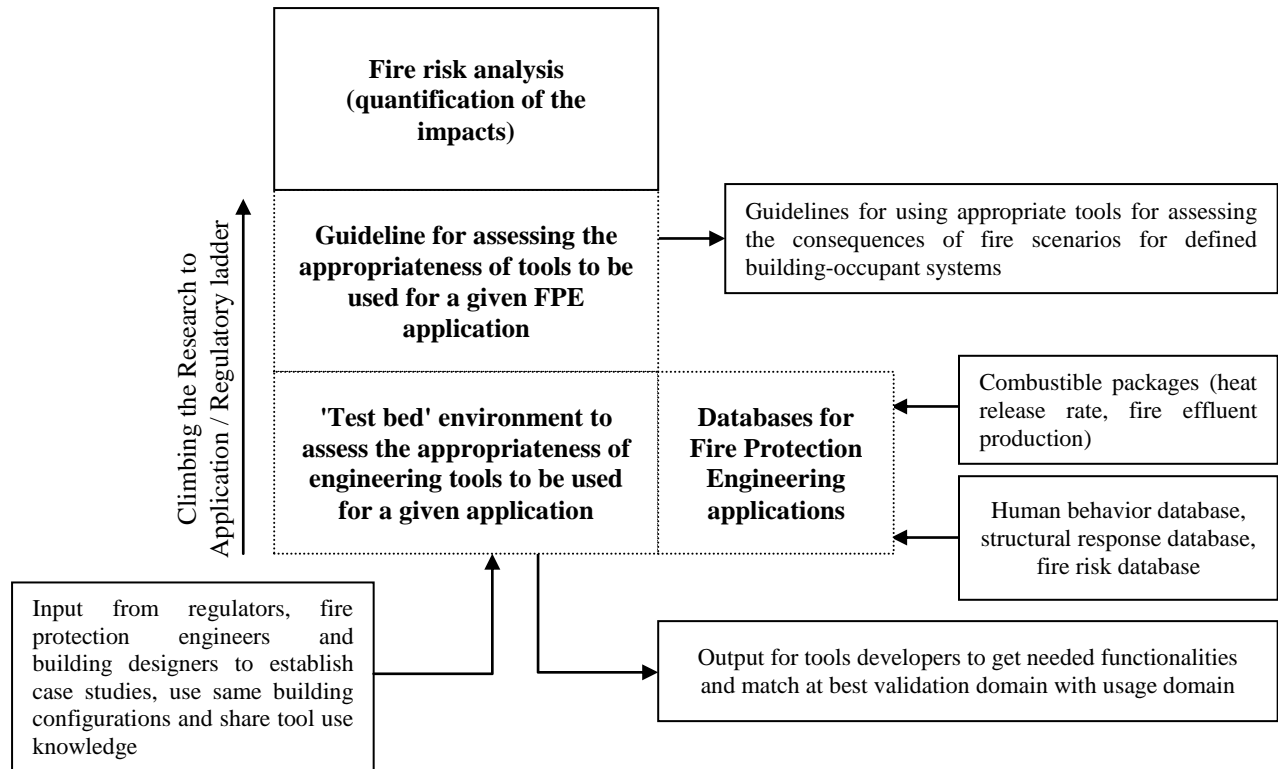


Fig. 5-10. Proposed path to the quantification of the impacts of fire events

5.3.4.2 Research to be carried out for the process step related to the quantification of fire events consequences

In the last two decades, fire research has made tremendous advances in elaborating models and providing tools which have helped the FPEs estimate the consequences of fires. At the same time, more tools became available for the FPEs to assess the evacuation process of building occupants.

Within Step 4 of the proposed PBFDP process, a coordinated action is proposed for assessing the appropriateness of engineering tools to be used for given applications, i.e. FPEs quantify the impacts of fire scenarios for specific "building-occupant" systems with tools validated for the domain characterized by these systems. This action involves the creation of 'test bed' environments where regulators, fire protection engineers and building designers establish case studies, use same building configurations and share tool use knowledge. More detailed explanations regarding the "test bed" environments are presented in [20,21].

It should be noted, that since not all of the necessary validated models and tools are ready for use, a possible output for tools developers from Step 4 research would be to get the functionalities needed by the users so as to match at best the tool validation domains with the tool usage domains.

Data required for the use of these tools is also a major concern. Database structures for fire effect tools and human behaviors exist and they could be used and populated for the common good of all the fire protection engineering community, not looking for all possible data but specific data designed system by system.

5.3.4.3 Establishing guidelines or standards for assessing the quantification of fire event consequences

Guidelines such as the ones published by SFPE [22], ASTM [23] and ISO [24] are important documents which help the fire protection engineer to demonstrate the appropriateness of a fire tool to be used for engineering purposes, describing how the tool validation process should be conducted. Nevertheless, these guidelines detail generic characteristics of the fire tools, such as particular fire phenomena: fire plume, fire spread or smoke transport while leaving the application side completely at the hands of the user of these guides. These documents have to be considered as a first step towards a more comprehensive and more coherent use of fire tools in the engineering community. Nevertheless, they still need to be completed with other guidelines which are application oriented that is to say guidelines which are not generic but are really applied to specific "building-occupant" systems.

These guidelines for the new PBFPD process will be centered around the application and they will concern all the tools which can potentially be used to solve the engineering problem, not only the ones dedicated to fire effects quantifications, but also evacuation process and response of the structures.

5.3.4.4 Using the guidelines for performing Step 4 in a PBFPD process

Once established for considered "building-occupant" systems, the guidelines for assessing the quantification of fire scenarios consequences are used by FPEs to help in the selection of the most appropriate tools to use, in conjunction with databases containing relevant values of input data for the tools. FPEs also use the guidelines to assess the effect of trial fire protection measure sets on the overall performance of the studied "building-occupant" system.

5.3.5 Proposed path to quantify Step 5: Evaluation of the integration of the fire protection measures in the system

5.3.5.1 Description of the step relative to the evaluation of the integration of the fire protection measures in the system and corresponding path of action

In the current SFPE conceptual design procedure for fire protection design [25], the evaluation of the integration of the fire protection measures in the system comes after the final trial design has been selected by the stakeholders and in a form of a testing plan including commissioning and acceptance testing and an Operation and Maintenance

manual. SFPE indicates that "during the design development and construction document phases, the conceptual designs evolve into detailed designs of systems and the plans and specifications that will be used for bidding and constructing the building. The design development and construction documentation are not described in [its] guide. However, guidance for the coordination of design documentation is given in chapter 12 [of its guide]". SFPE also indicates that "coordination between disciplines is critical during these phases in order to ensure proper interaction between systems".

The 2005 edition of the International Fire Engineering guidelines (IFEG) [26] includes paragraph 1.2.13 which states that "real-life safety over ensuing decades will be highly dependent on elements other than the approved design", such as construction, commissioning, management and use, and maintenance. IFEG differ from the SFPE guide [25] as they include these elements into the design brief (which they call the Fire Engineering Brief, FEB). In paragraph 1.2.13 of IFEG, it is mentioned that "the FEB should access any tangible measures addressing the question of how high, or how low, one can prudently expect standards for the above elements to be maintained over the life of the building". Nevertheless, it should be noted that IFEG do not provide more insight on how these elements should be determined, quantified and included in the overall process. Besides, when looking at Figure 1.3.2 of IFEG describing the analysis of trial designs, the incorporation of the elements established in its paragraph 1.2.13 only affect the final report, as is the case with the SFPE guidelines.

A challenge related to the application of current PBFPD processes concerns the difference in the fire safety provided by fire protection measures between the conceptual design phase and the reality of the building use has been partially taken into consideration by adding redundancies in the fire protection measures as illustrated in Fig. 5-11. Nevertheless, this challenge is amplified by the aforementioned "disconnection" between the fire protection measures and the rest of the "building-occupant" system, not only in terms of technical measures but also in terms of managerial measures.

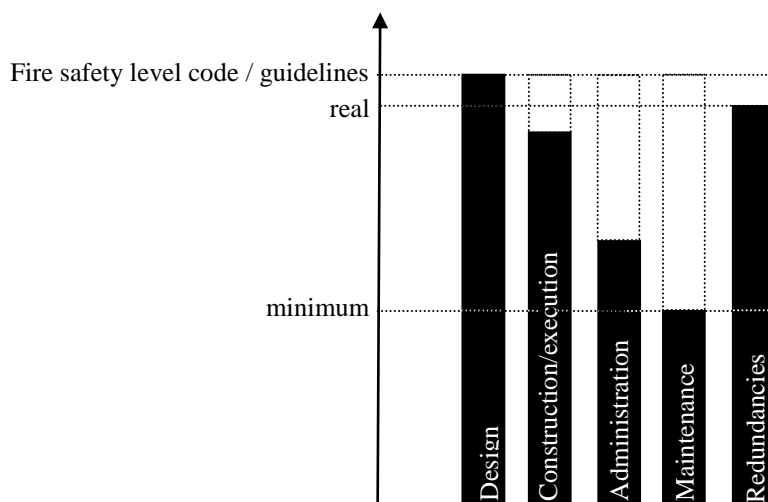


Fig. 5-11. Levels of fire safety as a function of building phases and the introduction of redundant fire protection measures, adapted from [27]

In the new PBFPD process, Step 5 relative to the evaluation of the integration of the fire protection measures in the system has to be done in order to be sure that the installation of these fire protection measures which are used for emergency situations are not counter-productive in the everyday use of the building. A feedback loop will be instituted for each fire protection measures or for sets of fire protection measures. This 5th important technical step is performed because of the challenges related to the maintenance and the possible changes of the building use once the design phase and the construction phase are completed (Cf. Chapter 2 of this dissertation).

The corresponding path relative to the PBFPD process step evaluating the integration of the fire protection measures into the system is illustrated in Fig. 5-12, and detailed in the following paragraphs.

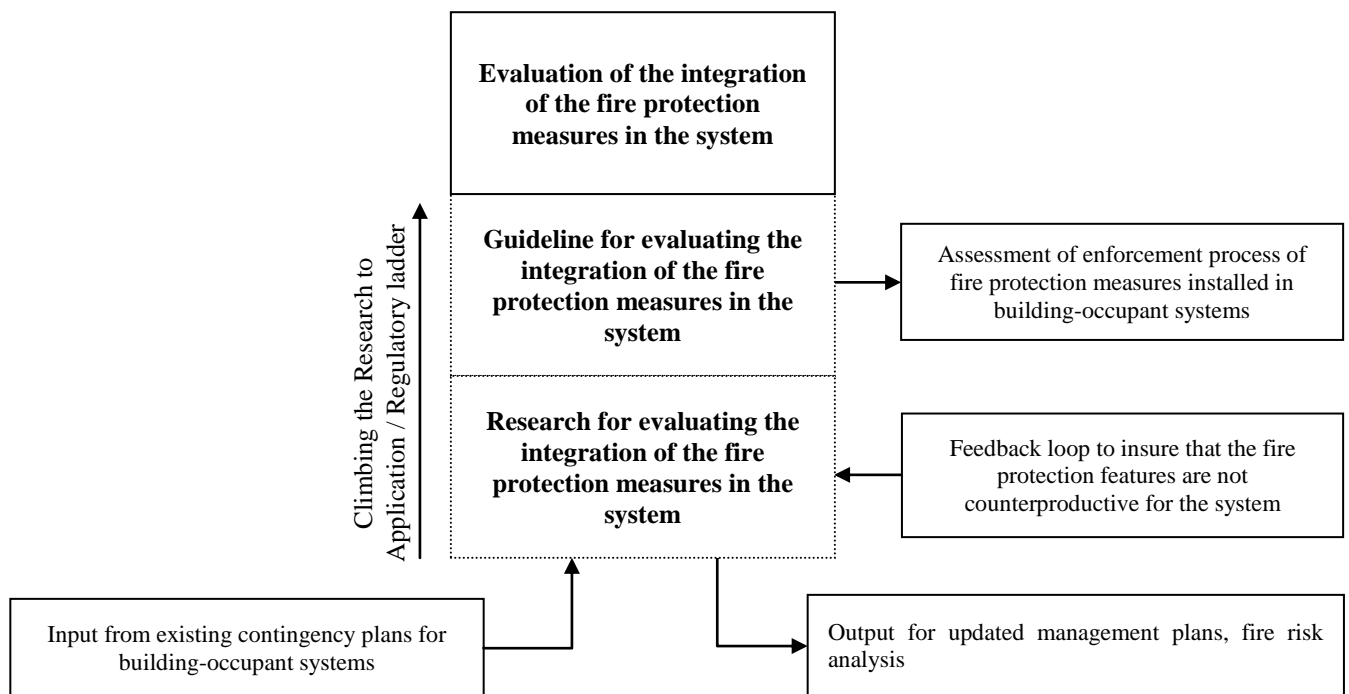


Fig. 5-12. Proposed path to the Evaluation of the integration of the fire protection measures in the system

5.3.5.2 *Research to be carried out for the process step related to the evaluation of the integration of the fire protection measures in the system*

Because the paradigm of study shifted from the fire event to the study of the effects of fire as a disruptive event of a "building-occupant" system, input from existing contingency plans are examined in order to verify that their own safety measures are not in contradiction with the proposed fire protection measures to be installed. Maximization of potential uses of the same measures dealing with different types of disruptive events or even "chronic" uses of the building can also be assessed in this process step.

Care will be taken in the associated documentation for the stakeholders so as to point them to the parameters of the fire scenarios that should remain under a certain range under pain of leading to a "worst case" scenario event. This integration or lack of, fire protection measures will then help the FPE focus on these particular parameters so the building owner, manager and occupants are required to keep them within a certain range. Interconnection is also made with the quantification of fire risk analysis: a sensitivity analysis should be performed for the most important parameters or sets of parameters in order to notably avoid the "worst case" scenarios from happening with a higher frequency.

5.3.5.3 Establishing guidelines or standards for assessing the integration of fire protection measures in a considered "building-occupant" system

One important foreseen output of the guidelines or standards related to the assessment of the integration of fire protection measures in a considered "building-occupant" system concerns the assessment of the enforcement process of these fire protection measures. The prescriptive requirements will also have their enforcement assessed this way, in a similar way Tsujimoto [15] looked at the effects of the installation of sprinklers in patient room in Japanese hospitals (cf. § 5.3.1.2 of this chapter) on fire casualties.

5.3.5.4 Using the guidelines for performing Step 5 in a PBFPD process

The output of this step is also an essential document for the different stakeholders concerning the possible interactions of the fire protection measures and the other components of the considered "building-occupant" system.

5.3.6 Proposed path to quantify Step 6: cost benefit analysis

5.3.6.1 Description of the cost-benefit analysis step and corresponding path of action

This step is carried out in order to assess the cost associated with implementing fire protection measures in the "building-occupant" system. Once again, the separation of the different "building-occupant" systems would make it easier to integrate the results of this cost-benefit analysis, considering these impacts would be different when looking at the same fire protection measure for a small new building, a small extension of a large building or a large new building (as illustrated by Charters and Ramachandran [28] about sprinklers in schools).

The corresponding path relative to the PBFPD process step performing the cost-benefit analysis of the fire protection measures into the system is illustrated in Fig. 5-13, and detailed in the following paragraphs.

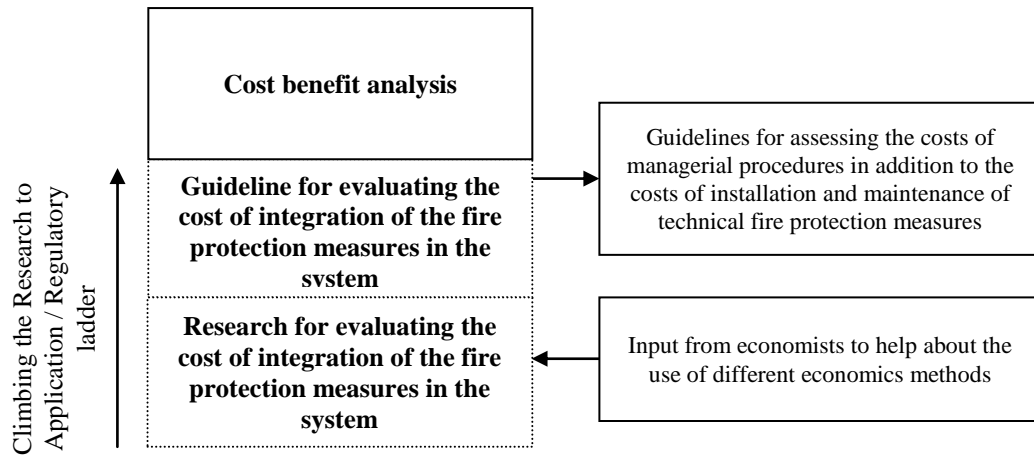


Fig. 5-13. Proposed path to the cost-benefit analysis of the trial designs

5.3.6.2 Research to be carried out for the process step related to fire protection measures cost benefit analysis

As research concerning the determination of the target vulnerability criteria (Step 2) requires the help from experts in toxicology, psychology, electronic engineers or structural engineers, this process step also requires a consequent input from experts outside of the fire protection engineering field: economists.

5.3.6.3 Establishing guidelines or standards for fire protection measures cost benefit analysis

For the process step related to the evaluation of the costs and benefits of fire protection measures proposed to be installed and maintained in well defined "building-occupant" systems, guidelines will be established to include the assessment of managerial procedure costs in addition to the costs associated with technical fire protection measures.

5.3.6.4 Using the guidelines for performing Step 6 in a PBFPD process

The output of this step is also an essential document for the different stakeholders concerning the costs and the benefits of installing and maintaining the fire protection measures proposed as a results of the fire risk analysis steps (Step 3 and Step 4) along with the document related to the integration of these fire protection measures into the "building-occupant" system, in the study paradigm.

5.4 *Conclusions for this chapter*

In order to overcome the shortcomings and challenges related to the application of current performance-based fire protection design (PBFPD) processes, a new PBFPD process has been developed within a "building-occupant" system paradigm.

Although the technical steps of the new process have been defined, guidance relative to the application of these steps still require research as well as the establishment of guidance specific to "building-occupant" systems.

This chapter detailed the actions fire protection engineers would be required to perform for each of the six technical steps of the new risk-informed PBFPD process and how these actions are similar to or different from the ones performed in the current PBFPD processes. For each step of the process, a plan of action has been proposed in order to describe the nature of the information that would be inscribed in the future guidance, and how this information would become a part of future guidelines and standards. Useful elements of information extracted from past and current research involving experts from a large spectrum of competencies and the systems stakeholders, as well as information from standardization efforts were presented for each step.

References

1. J. Taveau, Risk assessment and land-use planning regulations in France following the AZF disaster, *Journal of Loss Prevention in the Process Industries*, Volume 23, issue 6, (2010) 813-823
2. U.S. Nuclear Regulatory Commission (2007), *Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications – (NUREG-1824, EPRI 1011999) Volume 1: Main Report*, U.S. Nuclear Regulatory Commission and Electric Power Research Institute, 2007
3. NFPA 805, *Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants*, 2010
4. NFPA 99, *Health Care Facilities Code*, 2012
5. SFPE, *SFPE Code Official's Guide to Performance-Based Design Review*, Society of Fire Protection Engineers – International Code Council, June 2003
6. M.J. Karter, Jr., *Fire Loss in the United States during 2011*, National Fire Protection Association, September 2012 (available at: <http://www.nfpa.org/assets/files/PDF/OS.fireloss.pdf>)
7. U.S. Fire Administration/National Fire Data Center, *Fire in the United States 2003-2007*, Fifteenth Edition, October 2009
8. M.Ahrens, *Selections from the U.S. Fires in Selected Occupancies – Health Care Facilities, excluding Nursing Homes*, National Fire Protection Association, Quincy, MA (USA), March 2006
9. A. Alvarez, B.J. Meacham, *Towards an Integrated Performance-Based Design Approach for Life Safety Across Different Building Use Groups*, in: *Proceedings of the 12th International Interflam Conference*, Nottingham, UK, 2010
10. J.R. Thomas, "The use of fire statistics in guiding research and code development", *Interflam 2007*, proceedings of the eleventh conference, volume 2, pp. 1139-1147, Interscience Communications, London (UK), 2007, also

available as: J.R. Thomas, "The use of fire statistics in guiding research and code development", NRCC-49243, National Research Council Canada, 2007

11. M Salisbury, P Johnson, E. Yii and M.C. Hui, "QRA and fire safety – a beneficial experience...", Interflam 2007, proceedings of the eleventh conference, volume 2, pp. 1253-1263, Interscience Communications, London (UK), 2007
12. R. Fahy, Available Data and Input Into Models, chapter 4.3 of the "Workshop on Building Occupant Movement During Fire Emergencies, June 10-11, 2004, National Institute of Standards and Technology", NIST Special Publication 1032, NIST, March 2005
13. K. Tillander, "Utilisation of statistics to assess fire risks in buildings", VTT publication 537, VTT Technical Research Centre of Finland, 2004 (available at: www.vtt.fi/inf/pdf/publications/2004/P537.pdf)
14. Y. Kobayashi and H. Nozaki, A Statistical Method to Evaluate Fire Risks in Non-Residential Buildings in Japan," in: Fire Safety Science: Proceedings of the Eight International Symposium, China, International Association for Fire Safety Science, 2005, pp. 341-352
15. M. Tsujimoto, Death Risk by Building Fires in Japan and its Usage, Fire Science and Technology, vol. 23, no. 4, 2004, pp. 304-311
16. ISO/TR 16732-1:2012, Fire Risk Assessment
17. NFPA 557, Standard for the determination of fire loads for use in structural fire protection design, 2012
18. ISO/DIS 13571, Life-threatening components of fire — Guidelines for the estimation of time to compromised tenability in fires, revision of first edition ISO 13571:2007, 2011
19. T. F. Barry, Risk-Informed, Performance-Based Industrial Fire Protection, TFBarry Publications, Tennessee Valley Publishing, 2002
20. A. Alvarez and B.J. Meacham, "Ready-to-use" Building Layouts and Combustible Packages for 3-D simulations, proceedings of the Fire and Evacuation Modeling Technical Conference, 2011
21. A. Alvarez and B.J. Meacham, 'Test bed' environment process for assessing the appropriateness of engineering tools to be used in performance-based design applications, in: Proceedings of the 9th International Conference on Performance-Based Codes and Fire Safety Design Methods, Hong Kong. 20-22 June 2012
22. SFPE, SFPE Engineering Guide – Guidelines for Substantiating a Fire Model for a Given Application, SFPE G.06.2011, Society of Fire Protection Engineers, 2011
23. ASTM E1591-07, Standard Guide for Obtaining Data for Deterministic Fire Models, American Society for Testing and Materials, 2007
24. ISO16730:2008, Fire safety engineering -- Assessment, verification and validation of calculation methods
25. SFPE, SFPE Engineering Guide to Performance-Based Fire Protection, 2nd edition, Society of Fire Protection Engineers, 2007
26. IFEG, International Fire Engineering Guidelines, Australian Building Codes Board, Department of Building and Housing (New Zealand), International Code Council (USA), and National Research Council (Canada), 2005 edition
27. V. Stenstad and W.R. Bjørkman, A Systematic Approach to Fire Safety Design, in: Proceedings of the 5th International Conference on Performance-Based Codes and Fire Safety Design Methods, 6-8 October 2004, Society of Fire Protection Engineers, 2004, pp. 67-78
28. D. A. Charters and G. Ramachandran. Quantitative Risk Assessment in Fire Safety. Spon Press, 2011

6. CONCLUSIONS: MAIN OUTCOMES

The research presented in this dissertation is aimed at establishing the next generation of performance-based fire protection design (PBFPD). It originated from the fact that despite being in use for more than 20 years, the application of PBFPD remains limited, several shortcomings exist, and an increasing number of countries are moving toward 'prescribed performance' to address the gaps. There are many contributing factors. Research has been carried out in two principal areas: the relationship between occupants and fire safety measures in the contexts of holistic building performance expectations and the everyday use of the building, and into the lack of specifics within current PBFPD approaches.

This conceptual research, carried out in a paradigm centered around systems defined by building types and their associated occupants, led to the establishment of a functional new PBFPD process which would require all the actors involved in its application to shift to this system based paradigm from the current one related to the design of fire protection measures. Guidelines required to use the new process, for each of its steps and for relevant systems, were not established during this Ph.D. as they would require many years of research and development. Nevertheless, a plan of action dedicated to their establishment has been presented in this dissertation.

The main outcomes of the research are presented below:

- A review of two decades of application of PBFPD processes highlights challenges in applying these current processes both at technical and political levels. Challenges still exist concerning the definition/quantification of the strategic elements of any PBFPD process: the performance criteria (which current denomination should be changed to "fire effect criteria"), design fire scenarios, and the use of tools to quantify the trial designs.
- Despite efforts made to consolidate databases gathering information related to buildings, fires and occupant behaviors, it is still necessary to make such databases available to 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 "building-occupant" system has been defined, along with its main characteristics: "*Targets*" are the system agents responsible for the system daily performance (building occupants and components). During normal every day conditions or "*chronic states of the system*", they are located in "*functional zones*" where they carry out their activities associated with "*chronic objectives*", established in accordance with the system scope and performance. "*Utility zones*" include system support components such as electricity, HVAC and plumbing. "*Disruptive events*", such as fires, have to be considered between two consecutive "*chronic states*". In order to mitigate the "*event effects*" on the system performance, "*acute objectives*" have to be set up so to take into consideration "*direct effects*" and "*indirect effects*" with which the disruptive events can possibly damage the targets.

- The performance of a building is related to objectives set up for the normal use of the building and it is important to quantify how disruptive events can affect this performance.
- A building design agreed among different stakeholders covers many and sometimes competing objectives, not only dealing with normal building uses, but also during disruptive events.
- There is a need for a system approach to assess the overall building performance in order to prevent some installed building components being ignored or misused by the building occupants, especially during emergency situations.
- Within the "building-occupant" system paradigm, a risk-informed system specific performance-based approach has been established in order to quantify the effects of disruptive events on the overall building performance and to help verify that the protection measures installed in the system formed by precise building types and their associated occupants are well integrated in this system.
- The aforementioned system specific process was applied to deal with fire disruptive events, that is to say to quantify the effects of fire events on the overall performance of the system. The main difference between the current PBFPD processes and the new one is related to their respective problem definition: the current processes are focused on the design of fire protection measures that would mitigate the effects of fire scenarios defined between ignition and extinguishment while the new process is aimed to assess how fire protection measures, as an integrated component of the system, would help mitigate the effects of fire events, including the recovery period of the system.
- Being focused on the system, a fire risk analysis is performed centered on the study of the actors of the system in their everyday performance and how fire protection measures can mitigate the effects of fire events on this everyday performance. Besides, the new PBFPD process contains a technical stage dedicated to the evaluation of the integration into the system of the fire protection measures, selected after the fire risk analysis. A cost-benefit analysis finalizes the technical part of the process which has been performed independently and in a straightforward manner by fire protection engineers (FPEs). At the end of this technical part, FPEs have elaborated three documents detailing the results of the fire risk analysis, of the evaluation of the integration of the fire protection measures into the system and of the cost-benefit analysis. Based upon these documents, the stakeholders decide which fire protection measures they would have installed in their system. This process is then demonstrating a complete separation between the "political" decision-making process and the "technical" resolution of the engineering fire problem. As a consequence of this separation, the technical stage of the process becomes transparent, both for stakeholders who establish the performance targets (political decision) and for the engineers in charge of the evaluation of the disruptive effects on the system performance (technical analysis);
- As a proof of concept, it has been shown through text and examples how the new framework addressed the challenges with the existing approaches, operated within a more holistic "building-occupant" system paradigm,

illustrated how viewing fire as a perturbation within the larger "building-occupant" system would increase fire safety performance over the life of a building, and deliver a higher level of building fire safety performance.

- It is important to include the "building-occupant" system stakeholders not only in the making of the guidelines for each technical step of the proposed process, but also in the research process itself, as these stakeholders know the particularities of their systems;
- Multiple iterations would be required in order to establish the guidelines as the process steps are dependant in terms of input-output;
- Research for the different steps would require more or less time and resources, as well as the participation of engineers from disciplines other than fire protection engineers;
- Technical literature contents (including engineering tools and input data), as well as standards and codes relative to the different technical steps of the process would have to be examined and applied to specific "building-occupant" systems. Collections and examination of the past studies are still relevant even if the data might require to be updated (e.g. walking speed values were established in the last 1980's and pieces of furniture in the NIST furniture calorimeter experiments may be outdated as materials have evolved since then).

7. FUTURE WORK

The future work is aimed at the establishment of guidelines, specific to "building-occupant" systems and in elaborating each technical step of the proposed PBFPD process. One can imagine the difficulty in managing the development of guidelines for all the steps, for all the possible "building-occupant" systems:

- interactions between these steps have to be examined and assessed,
- the research needed for each step guideline is currently at different level.

In consequence, there is a need for coordination of all the efforts as well as a repository of the information gathered for each step, from the initial research gathering, to its analysis and to the establishment of the corresponding guidelines.

Such an environment which facilitates this coordination and stores the guideline development has been created in the form of a web-platform. The original idea of a web-platform was associated with the 'test bed' environments for fire effects tools as presented in Appendix A2. Along with the objective of performing studies to assess the appropriateness of tools to be used for performance-based applications, this first version of the web-platform was also intended to contain databases for "fuel packages" ready to use in 3-D simulations.

The development of this original web-platform was put on hold as the research presented in this Ph.D. dissertation was carried out. As the new PBFPD process was elaborated with its six different technical steps, it was found that the structure of the original web-platform could be used to facilitate the establishment of the process step guidelines and serve as a repository for input data.

Indeed, each step can be perceived as an engineer step aimed at the quantification of important parameters required to solve the engineering problem: how to quantify and mitigate the effects of fire events on the overall performance of a considered "building-occupant" system? In other terms, each step would require the use of corresponding tools, supplied with the input data needed to use these tools, in order to solve a specific step issue for a considered "building-occupant" system (Fig. 7-1). The latter part, solving a specific step issue for a considered "building-occupant" system, is precisely why the 'test bed' environments were created in the first place.

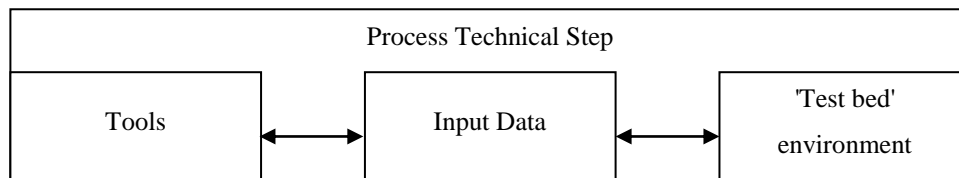


Fig. 7-1. Interconnections between tools, input data and 'test bed' environments

It should be noted that tools related to the "Target Vulnerability Criteria Estimation" Step are not primarily about using engineering tools but mostly using data established by specialists such as:

- toxicologists, clinicians and psychologists for assessing threshold damaging fire effects on people,
- material engineers and electronic engineers for assessing threshold damaging fire effects on valuable artifacts and pieces of equipment important for the system performance,
- structural engineers for assessing threshold damaging fire effects on building structures.

The importance of the use of 'test bed' environments is illustrated in a schematic way with the four following figures: Fig. 7-2. shows that different populations can be defined according to the buildings in which they are located. Due to the building configurations and contents, particular fire distributions can be determined for different types of buildings, as illustrated by Fig. 7-3. According to their characteristics, building occupants are more or less sensitive to the effects of a fire. Fig. 7-4. shows how the different populations could be more or less affected by the fire distributions established by building types. At last, Fig. 7-5. integrates the different domains linking buildings, their occupants and the types of fires that could occur in these buildings and it shows the importance of establishing 'test bed' environments, in order to concentrate the efforts of tool developers to validate their tools in priority for the domains defined by the "building-occupant" systems.

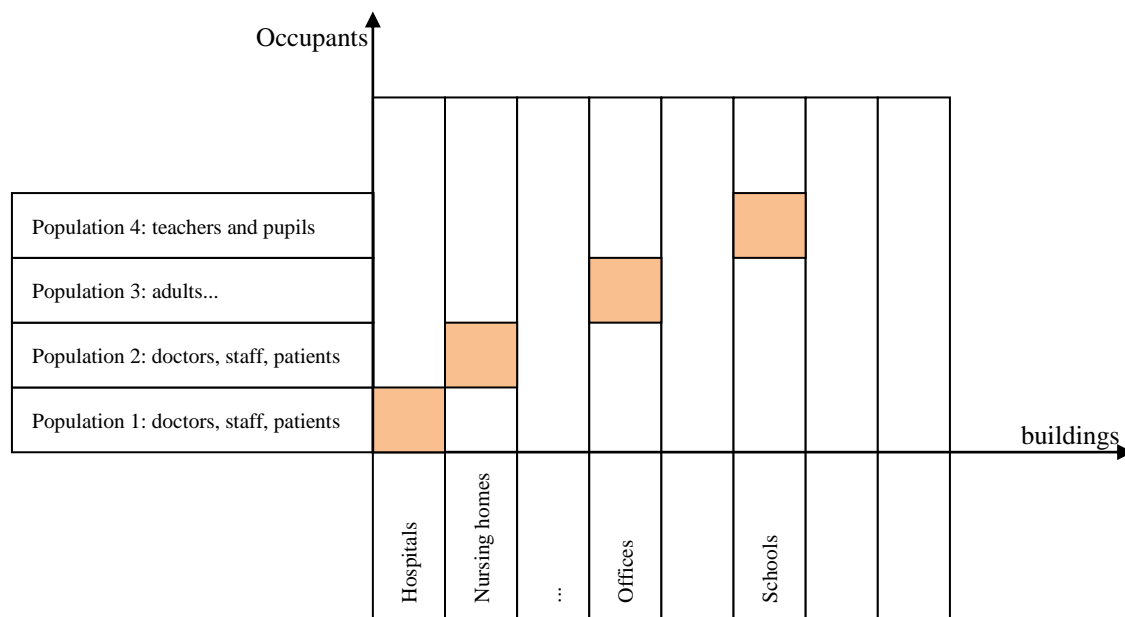


Fig. 7-2. Occupant populations as a function of buildings

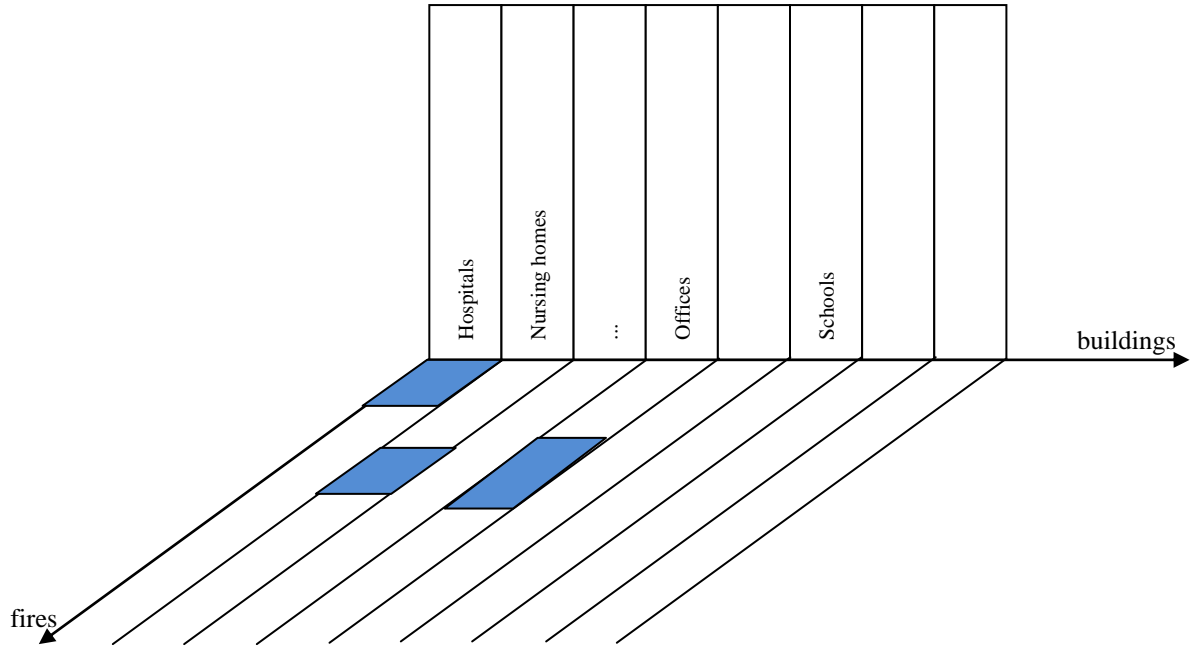


Fig. 7-3. Fire distributions as a function of buildings

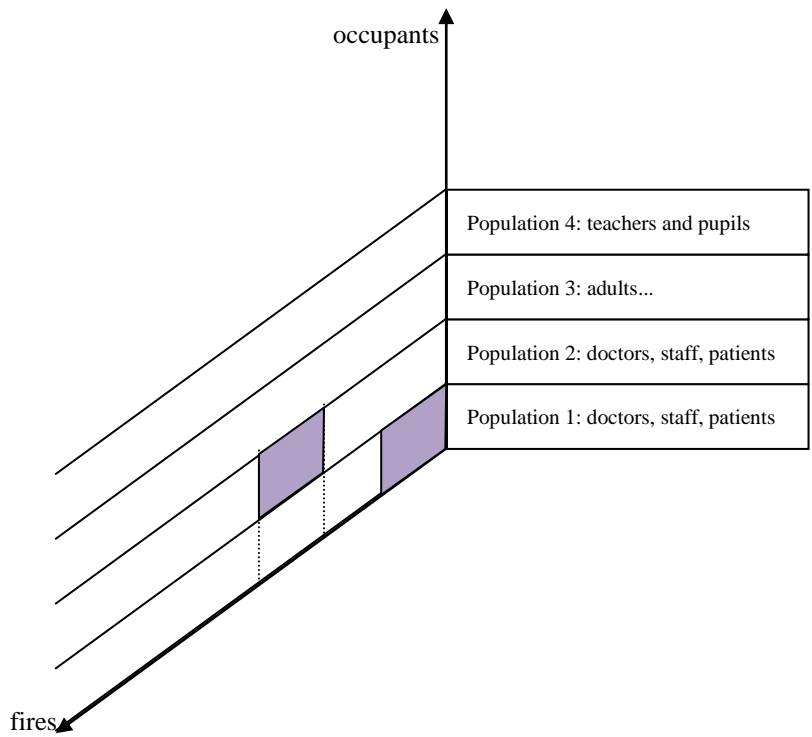


Fig. 7-4. Effects of fire distributions on building occupant populations

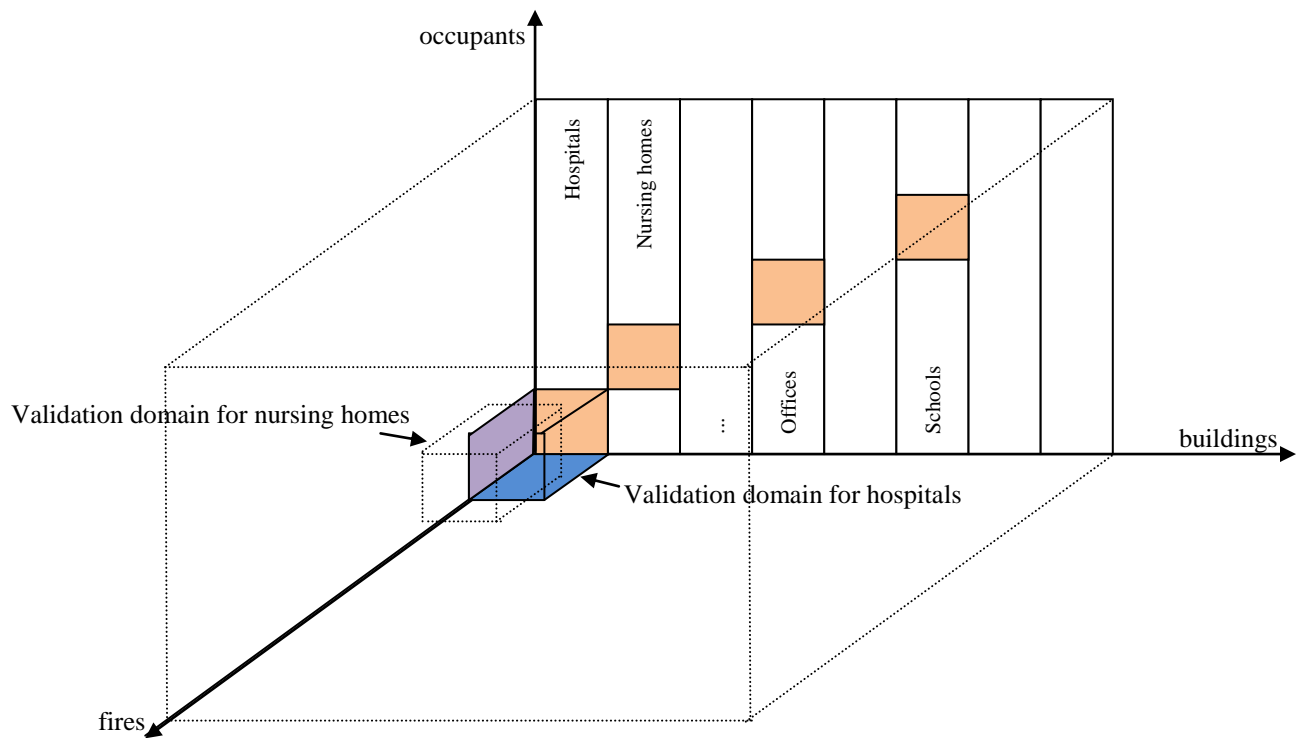


Fig. 7-5. Validation domains for different "building-occupant" systems, in comparison with the physical domain of possibilities involving buildings, fires and occupants

Future work will then consist in establishing relevant "building-occupant" systems and in communicating all their descriptive information to tool developers, as well as the important engineering issues related to each of these systems.

It should be noted that some informative structure has been developed in recent years in order to aggregate in one place all the information related to a building. Indeed, some future work will be related to incorporating into the web-platform, information collected via the use of Building Information Modeling (BIM). The National Building Information Model Standard Project Committee defines BIM as:

"Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.

A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder."

Appendix A1

"Towards an Integrated Performance-Based Design Approach
for Life Safety Across Different Building Use Groups"
presented at the international conference "Interflam 2010"

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TOWARDS AN INTEGRATED PERFORMANCE-BASED DESIGN APPROACH FOR LIFE SAFETY ACROSS DIFFERENT BUILDING USE GROUPS

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INTRODUCTION

A main advantage of Performance-based Design (PBD) approaches for fire safety is to allow for the engineering of design solutions that provide at least an equivalent means of protection to prescriptive building and fire code requirements, but without imposing undesired constraints on aspects of building design, such as design flexibility, innovation, or maximization of cost/benefit ratio. Another advantage of PBD approach is to consider multiple stakeholders' objectives: not only the life safety objective which is the primary objective of building codes, but also architectural and user objectives, as well as business interruption and property protection. Performance criteria established for each objective are the parameters used to evaluate the suitability of a PBD solution. Nevertheless, these parameters are not explicit and they need an agreement of the involved stakeholders. For life safety, performance criteria are associated with the assessment of fire effects on people, often in terms of threshold values of temperature, thermal radiation, toxicity, or visibility. This assessment is also based on design fire scenarios, which are developed upon representative design fire scenarios. These design fire scenarios also need the agreement of the different stakeholders.

A range of guides, guidelines and standards have been developed in order to help the engineer elaborate PBD solutions and the Authority Having Jurisdiction (AHJ) approve the final design⁽¹⁻⁵⁾. Even though these guidelines emphasize the importance of various parameters upon the acceptability of design solutions, they fail to provide a detailed framework for evaluating a specific building project, mainly because their scope of application is too broad. Known difficulties in achieving a homogeneous working framework for the engineer and the AHJ are related to, among others⁽⁶⁾:

- the definition of quantified acceptance criteria,
- the selection of design fire scenarios,
- the tools used to perform the fire consequence analysis,
- the quantification of the most important parameters of the overall fire risk estimation.

In considering the many challenges with PBD as currently carried out, a simple idea emerged based on the fact that fire safety requirements are defined in regulation according to the building occupancy use: PBD solutions should address the intent of the issues embodied in the prescriptive regulations. Since existing PBD guidelines have already introduced the importance of building and occupant characteristics to PBD solutions, albeit without quantifying that importance, a next logical step is to develop more specific PBD guidance around these characteristics, drawing upon supplemental data for the PBD analysis from operational and loss experience. This paper outlines the concept of an integrated approach to PBD that is based around building use groups and focused on life safety.

BREAKING DOWN A COMPLEX TRIPARTITE HETEROGENEOUS FRAMEWORK

Developing a good building fire safety design requires appropriate consideration of the interaction between the building, the people who occupy it, and the fire and its effects (Fig. 1). At present, this concept is embodied in existing guidance documents in a rather generic manner, asking engineers to consider building characteristics, occupant characteristics and fire characteristics.

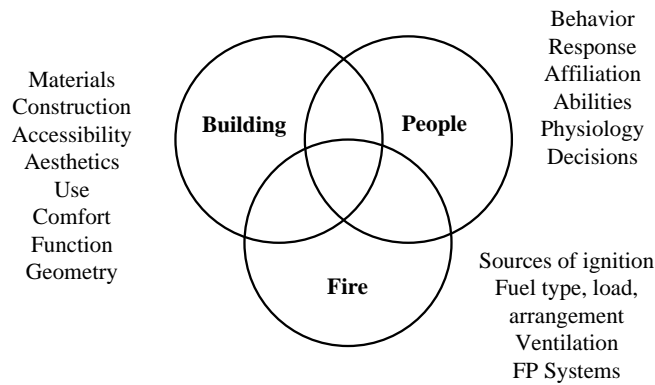


Figure 1. Building life safety design framework related to fire event

Since most of the current guidelines are rather generic, a gap exists in that critical differences between configurations found in assemblies, offices, hospitals and so forth are not necessarily addressed. More detailed guidance would be helpful, but it is difficult, if not impossible, to develop detailed guidelines without dealing with the elements that make a building occupancy specific. This is where a connection to building use / occupancy / type can be helpful. When used in building regulations, "building occupancy" is associated with characteristics of occupants that are going to use it on a regular basis: patrons in places of assembly, students in schools, elderly people in nursing homes, detainees in prisons, travelers in airports and subway stations, etc. In considering how this concept can be applied more specifically to the PBD process, the relationship can be viewed through the prism of the "building occupancy spectrum" (Fig. 2).

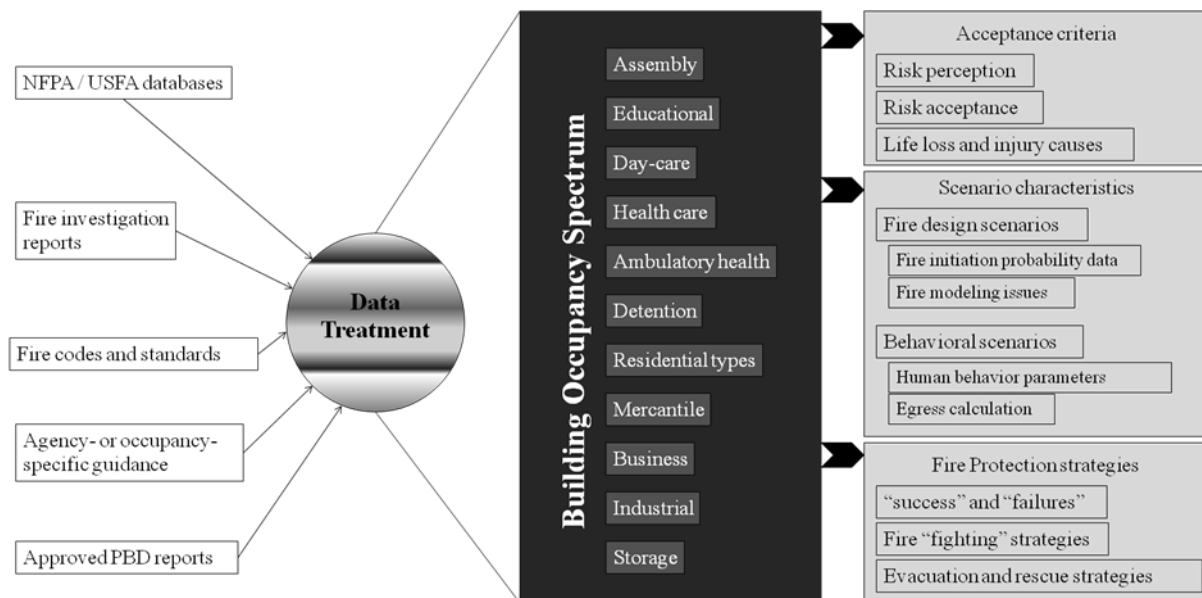


Figure 2. Data treatment schema of various sources, through the building occupancy spectrum, in order to get qualitative and quantitative parameters used in PDB approach

In order to develop detailed occupancy-specific guidelines, several steps are needed:

- First, the proposed framework is used to examine different sources in order to collect pertinent data for each building occupancy, and to try to solve issues related to the perception of risk, the level of risk acceptance the AHJ is prepared to accept (or has accepted in the past), and the nature of the causes that led to fire injuries and life loss (so to extract quantified performance criteria).
- Next, scenario characteristics will be elaborated considering the parameters of the fire development itself (fire design scenarios) and considering the human behavior parameters needed to perform egress calculations (behavioral scenarios).

- Finally, examination of different fire protection strategies would be conducted, including data from fire events where these strategies were either efficient or inadequate to ensure the fire safety function. As staff, rescuers and fire fighters are also components of the fire protection system, data will also be collected for each building occupancy type, since the nature, actions and number of this people vary with occupancy types.

At present, the development of the framework is based primarily on data available in the USA, with input to the proposed framework mainly composed of data gathered from:

- Fire statistics collected by the National Fire Protection Association (NFPA) and the US Fire Administration (USFA) - in their databases as well as fire investigation reports. This is seen as primary main sources for fire data. Indeed, information from fire statistics and fire investigations reports is important to collect and analyze as these past events are the most realistic ones. These sources are particularly valuable for estimating human behavior parameters as people were actually put into situation. Similar investigation reports may include coroner reports as they can appear very useful to determine the toxic doses absorbed by the fire victims and the circumstances of fire fatalities⁽⁷⁾;
- Building and fire codes and standards (International Code Council (ICC), NFPA, local). These are important to consider not only because they are the documents where prescriptive requirements are presented so they represent the point of comparison with Performance-based Design alternatives, but also because some valuable information can be extracted when examining the factors that contributed to regulation changes;
- Agency- or occupancy-specific guidance (e.g., General Services Administration (GSA), Department of Veterans Affairs (DVA), Joint Commission on Accreditation of Healthcare Organizations (JCAHO), etc). These are important to obtain occupancy-specific requirements that may go over and above minimum building and fire regulation, including operational guidelines for staff, employees and other who have an impact on fire safety;
- AHJ-approved Performance-based Design reports. These are important because they reflect approved parameters for acceptance criteria, scenarios and fire protection strategies. It should be noted that these collected parameters only give an indication of accepted values as it is intended that they are highly dependent on the decision making process that allowed the engineer and the AHJ (and the other relevant stakeholders) to approve these parameters on a particular project.

CHARACTERIZING THE BUILDING OCCUPANCY SPECTRUM

Although life safety is a key objective of the proposed PBD framework, the building occupancy spectrum has to be constructed from a much broader perspective than fire safety alone. This is because buildings are the creation of architects – designed for clients and occupants primarily for "normal" use. This is where many of the other guides fall short – they assume the emergency condition to be a primary driver in building and occupant response, when in fact this is not the case. As reflected in Figure 1, the integration of fire safety features, although vital to the building global safety, is not a primary, or at least not the sole concern of the building users/designers/owners. This is where building occupancy classification can help. However, classification of buildings by several agencies dealing with fire safety (i.e. ICC and NFPA for regulatory purposes or NFPA and FEMA for fire statistics) is not homogeneous.

A primary classification of the building uses is given in Figure 2, but this classification may not be detailed enough to capture all the specificities of all the possible uses of a building. For health care facilities, for example, ICC⁽⁸⁾ gathers the following buildings in its institutional group I2: child care facilities, detoxification facilities, hospitals and mental hospitals and nursing homes. The problem with all the different subdivisions in the building occupancies is that the sampling decreases in size as one selects one particular type of building. Table 1 provides the different sub-categories of US hospitals inventoried by the American Hospital Association (AHA) for 2008.

Number of U.S. Community Hospitals	5,010
Number of Federal Government Hospitals	213
Number of Nonfederal Psychiatric Hospitals	447
Number of Nonfederal Long Term Care Hospitals	129
Number of Hospital Units of Institutions (Prison Hospitals, College Infirmaries, etc.)	16
Total Number of All U.S. Registered* Hospitals	5,815

*An institution may be registered by the American Hospital Association as a hospital if it is accredited as a hospital by the Joint Commission on Accreditation of Healthcare Organizations (JCAHO) or is certified as a provider of acute services under Title 18 of the Social Security Act and has provided the Association with documents verifying the accreditation or certification.

Table 1. Classification of US registered hospitals by AHA⁽⁹⁾ in 2008

As presented in Figure 3, health care facilities ("inpatient" facilities) represent a "small" number in comparison with office buildings that were estimated⁽¹⁰⁾ to 824,000 in the USA in 2003. Figure 4 shows that the current stock of offices still contains a significant portion of buildings that were constructed prior to 1970 (an estimated 346,000 – about 42% of the existing office buildings in 2003).

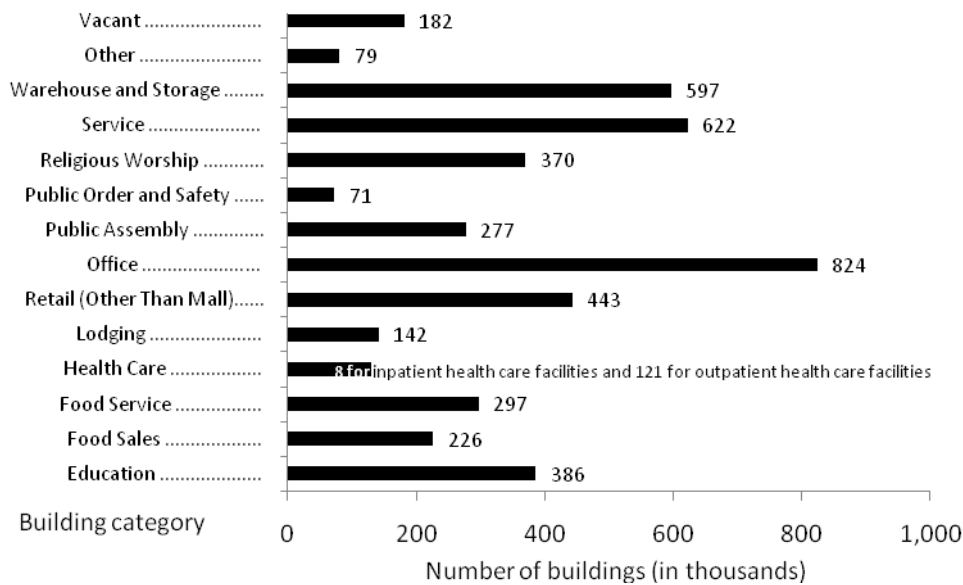


Figure 3. Commercial building distribution according to their occupancy type in the USA in 2003⁽¹⁰⁾

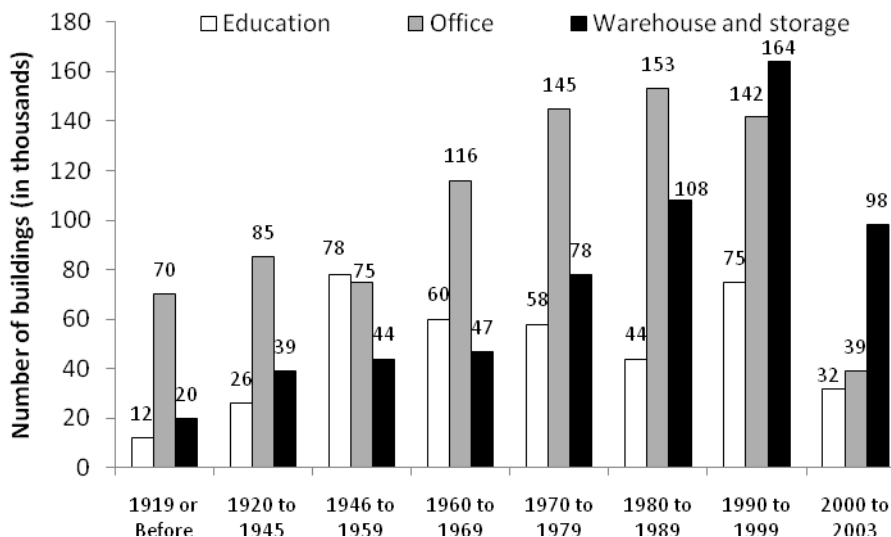


Figure 4. Construction year distribution of three building occupancy uses⁽¹⁰⁾

ASSESSING ACCEPTANCE CRITERIA FOR FIRE SAFETY OBJECTIVES

With respect to acceptance criteria related to the life safety objective(s) for different building groups, the aforementioned PBD guidance documents agree that data should be collected in regard to the targeted population (adult workers in offices are more "resistant" to the effects of a fire than children in schools, elderly people in retirement homes or patients in hospitals). Ideally, this means that the quantified criteria should take the different types and levels of vulnerability into consideration. However, specifics regarding the targeted populations and possible systematic methods to assess them are not provided. In addition, if the guides also consider the estimation of individual risk or societal risk, they do not provide a detailed method regarding the estimation of these risks for different building occupancies. At least, they should have made reference to studies⁽¹¹⁾ correlating the levels of "acceptable" risk with the population vulnerability and the level of risk control which are both functions of the building occupancies: societies and individuals are more concerned about the possible loss of multiple "vulnerable" persons who do not control their own risk than about the loss of the same amount of persons who seem to willingly take some risks (patients in hospitals and children in schools are highly dependent on other people to evacuate during emergency situations, whereas workers in industrial plants accept to be at the vicinity of hazardous materials, in exchange of a monetary compensation).

The use and occupancy classification for specific buildings or facilities, as described by ICC⁽⁴⁾ already takes into consideration the fact that some buildings can represent a "substantial hazard to human life in the event of failure" (jails and detention facilities are then classified in Performance Group III) or they can be "designated as essential" (hospitals are then classified in Performance Group IV). In a sense, this classification shows that buildings classified in higher performance groups, the magnitude of the design hazardous event or "perturbation" has to be moderate, if not mild.

This notion of "perturbation" - in the context of other stakeholders' objectives, such as business interruption - has been examined in some detail, with key observations summarized in the following paragraphs.

Specific building types have specific "chronic" demands

The concept of "competing objectives" is not new, and it has been noted that competing objectives should be addressed in PBD⁽¹²⁾. However, there has been little or no discussion with respect to how one prioritizes competing objectives. In a move toward understanding how users might prioritize objectives, the terms 'chronic' and 'acute' are introduced. As used here, the association between the building and its occupants during normal use is described through "chronic" objectives – those objectives which are based on the regular use of the building. In this taxonomy, hazard events (fire, flood, earthquake...) may be seen as "perturbations" of the "building-occupant" system. Objectives (or situations) associated with such events are then defined as "acute". Buildings are complex structures by essence; in addition to the building parts devoted to its chronic functions (e.g., auditorium in theater, classroom in school), buildings contain systems intended to support the chronic operation of the building (electricity, plumbing, heating, ventilating and air conditioning, etc). These support systems are used in an everyday basis, where as the fire protection systems (as part of all emergency systems) are meant to be used in the specific event of a fire (and unwanted false alarms). Because of this objective dichotomy, competing priorities may appear between the "chronic" objectives and the "acute" ones related to fire safety. This is important when trying to understand how people might respond in acute situations as compared with chronic conditions.

Tubbs and Meacham⁽¹³⁾ summarize some of these competing priorities related to hospitals:

- patients' comfort is offered by large, well-lit facilities that challenge the fire safety concept of compartmentation,
- design flexibility due to ever-changing programmatic needs may appear as a cost-benefit challenge for the fire safety design,
- security needs challenge safe egress capabilities.

Other examples related to the above include:

- open spaces in 'spec' office buildings, which are outfitted at the request of the entity renting the space, may conflict with compartmentation desires;
- during the lifespan of a building, contents and occupants may vary in characteristics and number, especially in the numerous buildings of multi-occupancy type;
- following the events of September 11, 2001, an increase of security points inside public places creates situations that challenge the chronic objective of providing uncongested pedestrian access and movement and the acute fire safety objective of easy egress (e.g., many spaces where airport security screening has been set up where probably not designed for large numbers of densely packed people queuing up and the exit system may not be designed to readily accommodate this).

Looking at hospitals in particular, other "chronic" objectives exist due to their very specific design: patients in Intensive Care Units (ICU) are often connected to machines that keep them alive, operating rooms are designed to be sterile and outfitted with life-sustaining equipment that cannot be quickly removed, etc. In addition to the criteria associated with the fire threat, performance criteria related to the safeguarding of the life supporting pieces of equipment should be established, not only as a result of the fire threatening conditions but also as a result of a potential application of a fire suppression system. For hospital wards, the main nurse station could be positioned in an open corridor so nurses have a constant view of the ICU (hospital stakeholder's objective), which is in not in accordance with the fire safety objective of limiting the smoke and fire spread by adding compartmentation features.

"Chronic" objectives may also appear in clear contradiction with the safety objective of evacuation in case of a fire in buildings such as correctional facilities where people have to be kept behind locked doors. Less obvious types of buildings such as casinos are primarily designed to have the patrons focused on staying at the same spot for long periods of time.

With respect to chronic objectives, perturbations, and acute objectives, a crucial concept to analyze and quantify is the duration of the shift between the "chronic" (normal) condition to the "acute" (fire emergency) condition – this can have a significant impact on establishment of required safe egress time (RSET). Another critical concept to analyze and quantify is the period required to restore the facility to "chronic" (normal) operations.

It is also important to note that in particular areas, safety objectives can also compete, especially when hazardous materials are involved. For example, in plants manufacturing nuclear fuel, PMMA based "glove boxes" that are specially treated with lead to absorb the effects of radioactive materials that operators manipulate are a very important source of combustible. Nevertheless, they may appear to be more effective for this safety purpose than the glass based "glove boxes" because the "chronic" objective supersedes the "acute" objective. Fire can also disrupt a safety procedure of a hazardous system; in that case, restoration of that safety procedure may also supersede fire safety protocols. In order to deal with this potential competition of objectives, a feedback loop between the different stakeholders should always been applied.

Chronic objectives and fire safety objectives also have to adapt in time. In day-care occupancies and health care occupancies, one of the biggest challenges is reducing the chances that a patient may acquire a health care-associated (nosocomial) infection. Related to this objective, the introduction of alcohol-based hand rubs was considered as a potential source of fire, especially when positioned above an electrical source. In consequence, NFPA had to study this fire hazard issue, introduced specific paragraphs in the 2006 version of the Life Safety Code and revised them in its 2009 version⁽³⁾ (paragraphs 18.3.2.6 and 19.3.2.6 for health care facilities).

To address the above issues, the proposed integrated approach requires describing the building's "chronic" uses and related demands, which comes before the integration of the stakeholders' objectives with respect to acute objectives associated with system perturbations. It also requires consideration of the transition between the chronic (normal) use of the building and the fire emergency period, which is a key issue in the evacuation.

Risk tolerance criteria and building uses

Some building occupancy uses are more regulated than others because the associated societal risk tolerance varies according not only to the likelihood and the consequence of fire events, but also to the number of simultaneous casualties, vulnerable populations and the level of safety control that the public concedes to third parties. A characteristic example of low fire risk tolerance applies to health care facilities, where vulnerable populations are present and where the public literally puts their lives into the hands of the healthcare facility staff.

As an aftermath of the Wincrest Nursing Home fire (arson) that caused 24 deaths on January 30, 1976, the City of Chicago and its Board of Health made several safety improvements including⁽¹⁴⁾:

- installing a sprinkler system in all new and existing nursing homes and that the new sprinkler systems must be connected with the fire alarm system,
- requiring emergency training for all nursing home staff which includes transporting patients during an emergency,
- abolishing dead end corridors in nursing home,
- organizing disaster plan and regular emergency drills made by the Board of Health,
- enforcing smoking rules so residents / visitors must smoke in designated areas supervised by staff.

In 2003, two fires occurred in two different unsprinklered nursing homes in the US: one fire in Hartford, Connecticut, causing 16 casualties and one fire in Nashville, Tennessee, causing 15 deaths. As a consequence, Centers for Medicare and Medicaid Services (CMS) of the US Department of Health and Human Services issued on August 13, 2008 a final rule regarding fire safety requirements for Long Term Care facilities and more particularly, the installation and the maintenance of automatic sprinkler systems in the whole building: "This final rule requires all Long Term Care facilities to be equipped with sprinkler systems by August 13, 2013. Additionally, this final rule requires affected facilities to maintain their automatic sprinkler systems once they are installed⁽¹⁵⁾".

Several lessons can be drawn from these two sets of events:

- because of the US regulatory system, cities, states and the whole nation can decide of their own requirements regarding fire safety. A tragic event occurring in one state (Illinois in 1976) was not enough to "trigger" the same level of requirements in other states;
- nevertheless, health care management has entered under a federal scope as the federal financial participation rate ranges from 50 to 83 percent of each dollar spent by a state which is then required to describe the nature and scope of its program in comprehensive written plans submitted to CMS⁽¹⁶⁾. If the regulation is enforced at a federal level, more facilities will be affected by the regulation and the corresponding sampling in fire statistics may get larger (even if the sprinkler requirement is adopted nationwide, states still have the possibility to increase the level of safety by requiring additional fire safety measures);
- the population is getting older so the public is going to be more and more concerned about multiple deaths fires occurring in nursing homes and other health care facilities (it should be noted that an average of about 2,300 of the nation's approximately 16,300 US nursing homes reported a structural fire each year from 1994 through 1999 and that annually, the average number of fire related nursing home deaths nationwide was about five⁽¹⁷⁾).

These two examples are relevant of the very low risk tolerance of the AHJ (local and federal) is prepared to accept in case of fires in nursing homes. As a consequence, the minimum requirements are associated with the installation and the maintenance of a sprinkler system, which efficiency to prevent the extension of a fire is quite high. For this particular case, it seems that any PBD approach would have to consider a sprinkler system in this type of facilities as a fire safety measure, as an imperative demand from the AHJ.

Going forward, the situation for nursing homes and requirements for sprinklers will serve as a basis for assessing other occupancies, as it is expected that similarities may exist for other highly regulated building uses, and capturing such experience is important to benchmarking "tolerable" safety.

SELECTING AND EVALUATING DESIGN FIRE SCENARIOS

Considering the elaboration and the selection of design fire scenarios upon which the PBD solutions are to be based, Chapter 8.3 of the *SFPE Engineering Guide to Performance-Based Fire Protection Design*⁽¹⁾ (SFPE Guide) presents various techniques that can be used in identifying possible fire scenarios, such as Failure Modes and Effects Analysis (FMEA), failure analysis, "what if?" analysis. It also states that "the scarcity of the [historical] data needed to assigning probabilities [to fires] can limit this approach for conducting Performance-based Design for a specific [new] project". Concerning past fire histories, it is indicated that they "can provide some very useful input by identifying potential failures of various items, as well as frequencies and severities of fires". It should be noted that the SFPE Guide presents various tools useful to describe the scenarios as possible chains of events; quantified data is still to be gathered in order to quantify the probabilities of these events. Unfortunately, like the SFPE Guide, most guides provide fewer sources about how to quantify the possible events than tools used to identify possible scenarios. Nevertheless, the guides suggest that data should be collected using fire incident databases as they provide some information regarding how fire started, spread and ultimately led to fatalities and injuries (or building damage for a property loss objective). Studies on the reliability of fire protection systems including smoke detectors and automatic suppression systems are also sparingly available, as often only single values are given in quantitative risk assessment studies. Here again, guidance documents on Performance-based Design are very generic, as they were not designed to provide detailed methods of conducting a PBD approach for a particular building project. They also propose different methods to achieve the fire safety goals of the PBD approach, using risk matrix or a quantified fire risk assessment, and they emphasize different aspects on the selection of design fire scenarios. Nevertheless, they all agree to obtain data for fire statistics and fire investigations reports of "historical fires".

As pointed out previously, it seems important to intensively examine fire incident databases and fire investigation reports in order to extract the most accurate parameters of "real" fires and therefore to constitute a validated, if not exhaustive, base for the parameters needed to imagine and ultimately select the design fire scenarios (with eventually their estimated incidence on the overall fire risk). Table 2 below is an example of data presented in the NFPA reports of US fires in selected occupancies⁽¹⁸⁾. This data shows a correlation between the extent of flame damage and the number of casualties and injuries as well as the direct property damage. A discrepancy appears between the fires that are related to the life safety objective as their maximum extent is the room of fire origin and the fires that are related to the property damage objective as the more the fire extents, the more damage it causes, which could indicate that the design fire scenarios for the life safety objective may not be the same for other business or property oriented objectives. This table, as well as the global results that are usually presented in the NFPA reports, is too general to be used in a Quantitative Risk Analysis. For example, 510 fires confined to room of fire origin led to 44 civilian injuries. What is the number of fires that led to multiple (5, 10, even 44) injuries? Did these fires occur in the same type of health care facilities, in the same state, with the same fire ignition conditions?

Extent of Flame Damage	Fires		Civilian Deaths		Civilian Injuries		Direct Property Damage (in Millions)	
	Count	%	Count	%	Count	%	Count	%
Confined or contained fire	560	18%	0	0%	8	9%	\$0.1	0%
Confined to object of origin	1,930	61%	0	0%	29	33%	\$3.8	18%
Confined to room of origin	510	16%	1	100%	44	51%	\$4.2	20%
Confined to floor of origin	60	2%	0	0%	1	1%	\$2.1	10%
Confined to building of origin	90	3%	0	0%	5	6%	\$10.3	49%
Extended beyond building of origin	10	0%	0	0%	0	0%	\$0.7	3%
Total	3,150	100%	1	100%	87	100%	\$21.3	100%

Table 2. Structure Fires in Health Care Facilities⁽¹⁸⁾, Excluding Nursing Homes by Extent of Flame Damage (1999-2002 Annual Averages)

NFPA reports, as well as USFA reports, are a good starting point in order to collect generic information about fires in selected occupancies. Nevertheless, results shown in these reports do not seem to be directly usable for populating event trees, as important parameters of the event trees were blended in making the data too generic. A possible way to overcome this situation is to analyze directly the data in the NFPA or USFA databases, by segmenting once again the problem and considering each type of health care facilities considered in Table 2. Investigation reports also are an alternative to the generic data found in the aforementioned NFPA reports. Some of them have been published as a consequence of multiple death fires.

The extensive work by Bryan⁽¹⁹⁾, DiNenno and Milke on 65 fires in health care facilities between 1977 and 1980, is to be analyzed thoroughly as it contains a lot of information about behavioral response patterns of staff and patients, as well as the efficiency of the different technical fire safety measures in these facilities.

According to Tillander⁽²⁰⁾, the best source of information regarding the necessary input for fire quantitative risk assessments is fire statistics, even she also stated that "the statistical approach can be used only existing buildings on which the data is not too sparse. When suitable statistics are available, the point estimates or the probability distributions can be derived". Nevertheless, Tillander as well as Salisbury⁽²¹⁾ *et al.* indicate that the predictive use of statistical data should be made with care, as the conditions which have made up the data may be different in the future. This remark is also valid when looking at statistics from the past, prior to a major change in fire safety requirements implementation or in building contents, such the one that occurred with the advent of plastic materials. Considering the case of nursing homes, fire trends over the years would have to be assessed in conjunction with the decrease of the number of nursing homes (sampling), changes in the fire safety tasks of the staff, as well as the ratio staff / patient, the patient pathologies and age distributions.

Another advantage of fire investigations is connected with the improvement of fire modeling when this technique is used, for forensic purposes, to analyze the development of a fire event. Data for fire models are sometimes estimated from specific experiments conducted with actual materials collected on the fire scene⁽²²⁾, which is a way to narrow the uncertainties associated with the variability of the parameters of fire modeling and human behavior for the incident being investigated.

PROPOSING AND EVALUATING FIRE SAFETY STRATEGIES

Building codes or fire safety standards are organized in the USA or around the world, in relation to the type of facilities or particular types of hazards that could be located in facilities. Comparisons between a prescriptive fire safety solution and an engineering solution are then based on the type of building occupancy.

Data from fire incident statistics and investigation reports can also be used in order to determine if the building where a fire occurred was defined according to the prescriptive regulations. This kind of data should be exploited in order to set up the level of safety of the prescriptive regulation at the time the building was constructed or renovated. By examining fire statistics for several years, it should be possible to quantify the benefits or eventually the drawbacks of the last implemented fire safety requirements. For health care facilities, regulated by the Joint Commission on Accreditation of Healthcare Organizations (JCAHO) and for all these facilities which established smoke-free environment / no smoking policies, it was observed that visitors were giving smoking materials to patients and residents without the health care staff's knowledge⁽²³⁾. This phenomenon was found as to explain why this type of ignition source was not decreasing in the corresponding fire statistics.

At last, a feedback loop, as designed in models used in system dynamics to investigate the knock-on effects of changes on a system, should always been applied to verify that the implementation of a fire safety management measure does not end up with creating an unsafe counterproductive measure.

Fire drills in health care facilities

Because of the lack of mobility of vulnerable patients, importance is given to the health care staff as components of fire detection, fire alarm, evacuation / defense in place strategy and even fire extinguishment. Fire drills appear to be an adequate means to quantify the level of skill maintenance by the staff in this matter. The American Health Care Association⁽²⁴⁾ (AHCA) presents the following review of the Life Safety Code by the Center for Medicare & Medicaid Services (CMS).

"Life safety surveyors have recently been citing facilities in which all staff members did not participate in at least 4 quarterly fire drills per year. Although this may sound like a simple and reasonable requirement, not all staff members are present when their shift has a drill. Staff members may be on vacation, sick, in training outside the facility, etc. Nowhere in the Life Safety Code does it require that all staff members must participate in a minimum of 4 fire drills per year".

The NFPA requirements in the Life Safety Code⁽³⁾, concerning staff training and fire drills, in health care facilities are mentioned in:

- paragraph 18.7.1.2: all employees shall be periodically instructed and kept informed with respect to their duties under the required [plan for the protection of all persons in the event of fire];
- paragraph 18.7.1.6: drills shall be conducted quarterly on each shift to familiarize facility personnel (nurses, interns, maintenance engineers, and administrative staff) with the signals and emergency action required under varied conditions;
- paragraph 18.7.1.8: employees of health care occupancies shall be instructed in life safety procedures and devices.

The Life Safety Code does require that a minimum of 4 fire drills per shift per year for a total of 12 fire drills be held by a facility. Sections A18 & 19.7.1.2 states that "the purpose of a fire drill is to test and evaluate the efficiency, knowledge, and response of institutional personnel in implementing the facility fire emergency plan". The purpose of the drill is to test the capabilities of the staff present during the drill. Nevertheless, it is very likely that during actual fires in facilities, all staff on the shift will not be present. An excellent opportunity to test this situation is to conduct a drill when all staff is not present.

For its part, NFPA⁽²⁵⁾ is aware that the purpose of fire drills is "not to disturb or excite patients" as paragraph 18.7.1.5 (and 19.7.1.5) states that "infirm and bedridden patients shall not be required to be moved during drills to safe areas or to the exterior of the building". NFPA also indicates that "many health care facilities conduct fire drills without disturbing patients by choosing the location of the simulated emergency in advance and by closing the doors to patients' rooms or wards in the vicinity prior to initiation of the drill".

It should be noted that inspections and surveys are also a good means to collect data, not only about installed and maintained technical fire safety measures but also for estimating the actual level of implication of staff and other operators in fire or other emergency situations.

CONCLUSIONS

Existing Performance-based guidance documents describe possible ways to create alternate solutions to prescribed requirements. However, even though they emphasize the importance of parameters such as the definition of the acceptance criteria or the selection of the design scenarios, they are too general in defining and quantifying these parameters for a particular project. In order to help identify and evaluate the relative importance of the most influential parameters of a PBD approach for a project, an integrated approach to PBD for life safety across different building use groups is proposed.

In creating the integrated PBD approach, a first task consisted of breaking down the analysis and design problem into manageable pieces categorized by building occupancy uses, defined in part by their own everyday or "chronic" objectives. The analysis of "chronic" objectives for occupancies such as healthcare facilities, casinos, airports, and offices has already illustrated a competition between their respective chronic objectives and the "acute" ones defined in emergency situations such as fires, which are perceived as a perturbation of the "building-occupant" system. Because of this competition, a tremendous effect exists of having building occupants "shift" from their usual activities to the emergency evacuation process, which is very important since this effect has to be quantified in egress calculations as it determines the "pre-movement" time of the RSET. It has also been found that, for objectives related to business interruption of buildings defined as "essential to the community", the period following the "perturbation" is also important. Thus, the examination of the "chronic" objectives, for every building occupancy uses, appears to be a necessary task to perform prior to any fire safety analysis. Techniques, derived from the field of system dynamics, appeared to be useful in order to analyze the effects of implementing the categorized "building-occupant" systems with fire safety measures and their use will tend to be generalized within the proposed PBD approach.

The benefit of looking more closely at regulatory, operational and loss history through the study of US certified nursing homes showed that the low fire risk tolerance of this specific building occupancy use had a tremendous impact on the minimal level of fire safety demanded by the Authority Having Jurisdiction, as the installation and maintenance of sprinklers are required for new and existing nursing homes. This situation and resulting requirements for sprinklers will serve as a basis for assessing other occupancies, as something similar could also appear for other highly regulated building uses.

When analyzed through the spectrum of the building occupancy uses, data sources, including but not limited to fire statistics and fire investigation reports, tend to provide more pertinent and applicable data for similar projects, therefore reducing uncertainties related to the use of generic data. Inspections and surveys related to very precise situations will also be included in order to gather specific data on fire management procedures, as it was shown that staff constitutes a showpiece of the fire safety strategy in nursing homes.

REFERENCES

¹Society of Fire Protection Engineers, SFPE Engineering Guide to Performance-Based Fire Protection, Second Edition, SFPE, Bethesda, MD (USA) 2007

²Society of Fire Protection Engineers, SFPE Code Official's Guide to Performance-Based Design Review, SFPE, Bethesda, MD (USA) 2004

³National Fire Protection Association, NFPA 101 "Life Safety Code[®]", NFPA, Quincy, MA (USA) 2009

⁴International Code Council, ICC Performance Code for building and facilities, International Code Council, INC., Whittier, CA (USA), 2009 edition

⁵International Fire Engineering Guidelines (IFEG), Australian Government, State and Territories of Australia, 2005

⁶Meacham, B.J., "International Experience in the Development and Use of Performance-Based Fire Safety Design Methods: Evolution, Current Situation, and Thoughts for the Future," Invited Paper, *Proceedings of the International Association for Fire Safety Science, 6th International Symposium*, Poitiers, France, July 1999, pp.59-76

⁷Ian Thomas, Dorothy Bruck and Michelle Barnett, "Is Consideration Of Evacuation Relevant to Most Fire Fatalities? Using the CESARE Coronial Database to Investigate the Utility of ASET/RSET Calculations", *Proceeding of the 4th International Symposium on Human Behaviour in Fire*, pp.411-420, Interscience Communications, London (UK), 2009

⁸International Code Council, International Building Code, section 308, (USA) 2009

⁹American Hospital Association, Fast Facts on US Hospitals, <http://www.aha.org/aha/resource-center/Statistics-and-Studies/fast-facts.html>

¹⁰US Energy Information Administration (EIA) - 2003 Commercial Buildings Energy Consumption Survey (CBECS) Detailed Tables – most recent available, released: September 2008 (http://www.eia.doe.gov/emeu/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html#enduse03)

¹¹Wolski, A., Dembsey, N. and Meacham, B., "Accommodating Perceptions of Risk in Performance-Based Building Fire Safety Code Development," *Fire Safety Journal*, Elsevier, London, Vol. 34, No. 3., pp.297-310

¹²Meacham, B.J., Editor, and Johann, M., Associate Editor, *Extreme Event Mitigation in Buildings: Analysis and Design*, National Fire Protection Association, Quincy, MA, April 2006

¹³Jeffrey S. Tubbs and Brian J. Meacham, "Design solutions", chapter 9 of *Egress Design Solutions – A Guide to Evacuation and Crowd Management Planning*, John Wiley and sons, 2007

¹⁴Emergency Management Higher Education Program Report – Federal Emergency Management Agency (FEMA) (training.fema.gov/EMIWeb/edu/ARRPT/January%2030,%202009.doc)

¹⁵Department of Health and Human Services – Centers for Medicare & Medicaid Services – 42 CFR Part 483 – [CMS-3191-F] RIN 0938-AN79 "Medicare and Medicaid Programs; Fire Safety Requirements for Long Term Care Facilities, Automatic Sprinkler Systems", *Federal Register*, vol. 73, No. 157, Wednesday, August 13, 2008, pages 47075-47092, 2008

¹⁶United States General Accounting Office, "Medicaid Financial Management - Better Oversight of State Claims for Federal Reimbursement Needed" – GAO-02-300, February 2002 (<http://www.gao.gov/new.items/d02300.pdf>)

¹⁷United States Government Accountability Office, "Nursing Home Fire Safety – recent fires highlight weaknesses in federal standards and oversight" — GAO-04-660, July 2004 (<http://www.gao.gov/new.items/d04660.pdf>)

¹⁸Marty Ahrens (NFPA), *Selections from the U.S. Fires in Selected Occupancies – Health Care Facilities, excluding Nursing Homes*, NFPA, Quincy, MA (USA), March 2006

¹⁹J.L. Bryan, P.J. DiNenno, and J.A. Milke "The Determination of Behavior Response Patterns in Fire Situations, Project People II. Final Report – Incident Reports, August 1977 to June 1980", NBS-GCR-80-297, Washington DC (USA), December 1980

²⁰Kati Tillander, "Utilisation of statistics to assess fire risks in buildings", VTT publication 537, VTT Technical Research Centre of Finland, 2004

²¹M Salisbury, P Johnson, E Yui and MC Hui, "QRA and fire safety – a beneficial experience...", *Interflam 2007*, proceedings of the eleventh conference, volume 2, pp. 1253-1263, Interscience Communications, London (UK), 2007

²²William Grosshandler, Nelson Bryner, Daniel Madrzykowski, and Kenneth Kuntz, *Report of the Technical Investigation of The Station Nightclub Fire*, report NIST NCSTAR 2: Vol. I and Vol. 2, National Institute of Standards and Technology, June 2005

²³Daniel J. O'Connor, "Health care occupancies", chapter 15, section 20 of the 20th edition of the *Fire Protection Handbook*, NFPA, 2008

²⁴American Health Care Association (AHCA) "Life Safety Update: Staff Participation in Fire drills" http://www.ahcancal.org/facility_operations/fire_life_safety/Pages/StaffParticipationinFireDrills.aspx

²⁵NFPA, Info on health care occupancies, [http://www.nfpa.org/itemDetail.asp?categoryID=792&itemID=20722&URL=Safety Information/For consumers/Occupancies/Nursing homes/Info on health care occupancies](http://www.nfpa.org/itemDetail.asp?categoryID=792&itemID=20722&URL=Safety%20Information/For%20consumers/Occupancies/Nursing%20homes/Info%20on%20health%20care%20occupancies)

Appendix A2

"Ready-to-Use" Building Layouts and Combustible Packages for 3-D Fire Simulations"

presented at the Fire and Evacuation Modeling Technical Conference 2011

“READY-TO-USE” BUILDING LAYOUTS AND COMBUSTIBLE PACKAGES FOR 3-D FIRE SIMULATIONS^(a)

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ABSTRACT

In recent years, complex 3-D computational fire effects models have been widely used by fire protection engineers to simulate the consequences of fire and to assess effectiveness of fire mitigation options. This has happened in part because these tools have become increasingly user friendly. However, it may not always be appropriate to use a complex model just because it is available. In addition, the use of these complex tools requires considerable time, both for users to create input data files and analyze the results, and for computers to produce the simulations. With respect to input files, independent of the description of the initial design-basis fire itself, information and data are lacking about the way the building itself should be described as input data, the degree of detail that is necessary in order to capture the elements that affect the validation of the simulation, and how to optimize mesh size so that critical elements can be properly incorporated without resulting in a prohibitively lengthy calculation time. In order to begin addressing these issues, this project aims to provide guidance on how to select the right type of tool to fit the engineering application, to collect and make available to the entire fire community, representative building layouts for common occupancy groups, such as schools, offices in high-rise buildings, and hospitals, which can form a common basis for estimating, assessing and verifying building-related model parameters, and to collect and make available a set of ‘combustible packages’ representing 3-D objects such as chairs, couches, and beds, which contain heat release rate, chemical reaction, and toxicity properties needed for the simulations. Together, the tool selection guidance, building configurations and combustible packages will help fire protection engineers become both more efficient and effective in applying the best tools for the application at hand.

INTRODUCTION

Within the performance-based fire protection design framework, tools are used in order to estimate the consequences of fire design scenarios, upon which different fire protection trial designs are evaluated.

A fire scenario describes the evolution with time of the fire, from its ignition to its extinguishment. Not only fire is a threat to the building occupants, but also to the building itself, to its contents and to its own structure. Life safety is a common objective for any built environment and concerning fire hazard, it is essential to evaluate the consequences of the fire in terms of heat effects (temperature and thermal dose) as well as in terms of toxicity and visibility loss which can prevent occupants from finding their way to a safe place so they subsequently succumb to untenable heat and toxic conditions. In order to conduct this analysis, a fire design scenario shall contain information necessary to evaluate the heat released during the fire and also fire effluent productions. This information is then added to the information related to the description of the built environment and incorporated, as user input, to fire effects tools. When selecting appropriate tools for analysis, several factors need to be considered.

Different levels of complexity

The Society of Fire Protection Engineers (SFPE, 2011) defines the three following types of fire effects tools, based upon their levels of complexity:

- algebraic models, which include empirical or analytical equations to describe localized phenomena such as the plume region (temperature and velocity), the ceiling jet, and smoke filling in an enclosed space;
- zone or lumped parameter models, which divide spaces into control volumes where the quantities are spatially homogeneous (and which often include add-on sub-models dealing with particular aspects of the fire description);
- Computational Fluid Dynamics (CFD) models, which can calculate flows through complex geometries by dividing the considered space in relatively small elements where a set of governing equations is numerically solved.

Hybrid tools combining a zone model with a CFD model, a fire effects models with a HVAC network model may also be considered when assessing fire consequences.

Understanding and recognizing the differences in level of complexity and outcomes delivered is the first step in matching tools to applications.

Different uses have different constraints

The next step in selecting a tool is to understand issues associated with objectives and constraints on the project, such as time, resources, and level of analysis required. At the start of a complex project in the consulting environment, for example, fire protection engineers (FPEs) are often asked to provide ideas of the possible fire protection measures, even when the project itself is not well defined. At this stage, the level of analysis required will be driven by the level of complexity needed given the scarcity of input data describing the project (i.e., building layout and combustible contents which provide potential fire sources) and the potential impact of the analysis on the project direction. As a project passes through the steps of feasibility, concept design and schematic design, FPEs are able to refine their initial ideas using more complex tools as appropriate.

Ultimately, many projects which require performance-based analysis involve complex building geometries, which present challenges for the use of algebraic and zone models. As such, given the availability of CFD fire effects tools, and the fact that they can handle more complex geometries, they can appear to be the 'best' candidates for assessing the fire protection design of such projects. However, due to computational constraints (in terms of processors which manage the computational time and in terms of usable memory which sets up the limits of the refined computational grid), it may not be practical or cost-effective to perform one, let alone a series of detailed CFD simulations. In such cases, a decision often needs to be made regarding the trade-off between complexity and time. In the end, it may be that the FPE has to rely on less complex fire effects tools from a time perspective, while demonstrating that the less complex tools are validated for handling the complex geometry (i.e., the FPE needs to demonstrate how the uncertainties related to adapting the complex geometry for less sophisticated tools is not significantly or inappropriately changing the outcome of the engineering solution).

While time constraints may be an issue for practicing engineers, and time and complexity trade-offs may be required, this is not the case in other environments, such as academia, research and high risk or hazard industries. In the academic or research environments, for example, it is not uncommon for multi-year studies to be conducted. Such studies may involve developing new tools, expanding existing tool

capabilities, and assessing better ways to apply existing tools to solve complex engineering problems.

An example of a long-term study dealing with better ways to use tools to solve an engineering problem can be illustrated by Francesco Colella's PhD thesis titled "Multiscale Modeling of Tunnel Ventilation Flow and Fires" (Colella, 2010), conducted at the Politecnico di Torino. His research objective is related to the design of smoke extraction in tunnels of several kilometers in length. In this case, a dichotomy exists between the needed accuracy to simulate the flows around the smoke extractors and the fire, which requires describing the local environment with cells of a few centimeters, and the smoke flow along the whole tunnel, which requires millions of cells and a manageable computational time to perform a series of scenarios to test the smoke control system. In the referenced work, this dichotomy led to the formulation of a method allowing the coupling of a CFD fire effects tool with a 1-D ventilation network tool. The outcome is a hybrid tool where information is transferred between the tools and a formula describing the minimum extent of the CFD computational domain where results are similar to the ones estimated with the full CFD representation of the tunnel.

For an example of a very particular and highly regulated sector which is high-risk / high hazard, one can consider efforts within the nuclear power industry, where multi-year projects involving nuclear power plant operators, researchers, governmental agencies and regulators, have been undertaken (Barrachin *et al.*, 2000; Siu *et al.*, 2008). In this environment, not only have there been sustained research projects aimed at tool development and assessment (e.g., NIST/NRC efforts), but also development of a process for applying different level of complexity tools at different stages in the assessment and design process within a general quantitative (or probabilistic) risk assessment (QRA or PRA) framework. For example, within a QRA process, different types of fire effects tools can be selected as follows:

- In the first instance, simple tools which can be quickly applied are utilized in order to screen out fire scenarios which would have no impact on the QRA. This first level of analysis primarily consists of applying algebraic models that can be edited in a spreadsheet for handling thousand of calculations. Since this application is aimed at the elimination of the fire scenarios which are not relevant for the QRA, it only requires coarse description of the domain and conservative assumptions of the fire development.

- A second more detailed level of analysis can then be conducted by applying more complex fire effects tools to the remaining scenarios. The specific application here is to determine quantities that would actually be input for the QRA related to fire risk. The events to be considered may be framed in time periods of several minutes (e.g., time to the first correcting action) to several hours (in cases where the fire has been spreading and more and more correcting actions have to be taken in order to maintain core safety). Because thousands of simulations may be required to understand the risk, and if the compartments can be characterized with simple geometries (e.g., "shoe box" shaped rooms), application of a zone model appears to be the optimum solution in order to get the corresponding fire QRA input data.
- Once specific areas of concern are identified, CFD tools can then be used to handle specific scenarios involving geometries, such as cable trays supporting the transmission of power or control information regarding core management or safety. In such cases, detailed local information is needed to describe the combustion and flame spread in cables trays, which constitute at the same time extended fire areas and targets important for the core safety in the global QRA.
- material properties not only describing the combustible contents but also the other building elements which "absorb" heat and fire effluents as well as the load-bearing elements,
- initial and boundary conditions, including initial temperature in and outside the built environment and the ventilation conditions (initial conditions including the window and doors status (opened or closed) as well the boundary conditions (how the doors are leaking or how the mechanical ventilation network is set up).

The final attribute which can be used to assess the appropriateness of a tool for a given application is related to the application itself; what is being assessed, and what features of a tool are required to support that assessment. For example, an application could be related to assessing fire propagation inside the room of fire origin with respect to the safety of the occupants in the room. In that case, tools would be needed to assess the fire spread from the 1st burning item to the subsequent ones until the flashover is reached. Fire effects tools including models assessing flame characteristics, ignition by radiation fluxes, etc. would then be considered. Using a tool which is too coarse for the application may not yield the level of information required to make a good assessment. By contrast, the application purpose may be to consider the safety of occupants remote from the compartment of fire origin, without a need to focus on how the fire initially develops. In this case, the application is more concerned with species production and spread outside of the room of origin than with the fire development. In these cases, the same tool may be appropriate to solve different parts of each problem, but in different ways and at different levels of complexity. In the first instance, a CFD model may be needed to obtain the degree of analysis needed in the room of origin, and a zone-model may not yield sufficient detail. In the second case, however, a zone model may be appropriate for simulating initial conditions in the room of origin, with a CFD model need to assess smoke and hot gas spread outside the room of origin.

Data availability and fire phenomena

Two additional critical criteria in the selection of a candidate tool for a given application are the availability of the input data required to effectively apply the tool, and the making sure that the fire phenomena that the tool simulates matches the assessment needs.

Assuming for this discussion that the three types of fire effect tools are available and have been validated to correctly represent the physics for a given application, the next criterion regarding appropriateness of a tool for an application could then be determined by the amount and goodness of information that can be collected for the data input needed by the different tools. The recently published *SFPE Guidelines for Substantiating a Fire Model for a Given Application* (SFPE, 2011) provides a good starting point, noting for example the need to identify:

- details of the spatial domain representing the built environment,
- fire design scenario timeframes (from several minutes for a single room flashover application to several hours for assessing the collapse of a structure due to a generalized fire),

EXAMPLES OF STUDIES TO BE CONDUCTED RELATED TO THE USE OF FIRE EFFECTS TOOLS FOR GIVEN APPLICATIONS

It is suggested that the above issues form the basis for development of 'best practice' guidelines for selecting fire effects tools based on their appropriateness to the application at hand. These guidelines would be used in collaboration with related guidance, such as the *SFPE Guidelines for*

*Substantiating a Fire Model for a Given Application*¹ and *SFPE Guide to Predicting Room of Origin Fire Hazards* (SFPE, 2007a) and other such guidance, and would support a wide range of industry stakeholders, including:

- FPEs, to select the appropriate tool to solve their engineering problems,
- researchers to develop more tool functionalities and to increase tool validation, and
- the regulators and authorities to have more confidence in the engineering solutions when these tools are used.

However, in order to ultimately produce comprehensive ‘best practice’ guidelines to assess the appropriateness of a fire effects tool for a given application, it is suggested that a series of both generic and specific studies need to be conducted. The intent of these studies is to utilize multiple participants to develop data and case history to illustrate a wide range of issues, such as level of detail needed in building configurations for different types of problems or occupancies (e.g., life safety in hospitals versus apartments), or detail required in characterizing ‘fuel packages’ for use in models to meet assessment objectives. Below is the outline of the selection process and examples of generic studies that can be conducted for supporting the tool selection process. As described in the previous section, these studies ultimately have to be based on cases representing a given application, as results of such studies are highly dependent of the given application definition and context.

Process outline and generic ‘test bed’ environment for guiding selection of the right tool for a given application

In this effort we aim to demonstrate that by applying a specific process for a set of ‘test bed’ building configurations of a particular use (categorized by building occupancy groups), for a particular range of configurations (determined by design fires scenarios) targeting a particular outcome (safety objectives including life safety, property protection, business continuity, etc.), the results of each ‘test bed’ study, defined in that context, will yield data which will lead to a guideline of the selection of appropriate tools for that type of situation.

¹ The difference between the existing SFPE Guide and the proposed approach is that the existing guide helps to justify use of a tool, once selected, and the proposed approach helps guide selection of an appropriate tool.

The reason for collecting ranges of buildings by building occupancy groups is to obtain an extensive database of information related to layouts of representative buildings, rather than individual building layouts, which can then serve as the basis of guidelines that are occupancy group based (e.g., guide to application of fire effects tools in healthcare occupancies). Also, in a broader context, determining the building occupancy group is the first step in assessing its fire protection requirements whether one follows prescriptive building regulations or the performance-based design process (a first step being to define the scope of the project, notably by identifying the intended use and occupancy of the building (SFPE, 2007b)).

The process that is envisaged to conduct a ‘test bed’ study case is composed of the following steps:

1. Identify occupancy group for study focus
2. Collect building configurations for study
3. Identify study parameters (e.g., selection of tool for assessing safety objectives)
4. Set up building layouts for fire effects (zone models, CFD models) and their evacuation counterpart
5. Identify objectives and criteria (life safety, property protection, mission continuity)
6. Select fire scenarios for study (additional guidance in other work)
7. Perform the fire (and evacuation) simulations with the different sets of tools (and for different mitigation strategies, as appropriate)
8. Analyze the results in terms of the safety objectives
9. Assess ability of tool to address defined performance issue
10. Conclude by establishing guidelines related to the tool comparison process and its outcome.

With respect to the ‘test bed’ studies, it is important to note that each individual case does not need to be validated; that is, the objective of performing the case studies using different tools is not to increase the validation domain of the tools, but to obtain information about the application of the different tools for attaining different objectives. Likewise, the case studies themselves do not result in *de facto* design fire scenarios for the considered building occupancy group. These two objectives (increasing the validation domain of tools, selecting fire design scenarios for performance-based applications), while important to the overall process, are out of the scope of the studies presented in this paper. Cf. (Alvarez and Meacham, 2011) for more information.

Also, it is important to have participants undertaking the case studies from across the whole spectrum of the fire engineering community – from consulting engineers to regulators, and by engineers and regulators from around the world. Such diversity and breadth of participation would provide the potential to add more tools, more fire scenarios, and more variants in the building configurations, and the resulting ‘test bed’ study guidelines would be more directly included in the larger performance-based fire protection design framework. (Having 20 engineers from 10 countries apply tools and fire scenarios that they select for a common set of objectives for a set of 5 healthcare configurations would yield much more robust data than 2-3 engineers applying the same tool to a single building configuration.)

While processes similar to the above exist at a generic level (e.g., *SFPE Guide to Performance-Based Fire Protection*) they lack the detail and the data to help users make informed judgments. This approach aims to both provide added detail to the process and data to support the justification of the tool selection.

Specific case studies: issues related to the use of CFD fire effects tools

The use of CFD fire effects tools is quite complex and necessitates that the user also deals with uncertainties related to the use of these tools. Here are some examples of issues related to the “user effects” related to CFD fire effects tools – issues that would have to be addressed when using this kind of tools in Step 7 of the ‘test bed’ study process.

Grid selection for a better optimization of computational meshes of a CFD fire effects tool

Spatial domain can be categorized as one source of "user effects" uncertainty (SFPE, 2011). For a CFD fire effects tools, grid sensitivity should be performed in order to determine at what grid refinement the desired outcomes become grid independent. However, care should be taken to assure other design objectives are met as well.

For example, Sztarbala (2011) indicates that "when LES model is used, the number of grid elements must be increased. A maximum edge length of 0.15 m is recommended for grid elements in flow-relevant areas. For other areas the maximum edge length should not exceed 0.50m". However, these grid cell sizes may not be compatible with the time and computing resources of FPEs in the consulting environment, as they would require extensive parallel processing power and memory. In addition, these grid sizes may not be needed for the resolution of analysis required. In addition, some CFD tools allow the

definition of multiple meshes with different grids, which allows some flexibility. However, communication between the different grids may affect the results. Looking at this issue in a more comprehensive manner can lead to developing user guidance when designing for all computational grids.

Influence of detailed geometry on the results of the simulations

It is known that the computational mesh, which simulates the spatial domain of the project of interest, has an influence on the results provided by CFD fire effects tools. However, there is no real guidance on how to deal with this issue. For specific outcomes of fire scenarios, it may be necessary to perform a simulation with a high level of details. Because of calculation time it would require, such simulations which include details of building contents and structural elements are rarely performed in practice because they are not compatible with the time constraints of engineering studies. To address this issue, it would be beneficial to establish guidance on the degree of detail needed for particular design aspects (e.g., contents, structural features) that are "just" needed with respect to the degree of details required in the description of the building geometry.

Looking at this issue would help to:

- indicate whether the simulation of all a building in 3-D is necessary,
- determine the minimum degree of details needed to get access to the information, describing temperature profiles, smoke and toxic fire effluent propagation required to perform an analysis of the evacuation of building occupants.

In addition, by looking at different safety objectives for the same building configuration, one could verify if the building description established for an occupant evacuation could be used for design fire scenarios related to property protection or business interruption.

Detailed geometry description v. computational time and result accuracy

CFD fire effects tools allow a refined description of the building structural elements and contents, which represent heat sinks and obstacles that can modify the buoyant smoke and hot gases trajectory. Whereas these structural elements and contents can be described in detail in 3-D simulations, and these details may influence the results of the simulations, but at a cost of an increased computational time, a series of simulations should be performed in order to estimate how the detailed geometry description affect the result accuracy to the detriment of computational time.

Verification of the consistency of results

As indicated in Chapter 5 of the *SFPE Guidelines for Substantiating a Fire Model for a Given Application* (verification and validation), using multiple tools for the same configuration may demonstrate that the "results make sense. Especially for more complex models, performing an analysis with another tool could result on a non-sensical result" (SFPE, 2011). While this kind of analysis is not a primary objective of the ‘test bed’ studies presented in this paper, results from the ‘test bed’ studies of fire effects tools for a given application can serve as a basis for a verification of the consistency of results between different types of tools.

Inclusion of Hybrid modeling in the ‘test bed’ studies

As presented previously, attempts have been made to create hybrid tools which can combine the accuracy of the CFD model with the computational speed of zone models. Other recent examples of such hybrid tools for estimating fire effects concern:

- the simulation of large geometries such as large buildings or large passenger ships, with a CFD model / zone model hybrid developed by the University of Edinburgh (Burton *et al*, 2011),
- the estimation of HVAC flows in case of fire in a building based on a coupling of a HVAC network model with the Fire Dynamics Simulator (FDS) developed by Floyd (2011).

Hybrid tools appear to be promising new tools, which can also be included in the ‘test bed’ studies presented above. It will also be important to analyze the process the hybrid models underwent so to collect information not only about the computational time gain with minimum accuracy loss, but also the assumptions related to the fabrication of the hybrid tools as these assumptions may be highly dependent on the applications of the tools, that is to say the set of configurations the tools were designed for.

ORGANIZATION OF THE ‘TEST BED’ STUDIES

As presented above, the first steps in the process are obtaining layouts for occupancy groups and defining analysis objectives. Once this has been done, the analysis starts with setting up the building layouts.

Setting up building layout (Step 4)

The following process for generating building layouts for FDS from different building configuration sources has already been established and is presented below.

Process to generate “ready-to-use” building layouts for Fire Protection design purposes

Architects design the overall building layout using 3-D software that is able to render the geometry of the rooms, spaces and exit pathways. Furniture and building contents, as well as nature of the structural elements would be described in this software files. Architect engineers dealing with the description of the building systems, such as the HVAC system, also describe their data using 3-D software. To facilitate the ‘test bed’ studies of real building geometries for a range of occupancy groups, it would be helpful to have a set of ‘ready-to-use’ building layouts. The process in order to get these layouts for FDS simulations, from architect design files, is described in Figure 2 below.

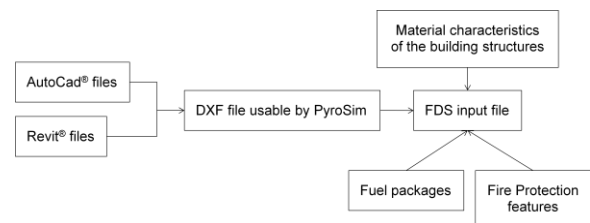


Figure 2: Process currently followed to create FDS building layouts.

In the 8th *International Conference on Performance-based Codes and Safety Design Methods* (SFPE, 2010) the case study was related to a 6 story office building where 4 stories had to be converted into a night club. Table 1 presents the different fire effects and evacuation tools used by the participating countries. Compiling the building layouts presented in Table 1, as well as the fire scenarios selected by the different countries would constitute a fast way to carry the 1st tasks of a ‘test bed’ study case related to that configuration.

Table 1: Fire effects tools and evacuation tools used by different countries (SFPE, 2010)

Country	Fire effects	Evacuation
New Zealand	Zone model (BRANZFIRE)	Algebraic models
USA	CFD model (FDS)	Algebraic models
Australia	Zone model (CFAST)	PATHFINDER
France	Zone model (CIFI2009) and CFD model (FDS)	Algebraic models
Hong Kong	CFD model (FDS)	MODELMAKER
Japan	Algebraic models and zone model (BRI2002)	SimTread
Sweden	CFD model (FDS)	STEPS

In addition, other potential sources of building layouts are NIST investigation reports (Station nightclub, office building of the Cook County hospital or part of the World Trade Center) or published articles including building layouts for estimating fire consequences or even crowd evacuation.

Going forward, however, it would be helpful to obtain building layouts, from architects, which represent a wide range of building configurations over a spectrum of building occupancy groups. Table 2 presents a list of building configuration layouts to be implemented in the near future, with a focus on getting the description of the spatial domain in FDS.

Table 2: List of building configuration layouts to be implemented in the near future

Building occupancy type	Example
Assembly	Library
Health care	Hospital
Educational	High school
Residential	Dormitory

Examples of building layouts are included in the conference presentation slides.

To facilitate use by a broad range of stakeholders, the building layouts will ultimately be distributed to a Google user group to be tested across the world (as materials and fire protection features vary with countries) and versions of these layouts usable for other fire effects tools as well as for evacuation modeling will also be developed. Before the end of the year, the layouts will be distributed to a small group of fire protection engineers across the world for some feedback. It should be noted that these configurations will not include any fire components or fire protection features. The information gathered in the Google user group on the building configurations is aimed to be as exhaustive as possible in describing the building contents and occupants so to remain accessible and usable even for upgraded versions of the current tools or future tools.

Selecting fire scenarios (Step 6)

Whatever the fire effects tool, be it based on algebraic models, zone models or CFD models (when not using a pyrolysis model), the description of the fire remains a user input data of crucial importance. A primary component of the fire design scenario is the fire design curve which represents the evolution with time of the heat release rate (HRR) of the corresponding fire. This “HRR curve” will allow the calculation of the heat hazard component of the fire.

In parallel to the evolution with time of the HRR, the evolution of the fire effluents (smoke, toxic and irritant products) is also essential to estimate the toxic hazard component of the fire.

When using fire effects tools, two options for establishing the HRR curve are possible:

- the HRR curve can be predefined, from ignition to extinguishment, and used as an input for all the different types of fire effects tools, or;
- the HRR curve can be left to the different fire effects tools estimate as follows: the location and nature of the 1st burning item are given and the tool has to assess fire propagation to the other fuel items which nature and position are known.

Whatever option is selected, and because no pyrolysis model is intended to be used in the present scope of the ‘test bed’ studies, the user has to provide HRR curves for single fuel packages, describing the evolution of the HRR they can individually produce once ignited.

HRR curve database

When looking for heat release rates for building contents, from furniture to curtains, from appliances to even cars, a primary source of information is the SFPE Handbook chapter dedicated to heat release rates, written by Babrauskas (2008). This chapter contains numerous references that can lead to a significant amount of data from furniture calorimeters, including heat release rates evolution with time, soot and toxic component yields. In addition, by reviewing NIST publications alone, some fifty different experiments have already been included in a database, along with the available snapshots and videos. This number will be expanded by looking at more NIST studies, as well as tapping into test data from around the world. Before the end of the year, it is planned to distribute the database to a small group of fire protection engineers across the world for feedback and contribution to the database.

Smoke and fire effluents

Smoke and fire effluent production and movement quantification are an important part of the engineering problem, related not only to life safety objectives, but also to property damage, and environment protection. Products of combustion can have an impact on people safe evacuation (affecting their safe escape), on building contents (damaging costly pieces of equipment or historical artifacts), on business continuity (causing the malfunction or the destruction of manufacturing goods, processing chains, or equipment assuring the safety of the process), or on the environment (when toxic or hazardous materials are released in quantities that can impact the environment). Thus, it is essential to

estimate the nature and the kinetics of the fire effluents.

In solving engineering problems related to fire effluent impact on building occupants and contents, it is necessary to assess the production, transport and deposition/absorption of these effluents inside the building and also outside for environmental safety objective. Transport and deposition of airborne particles constitute very complex subjects by themselves and these phenomena are greatly influenced by the building layout, which adds another study to the ones already presented in the previous sections dedicated to the building layouts. Production of fire effluents are related to the fire spread on the burning combustibles, which include the also complex pyrolysis processes of usually heterogeneous materials, as well as the ventilation conditions around the fire scene (i.e. the fire is under-ventilated or not).

When reviewing NIST furniture calorimeter tests, it was noted that the information related to the production of fire effluents was rarely provided. Additional information may be collected when material properties are collected, i.e. at laboratory scale, such as soot yields, CO yields, CO/CO₂ ratios, etc., if possible for pre-flashover and post-flashover conditions, as these values are dependent of the ventilation conditions around the burning fuel item.

'Combustible packages' for 3-D simulations

The objective of providing 'combustible packages' ready for 3-D simulations came from the FDS user point of view and the availability of third party software developed in order to facilitate the creation of FDS input data files. Indeed, if such software is able to create and duplicate building elements as presented in the previous section, why not trying to do the same for combustible elements.

For FDS, the heat release rate is defined by a surface area, that is to say, that the specification of the burning areas is required. Because of this requirement, the evolution with time of the burning areas has to be included as an input data. In some cases, the burning area is set up as a constant and at the maximum of the combustible object area(s). Nevertheless, for complex setups of combustible building contents, which have been burnt in furniture calorimeter, videos clearly show the flame propagation from the ignition localized point to the complete flame engulfment of the set up, which can occur several minutes later as a peak of HRR.

The description of the flame spread over the combustible building content is necessary when

assessing the fire spread inside the compartment or space where the content is located, as the estimation of the ignition of the second burning item is dependent on the radiation received by this target from the 1st burning building content. This heat transfer mechanism can be estimated using a CFD fire effects tool so it requires the flame characteristics which are dependent on the evolution with time of the HRR and of the burning areas. It should be noted that such a detailed characterization is not required in the far field, that is to say when the given application is related to the phenomena that occur outside the room of fire origin, i.e. for example when assessing the smoke spread in exit pathways outside the room of fire origin. The degree of details for the 'combustible packages' is also dependent of the given application, as well as the other input parameters presented in the previous sections.

Even for relatively simple building content geometry, such as a wood dresser, the question of the burning areas remains: if all the HRR is distributed at the top area of the wood dresser, activation of a heat detector would be quicker than if the HRR is distributed on the lateral areas of the wood dresser. In the latter distribution, ignition of a second burning item located in front of the wood dresser would be quicker.

Since some snapshots and videos are available from the NIST for different building contents including a wood dresser, it was then decided to study the influence of the burning areas evolution with time on the ignition of a second burning item and on heat detection at the ceiling level.

NIST/BFRL experiments related to the combustion of a loveseat, a mattress (with center ignition and corner ignition) and a wood dresser were selected. Burning areas were defined according to the flame spread pattern on the burning item. Fractions of the HRR were then distributed among the defined areas so the resulting modeled flames would have the same length as the ones in the snapshots or video. In the corresponding FDS simulations, devices were located in front and at the periphery of the burning item and temperatures were recorded under the ceiling to estimate the activation time of thermal elements located there.

Detailed analysis of the results will be available in the near future. Even so, thus far the particular study shows the feasibility of such a detailed description of combustible burning items. By the end of the year, a primary series of 'combustible packages' will be set up and distributed to a small group of fire protection engineers across the world for some feedback.

Examples of 'combustible packages' for FDS are given in the conference presentation slides.

Creation of a fire protection engineering 'test bed' study pool (Step 7 to Step 10)

Performing Step 7 and Step 8 of the 'test bed' study process requires significant time and resources to collect the targeted data. It is not feasible for a single entity from within the fire protection engineering community to conduct all the needed studies – not only from a resource perspective, but because each sector within the FPE community has its own goals and objectives, prerogatives and time and resources constraints. In addition, Steps 5-10 require participation of people from all sectors in any case.

Conducting such studies with all these different people would benefit all of them in different manners:

- The consulting companies would acquire better understanding of the use of tools for a given engineering application, optimizing their resources and time;
- The students and professors in Academia could use the case studies as practical examples of engineering problems;
- The governmental agencies could set up research programs focusing on the problems and needs of the engineering community;
- Engineering societies could elaborate guides and guidelines improving the use of engineering tools for given applications, where appendices would be added with the results of specific cases;
- Regulators and Authorities having jurisdictions would consider the improvements in the use of tools in projects based on performance based design fire protection options.

The aim, then, is to encourage the establishment of a sector-wide and world-wide group of users to participate in the 'test bed' studies outlined above, with the objective of developing data which will lead to a guideline for the selection of appropriate tools for specific building occupancy types and configurations.

REFERENCES

Alvarez, A. and Meacham, B. J. (2011), "Towards the next generation of performance-based fire protection design for the built environment", manuscript to be submitted for publication in September 2011

Babrauskas, V. (2008), "Heat Release Rates," SFPE Handbook for Fire Protection Engineering, 4th edition, section 3, chapter 1, (3)1-(3)59

Barrachin, G., Chaussard, M., Bertrand, R., Bonneval, F and Mattei, J.M. (2000), "Insights from the Blayais 1 NPP Fire PSA," Proceedings of the 5th International Conference on Probabilistic Safety Assessment and Management, volume 3/4, 2093-2098

Burton D., Grandison A., Patel M., Galea E., Ewer J. (2011), "Development of a Hybrid Field/Zone Fire Model," Proceedings of the Tenth International Symposium of IAFSS

Collela, F. (2010), "Multiscale Modelling of Tunnel Ventilation Flows and Fires," British Research Establishment PhD thesis collection

Floyd, J. (2011), "Coupling a Network HVAC Model to a Computational Fluid Dynamics Model Using Large Eddy Simulation," Proceedings of the Tenth International Symposium of IAFSS

Society of Fire Protection Engineers (SFPE) (2007a), Guide to Predicting Room of Origin Fire Hazards

SFPE (2007b), SFPE Engineering Guide to Performance-Based Fire Protection

SFPE (2010), Proceedings & Case Studies of the 8th International Conference on Performance-based Codes and Safety Design Methods

SFPE (2011), Guidelines for Substantiating a Fire Model for a Given Application

Siu, N. O., Hyslop, J. S. and Nowlen, S. P. (2008), "Fire Risk Analysis for Nuclear Power Plants," SFPE Handbook for Fire Protection Engineering, 4th edition, section 5, chapter 14, (5)258-(5)273

Sztarbala, G. (2011), "Computational Fluid Dynamics as a tool of fire engineers – good practice," Presentation at Eurofire 2011

INFORMATION

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Appendix A3

'Test bed' environment process for assessing the appropriateness of engineering tools
to be used in performance-based design applications
presented at the 9th International Conference on Performance-Based Codes and Fire Safety Design Methods,
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'Test bed' environment process for assessing the appropriateness of engineering tools to be used in performance-based design applications

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TOPIC

There is a need for guidelines to aid the selection of appropriate fire consequence analysis tools for specific types of fire protection engineering applications. This is not to be confused with the recent SFPE Guide [1], which aims to help engineers justify (substantiate) why they selected a particular tool, but rather, to help engineers choose wisely before analysis begins. Within the fire community, the primary beneficiary of such guidelines is the fire protection engineer who applies the tools (dedicated to assess fire effects, evacuation processes and response of structures) and analyses the results in terms of safety objectives. However, other stakeholders involved in evaluating and accepting the performance of a building or structure to withstand the fire risk, such as building owners or managers, other members of the design team, insurers and authorities having jurisdiction would also benefit, since part of the evaluation/acceptance process is based on the analyses performed using the aforementioned tools. Researchers from academia, the government or the private sector who are involved in developing such tools would also benefit from the guidelines as they would re-enforce the link between the scientific research domain and the engineering application field. The need for such guidelines, and a structure for a 'test bed' environment for assessing the appropriateness of tools for different engineering applications, is discussed.

PROBLEM CONTEXT

In general, performance-based design approaches for fire protection design require:

1. The definition of goals, objectives, performance criteria,
2. The selection of fire design scenarios upon which trial designs are evaluated,
3. The assessment of the consequences of the fire design scenarios using fire effects tools (and evacuation tools...) that are selected according to the needed degree of analysis.

In order to assess consequences (third point), input data that describes the considered built environment and the fire scenarios is required. Tools that are currently used for fire consequence analysis address a range of phenomena: for example, fire effects (temperature increase, production and movement of smoke and toxic effluents, loss of visibility), occupant response and movement (occupant behavior and travel speed), and material, equipment and structural response to fire. In addition to the range of tools available, the tools have different levels of sophistication in being able to incorporate more or less detail, e.g., more or less physical phenomena for the fire effects tools, more or less psychological phenomena for the evacuation tools, and more or less details of the considered built environment components and systems for the structural response tools.

Guidelines have recently appeared to help the fire protection engineer "substantiate a fire model for a given application" [1]. This is in addition to guidelines that help the engineer understand the performance-based design process [2] and one which assists code officials in the review of performance-based designs [3]. In addition, websites are emerging which bring together users and developers of various fire engineering tools. This includes a site focused on Fire Dynamics Simulator (FDS) from the US National Institute of Standards and Technology (<http://groups.google.com/group/fds-smv>) and a site focused on users of evacuation models (<http://www.evacmod.net/>). Such sites and the people who use them collect considerable information related to the use of these tools. The International Conferences on Performance-Based Codes and Fire Safety Design Methods, managed by SFPE, have been presenting case studies where fire protection engineering national teams provide their analysis.

However, linkages between the guidelines and websites on processes, applications, data, and tools are lacking. In addition, there is significant diversity in the scenarios and buildings being used for developing and testing tools and methods. If better linkages are made, and a set of comprehensive 'test beds' can be developed – which can be used for testing all types of fire engineering tools – for a variety of applications – there are significant benefits to be realized by those who develop, use and review the tool applications.

This paper introduces a new holistic approach related to the selection of engineering tools to be used in performance-based fire protection design applications. When completed, this approach will differ significantly from current practice, taking into consideration not only tools for modeling fire phenomena, but also tools for modeling building occupant evacuation, structural response and even risk analysis. In addition, the context for use of the tools will be integrated in the method for selecting appropriate tools.

DEVELOPING A NEW HOLISTIC APPROACH FOR SELECTING TOOLS TO BE USED IN PERFORMANCE-BASED FIRE PROTECTION DESIGN APPLICATIONS

For performance-based fire protection design (PBFPD) applications, engineering tools are used to assess the outcomes of the design fire scenarios. In the past decade, fire protection engineering appeared to have left its infancy stage, as it started to incorporate scientific elements from outside its core fundamentals (i.e. fire science), from toxicology, human behavior, computing, statistics, etc. The result is that the fire protection engineer has a wide range of tools available for PBFPD applications, as outlined above. Since arguably more work has been carried out concerning development of fire effects tools than the other types of tools, the initial focus of this work is on fire effects tools.

Assessing appropriate applications of fire effects tools

In the USA, significant efforts have been undertaken in recent decades regarding uses, applications and limitations of fire effects tools, mainly originating from a collaborative project initiated by the US Nuclear Regulatory Commission (NRC), which led to an extensive series of reports [4], freely available spreadsheets and more. The SFPE Guidelines for Substantiating a Fire Model for a Given Application [1] was based on this body of work. The SFPE Guidelines,

recently published, not only includes an extensive appendix related to the fire-related phenomena which are relevant to PBFPD (such as gas layer temperature and depth, heat flux or gas concentrations) but it also notes the need to identify elements that of concern to the considered design fire scenarios for PBFPD applications [5], for example:

- Details of the spatial domain representing the built environment,
- Fire design scenario timeframes (from several minutes for a single room flashover application to several hours for assessing the collapse of a structure due to a generalized fire),
- Material properties not only describing the combustible contents but also the other building elements which "absorb" heat and fire effluents as well as the load-bearing elements,
- Initial and boundary conditions, including initial temperature in and outside the built environment and the ventilation conditions (initial conditions including the window and doors status (opened or closed) as well the boundary conditions (how the doors are leaking or how the mechanical ventilation network is set up).

Chapters related to verification and validation of fire effects tools, as well as the user effects and documentation, nicely complement the key aspects that a Code's Official is looking for when assessing a PBFPD report [3].

While these recent works are all helpful, it is worth noting that concerns related to appropriateness of tools used in PBFPD appeared as early as the developments of these tools and the PBFPD methods themselves. For instance, in 1992, Friedman [6] dealt with how well a model could predict quantities, what procedures would have to be followed to assess the accuracy of a model. He proposed two options to perform such a task:

1. The first one is to express the accuracy of a model as a percentage deviation of prediction for measurement. Using that option would arise problems related the cost of performing necessary full-scale tests, assessing the errors of the experimental devices as well as the poor reproducibility of such tests due to the stochastic nature of the fire phenomenon;
2. The second option is to focus on the capability of a model to answer the following questions: will the second combustible item ignite? Will a relatively small fire be able to actuate a nearby sprinkler? Will toxic conditions in a corridor near the fire compartment be such as to prevent escape through the corridor? Will an exposed beam fail, causing collapse?

As Fire Protection Engineers, we are more concerned about the second option and how confident we would be in answering the aforementioned questions, in a holistic context regarding the fire safety of a building. The first option is related to the verification process and it is undeniable that FPEs would prefer to support their analysis with using a model which describes fire phenomena as closely as possible. Nevertheless, the second option is still FPE prime concern as recognized by Friedman: even if a "perfect" model able to describe the reality of the fire phenomena existed, uncertainties in the input parameters, which the users had to select, would introduce a decrease in the reliability of the model to answer the questions in point 2 above with an a clear "yes or no". Examples of uncertainties in the user input parameters are: the composition of the combustible items, which would influence the evolution with time of the heat release rate and the production of smoke and toxic effluents, the percentage of absorbed moisture, which would influence the thermal inertia of a gypsum board.

Friedman stated that the decrease in the tool reliability could be as low as 50% (random guess) as illustrated in Figure 1a, when considering a single input parameter. For an actual tool, which itself bears uncertainties in terms of the simplification of the physical world and use of numerical techniques, Figure 1b shows that the uncertainty range due to a single input parameters gets bigger.



Figure 1: Reliability of the predictive capability of a model to clearly state "yes or no" to an engineering question, as a function of single input parameter values, a) for a "perfect" model and b) for an actual model [6]

In 2002, Mowrer [7] used a similar concept to describe the capability of a tool to clearly state if a performance criterion used in the PBFDP option has been achieved or not. This time, the range of uncertainties is associated with the power of the analytical tools (i.e. the capability of the tools to simulate the fire phenomenon). His concept is presented in Figure 2, where he stated that the perfect analytical tool would be the one that eliminated the uncertain middle area. His point of view differed from Friedman's one for addressing the concept in Figure 2, but he joined Friedman in stating that "perhaps the worst mistake a fire modeler can make is to run a model only once and then rely on those results as conclusive without considering how variations in input parameters might affect the results".

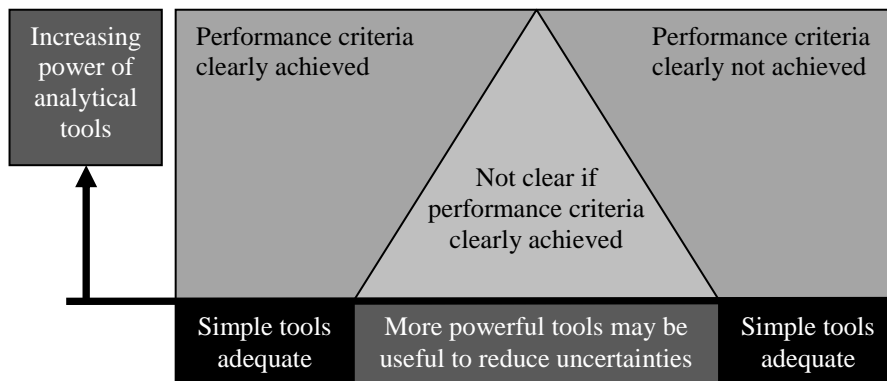


Figure 2: Ideal representation of calculation results as a function of the increasing power of the analytical tool employed [7]

Nevertheless, by mixing Figure 1 and Figure 2, the following concept emerges: (a) there are ranges of input parameters to be used in conjunction with simple tools that allow the fire protection engineer to clearly state if a performance criterion is achieved or not, so that (b), for the cases delimited by the ranges of all input parameters, it would be possible to use even the simplest tool to perform an engineering analysis, without sacrificing any certainty concerning the achievement, or not, of the performance criteria, and (c) for the other cases, the use of more "powerful" or more complex tools would reduce the uncertainties when dealing with

configurations not covered by the simple tools. Furthermore, (d) the transition between the two cases (from the case where the performance criteria are clearly achieved, or not to the case where they are not clearly achieved) is where a switchover analysis, related to the use of the tools (Mowrer's concept) in addition to the one related to the values of the input parameters of a tool (Friedman's concept), should take place.¹

Tools are only as accurate as their weakest link: developing the design fire curve

It is not surprising that the most influential parameter of fire effects tools is the design fire curve, which "usually establish[es] a relationship between heat release rate and time"[2], as it is the generating driver for temperature increase, smoke and toxic effluent production that ultimately impact targets such as building occupants, contents and structure.

SFPE [2], for example, indicates that "several methods can be used to define a design fire curve: using published data, fire testing, or calculating a theoretical fire size. In a fire protection engineering design, it can be useful to consider more than one of these methods". It should be noted that some of these methods are based on a series of standardized tests because there was always a need to connect test data serving to characterize materials with scientific data used for engineering calculations. Indeed, fire rating elements (door, floors...) cannot be tested according to every possible design fire curve.

Let's consider, for example, how fire propagation from a burning item to a combustible: there are some empirical correlations and procedures which allow quick estimations of the possible ignition of a second fuel source from the radiation emitted by a first fuel source. The International Fire Engineering Guidelines (IFEG) [8] identifies the following methods:

- Mikkola and Wichman (1989) consider both thermally thin and thermally thick materials,
- Tewarson (2002) requires data related to the TRP, or ignition temperature and some material characteristics, in order to calculate delay before ignition
- Quintiere and Harkleroad (1985) used LIFT data in a simplified thermally thick solution,
- Toal et al. (1989) used cone calorimeter and ISO Ignitability Apparatus,
- Babrauskas (1981) performed series of tests burning combustibles and established three different curves relating the ignition distance of the second burning item to the peak mass loss rate of the first one and according to the second item ignitability.

Based on the review of these elements, it seems that the most sophisticated fire effects tools (existing so far) are still dependent on the user evaluating, on his/her own, the most influential parameter of fire effects tools: elaboration of the design fire curve prior to its introduction into the tool as an input file.

¹ Switchover analysis is one of the many types of evaluation techniques accounting for known variations and unknown effects [2], so not only this concept established above is useful for tool selection but also could serve as a basis for establishing sets of tool input parameters which lead to a switchover of the analysis conclusion.

Assessing appropriate applications of tools for solving PBFPD problems: the technical layer

Another layer of complexity appears when considering that not only are fire effects tools used to estimate the outcome of a design fire scenario, but also:

- evacuation tools are needed when assessing whether life safety performance criteria are achieved, and
- structural response tools are needed when assessing whether a built structure would withstand the design fire scenarios.

Comparison between the required safe egress time (RSET) and the available safe egress time (ASET) is widely accepted as an approach when dealing with time-based egress calculations. In the ASET/RSET approach, calculations regarding the "fire" side (ASET) and the "people" side (RSET) are usually performed separately. Fire Protection Engineers have to estimate the time before untenable conditions are reached versus the time required for the building occupants to safely evacuate and manually assess interactions. Using different tools to assess both times, and relying on the engineer to integrate the outcomes, results in concerns and constraints as well. It should be noted that research tools such as FDS+EVAC allows simultaneous calculations of fire propagation and evacuation process, Building_EXODUS allows input from the fire effects tools SMARTFIRE and the evacuation software STEPS allows input from the fire zone model CFAST and FDS. Nevertheless, even with these most elaborate tools, not only the influence of the fire on the people ability to evacuate still needs more integration, mostly about decision making, but also the effect of people actions on the fire needs to be modeled within these tools.

Looking at the pre-movement time, for example, there is a "large" range associated with the time occupants take before starting their evacuation, as illustrated in Figure 3. The time when people receive the first clue that a fire event is occurring is also based on a distribution rather than a single value, as people can be notified by various means other than a smoke alarm, or centralized fire notification system connected to the automatic fire detection system.

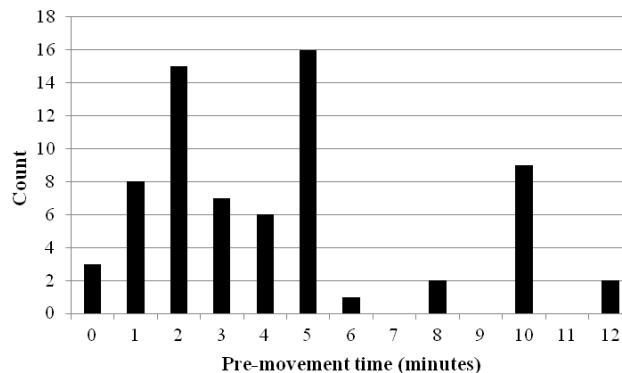


Figure 3: Pre-movement time reported after the fire in the Cook County Administration fire, October 17, 2003 Chicago, IL [9]

Mixing the estimation of the RSET and the ASET in a probabilistic risk assessment, authors have come out with the schematic representation of Figure 4: $f_e(t)$ the probability density distribution function of individual evacuation time. $f_A(t)$ is the probability density distribution function of ASET. This figure has been established considering uncertainties of the design fire curve and

characterizing occupant pre-movement time as a normal distribution, as an analogy with the result presented in Figure 3. Chu et al. [10] stated that "two curves are overlapping which indicates there is a probability that untenable conditions may occur before all occupants evacuate to a safe place".

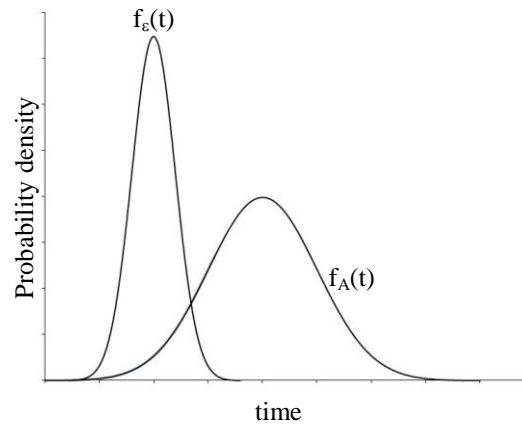


Figure 4: Hypothetical probability density distributions of individual evacuation time $\{f_e(t)\}$ and ASET $\{f_A(t)\}$ [10]

Looking at risk assessment would lead to different results when considering different tools, as the overlapping portions of the two probability functions may be different. The advantage of this type of result is that uncertainties are taken into consideration in the result shown to the AHJ, so we are now introducing the concept of probability of failure/success and not giving "absolute numbers" (this current situation then tends to increase the liability of the fire protection engineer as the AHJ is asking for some certainty of analysis outcomes, when in fact fire protection engineer is dealing with events that can potentially occur within a wide realm of possibilities).

Assessing appropriate applications of tools for solving PBFPD problems: the usability layer

Figure 5 illustrates the 'usability' concept (right tool at the right time) for a fire protection engineer (FPE) dealing with a new building design project. In this concept, the use of tools needed to conduct analysis varies along the timeline of the project:

- At the start of the project, in the feasibility and concept design phases, the level of detail in the analysis is quite low as the FPE can only provide an idea of the measures to install (based on the prescriptive requirements and the possible deviations to them) as data required to perform any analysis is still scarce. If fire effects tools are needed, algebraic models are mainly used, with a high calculation speed;
- During the scheme design, data related to the interior design of the building becomes available and more sophisticated tools can then be used, such as zone models;
- In the detailed design phase, the details of the project are known and 3-D simulations can be used – if needed and if time allows – as the time for analysis is shorter as we go along the project, running these complex simulations requires a considerable amount of time, compared to the use of previous tools, and since these tools generate a lot of useful information, data treatment of 3-D simulations is also time consuming.

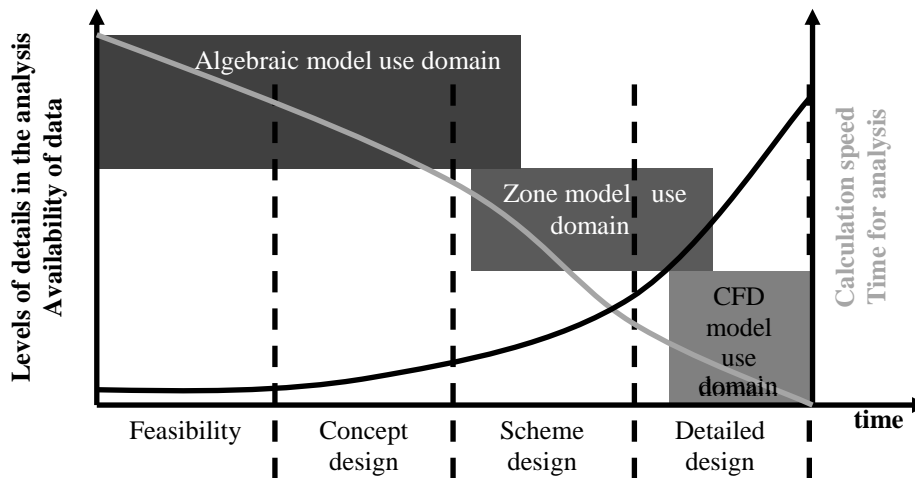


Figure 5: Fire effects tools domains as a function of a new building project phases

Figure 5 is applicable to the whole considered building project. If a specific safety point is known at the concept design phase, and if it is also known that the degree of details would require a more complex tool than an algebraic model or even a zone model, the FPE would have to somehow obtain, from the design team, the data needed in order to use such a more complex tool at the earlier stage. As stated previously, performing such calculations uses significant time and resources and the results are highly dependent on the input parameter values. Using input parameter values at the start, which in the end would be quite different from the ones that would be finally needed, could lead to dramatic changes in the design, not only of the fire protection features but also in the design of the building itself, and could mean expending considerable resource for limited value. However, if a set of 'test bed' studies existed, which reflect similar projects, the information could place the FPE in a better position to ask the design team for needed input parameter values, or at least range of values, based on the experience of the test bed studies.

For PBFPD applications, another constraint that has to be considered appears in the regulatory environment. National standards, such as NFPA 204 for smoke and heat venting [11], NFPA 92 for smoke control systems [12], and so forth may be used in conjunction with building code regulations, to help a project to be accepted by the Authority Having Jurisdiction (AHJ) because these standards are recognized by these AHJs. An engineering analysis incorporating the analytical methods of such standards would not require so extensive justification as the ones purely based on more sophisticated engineering methods.

In conclusion, within a PBFPD framework, the selection of appropriate tools for a given application depends on many layers:

- a technical layer where tools differ on how well they describe physical phenomena that are relevant to a given application, on how well the user has to consider the input parameters (mainly the design fire curve), how well the specialized tools communicate with each other (fire effects tools with evacuation models and so forth),
- a usability layer where tools are used in a specific context, where input data may not be available as needed, analytical methods from already existing standards may be preferred to more sophisticated engineering methods based on their better acceptance by the AHJ.

ORGANIZATION OF A 'TEST BED' ENVIRONMENT TO SUPPORT THE NEW APPROACH

To address the challenges outlined above, a new approach is suggested in order to advance our ability to more appropriately apply the diversity of engineering tools that are available for the range of building fire challenges that FPEs face and the stage of the project at which the tools are needed. This approach involves two primary components:

- Development of new guidelines for the selection of appropriate tools for a given fire protection engineering type of application, and
- Development of a web-based 'test bed' within which to apply, assess, evaluate and expand upon the capabilities of the tools and of the profession.

Appropriate selection of a tool depends not only on its capabilities to “correctly” simulate the aimed physical phenomena, but also on the context in which the tool is used. At the same time, there is not always ‘unlimited time’ to undertake analyses, and having prior knowledge about the appropriate applications for the tools can help increase the efficiency and effectiveness of performance-based analyses. In order to help the fire protection engineering community to be better able to address such resource and time constraints related to the use of fire consequence analysis tools, a process for tool selection and a ‘test bed’ environment are proposed. The ‘test bed’ environment allows a wide variety of tools to be applied to common building configurations and fire protection challenges in order to build up knowledge and experience on selection and use of tools for various levels of fire protection analysis. The ‘test bed’ environment process is mainly composed of three following phases:

1. A "pre-processing phase" where study topics are selected and organized according the common interest of different participants (including not only the usual stakeholders involved in PBFDP projects but also researchers and people in academia) and availability of input data and building layouts,
2. A "performing and analyzing phase" where participants identify common safety objectives, safety functions and criteria, select together fire design scenarios to study with the tools and methods of their choice, upload the results to the website,
3. A "post-processing phase" where results of the tool applications are discussed in terms of their ability to address the defined performance issue, which discussion would eventually lead to the establishment of guidelines related to the tool comparison process, their usability and their relative outcome.

A more detailed process is presented in [5]. Each considered study topic will be associated with a portion of a website available to the 'test bed' participants, allowing free exchange of information and analysis. This organization is intended to maximize the number of participants and thus to contribute to a more extensive and validated study (with participants using differently the same tool so user influence would be addressed or with participants using different tools).

In the pre-processing phase, building layouts are collected from existing architectural projects or fictional ones, as long as they provide enough information to be used from correlations to CFD tools. Additional information for evacuation or structural response calculations may be also

collected for use in upcoming hybrid tools such as the ones between a fire effects tool and a HVAC network model, as developed by Floyd [13]. During this phase, relevant information on a particular building or built environment is collected, including plans in AutoCAD® or REVIT®, interior layouts, and in some cases contents. Whatever tools are used by a fire protection engineer for his/her own purposes, these types of information are usually the basic information for the design team. Of course, as explained in the previous sections of this paper, not all the design information is available at the start of a project. Nevertheless, one of the primary aims of the 'test bed' environment studies is to assess the differences in the tool answers in relation to an engineering problem. This pre-processing phase would then be used as a feedback for the design team so they would know what information/data to provide the FPE as soon as possible so the FPE could use it in his/her analysis, especially for tools that would require lots and precise input data.

An initial 'test-bed' environment has been set up already, and several building configurations have been obtained. Examples of already collected building configurations are: hospital, library, high-rise office building, high school and dormitory. To supplement this set of configurations, examples of case studies could also be collected from the International conferences on performance-based codes and fire safety design methods [14].

In recent years, extensive work has been done in order to facilitate the transfer from architect's files to files usable for CFD fire effects tools (FDS via the software PyroSim or SMARTFIRE), evacuation models (Building_EXODUS or STEPS). Besides this project and all the work carried out by the aforementioned tool developers, Pin and Wu also [15] considered the use of the imported CAD file (ge1 extension file) in order to visualize the results in the SMOKEVIEW tool. This paper led us to consider how this representation might be misleading for the stakeholders, while judging the results provided by FDS, which performs the CFD calculations and the SMOKEVIEW layer which helps presenting the FDS results in the 3D geometry: if the geometry of the building is shown as very refined, the AHJ could think that the FDS calculations are refined at that level, which is usually not the case. The import of the geometry has to be considered as only making the process easier and faster for the FPE to build the geometry for calculations.

In the "performing and analyzing phase", which is really the core of the studies, safety objectives, safety functions and fire design scenario types are defined for each 'test bed' study. Given this information, participants are asked to perform simulations with the tools of their choices and upload the results in the website, providing details not only on the results but also on the use of the tools. Specific studies related to the use of CFD fire effects tools are presented in [5], including issues related to grid selection for a better optimization of CFD computational meshes, influence of detailed geometry on the results of the simulations, detailed geometry description versus computational time and result accuracy. Some specific studies related to evacuation models may also be defined and conducted among the participants.

In addition to studies related to the use of fire effects tools, studies related to the use of evacuation models, structural response models and fire risk models would also be included in the 'test bed' environments. The website would also be dedicated to facilitate information exchange about all types of engineering tool applications examples. Comparison studies such as the one

performed by Lord *et al.* [16] on evacuation models would be welcome, rather based on study topics selected in the first phase of the 'test bed' studies than on a generic parametric analysis. This idea is linked to how the validation domain of the tools from research laboratory experiments could be extended in order to include all the diverse real life complex multi-story facilities which are the subject of PBFDP applications. The current process tends to involve a simultaneous and quite independent increase of the experimental input data ranges to correspond to real engineering projects. It is thought that (a) establishing a list of non-dimensional parameters which characterize related phenomena [17] and (b) describing the engineering projects with these parameters, would may cluster the application domain and this way lead to specific research to ultimately include these application clusters in the validation domain of the tools. McGrattan [17] stated that "the burden of [verification and validation] V&V must be shared by the model developer and the user". In this matter, the 'test bed' environment is then designed to increase the collaboration between tool developers and users.

In parallel to collecting building layouts, a set of 'combustible packages' representing 3-D objects such as chairs, couches, and beds, which contain heat release rate, chemical reaction, and toxicity properties needed for the simulations, has been developed. The benefits of such data are that scenarios describe burning elements in the same way so that the focus of the 'test bed' studies remains the use of the tools for fire consequence analysis. A separate study, using different 'combustible packages' in FDS, shows that the same fuel item can be described differently whether the fire consequence analysis concerns the near field of the spreading fire or the far field. This study purpose is then to help the users of fire effects tools when characterizing the degree of details necessary to describe the design fire curves for a particular design fire scenario [18].

The third phase is dedicated to the analysis of the provided results by all participants of the previous phase and by the stakeholders who helped defined the safety objectives. This phase is aimed to provide the guidelines for selection of tools for a given application.

Benefits of conducting such 'test bed' studies are as diverse as the different participants to the studies [5]. Such guidelines related to the use of tools for PBFDP applications would be beneficial not only to consulting companies, engineering societies, regulators and AHJ, but also students and professors in Academia and governmental agencies which could set up research programs focusing on the problems and needs of the fire engineering community.

ACKNOWLEDGEMENT

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REFERENCES

1. SFPE, Guidelines for Substantiating a Fire Model for a Given Application, 2011
2. SFPE, SFPE Engineering Guide to Performance-Based Fire Protection, 2007
3. SFPE/ICC, Code Official's Guide to Performance-Based Design Review (chapter 11), Society of Fire Protection Engineers and International Code Council, 2004

4. NRC-EPRI, Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications, vol. 1-7 (NUREG-1824 and EPRI 1011999, 2007)
5. Alvarez, A. and Meacham, B. J., ""Ready-to-use" Building Layouts and Combustible Packages for 3-D simulations", proceedings of the Fire and Evacuation Modeling Technical Conference, 2011
6. Friedman, R., "An International Survey of Computer Models for Fire and Smoke," Journal of Fire Protection Engineer, 4 (3), 1992, pp 81-92
7. Mowrer, F.W. (2002),"The Right Tool for the Job," Fire Protection Engineering Magazine (SFPE), Vol. 13, Winter, 2002, pp. 39–45
8. (ABCB) Australian Building Codes Board (2005), International Fire Engineering Guidelines, 2005
9. Proulx, G., Reid, I. and Cavan, N.R., Human Behavior Study, Cook County Administration Building Fire, October 17, 2003 Chicago, IL, Research Report No. 181, April 2004
10. Chu, G.Q., Chen, T., Sun, Z.H. and Sun, J.H., "Probabilistic risk assessment for evacuees in building fires," Building and Environment 42, 2007, pp. 1283–1290
11. NFPA 204: standard for Smoke and Heat Venting, National Fire Protection Association, 2012
12. NFPA 92: standard for Smoke Control Systems, National Fire Protection Association, 2012
13. Floyd, J., "Coupling a Network HVAC Model to a Computational Fluid Dynamics Model Using Large Eddy Simulation," Proceedings of the Tenth International Symposium of IAFSS, International Association for Fire Safety Science, 2011
14. SFPE, proceedings of the 8th International conferences on performance-based codes and fire safety design methods, Society of Fire Protection Engineers (2010)
15. Pin, Yat Fat and Wu, Kwun Hing, "Fire Modeling with CAD/GE1 Techniques," proceedings of the Fire and Evacuation Modeling Technical Conference, 2011
16. Lord, J., Meacham, B., Moore, A., Fahy, R. and Proulx, G, "Guide for Evaluating the Predictive Capabilities of Computer Egress Models", National Institute of Standards and Technology, NIST GCR 06-886, 2005
17. McGrattan, K. and Myers, T., "A Way to Characterize the Range of Validity of a Fire Model, proceedings of the Fire and Evacuation Modeling Technical Conference, 2011
18. Alvarez, A., Dembsey, N. A. and Meacham, B. J., "Combustible packages for 3D simulations using FDS – Simulating experiments in the FDS Chamber", manuscript to be submitted for publication in June 2012