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Development of a holistic approach to integrate fire safety performance with building design

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DEVELOPMENT OF A HOLISTIC APPROACH TO INTEGRATE FIRE SAFETY PERFORMANCE WITH BUILDING DESIGN

by

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Abstract

Building fire safety is significantly influenced by building and fire safety regulations (often codes and standards). These regulations specify what fire safety measures should be included in a given building as a minimum requirement. Since fire engineers develop fire safety designs based on the regulations, they are often viewed as the primary agents in ensuring the fire safety of buildings. However, their mission often starts with given building design features, such as interior spatial layout, exterior shape, site plan, and so forth, which are mostly determined by architects (or architects). Although architects design buildings within the boundaries of the regulatory requirements, their focus is not generally on fire safety, but more on visual and spatial aesthetics of buildings. These objectives are linked to building form and functionality, which are not subject to the building and fire safety regulations. These objectives can sometimes compete with fire safety objectives in such a way that buildings can be unsafe in certain situations due to unintended effects of building design features on actual fire safety performance.

To determine whether a building has design features which work against fire safety performance, evaluation of building fire safety performance must take into account the effects of building design features. If fire safety performance is significantly decreased by building design attributes, additional fire safety measures or modifications of the building design should be incorporated to provide an appropriate level of fire safety performance. While there have been various building fire safety evaluation tools developed over the last forty or so years, none of them comprehensively considers building design features and their associated effects as key performance parameters. In this context, the current study develops conceptual models for fire safety performance assessment in both qualitative and quantitative manners.

After scrutinizing previous fire incidents and the building features which contributed to their outcomes, various fire safety performance attributes, including building design features, are identified and cause-effect relationships among the attributes are established. Then, the attributes are organized hierarchically like a tree diagram such that the performance of one upper level attribute is determined by the combined performance of multiple lower level attributes. In this way, the performance of bottom level attributes propagates upward to the upper level attributes. Two tree diagrams are established for the most common fire safety objectives, life safety and property protection.

Each attribute in the tree diagrams has two quantified values: performance value and weighting factor. The current study uses three different performance values (0.01, 0.5, and 1) for bottom level attributes representing poor, average and good performance, respectively. In addition, as each attribute

can have different contribution to upper level attributes, a weighting factor between 0 and 1 is assigned to each attribute which represent the relative importance. With these two values, the performance value of an upper level attribute is calculated using the weighted sum method (summation of multiplied values of performance value and weighting factor) which is commonly used in the Analytical Hierarchy Process. As the performance of an attributes is a function of specific designs, building uses, occupants, and site conditions, in the first instance, judgments of the fire engineers can be used to assign weights and performance values, but they can also be determined jointly among stakeholders.

Generally speaking, the details of attributes for fire safety performance are not determined at once. Rather they are gradually determined as the building design progresses. This means that in early design building design phase, many of the attributes are unknown as well as fire safety performance. Once appropriate information can be provided to architects by fire engineers at each building design phase, it is likely to avoid possible conflicts between design details and fire safety performance. Using the fire safety evaluation model, weak attributes for fire safety performance can be identified and possible make-up strategy and building design approach can be developed in advance. This provides the potential for the collaboration between fire engineers and architects and at the end for increasing building fire safety performance of buildings.

Acknowledgement

I thank God, my family, my advisors, and WPI mates.

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1 Introduction

This research was motivated by a brief comment of a presenter in a conference for green building regulations and technologies. The presenter pointed out the significant impact of building design features on the energy efficiency of a building; it can be even more dominant than various practices of advanced technologies such as rain water reuse systems and solar panels.

This raised a question of importance to me: “Is the building design also critical to fire safety?” This simple question led to many other questions, such as:

- What is the relationship between building design and fire safety design?
- Do architects and fire engineers recognize how building design features impact building fire safety?
- What is the process of building design and fire safety design and what criteria are used in the process? Is there any standardized work flow?
- How do fire engineers get involved in the building design process?
- What are the basis of decisions of architects and fire engineers?

Answers to most of these question were not easily obtained, which led me to this research with the objective of increasing building fire safety performance bridging the gap between architects and fire engineers. The work embodied in this dissertation aims to answer these questions and develop a logical thought process to incorporate fire safety performance into building design process. The main themes are presented in three chapters:

Chapter 2: Influence of building design features on fire safety performance
Chapter 3: fire safety performance evaluation
Chapter 4: Incorporation of fire safety performance into building design process

Chapter 2 explores the differences in how architects and fire engineers look at the three key performance parameters of building fire safety, building, people, and fire. Two exemplary cases: one from an actual fire incident and the other from experimental study in which their different perspectives are well-reflected are analysed to show the influence of building design features on fire safety performance. In addition, discussion on whether the current fire safety design approach and analysis is appropriate to comprehensively account for the effects of building design is included. From this research area, it is found that fire engineers and architects need to collaborate together to increase building fire safety as building design can significantly influence fire safety performance. This chapter formed the basis for a paper published in Fire Technology (Park H, Meacham BJ, Dembsey NA, Goulthorpe M, Enhancing building fire safety performance by reducing miscommunication and misconceptions, Fire Technology, 2013, DOI: 10.1007/s10694-013-0365-2).

Chapter 3 presents two conceptual building fire safety performance evaluation models, one at a general level and one at a detailed level, which considers both holistic design objectives and fire safety objectives. These models are needed so that the negative effects of building design features can be holistically understood with respect to building fire safety performance. The bases of the models are presented. Additional details about the model development are provided in Appendix A, which provides a more in depth discussion of how study of fire incidents in the context of specific building configurations was used to develop interactions between building attributes, assumed fire safety system performance, and overall performance in fire events. In addition, an exemplar quantified evaluation tool, based on the detailed conceptual model, is also presented. The conceptual models and quantitative assessment tool presented here are targeted for fire engineers for holistic building fire performance analysis. This chapter formed the basis of a paper accepted for publication in Fire Technology (Park H, Meacham BJ, Dembsey NA, Goulthorpe M, Conceptual model development for holistic fire safety performance analysis, Fire Technology, 2013, DOI: 10.1007/s10694-013-0374-1).

Chapter 4 illustrates how the models presented in Chapter 3 can be incorporated into building fire safety performance analysis at various stages of the building design process. As discussed in this chapter, the key player is the fire engineer who holds a comprehensive understanding of building fire safety performance. Once a fire engineer identifies problematic building design features, appropriate feedback needs to be provided to architects. If architects do not accept the feedback, fire engineers need to develop alternative fire safety designs or even building design features and be proposed to the stakeholders including architects. Using the conceptual models and quantitative assessment tool, the alternative fire safety designs and building design features can be also identified. This is illustrated through a proof of concept example. This chapter formed the basis of a manuscript under review by the journal, Building Research & Information (manuscript ID 13BR0010-RE submitted in November 2013).

Chapter 5 summarizes the main findings of this research.

Chapter 6 introduces the future work to make the developed holistic performance evaluation models more concrete for further applications and provides rationales for the necessity of the models especially in the context of Building Information Modeling (BIM).

A total of two appendices are included. Appendix A is a paper published in the proceedings of the 9th International Conference on Performance-Based codes and Fire Safety Design Methods, Hong Kong, 2012, which identifies the gap between architects and fire engineers and resulting decrease of fire safety performance. It also proposes a conceptual means to improve fire safety performance by decreasing the gap. Appendix B is a research draft for journal publication which suggests more integrated building performance evaluation tool in the BIM-based building design environment. Since BIM-based design tools comprehensively include material data as well as design details, they have a great potential to be utilized for both design and performance evaluation for buildings. This also includes fire safety performance. The draft also illustrates a recommended structure of the fire safety performance evaluation tool within a BIM-based building design tool.

2 Influence of building design features on fire safety performance[1]

2.1 Introduction

Architects make numerous design decisions which take into account various functional and aesthetic features needed to satisfy the needs of clients and stakeholders as well as compliance with building codes and regulations. Fire safety is an important need, although it sometimes has a lower priority than other design objectives due to its intrinsic nature and the low level of risk perceived from fire: fire safety features do not generate any explicit benefits such as comfort, convenience, or aesthetic pleasure, and they are only useful for a fire incident, which is not likely to occur. Considering the common and widely accepted perception that architects place more importance on artistic and aesthetic expression in building design (i.e., form over function), a lack of focus on fire safety may not be an exaggerated concern [1]. A proper level of fire safety, however, as a public good, should be provided to all buildings regardless of the design priority of architects. Therefore, fire protection measures have been enforced in the form of regulations, commonly via building codes and standards, in which various requirements are listed. As such, although the design concept may originate from visual sense or aesthetics of buildings – attributes which are not subject to the building codes [2] – the architects' design decisions may need to be changed to satisfy the codes. This may be one of the reasons that some architects perceive code requirements as design constraints [3, 4].

There are largely two forms of building and fire codes: prescriptive-based and performance-based. A prescriptive code includes detailed requirements based on the specific occupancy type or building use. Fire safety design based on prescriptive codes has been conducted for about a century, but there has been criticism that such codes lack scientific bases for several of the requirements, and considering the variability of building objectives, they do not readily facilitate fast-developing building technologies and innovative designs. To address these concerns and others, functional- and performance-based approaches to building and fire regulation began to emerge in the 1980s [5]. This form of regulation was intended to facilitate innovation, while at the same time reducing regulatory burden and unnecessary costs. An important aspect of performance-based regulatory systems was the need for more complete and well-justified engineering analysis and design, since the previously prescribed requirements for fire safety and other features were no longer required. This gave rise to the development of the performance-based design (PBD) concept, which was adopted for fire safety, seismic engineering and other engineering disciplines in many countries [6]. At present, many developed European and Asian countries have adopted or in the process of adopting performance-based codes and PBD for fire. PBD for fire is also seen

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[1] Unformatted text of paper published in Fire Technology, DOI: 10.1007/s10694-013-0365-2

in countries which have only prescriptive-based building and fire codes, such as the USA, employed in demonstrating ‘equivalency’ to the intent of the code under the auspices of the ‘alternate methods and materials’ clause [7].

With this paradigm transition from prescriptive-based to performance-based fire safety, reexamination of the traditional roles of architects and FPEs with respect to building fire safety performance is warranted, as real or perceived limitations imposed by prescriptive requirements on building designs are decreasing, leading to more innovative, creative, and challenging building designs, systems and features, which in turn may require that performance-based fire safety design (PBFSD) approaches be applied. In such an environment, having the FPEs understand how architects view building performance and how the processes of architectural design works, and vice versa, is essential. To date, however, little research has been conducted on the extent to which architects influence fire safety and how well FPEs perceive the effects of building design on fire safety. In this context, the current research aims to expand the understanding of building design features on actual fire safety performance, and explore how FPEs can use this knowledge to increase building fire safety performance and assist architects to design better and safer buildings.

2.2 Background

Architects may be defined in many different ways as they practice in a variety of specialties, from urban city planning to furniture design. In the current study, the definition of architects is confined to buildings and the associated component and space design: the built environment. In this narrowed definition, the mission of architects may also vary depending on the project environment, such as the project scale or project delivery system. Architects may play the role of project manager, overseeing the entire project from the design stage to construction completion or even to the stage of building occupation. In other cases, architects may be design specialists as part of a design team led by a separate project manager and offer only building design services to the project. Regardless of this difference, the term, architects, throughout this paper, represents entities who determine the details of building design features such as site plan, exterior shape, interior space layout, landscaping, and interior design.

A building accommodates various stakeholder and social objectives, including the purpose, function, owner’s requests, aesthetic aspects, occupants’ needs and wants, and societal expectations. Some design objectives may cooperate well, contributing to the holistic goals for the building, while others may compete with each other, resulting in the need for some to be sacrificed in whole or in part. Generally, architects manage the relationships among the design objectives, prioritizing them and finding the most appropriate design solution with the assistance of the broader design team. Figure 1 summarizes key building design objectives as identified in a variety of sources [8-11].

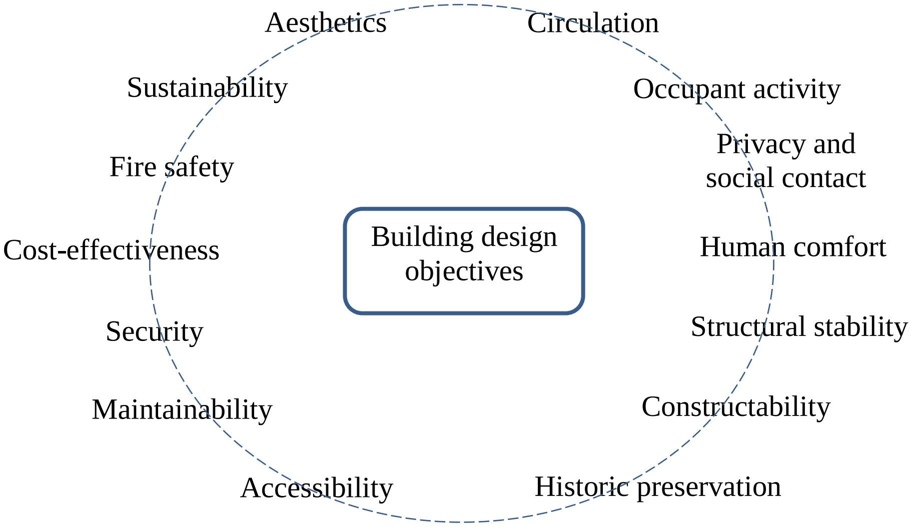


Figure 1. Various design objectives of architects

Fire safety has not drawn much attention from architects for a large majority of buildings although it is one of the critical design objectives as shown in Figure 1. This is largely a function of the regulatory environment. In the prescriptive-based fire safety approach, for example, code compliance may not be a significant concern to most practicing architects as a good understanding of code intent or the comprehensive fire safety performance is not required given that the detailed requirements in the code can be directly applied to the building without exception. In this environment, the mission of FPEs that architects understand tends to be designing fire protection systems such as automatic sprinkler systems, smoke control systems, or alarm and communication systems following the code specifications, which can be also conducted by mechanical or electrical engineers, or checking code compliancy of building design. As such, architects often do not perceive the necessity of early involvement of FPEs in most building design projects unless there are critical competitions between code compliancy with other design objectives. In fact, FPEs are often requested to participate in the project after the building design features are almost finalized. In this late design stage, the experience and engineering expertise of FPEs have less opportunities to be reflected in the building design as building design modification is only feasible when time and budget burden are not significant and a high percentage of design work is not achieved yet [12].

In the performance-based fire safety approach, performance-based codes do not generally include detailed requirements as part of the legislatively-enforceable document, as shown in Figure 2 [13], but rather allow for two means to demonstrate compliance: application of detailed means and methods to achieve the performance requirements as embodied in non-compulsory ‘deem-to-satisfy’ compliance documents (essentially prescriptive solution), application of fire engineering analysis under the general performance-based design, or some combination thereof. However, as the deemed-to-satisfy solution does not require rigorous fire engineering analysis and evaluation of fire safety design, it becomes more dominant than developing a comprehensive PBD solution, or a large portion of the final design solution is based on deemed-to-satisfy solution with only a small portion being derived from fire engineering analysis, which in the end, may not be much different from a prescriptive-based fire safety design in many cases.

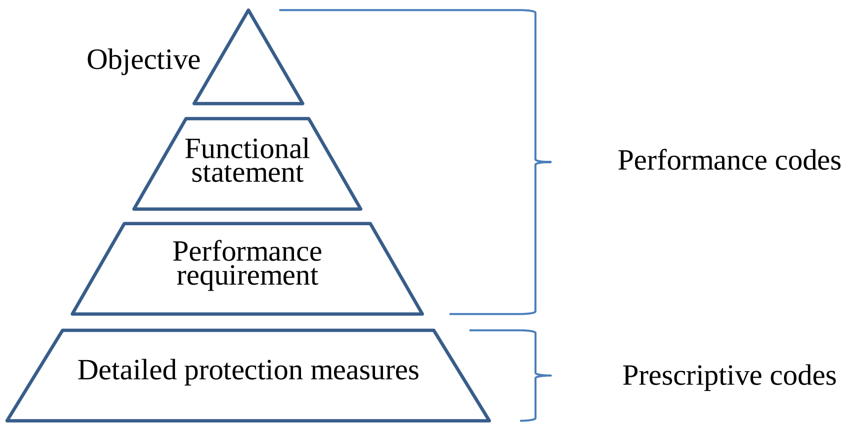


Figure 2. The relationship of codes and the level of requirements

Therefore, unless the comprehensive PBD approach is taken, fire safety as building design objectives may not attract more attention of architects, and the perspectives of architects on the FPEs’ mission may remain the same, resulting in the late involvement of FPEs in the project. In this environment, buildings mostly tend to be designed by architects without much consideration of fire safety, and fire safety features are designed without a comprehensive understanding of possible fire safety performance with the given building design from architects.

To improve this situation, a collaborative work environment is necessary between architects and FPEs, with a focus on holistic building performance, starting from with a better understanding of the perspectives and motivations of each other with respect to building performance. The current study examines the following items, and proposes a necessary step that FPEs take in the context of building design and the design of fire safety measures (or architects and FPEs):

- The gap between the way architects and FPEs think and communicate

- The effects of building design features on the actual fire safety performance
- More comprehensive fire safety performance evaluation by FPEs

2.3 The gap between architects and fire protection engineers

Broadly generalizing, there are a number of intrinsic differences between architects and engineers. Some of these differences, highlighted by previous researchers, are referenced below. As it is inevitable for architects and engineers to work together in most building projects, failing to understand these differences may inadvertently undermine effective collaboration.

(a) Communication style [14]

Generally speaking, architects are creative, 'right-brain' dominated people. They are visually- and spatially-oriented, materializing even scientific or engineering concepts articulated by 'left-brain' engineering types into a shape of spatial form. From an architectural perspective, a project starts with a sketch, develops into conceptual and schematic drawings, and ends with detailed drawings. In other words, pictorial representations and non-quantitative and sometimes abstract expressions are used to describe their vision and their work product. However, engineers are generally more 'left-brain' dominated analytically oriented people. Engineers use mathematical equations and correlations and express the outcome of their work in concrete, quantitative terms. As a consequence, when engineers listen to architects, they may think that the architects' expressions are vague or imprecise, and may struggle to understand essential points. Likewise, when speaking to architects, the engineers' analytical explanations may be lost in translation.

(b) Language problem - same words with different understanding [15]

The expression "barely enough to live on" may mean conditions completely different to a middle class family in a developed country than to a family in a developing country. The same words can be interpreted differently in terms of precision, amount and level (context matters). The expressions used by creative, 'right-brain' dominated architects may be verbally exaggerated to some extent, such that "fantastic" or "fabulous" may be benchmarks used to mean "good enough", and "good enough" may actually reflect passive acceptance of even "unsatisfactory." Engineers, whose analytic, 'left-brain' dominance can be more literal, may interpret "good enough" as the green light to move forward without a second thought. In such a case, the same term is used, but can be interpreted differently.

(c) "Most of all, the very typical beliefs of the architects themselves that their artistic task surpasses its practicality and that they have responsibility not only to their clients but also to society at large." [16]

As artists do not often compromise their artistic desire with worldly value, some architects have a passion for artistic expression, which sometimes surpasses the basic functionality of buildings. This may be one of the reasons for the general impression of architects being stubborn and non-negotiable. In addition, architects tend to give social meanings to building design in relation to other buildings and environments.

The differences mentioned above are applicable to how architects and FPEs may view their role in the building process. This can be illustrated using the diagram in Figure 3, which is often used in the FPE community. The diagram consists of the three components: building, people, and fire, with each component having its own characteristics. The intersected areas represent the interactions among the characteristics. One often cited example for the interaction is the scenario that occupants leave a door open which does not have an automatic door closing device during evacuation, and fire spreads via the door opening. These characteristics of the building (no automatic door closing device), the fire (fire spread through the opening), and the people (non-adaptive behavior leaving the door open during evacuation) interact together and create more fire hazards beyond the room of fire origin.

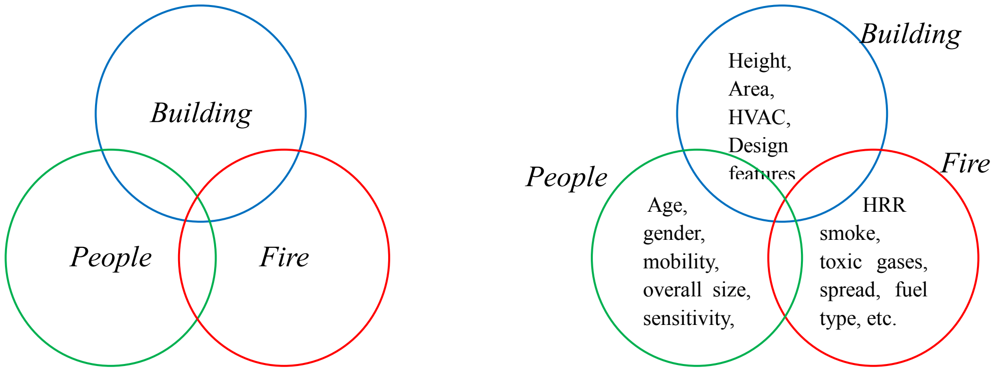
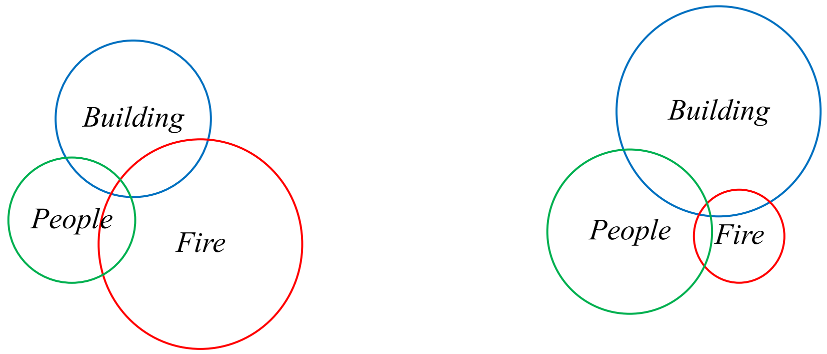


Figure 3. Common components in building fire incidents

While the diagram generally is not used to represent perspective for the purpose of comparison, it can be modified to do so. If it is assumed that circle size is used to represent the relative importance of each component, it may look like Figure 4 from the perspective of FPEs and architects. The larger the circle size is, the more emphasis is assigned.



(A) From fire protection engineers (B) From architects

Figure 4. Different perspectives of fire protection engineers (A) and architects (B) on the well-known key components in building fire safety

From the perspective of FPEs, the fire component may have a larger area than the building or people component as shown in Figure 4 (A). This does not mean that fire protection engineers consider building or people components less importantly than the fire component, but that the mission of FPEs is more focused on fire. Therefore, even the building or people characteristics that FPEs consider are derived from impacts on or from the fire. For example, means of egress and fire separation features in the building component, and occupant number and egress capability in the people component, have been emphasized by FPEs, while factors such as access, normal pedestrian flow and visual environment are may sometimes not be considered.

On the other hand, architects, as master architects, are focused mostly on the building component as they are largely in charge of determining exterior shape and interior space layout taking into account a variety of design objectives shown in Figure 1. Architects also emphasize occupants' needs and wants relative to environmental conditions, so as to provide more attractive and pleasant spaces and to accommodate various characteristics such as occupants' lifestyle, culture, age and gender. Naturally, the building and people components have been more critical to architect's mission than the fire component. In fact, from an architect's perspective, the 'fire' circle would likely be much smaller than shown in Figure 4 (B).

The different perspectives of architects and FPEs can be also found from the categorization of building use. In the International Building Code (IBC) [17], the most widely used prescriptive building code in the U.S., largely 10 occupancies are defined, and some of the occupancy have several sub-occupancy groups. Fire safety requirements are generally differentiated following the occupancy categorization as well as other building or fire safety features such as construction type and building size, installation of automatic sprinkler system. As different requirements represents different level of fire hazards perception, it may be said that the 10 building occupancies in IBC suffice the need of fire hazards categorization in terms of building use. The Architects' Handbook [18], however, lists 30 building uses referring to them as "most building types likely to be encountered by architects", and states various consideration points under each use that architects take into account for building design. This means that architects perceive different design concerns from at least 30 different building uses. Of course, each of the 30 building uses certainly belongs to one of the occupancies listed in IBC, but the perspectives on fire hazard perception and building design concerns based on building use are clearly incongruent, which represents the different perspectives of architects and FPEs.

2.4 The influence of building design on actual fire safety performance

The different perspectives of architects and FPEs may be natural as their main mission is different in building design projects, although they should have the ultimate goal of producing a building that meets the client's needs and budget and the regulatory requirements of health, safety and amenity. If one assumes that building design does not affect fire safety performance, the differences may not be problematic, as design and fire safety could be considered separate independent variables. However, building design does influence fire safety. Some building design features are captured in the fire protection community and have been subject to regulations such as means of egress, but there are others which may not be handled by both architects and FPEs as they generally occur only in certain building-people-fire circumstances inadvertently. In this section, two exemplary case studies are presented representing the influence of building design on actual fire safety performance in terms of fire development and human behavior.

2.4.1 The effects of building design on fire development

On May 13, 2008, a fire occurred in the Faculty of Architecture Building (called Bouwkunde) at the Delft University of Technology in Delft, The Netherlands [19]. The fire started in a coffee vending machine at the 6th floor of the south tower around 9:00 AM and quickly spread vertically to the 11th floor. The fire continued to develop and spread to the north tower, with a portion of the north tower collapsing around 4:40 PM, about 7 hours 40 minutes after the ignition. The relative location of the fire origin and collapsed portion of the building are shown in Figure 5 and Figure 6.

Figure 5. Fire origin (red circle) and collapsed portion of the building (blue dotted lines)

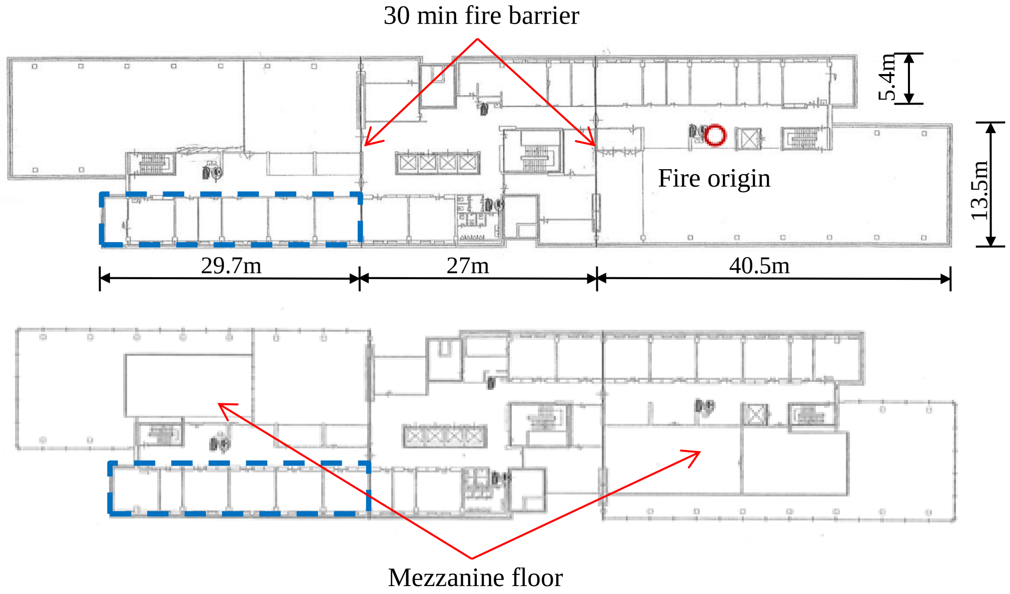


Figure 6. Typical floor plans of even floors (upper) and odd floors (lower)

As the home of the Faculty of Architecture, a critical characteristic of the building was the presence of design studios on each of the even floors. A portion of the design studio areas was characterized by 2-story high ceilings while the rest of the studio had a single story height. This was due to the mezzanine floor being hung from the floor above as shown in Figure 6 and Figure 7. The exposed bottom surface of the mezzanine floor was finished with acoustic ceiling panel to provide better sound quality as lectures were also held in this space. The Bouwkunde fire incident has much drawn the attention of fire and structural experts, as this building was basically made of steel and concrete, excellent fire resistance materials, and complied with the building code for existing structures of The Netherlands. Vertical fire spread was not expected to the extent that occurred, and horizontal 30 minute fire barriers were expected to contain the fire in the room of origin until fire service suppressed or controlled the fire. However, neither control of vertical fire spread nor horizontal fire spread was achieved, and fire fighters could not actively conduct their fire suppression mission as the fire had developed and spread faster than anticipated.

Figure 7. Internal space layout of studio area and mezzanine floor

Architecturally this building was attractive. Horizontally continuous windows were installed throughout the building perimeter, and the partial mezzanine floor which is hung from the floor above allowed a sense of openness and closeness together. Pilotis in the ground level allowed free occupant circulation with a sense of lightness of the massive tower section, and the design studio area as one large space promoted various design activities for students. The architectural attractiveness of this building can be easily confirmed as it was originally designed for the department of architecture and had been used for about forty years [20]. Recalling the diagram with three circles in Figure 4, the Bouwkunde must have been a good design from the architects' viewpoints.

There was an upgrade of fire safety features in Bouwkunde following a fire inspection in 2003, adding a fire escape, and this building satisfied local fire regulations for existing structures. However, considering the building in retrospect, there are several building features which contributed to the fast fire development and vertical spread.

- There were a large amount of combustible materials over the wide floor area of the design studio.

- The combustible acoustic material on the bottom of the mezzanine floor contributed to a fast heat release rate (HRR) development by providing more radiation to the unburned items after it was ignited based on fire model simulation. The acoustic material itself worked as an additional burner located on the ceiling.
- The 30 min fire barrier was not good enough to contain the fire in the room of origin as the fire was developed very fast, which did not allow fire service to conduct the suppression mission.
- The large open space in the design studio area supported enough oxygen for the fire to grow fast at the initial stage of fire development.
- The 4.95 m tall exterior window height was high enough to facilitate large flame extension which could annul the 2.05 m vertical separation. The extended flame height out of the opening reached more than 7 m as shown in Figure 8. This vertical separation distance incidentally complied with the IBC requirement, and therefore the same design features could also satisfied the prescriptive requirements in the U.S. and could result in the vertical flame propagation.
- Horizontally continuous exterior windows became the channel of horizontal fire propagation allowing the fire to spread around the fire barriers.

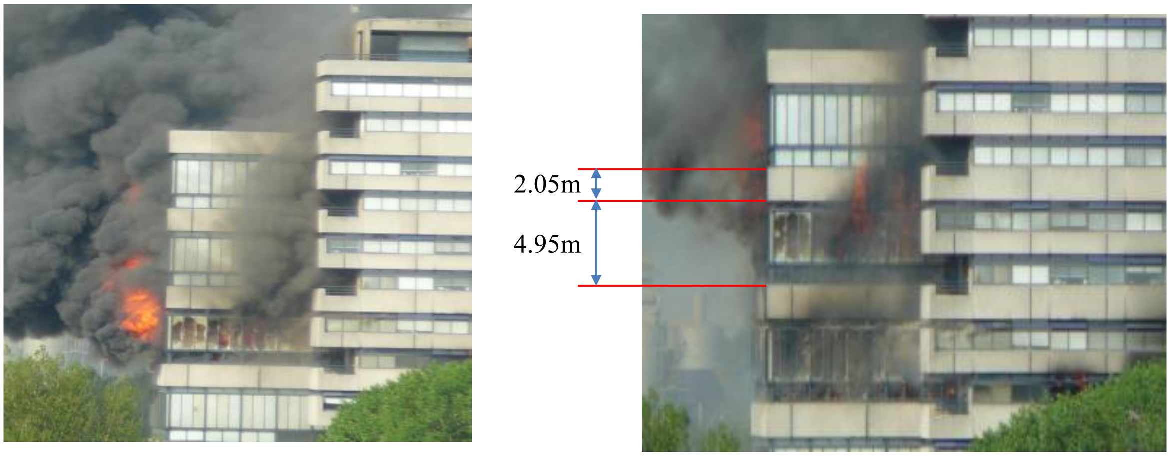


Figure 8. Extended flame over two-story high (left) and fast fire spread (right, 12 minutes after the left picture was taken)

2.4.2 The effects of building design on human behavior

Full scale experiments to measure the fire brigade intervention times were conducted at the Crowne Plaza Hotel in Copenhagen, Denmark [21]. The building is 25-story high and commissioned in November 2009 complying with the recent building regulations of Denmark. The experiments were conducted assuming three different fire locations and two different paths for firefighters to reach the floor of origin.

- Fire at 10th floor and fire fighters using stairs
- Fire at 10th floors and fire fighters using elevator
- Fire at 24th floors and fire fighters using elevator

Each of the three experiments was repeated three times with three different firefighter crews to prevent familiarity improving the performance of participants. In the experiments, using the elevator to approach the floor of origin, firefighters were expected to reach the room where the central fire alarm panel was located, and to obtain the key there to operate the fireman's elevator. The fireman's elevator is located behind another door from the public café area as shown in Figure 9.

The activities of firefighters were divided to several steps and times to start (or finish) the activities were measured by test operators using stopwatches. For example, in the second test set up with fire on 10th floor and firefighters using the elevator, the time to leave the room where the central fire alarm panel is located, the time to locate the door of the room (marked as 'A' in Figure 9) for fireman's elevator, and time to operate the fireman's elevator were measured. Among these, the time period between leaving the room with the keys and locating the door of the room for the fireman's elevator were recorded as being between 7 minutes 26 seconds to 9 minutes to 12 seconds with the average of 8 minutes 16 seconds. This means that firefighters spent over 8 minutes to just find the door to reach the fireman's elevator which is located within less than a 30 m radius. In the time frame of fire development, 8 minutes is not a trivial duration. It can dramatically change the incident outcome.

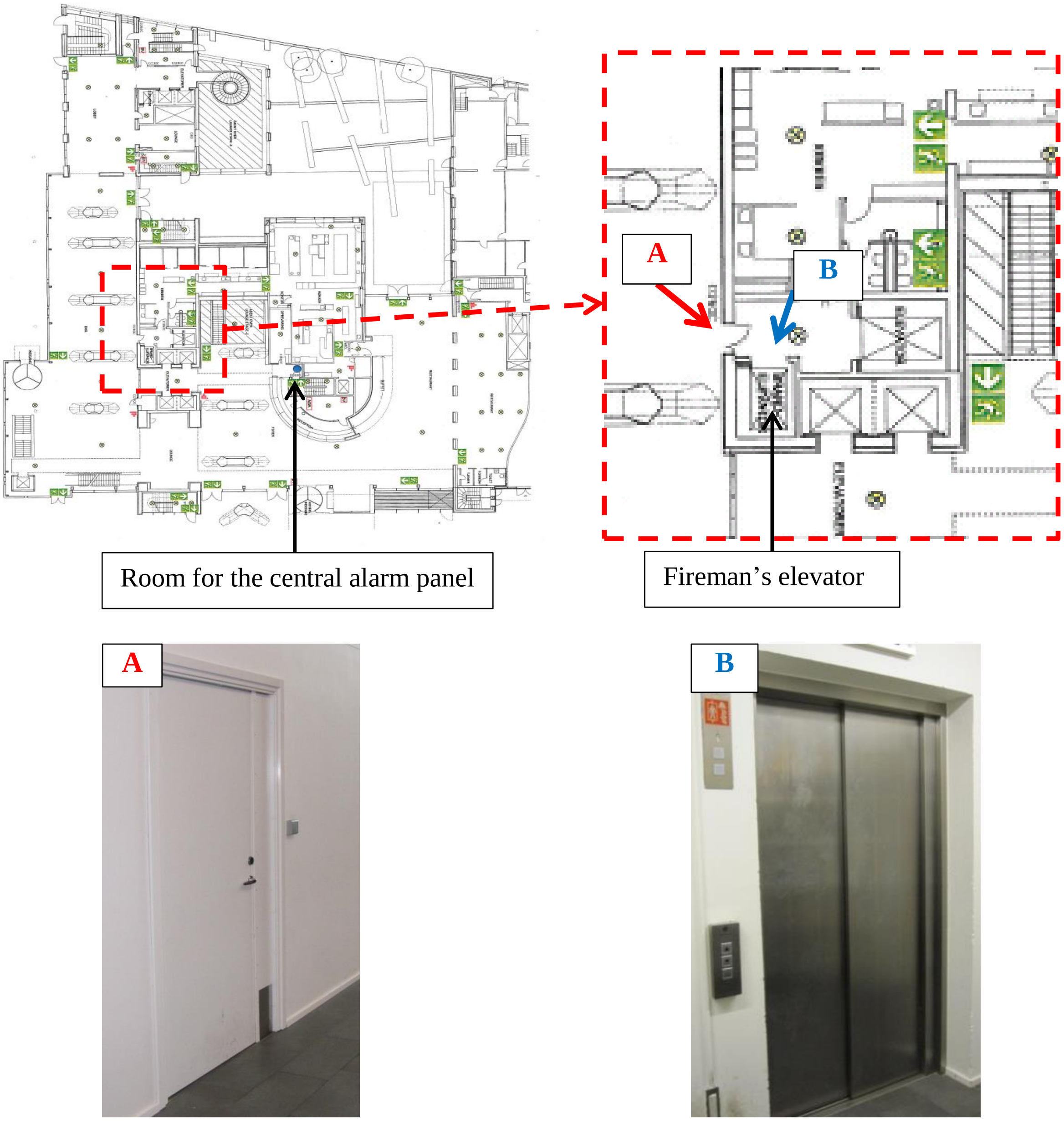


Figure 9. Floor plan of ground floor and actual view of doors to reach fireman’s elevator

The reason that it took firefighters so much time to locate the right door can be identified by looking at the door itself which is marked as ‘A’ in Figure 9. First there is no sign to identify the fireman’s elevator, and the color of the door is identical to its background color, which make the door itself blend too much into the wall. With current design, the door seems very trivial, for instance, for a little closet where cleaning equipment or toilet papers are stored. This door design seems to be saying “you don’t have to see the space behind me.”

From the viewpoint of architecture, this design is effective as it gives a sense of a secret or hidden space. Behind the door ‘A’, there are a kitchen area and another elevator, both of which are intended to be used by only hotel staffs, and general hotel and café customers are not supposed to reach the space. Therefore, to architects, the area needs to be separated from public space to a certain extent, and the identical color of the door and background wall is one of the design methods to achieve this. However, the fireman’s elevator is also included in this space and firefighters, like other public customers, did not check this door either, which caused a critical delay of firefighter’s presumable rescue and suppression activities. In this case, the space layout for the fireman’s elevator or its noticeability needs to be improved by architectural or fire safety design approach. Clear signage for the fireman’s elevator or space design allowing visual access to the fireman’s elevator could have decreased the delay time, which can be achieved by proper collaboration between architects and fire protection engineers with a good understanding of fire safety performance.

2.4.3 Summary of building fire safety performance

In the previous sections, the effects of building design features on fire safety performance were examined in terms of two aspects: the fire development and human behavior (firefighters’ response). Based on these two examples and the gap between architects and fire protection engineers, a structure for building fire safety performance is established in the context of architects, FPEs, and their mission as shown in Figure 10.

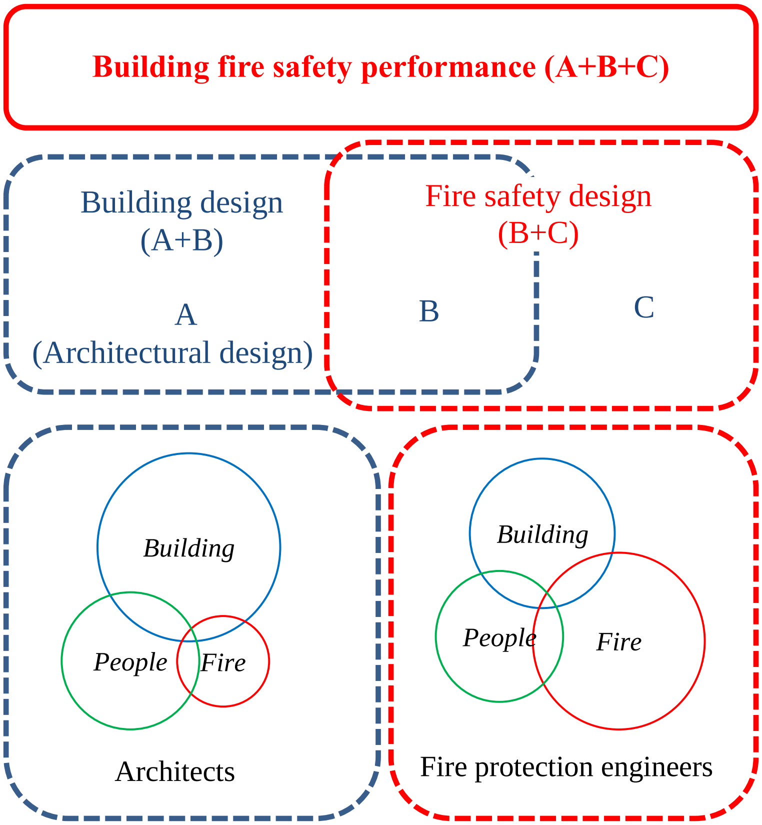


Figure 10. A structure of the actual fire safety performance with the perspectives of architects and fire protection engineers considered

Architects and fire protection engineers conduct their mission (building design and fire safety design) with different perspectives on the building, people, and fire components; architects generally emphasize performance more during the normal building operation, and fire protection engineers are focused more on fire conditions. Then, the relationship of building design and fire safety design is established consisting of three areas noted A, B, and C in Figure 10. The area, A, indicates the building design features which are seemingly not related to the fire safety of buildings and have not been included in the realm of fire safety approaches. The intersection area, B, indicates the features or decisions that both fire safety and building designs are entwined. Fire safety features such as means of egress, combustible interior finish, exterior vertical separation, and fire barriers are associated with building design features such as floor plans and exterior shapes of buildings or other building design features. The area, C, indicates the fire safety features and decisions that fire protection engineers mostly govern. This may include various fire suppression systems, smoke control, detection / alarm / notification systems, and fire emergency plan. Traditionally, the missions of fire protection engineers have been largely involved with the areas of B and C.

From the two examples, Bouwkunde fire incident and Copenhagen fire brigade experiments, two issues are identified as below in order to improve fire safety practices associated with building design.

1. The area, A (hereinafter 'A' is named architectural design features to be differentiated from the building design features which include both 'A' and 'B'), has not been taken into account well enough by many in the fire protection engineering field although it actually affects building fire safety performance. The relevant building design features in the two examples are the 2-story tall exterior window openings and the large floor area of the design studio in Bouwkunde fire which contributed vertical fire spread and fast fire development in the initial stage, and the door design to the fireman's elevator which made the door look trivial in the Copenhagen fire brigade experiment which delayed fire fighter's response time.
2. Although the area, B, has been considered in fire safety design and generally included in prescriptive regulations affecting building design, more effective communication between architects and FPEs is necessary to better account for the effects of building design features on fire safety performance or vice versa. As shown in Bouwkunde fire incident, building features such as exterior shape, space layout, acoustic tiles in the design studio associated with fire safety features such as vertical separation distance, 30 min fire resistance barrier, and additional ceiling fire spread via the tiles, respectively, affected the actual fire safety performance inadvertently. In the Copenhagen fire brigade experiment, proper signage to indicate the fireman's elevator which is an approach taken in fire safety community, or visual access to the fire man's elevator which is an approach that can be taken by architects could have reduced the time to find it, but neither of them was applied.

2.5 Performance evaluation by fire protection engineers

Fire protection engineers often use computer models to estimate the development of fire and fire products and time to evacuation of occupants as part of the verification process for selected design packages of fire safety measures, or trial designs. In the current life safety criteria in PBFSD which is:

available safe egress time (ASET) > required safe egress time (RSET)

the role and use of computer models has increased significantly. However, an excessive emphasis on using computer models without due consideration of right problem in the beginning and the limitations of the models can mislead fire safety designers and lead to errant designs. The difference between the actual capability of computer models and a high trust level of fire protection engineers in the simulations may result in the ‘garbage in, garbage out’ condition. Most computer models provide relatively simple user interfaces presenting a low barrier for FPEs to enter the field of computational modeling. However, there is a much higher barrier to use them correctly and to interpret the results properly. This is partly because software developers generally advertise the capability of their products, but do not explicitly mention incapability, limitations, and assumptions. It is also because many FPEs do not understand their own limitations, and fail to understand how poorly a misapplied tool, or using the wrong tool for the job, can result in unrealistic or inappropriate outcomes. As such, FPEs need to identify the purpose of computer modeling, need to find proper models, and critically analyze the application of the simulation results to check whether their design decisions are correct or not..

This careful approach is required especially for egress models, since the results need to be interpreted based on not only human factors [22] but also architectural design features [23]. Human factors including fire drill experience, activity, role and responsibility, social affiliation, and learned irrelevance [24], and architectural design features such as floor plan complexity [25, 26], visibility and noticeability of exit doors and exit signs [27] have not been featured in most egress models. In some models, individual and social interaction parameters such as familiarity, social affiliation, and patience level are featured, but the user needs to thoroughly understand the way how each attribute affects what performance. If certain parameters only increase or decrease the evacuation time with unrealistic occupant response or movement, for example, occupants staying in the same location without searching for exits or following other occupants with the input of a low familiarity value, FPEs need to investigate how the model interprets the familiarity value and what parameters are influenced by it.

In the current study, egress times were compared using two commercially available egress models to show the gap between model representation and user interpretation, for the two different floor plans of a hotel occupancy shown in Figure 11: one with hidden exit doors and the other with exposed exit doors based on line of sight from most of the public corridor area. Each floor plan has two exit doors drawn in dotted circles in Figure 11. The floor plan Figure 11 (A) was designed by the authors, but was based on a hotel floor plan actually built in South Korea to represent a realistic design, and Figure 11 (B) is slightly modified by changing the exit door locations from Figure 11 (A).

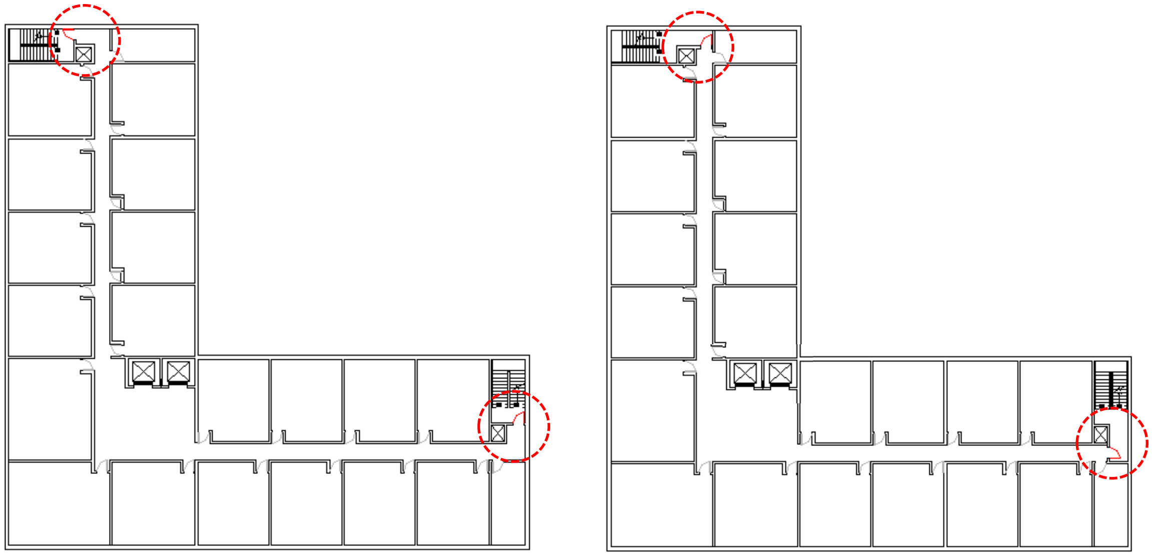

(A) Floor plan with hidden exit doors
(B) Floor plan with exposed exit doors

Figure 11. Floor plans for egress modeling

Before seeing the results of egress models, it might be expected that the evacuation time of Figure 11 (A) would be generally longer than that of Figure 11 (B), if one assumes that occupants are expected to have a low familiarity in hotel occupancy and that they rely on visual cues to find exit doors. While proper exit signage may help to some extent, previous research has revealed that occupants do not rely on exit signs as much as expected in fire conditions [25, 28, 29], in fact learning to ignore the signs because they never use exits (learned irrelevance). For that reason alone, direct visual access to the exit door plays a critical role in this building design. Without proper exit signage, which could make the situation worse (lack of any cues), the evacuation time difference could become larger in an actual fire condition (ignoring at this stage the presence of smoke or flame).

The simulation results using two egress models are compared in Table 1. For each evacuation simulation, default occupant parameter settings are used with walking speed of about 1.2 m/s. A total of 57 occupants are assigned in the guest rooms, corresponding to 3 occupants per room. No specific exit is designated for occupants to use such that each simulated occupant chooses whichever exit can be reached in the shortest time. Despite different default parameter settings and movement logics of model 1 and model 2, the total evacuation times are in the same range for this particular building floor plan. In the simulation of model 1, it takes about 2 seconds more in Figure 11 (A) than Figure 11 (B). This is caused by the difference in travel distance of about 2 m, without cueing phenomena in both exits. In the simulation of model 2, which allows slightly different parameter values randomly selected within a certain range, the total evacuation times range between 35~38 seconds for both floor plans. The evacuation times in Table 1 were obtained from 5 different runs. From the simulations, it is found that the total evacuation times and occupant's behaviors and movement toward the exit are practically identical for both floor plans, which is due to the internal logic that model agents representing occupants do not search for the exit based on lines of sight from their local locations, but move towards to the coordinates of exits which are given to the agents from the beginning of the simulation. This is quite different from the actual occupant's behavior, searching for exits in an unfamiliar space like hotels [30]. Therefore, without a correct understanding of the capability and limitation of egress models, FPEs may estimate the total evacuation time unrealistically, which also affect the results of the ASET/RSET analysis.

Table 1. Egress modeling input and results

Models	Occupant number	Total evacuation time (sec)	
		Figure 11 (A)	Figure 11 (B)
Model 1	57	37.3	35.3
Model 2	57	35~38	35~38

The number of practically available exits and occupant distribution per each exit also require a critical analysis by FPEs as these are influenced by the floor plan, interior space layout and occupant flow design by architects. The number and relative locations of exits have been regulated to ensure the completion of evacuation within a proper duration. Previously the requirements for exit capacity were based on the assumption that occupants would disperse relatively evenly to each exit door, which is not realistic as more people tends to move towards the main exits or the exits that they use more often [31]. This phenomenon was reflected in the recent IBC update by requiring that the main exit should handle at least ½ of total occupant loads. However, there are various situations in which more than 50% of occupants try to use the main exit as proven by the Station Night Club fire incidents, RI, USA in 2003. A good example for the analysis of practically available egress capacity may be emergency exit doors. In an emergency exit door, warning signs such as "Alarm will sound if door is opened" are usually attached on the door as shown in Figure 12 (left). This type of warning sign is to make occupants refrain from using the emergency exit in normal operations, but since occupants are not familiar with the emergency exits and particularly what routes they follow to get out of the building, even in emergency conditions, occupants hesitate to use them. Combined with the tendency for architects to hide exit doors from the line of sight, or paint them the same color as the surrounding walls to make them not stand out, the space near the emergency exit doors can be transformed as a storage space as shown in Figure 12 (right). The items in this space decrease egress capacity or even make the door unavailable. Considering the fact that visually hidden exit doors or emergency exit doors are common design features, and exit capacity decrease due to ill-located items in the egress path happens chronically, more critical analysis of FPEs is expected in estimating the evacuation time more realistically.

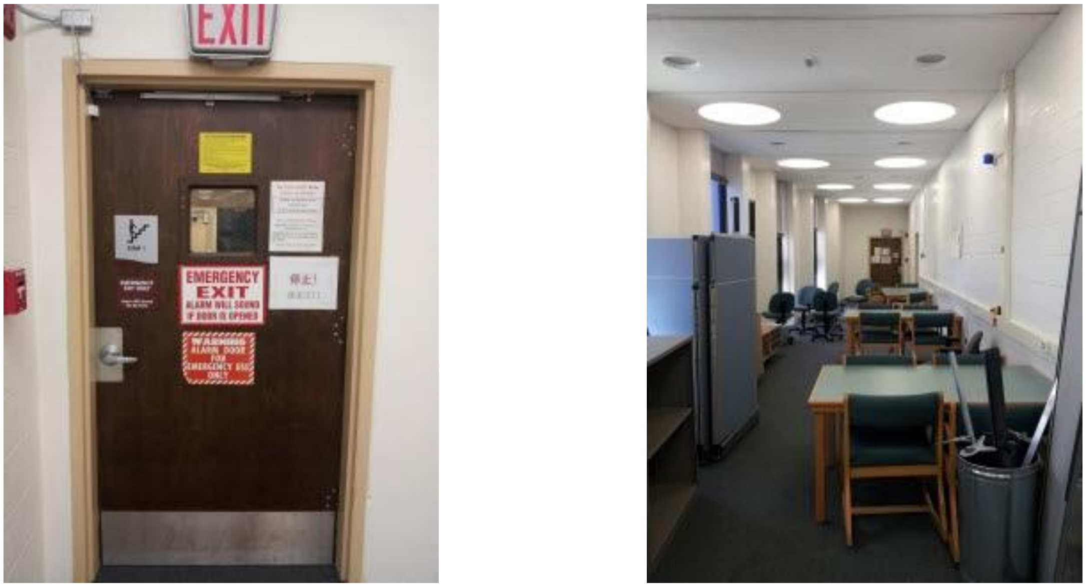


Figure 12. Emergency exit door (left) and nearby space (right)

2.6 Steps forward for fire protection engineers

As the discussion above illustrates, architects determine building design features which may inadvertently decrease actual fire safety performance. Some of the design features have not been regulated in the prescriptive-based fire safety system, and others are regulated, but their effects on actual fire safety performance have not been effectively discussed between architects and FPEs, with often each having different perspectives on key components in fire safety. Even by implementing computer model analysis routinely used in PBFSD, the effects of architectural design features on fire safety are not easily captured. To resolve this condition, after all, the capability of fire protection engineers needs to be improved such that building fire safety performance can be better estimated. In this study, three components are proposed to achieve this.

1. Proactive approach in collaboration with architects

Architects may not know available options for fire safety design (fully prescriptive-based, alternative methods in prescriptive-based regulatory system, comprehensive PBFSD, or deemed-to-satisfy solution in performance-based regulatory system), and the current developments of fire science and modeling technology. More importantly, they may not fully realize how much their design features can impact the fire safety performance. FPEs need to convey these to architects and try to draw their attention more into fire safety. FPEs also need to recognize architects as key players for building fire safety and to perceive the opportunities from architects to embed fire safety design into their architectural approach. They would benefit from more fire safety design and engineering teaching in their architectural courses and practice. For example, a floor plan in which exits are distributed considering the locations of occupied rooms, the number of occupants, and daily occupant flow can contribute to the decrease of evacuation time in fire conditions. Spatial differentiation using specific interior colors, lighting concepts, or iconic objects can improve the occupants' cognitive perception of the space, which helps prevent disorientation in such spaces of low familiarity as hospitals or shopping malls. Designing exit stairwells used more frequently in normal building operations can increase familiarity of exits decreasing the perception of learned irrelevance.

2. Acknowledgement of the effects of building design features on the fire safety performance

Fire protection engineers also need to be educated in terms of the effects of building design features on fire safety performance and in the whole discipline of the design process and their best part in it.. For about a century, fire protection engineers have been more focused on building design features which are effective only in fire conditions. These are generally regulated, but the potential for adverse effects on fire safety in certain conditions have not been discussed much. In addition, architectural design features which are not even subject to regulation can also affect fire safety performance. These design features are often involved with the design objectives for normal building operations, or non-fire conditions. In addition, occupants' responses in fire conditions can be also influenced by daily interactions of occupants with architectural environments in non-fire conditions. For example, space use near the emergency exits which are rarely used in normal building operation turns easily to a storage space decreasing egress capacity in fire conditions. Therefore, it is necessary for FPEs to take into account the effects of building design features on fire safety, especially for adverse effects to evaluate the actual fire safety performance and to design fire protection measures to meet the expected performance.

3. A holistic perspective of building fire safety performance

A building is a complex system consisting of multiple sub-systems: not only the physical equipment but also the other building design features. Its performance depends on the level of interactions of these systems as a whole as well as each system's functionality. If one sub-system is not operating well or interacting improperly with other sub-systems, the entire system, the building, would not perform as intended. In terms of fire safety performance, people are also additional dynamic variables who interact with building design features and physical fire protection systems. As such, to have a better understanding of fire safety performance, it is critical for FPEs to have a holistic perspective to observe the interactions of building and people in fire conditions. This will be elaborated in a future paper.

2.7 Conclusion and future work

Building fire safety is generally controlled by building codes and fire safety regulations. As building and fire codes are established to avoid any unacceptable losses without incurring unnecessary costs, only minimum fire safety levels accepted by the society have been stipulated in the codes and pursued by fire protection engineers (FPEs) in complying with the codes. As such, the difference between minimum levels of requirements across a broadly defined class of buildings versus specific issues for a certain building sometimes results in unsafe code-compliant buildings or sometimes over designed fire safety provisions which are no longer cost-effective. One of the causes for this discrepancy originates from the influence of building design features on fire safety performance.

Architects as master architects tend to determine building design features in most cases, based on various building design objectives. Fire safety is one of them, but again tends to not draw architects' attention much. Some building design features have critical impacts on actual fire safety performance as discussed earlier, but in many cases both architects and FPEs have not seemed to fully recognize the architects' critical role in determining fire safety for designs based on the prescriptive-based regulations.

As performance-based fire safety design (PBFSD) has gained wider popularity and different means and methods are allowed as an alternative to the prescriptive-based regulatory environment, the influence of building design features on fire safety performance should be included in the performance analysis conducted by FPEs. In this context, the current study proposes three items for FPEs;

1. Fire protection engineers needs to recognize architects as key players for fire safety, and help them understand their capability to increase fire safety performance in architectural ways in order to reflect fire safety in building design from the earliest building design stages.
2. Fire protection engineers needs to understand the adverse effects of building design on building fire safety performance in order to design appropriate mitigation protection methods.
3. Fire protection engineers needs to understand a holistic building fire safety performance considering the characteristics of building's physical components, its design features, people (occupants and firefighters), and fire as a system in order to estimate what can actually happen as these are all influencing each other determining the final performance.

Work presented here reflects an initial step in a larger effort to improve building fire safety by bridging the gap between architects and fire protection engineers. In the near future, more practical methodologies and a framework for analysis will be presented. For fire protection engineers, two models have been developed which facilitate development of a holistic perspective on fire safety performance and identification of alternative fire safety designs accounting for the adverse effects of building design features: a fire safety strategy model and an integrated interaction model. In the fire safety strategy model, generic procedural responses of the three components, building, people, and fire, during fire incident are defined in order to identify a proper fire safety strategy based on the current available fire safety features. In the integrated interaction model, detailed cause and effect relationships among the three components are established including architectural design features as building characteristics which were identified from the previous fire incidents.

For architects, a roadmap to incorporate building design features and their effects on the fire safety performance into building design process have been developed in the context of building design software for building information modeling (BIM). Since there may not be practical motivations for architects to consider fire safety as a critical design objective currently, by informing the effects of building design features on fire safety performance in their work environment, building design software in the BIM environment, it is intended that architects be exposed to the concept of building fire safety performance, and realize the necessity of involvement of fire protection engineers in the building design project, especially in the early building design stage.

Both architects and FPEs and ultimately building outcomes will benefit from more dialogue between these two professions, and further education on the respective design roles of the other discipline in the overall process of designing functional, aesthetically pleasing, and cost-effective buildings with the required levels of safety.

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3 Fire safety performance evaluation[2]

3.1 Introduction

Building fire safety performance is largely a function of building, people and fire attributes, and is independent of the regulatory system or fire safety design approach applied. It should be noted that while the regulation prescribes necessary elements required to a given building which significantly influence the fire safety performance, the regulatory system generally defines the design and assessment approach for the necessary elements. In a prescriptive-based building regulatory system, the codes which prescribe detailed requirements for fire safety design serve as the criteria for both design and performance evaluation. In other words, once a building complies with the code requirements, fire safety design and subsequent building fire safety performance are considered to be appropriate and acceptable. If the expected performance changes, or critical flaws in the code requirements are found, the codes are revised and updated to satisfy a new level of fire safety performance. This is why major updates of the codes are often seen after large loss fires.

In a performance-based building regulatory system, building fire safety performance analysis draws more attention from the fire engineers, as they are generally expected to demonstrate that the proposed fire safety design solution satisfies the performance objectives stated in the code. Various trial fire safety designs may be evaluated, but only those which achieve the performance criteria can be accepted as the candidate fire safety design solutions [1]. Although means and methodologies for the evaluation are not generally included in the codes, guidance materials are available such as the International Fire Engineering Guides [2] or the fire engineer engineering guides for various topics.

Despite these guides, it is very challenging to comprehensively and adequately assess the fire safety performance of a building and reflect the outcome of the assessment into the fire safety design solution. There may be various reasons for this. First, predicting building fire safety performance is a very complex problem. Slight changes of influencing characteristics, such as the amount of fuel contents and occupant locations, can lead to significantly different outcomes, and these characteristics are typically not readily known and randomly vary. Second, experiments in a real environment, which are often conducted in other engineering fields to evaluate the performance of designs, are almost impossible in fire engineering. Due to the fire damage and ethical concerns, fire and evacuation experiments are generally conducted in a controlled environment which may not represent real conditions. Small and intermediate-scale experiments are often conducted, but no valid methodology exists to comprehensively predict the full

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[2] Unformatted text of paper published in Fire Technology, DOI: 10.1007/s10694-013-0374-1

scale results from the small and intermediate scale tests. Thirdly, challenges such as uncertainty regarding the tools and data used in the analysis, the capability of fire engineers conducting performance analysis, and justifiability of design fire scenarios are also understood as the reasons for the difficulties of fire safety performance assessment. In addition to these, building fire safety performance is influenced by so many individual factors and their interactions during fire incidents that it is difficult to identify and formulate them thoroughly in the analysis.

To address the complexity by reducing the problem to manageable components, and to account for some of the uncertainty and variability in the process, multiple approaches for evaluating building fire safety performance and informing design strategies have been developed. While the prescriptive-based approach continues to be dominantly practiced in some countries, a systems approach for fire safety performance evaluation and design was introduced and explored by fire safety researchers in the 1970s [3], the outcome of which resulted in basis for current performance-based design approaches. In the systems approach, the building and the fire are viewed as critical system components, and the fire safety performance such as life safety and property protection was considered as a result of influences among the system components [4]. Several pioneering research results from the USA context may be summarized as below [5, 6].

1. Fire safety systems guide sheet for the Seattle Federal Building
2. Fault tree event logic analysis for the control of building fire by National Bureau of Standards (NBS, the former National Institute of Standards and Technology (NIST))
3. General Service Administration (GSA) fire safety decision tree
4. National Fire Protection Association (NFPA) systems concepts tree
5. GSA’s guide to goal-oriented systems approach to building fire safety

In particular, the GSA’s guide utilized both a quantitative feature of risk concept with probability use in an event tree logic and a qualitative feature of an anatomy of goals and workable components following basically a fault tree format [7]. It also became an impetus for further development of other models such as the Building Fire Safety Evaluation Method (BFSEM) developed by Fitzgerald, the Fire Safety Evaluation System (FSES) in NFPA 101A, Guide on Alternative Approaches to Life Safety, and NFPA 550, Fire Safety Concepts Tree (FSCT).

The BFSEM uses network diagrams which follows the sequential fire development from ignition to fire spread beyond the room of origin with various sub-level events. By assigning subjective success or failure probability of each event in the network diagram, the likelihood that any target event will occur is calculated [8, 9]. The FSES is fundamentally a parameter ranking method for the evaluation of life safety performance. It basically assigns weighted points to various fire safety parameters such as construction type, alarm, detection, or sprinkler system, and the accumulated point represents the level of fire safety. Similar parameter ranking approaches were also developed in UK [10, 11] and Hong Kong [12, 13]. Whereas the BFSEM and FSES use quantified values, the FSCT is a structured tree diagram without any quantification. It divides the fire safety objectives into two: prevent fire ignition and manage fire impact, and each objective branches further being connected with necessary means and strategies to achieve the objective using “and” or “or” gate. Necessary fire safety measures to prevent fire and to control fire damage can be identified by following the tree structure from upper levels to lower levels. Thanks to this simplicity, the FSCT provides an easy-to-follow process to understand the variability of fire safety design solutions to achieve a target performance and to establish necessary fire safety features for a selected fire safety strategy.

There are, however, criticisms and limitations associated with each of these models; quantitative approaches are often criticized due to the subjectivity of the quantified values such as the probabilities in BFSEM and the weighted points in FSES, and FSCT does not incorporate interactions among fire safety concepts, chronological sequences for fire development and responses of fire safety measures, and multiple objectives. In addition to these limitations, most of these models have focused primarily on ‘hard’ characteristics such as physical building systems and components and fire protection measures which were typically included in prescriptive codes. They did not comprehensively take into account ‘soft’ characteristics such as building design features, occupant activities, and the interactions among the soft characteristics and between soft and hard characteristics. This is partly because soft characteristics have not been considered as proper subjects of prescriptive codes due to their high variability and difficulties to control by codes, despite the recognition of their significant effects on building fire safety performance [14]. However, in performance-based fire safety design scheme, both hard and soft characteristics need to be included in the performance analysis since they are also significant attributes to the building fire safety performance.

Since many developed European and Asian countries have already adopted or are moving toward performance-based codes, and alternative fire safety design methods are allowed even in the countries that implement the prescriptive-based codes, such as the USA, the importance of appropriate assessment tools and methodologies of building fire safety performance will become increased and demanded. In this context, the current study proposes models to evaluate building fire safety performance and to develop alternative fire safety design solutions. Two conceptual models are first developed to have a better understanding of the holistic aspects of building fire safety performance considering both hard and soft characteristics and the interactions among them. Based on the conceptual models, a quantitative model is developed as a tool to evaluate building fire safety performance and to assist decision making process of developing fire safety design solutions.

3.2 A holistic approach for building fire safety performance

As implemented in the systems approach, building fire safety performance is largely a function of the influence of building, people (occupants and firefighters), and fire (fuel contents) characteristics on the development, spread, and impact of fire on a building and people. For example, proper exit signage as a building characteristic can guide occupants to proper exits in time avoiding fire-induced hazardous environments during fire conditions, which increases the fire safety performance in terms of life safety. Likewise, any individual fire protection measures such as fire suppression systems, detection, alarm, and notification systems, means of egress, and fire and smoke barrier as building characteristics can increase the fire safety performance.

In addition, occupant familiarity to the exit location as a people characteristic can influence the fire safety performance. Choosing a proper exit route is one of the critical characteristics for effective occupant egress, and it generally takes less time for occupants who are familiar with the space layout to understand the fire situation and to plan appropriate exit routes. A simple and intuitively designed floor plan can increase the occupants’ space familiarity, especially in building uses such as hospitals, large shopping malls, or hotels. In this case, the interactions between building characteristics (building use and floor plan) and a people characteristic (occupant familiarity to the space) influence the fire safety performance. Similarly, many characteristics of building, people, and fire have some degrees of dependency on each other and their interactions can influence the building fire safety performance.

The occupant familiarity also bring about the effects of building-people interactions during the normal building operation (non-fire or non-emergency conditions) on the building fire safety performance during fire conditions. Although occupant familiarity may vary depending on the floor plan complexity and building uses, it is generally expected to be gradually established while occupants experience the space of a building during the normal building operation. Therefore, occupants’ exit route selection during fire conditions which is affected by the familiarity is influenced by the occupants’ space perception during normal building operation. In other words, if occupants often use a specific exit in a normal building operation, it is highly likely that the occupants would use the same specific exit in fire conditions, and the rest exits are not much accessed by occupants due to the learned irrelevance regardless of their proximity or convenience [15].

The characteristics identified above may be categorized into two sets: hard characteristics and soft characteristics. The exit signage is a physical component specifically designed for fire conditions, and generally fire engineers pay good attention to them. However, building use, floor plan complexity, familiarity, and occupant's space experience can be widely different from building to building. They are also associated with other building objectives than fire safety such as aesthetics, space efficiency, and occupant comfort and their design is determined (or influenced) by other stakeholders with a less focus on their effects on fire safety performance. Some of the soft characteristics such as building use have been included both in the prescriptive codes and in various performance-based fire safety analysis methods, but others such as the relevance of occupant familiarity to floor plan complexity and occupant space perception have not been fully perceived by fire engineers. These characteristics are more related to architects as they are linked with space programming, floor plan, and the interactions of occupants with the built environment [16].

To help understand the exit route selection phenomenon during fire conditions, several characteristics from building and people components, occupant interaction with the space during the normal building operation, and multiple stakeholders who may have different perspectives and objectives, are identified above. Considering that occupant egress is associated with perception of fire, evacuation initiation, and movement in addition to the exit route selection, and that fire safety performance is also involved with other phenomena such as the responses of building fire safety systems and fire development phenomena in addition to occupant egress, the number of characteristics, interactions among them, and relevant stakeholders and their objectives become significantly increased. In addition, as these phenomena also depend on the conditional and chronological occurrence in the course of fire development, the building fire safety performance is, in fact, an extremely complex matter. This is why a comprehensive perspective is critically required to understand and evaluate the building fire safety performance.

3.3 Development of qualitative models

To holistically understand, examine, and interpret complex phenomena like the building fire safety performance, qualitative approaches are generally more beneficial than quantitative ones in the initial stages [17]. Two qualitative models, Generic Fire Response Model (GFRM) and Integrated Characteristic Interaction Model (ICIM), are developed. The GFRM is intended to assist various stakeholders in understanding dynamic features of the interactions between fire development, building response, and human activity from a broad perspective whereas the ICIM represents in some detail the relevant characteristics and the cause-effect relationship which exist between the characteristics.

3.3.1 Generic Fire Response Model

The GFRM is shown in Figure 13. It was designed to be a low resolution but comprehensive model that includes generic features and relationships of building, people, and fire responses. Even though it sacrifices some level of detail, it is beneficial as a 'first order' model when fire engineers need to look at the big picture of the fire safety performance and to discuss available fire safety strategies with stakeholders who may not be familiar with the fire-induced phenomena. The GFRM has a synergic effect when used with the FSCT as chronological features of fire development, building responses, and human activities which are pointed out as one of the limitations of FSCT [18] are implemented here.

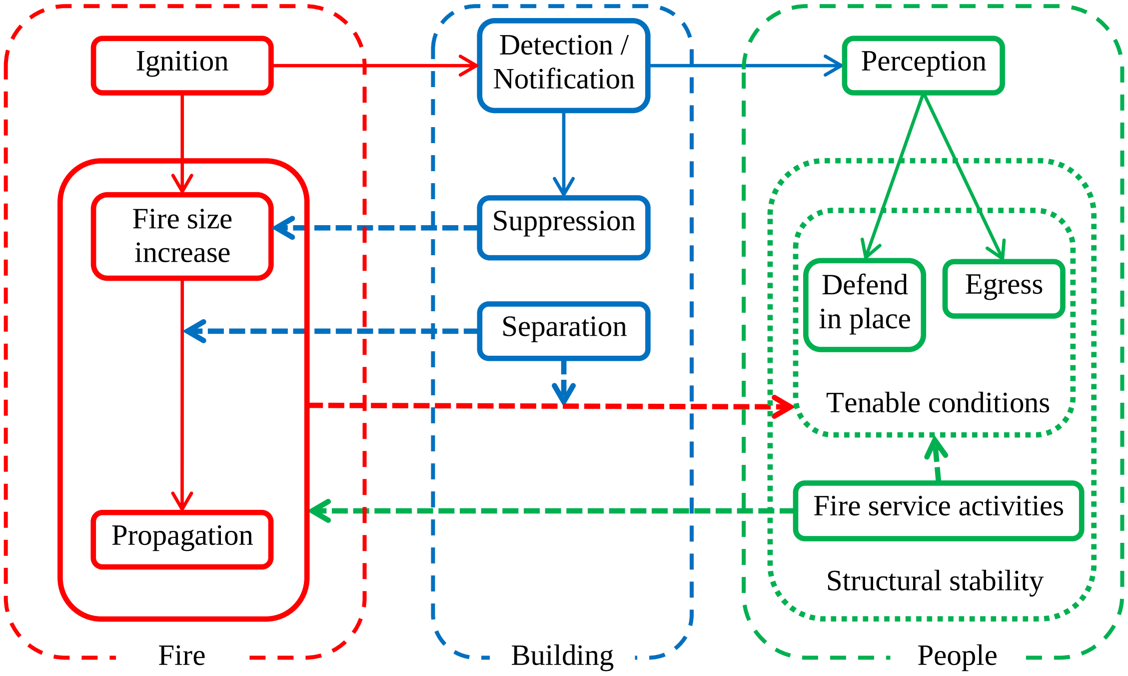

Figure 13. A Generic Fire Response Model (GFRM)

In the GFRM, red, blue and green colors are used to represent the fire, building, and people component, respectively. Solid arrows indicate chronological event occurrence, and dotted arrows indicate the effects of one sub-component on the other.

The fire component comprises the three sub-components: ignition, fire seize increase and propagation, which follows the generic fire development process. The building component is composed of detection / notification, suppression, and separation. Ignition and subsequent combustion products activate the detection component which activates notification and suppression components. The suppression component controls fire size by preventing continuous combustion. The separation component has two effects: inhibiting the fire spread beyond the room of origin and physically separating hazardous fire products from people. This may include compartmentation, fire-rated building components and assemblies, and smoke control systems. The people component consists of two types: occupants and fire services. Occupants defend themselves where they are located or move to a safe place inside or outside the building once perceiving fire occurrence. Fire services conduct the mission of fire suppression and occupant rescue. With this simple model, one can quickly identify not only relationships, but importance of remaining components if some components are absent (e.g., if ‘suppression’ does not exist, ‘separation’ and ‘detection’ become more important as the only building systems). Note that the terms used for the components are conceptual explaining phenomena, not indicating specific fire safety measures.

Since the GFRM includes generic phenomena, there exist some exceptions which cannot be captured by literal interpretation of the model. For example, some suppression systems activate notification systems instead of being activated by detection systems. Occupants can perceive fire incidents not through a building notification system, but by directly seeing the fire or hearing from others. Occupants can also fight the fire instead of defending themselves against fire or moving to a safe place. To include these cases, more arrows and sub-components are required in the model, which makes the model more precise, but the level of complexity is increased, which is not targeted in the GFRM.

The GFRM was constructed assuming that the users understand the dynamic features of the three components and their interactions along the fire development, from which they can communicate with other stakeholders more easily and develop proper fire safety strategies from a broad perspective. Important fire safety objectives are embedded in the GFRM. Property protection and life safety which are the most common building objectives can be identified by the fire component and people component. The GFRM shows that by controlling fire size and propagation, property protection from fire is achieved and by separating occupants from fire products, life safety is achieved. As noted above, it also shows and helps to describe impacts if certain components are unreliable or missing. For example, if a building site is located far away from the nearest fire station or heavy traffic conditions are generally expected in the fire service’s travel route to the site, timely fire service activities may not be considered as a reliable option. In this case, other fire strategies such as suppression or separation whose effects are compatible to fire service activities need to be reinforced to mitigate the probable absence of fire services. If water resources are limited to the site and an automatic sprinkler system is not a reasonable option, reinforcing the separation component can be a design solution sacrificing the room of origin or the fire area as an acceptable loss. When stakeholders only concern the life safety of occupants and are ready to accept any building damages or following business interruption, both suppression and separation components may not need to be emphasized if early detection, fast perception, and occupant movement to a safe place outside the building are highly expected and fire services are expected to prevent further fire development to neighboring environment. As structured, the GFRM helps to explain the relative importance of the various components to achieving life safety objectives.

3.3.2 Integrated characteristic interaction model (ICIM)

While the GFRM was developed to help, assess, and communicate concepts at a high level, it is recognized that much greater detail and complexity is needed to describe specific interactions within any given building or scenario. The ICIM was developed to provide this detail. The ICIM is a combined model consisting of three individual interaction models between building-people, people-fire, and fire-building. It can be viewed as more detailed version of the GFRM keeping its two core concepts: the chronological fire development and occupant egress which are respectively connected with property protection and life safety objectives, and the interactions among the components. In each interaction model, various characteristics and cause-effect relationships among them are extracted from the analysis of 15 previous fire incidents. Considering building code updates and construction technology development, relatively recent fire incidents which caused any casualties, or the fire incidents which caused significant number of casualties are selected focusing on the occupant life safety. The 15 fire incidents used for the analysis are listed below.

A. 5 assembly buildings
    1. Dance hall fire, Gothenburg, Sweden, Oct 28, 1998, 63 fatalities
    2. Beverly Hills supper club fire, Southgate, KY, USA, May 28, 1977, 165 fatalities
    3. Cocoanut Grove night club fire, Boston, MA, USA, Nov 28, 1942, 492 fatalities
    4. Indianapolis athletic club, Indianapolis, Indiana, USA, 1992, 2 fatalities
    5. Station night club fire, West Warwick, RI, USA, 2003, 100 fatalities

B. 4 health care buildings
    6. Arlington, Washington, USA, April 27, 1998, 8 fatalities
    7. Hospital Petersburg, VA, USA, Dec 31, 1994, 5 fatalities
    8. Health Care Center Memphis, TN, USA, Mar 21, 1988, 3 fatalities
    9. Nursing home fire Dardanelle, ARK, USA, Mar 13, 1990, 4 fatalities

C. 2 non-residential high-rise buildings
    10. One meridian plaza, Philadelphia, PA, USA, Feb 23, 1991, 3 fatalities
    11. Bouwkunde, Delft University of Technology, Netherlands, May 13, 2008

D. 1 residential high-rise building
    12. High-rise apartment, North York, ON, Jan 6, 1995, 6 fatalities

E. 1 dormitory

    13. Fraternity house fire, Chapel Hill, NC, May 12, 1996, 5 fatalities

F. 2 hotels

    14. Residential hotel, Reno NV, Oct 31, 2006, 12 fatalities
    15. Paxton hotel, Chicago IL, Mar 16, 1993, 20 fatalities

Among these, the dance hall fire in Gothenburg, Sweden is exemplified below to show how characteristics were extracted and cause-effect relationships among them were established.

In 1998, a fire occurred in a nightclub located in the second level of a 2-story building in Gothernburg, Sweden. Approximately 400 people were attending a party in the nightclub which was permitted for 150 occupants. Two exits were provided at both ends of an open plan rectangular floor area (32 m by 9.5m). Fire has started at one of the exit stairwells and the disc jockey who found it for the first time reported the fire to the fire brigade and evacuated through a nearby window without an announcement about the fire to the party attendees. Firefighters had difficulties to get into the nightclub due to injured people along the path and bodies stacked at the entrance door.

The extracted characteristics and interactions from this fire incident are as below.

A. Night club (building use) → occupant (activity) of having parties→ delayed (perception) of fire and (evacuation initiation) due to background noise and a low occupant caution level being focused on a party
B. Night club (building use) → open and flexible (floor plan) → (occupant number) increase
C. Fire (ignition)→ disc jockey's non-adaptive behavior (behavioral response) → late (perception) of fire and delayed (evacuation initiation) of occupants
D. Fuel items in a stairwell (fuel location) → one exit unavailable (means of egress) → occupant evacuation (movement) → (fire fighter's travel path) to the room of origin

Each characteristic is then assigned to one of the three components: building, people and fire, further into the category of either intrinsic or influenced depending on the paired component. For example, from the first case above, "building use" is certainly a building characteristic, and "perception", "evacuation initiation", and "activity" belong to people characteristics. Since "building use" is rather determined by the building owners independent of occupants or fire service, it falls into the category of the intrinsic building characteristics. Since "perception" and "evacuation initiation" in the people characteristics are generally observed phenomena in fire conditions regardless of building characteristics, they are under the intrinsic people characteristics while "activity" falls into the category of the influenced characteristics by building since it is influenced by "occupancy / building use". In the same way, characteristics and cause-effect relationships among them from the night club fires and the other 14 fire incidents are identified and the three interaction models between building and people, people and fire, and fire and building are established as shown in Figure 14, Figure 15, and Figure 16.

Arrows are used to indicate the cause-effect relationships: arrow root for cause and head for effect, and dotted lines between two characteristics indicate that one is considered as a sub-characteristic of the other. Each of the three interaction models has two components assigned to the five columns: the first two columns are used for one of the two components, the next two columns are for the other component, and the first component is repeated in the last column. Since only one-directional arrows are used in the three interaction models, the fifth column is repeated to show the influence of the first component on the other components.

The two layers of the intrinsic and the influenced characteristics under each component are intended to show the interdependency of the building, people, and fire components, which further confirms that the building fire safety performance is a function of not only each component's characteristics but also their interactions. In addition, especially for the building characteristics, the layering of characteristics and the interactions within the building characteristics reveal critical information:

A. Soft characteristics such as site / environment, room size, floor plan, exterior design, emergency management and most occupant characteristics influence and are influenced by hard characteristics.
B. Most soft characteristics in building components are determined by architects with little influence of fire engineers.
C. Hard characteristics such as electrical power equipment, HVAC system, means of egress are concerned by both fire engineers and other stakeholders such as building manager, electrical / mechanical / thermal engineers, and architects. The collaboration among the relevant stakeholders based on a clear understanding of the effects of the characteristics on the respective performances is required to avoid unnecessary competition between different objectives.

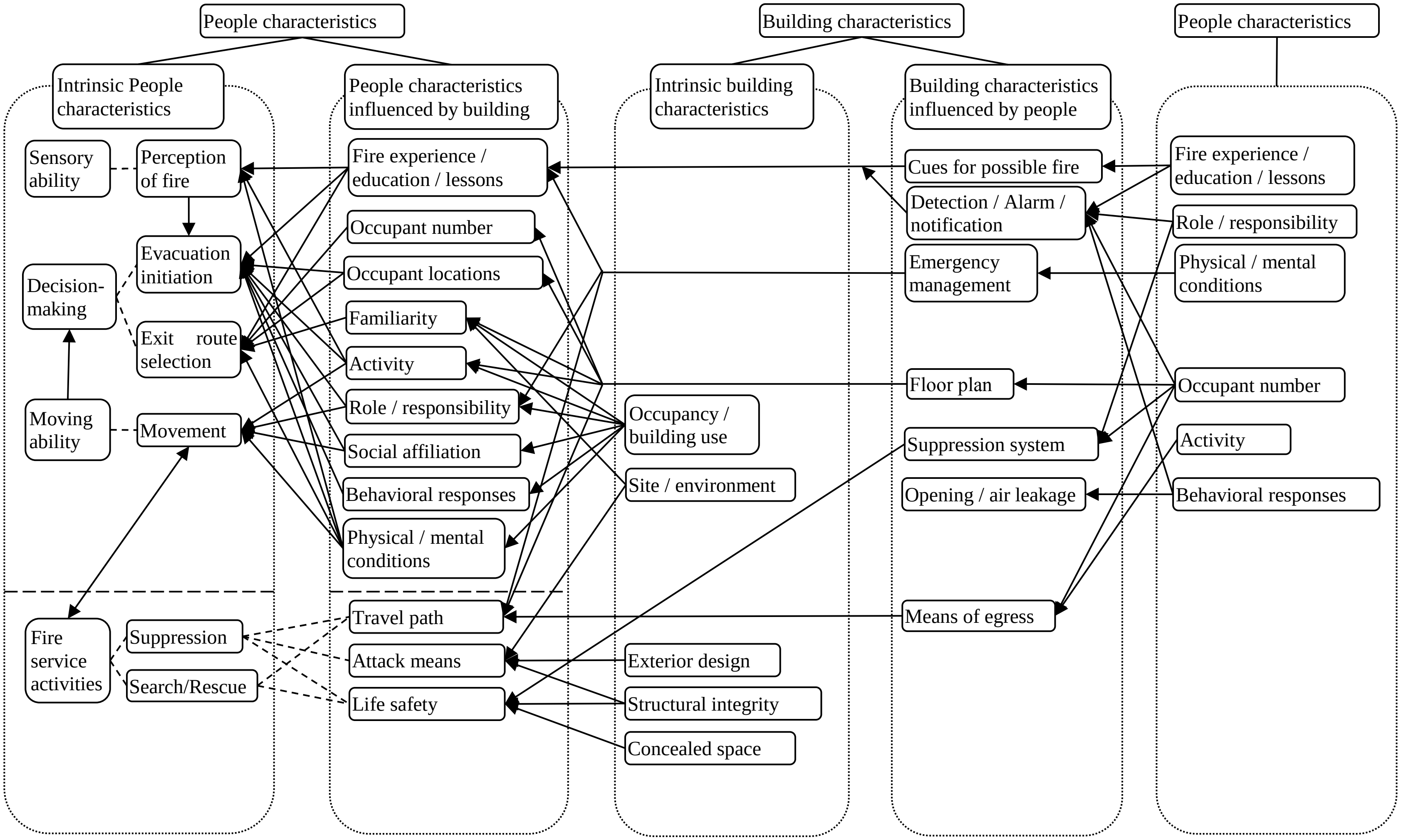

Figure 14. The relationship between building and people characteristics

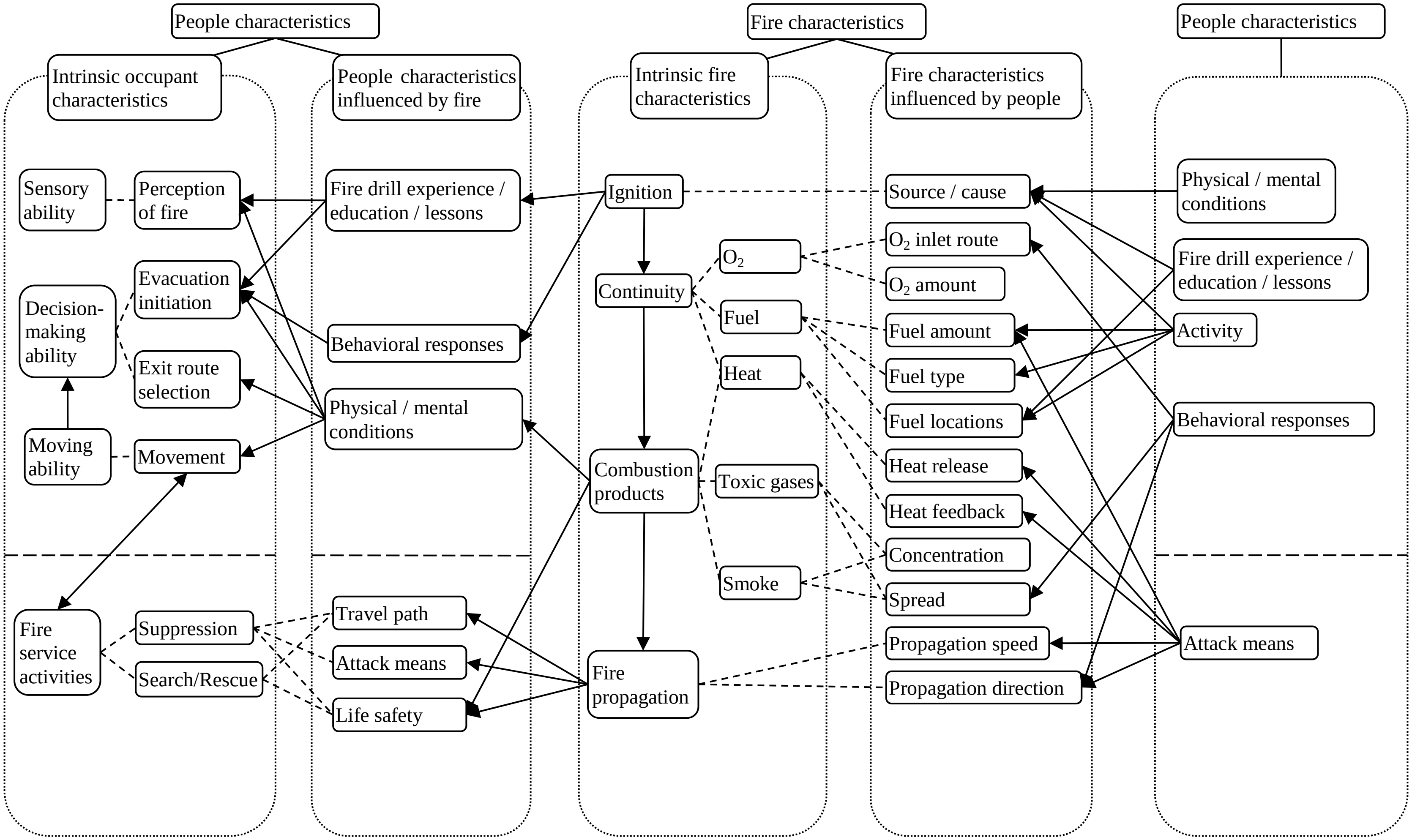

Figure 15. The relationship between people and fire characteristics

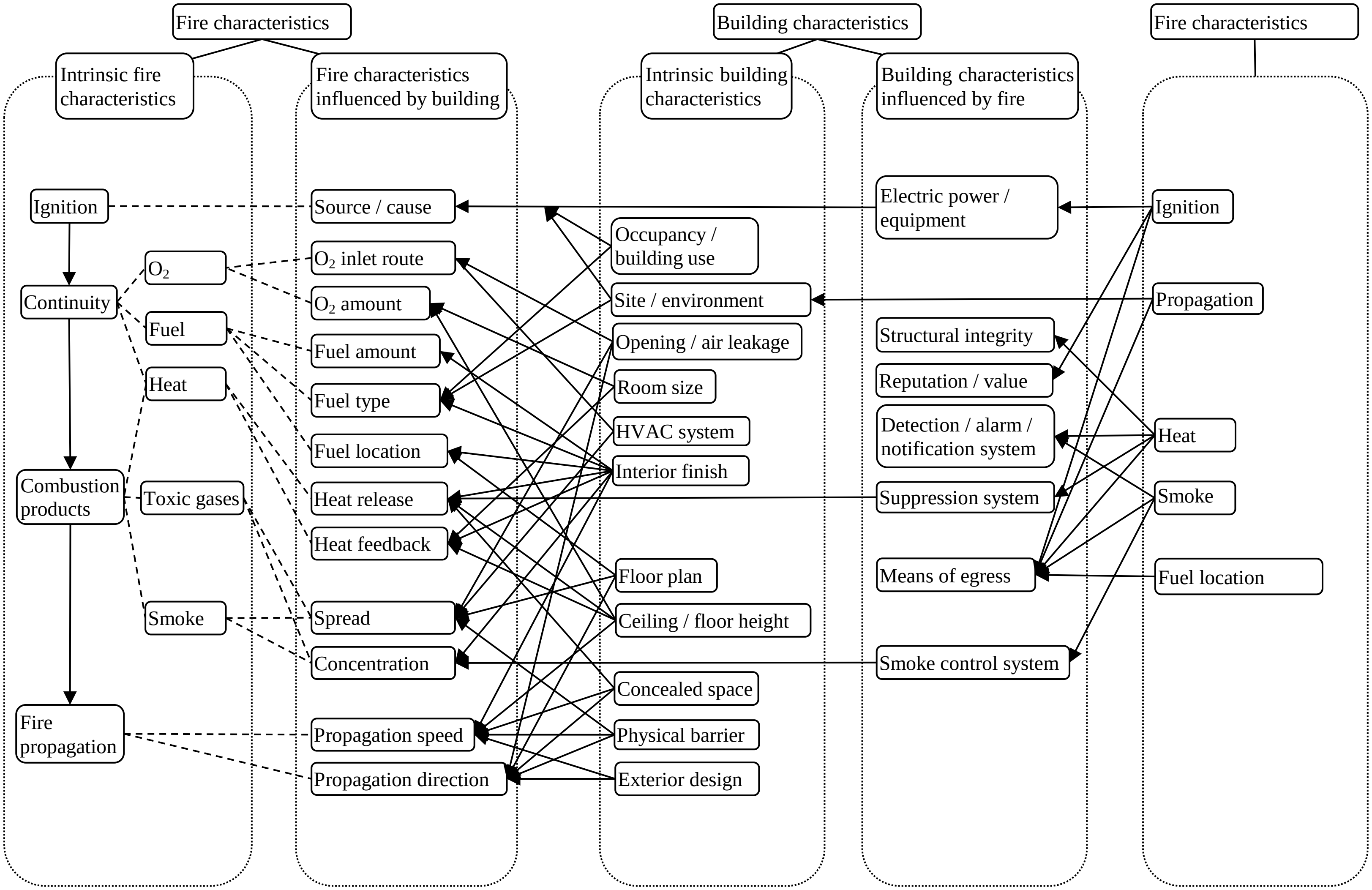

Figure 16. The relationship between fire and building characteristics

The interactions within the people and the fire components are defined at the level of intrinsic characteristics while those within the building characteristics are separately included in Figure 17 due to the complexity of the interactions.

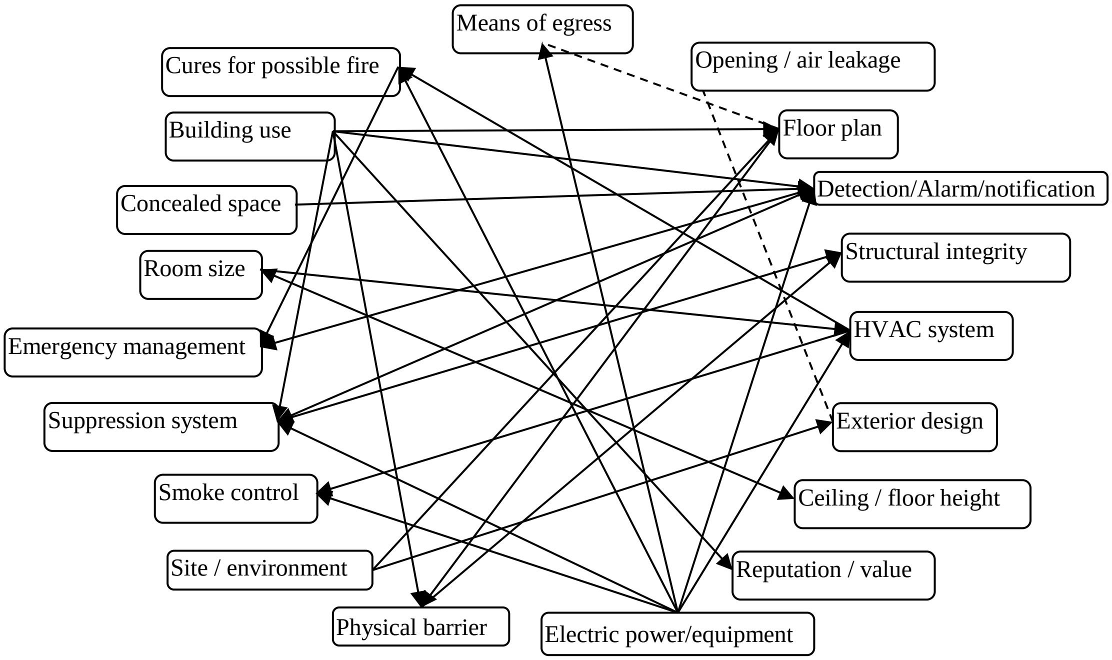

Figure 17. Interconnections within the building characteristics

Most characteristics and interactions from Figure 14 to Figure 17 are self-explanatory, but some of them need to be defined for clarification. In building characteristics, “cues for possible fire” indicate possible precedent events before fire such as water rupture / leaks, unstable electricity, precedent signs of earthquake, or any frequent malfunction of heating appliances, etc. These may or may not cause an ignition, but once these are observed, the chances become increased. The one who has previous fire experience, or who are educated about ignition causes from these factors can think ahead and prepare fire conditions connecting these with ignitions. “Emergency management” implies building and people management for emergency conditions which may include regular fire drills, occupant education for fire risk, in-house emergency responders (firefighter, liaising personnel with fire services, or trained staff assisting evacuation), watchdog system for fire hazards, etc. “Site / environment” indicates the built and natural environment near and in the building site which may have already existed or newly added in the current project. Nearby buildings, infrastructures such as traffic conditions and water resources, proximity of hospitals, fire and police stations, environmental conditions such as temperature, humidity, wind, vegetation, and seismic zone, and site plan including the building orientation, topography, landscape, and parking lot, are all included in the "site / environment." Among these, the site plan influences occupants' daily travel paths which become more familiar to the occupants and which tend to be the evacuation routes in fire conditions. "Physical barrier" represents the vertical and horizontal separation using fire-rated assemblies such as fire / smoke barriers, fire walls, horizontal exits, etc.

In people characteristics, "occupant location" which influences the evacuation initiation can be largely divided into two: in the room of origin or a remote location where fire cannot be directly observed. "Familiarity" indicates the occupant's knowledge about the space, especially about the locations of exits. Due to learned irrelevance, occupants with a good space familiarity may not use the closest exit if they have not used which can be easily applied to emergency exits [15]. "Activity" can represent the level of concentration on specific activities or the awareness level about fire risk. Sleeping, shopping, partying, or even watching movies or shows belong to "activity." The "Role / responsibility" of occupants can affect evacuation initiation. In a hierarchical environment such as employer-employee, supervisor-supervisee, teacher-student, or nurse-patient, the opinions of people with a higher hierarchy on whether to stay or move can determine the mass behavior in emergency conditions. For those who have the responsibility of assisting people's movement, they generally initiate their movement late and their movement speed is also determined by the one they are assisting. "Social affiliation" such as the relation among family members, friends, nearby neighbors, or co-workers can also delay the evacuation as they tend to try to find ones before evacuation. "Behavioral responses" represents various behaviors in fire conditions which may include fighting fire, notifying others, searching for fire, etc. It also includes non-adaptive behaviors which are against the safety of others and fire development. Among these characteristics, occupant location, familiarity, and activity are recognized as key performance variables and included in the recent building regulation of New Zealand [19]. It specifies different pre-movement times based on them.

In fire characteristics, "heat feedback" represents the radiation energy back to the original fuel surface. Generally, a small room or a space with a low ceiling height is heated fast and provide more radiation to the fuel surface increasing the fuel burning rate. Similarly, ignition of combustible interior finishes not only adds more heat energy to the room, but also provides more radiation energy back to the original fuel surface increasing the peak heat release rate and fire development speed.

The interaction models described from Figure 14 to Figure 16 are then integrated into a single model, the ICIM, which is composed of two figures, Figure 17 and Figure 18. Note that the building characteristic model in Figure 17 is shared by the interaction models and the ICIM. The same color code as the GFRM is used for the components in the ICIM, and black color two-way arrows indicate that the two characteristics influence each other. It is recognized that the ICIM representation is quite challenging to decipher at first glance, but the complexity is needed to adequately represent the interrelationships. If one studies the model, one gains a good appreciation of the influences of people, building and fire on each other. It is anticipated that the ICIM can form the basis of a computerized tool which, quickly and given a variety of plausible assumptions which can be made by the design team, reflect strengths and weaknesses in proposed fire safety strategies. The foundation for such tool is discussed below.

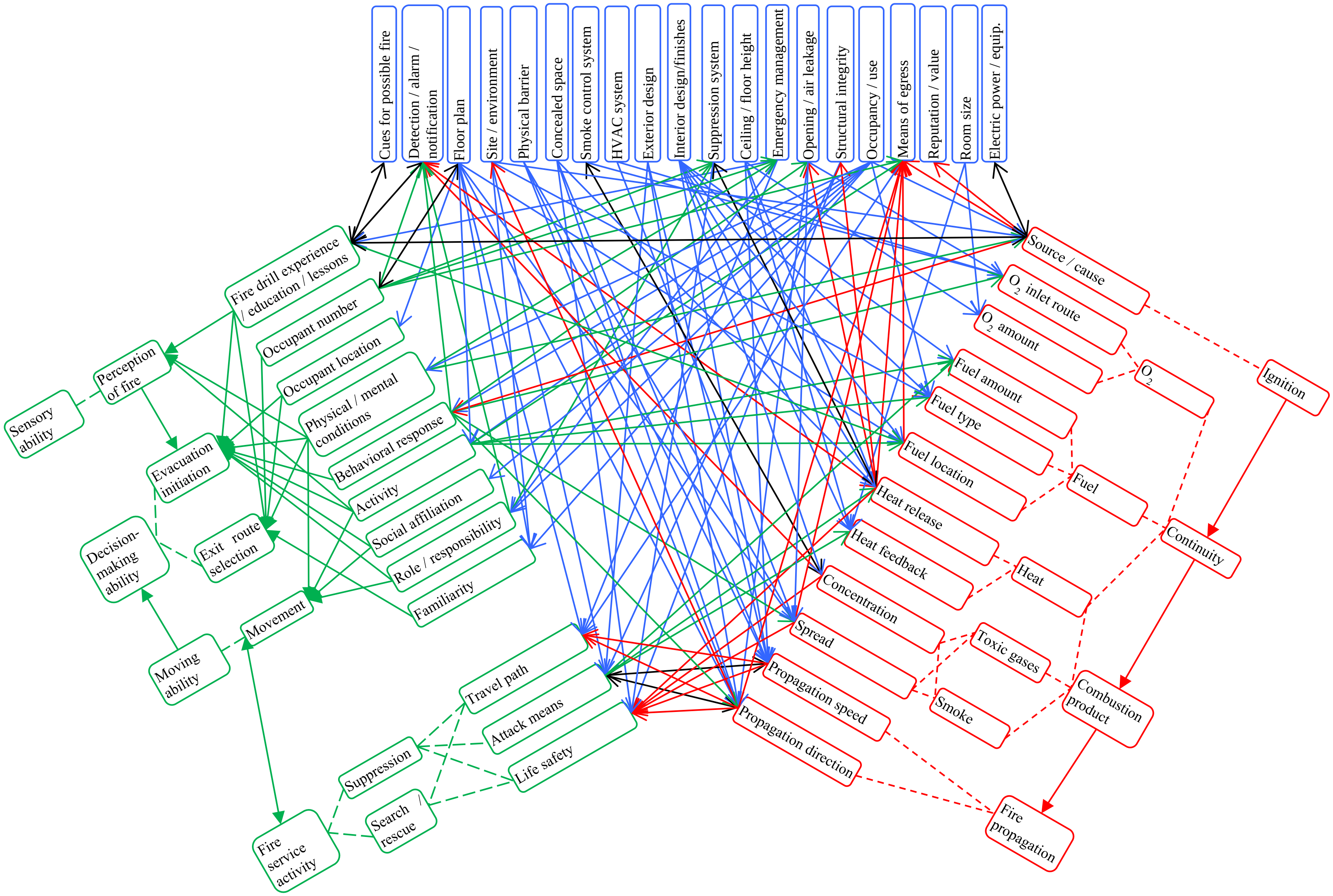

Figure 18. The Integrated characteristic interaction model (ICIM)

3.4 Development of quantitative model based on the ICIM

As shown in Figure 18, the building fire safety performance is involved with various characteristics of building, people, and fire components and the cause-effect relationships among them. In other words, a holistic perspective accounting for the effects of not only individual characteristics but also the various interactions among both hard and soft characteristics is required in order to properly assess the building fire safety performance. With the holistic understanding as a prerequisite, a quantification method commonly used in analytical hierarchy process (AHP) is adopted to further illustrate the application of the ICIM.

3.4.1 Formulation of characteristics for quantification

Despite the complexity of the ICIM, its conceptual origin is the simple GFRM in which largely two fire safety objectives are incorporated: property protection and life safety, which are represented by fire propagation and egress characteristics. As such, the ICIM can be modified or restructured locating the property protection and life safety at the top level with multiple branches of sub-level characteristics in a hierarchical manner. Top characteristics are influenced by intermediate characteristics which in turn are influenced by bottom characteristics. By modifying bottom characteristics, changes propagate through the system upwardly.

The hierarchical structures of quantitative models based on the ICIM are presented as two diagrams: one for property protection and the other for life safety, in Figure 19 and Figure 20, respectively. In these diagrams, characteristics are modified from the ICIM; some are excluded such as electrical equipment, some are divided into more detailed characteristics such as occupant activity and building use, and some are combined into a single characteristic such as oxygen availability, to fit better for the quantification scheme. It should be noted that the ICIM and the quantitative model diagrams serve different objectives: the former for the holistic understanding of the building performance during fires and the latter for the quantitative performance evaluation. Red boxes, blue boxes, and white boxes represent the top, intermediate, and bottom level characteristics and characteristics in gray boxes are shared by both property protection and life safety performance.

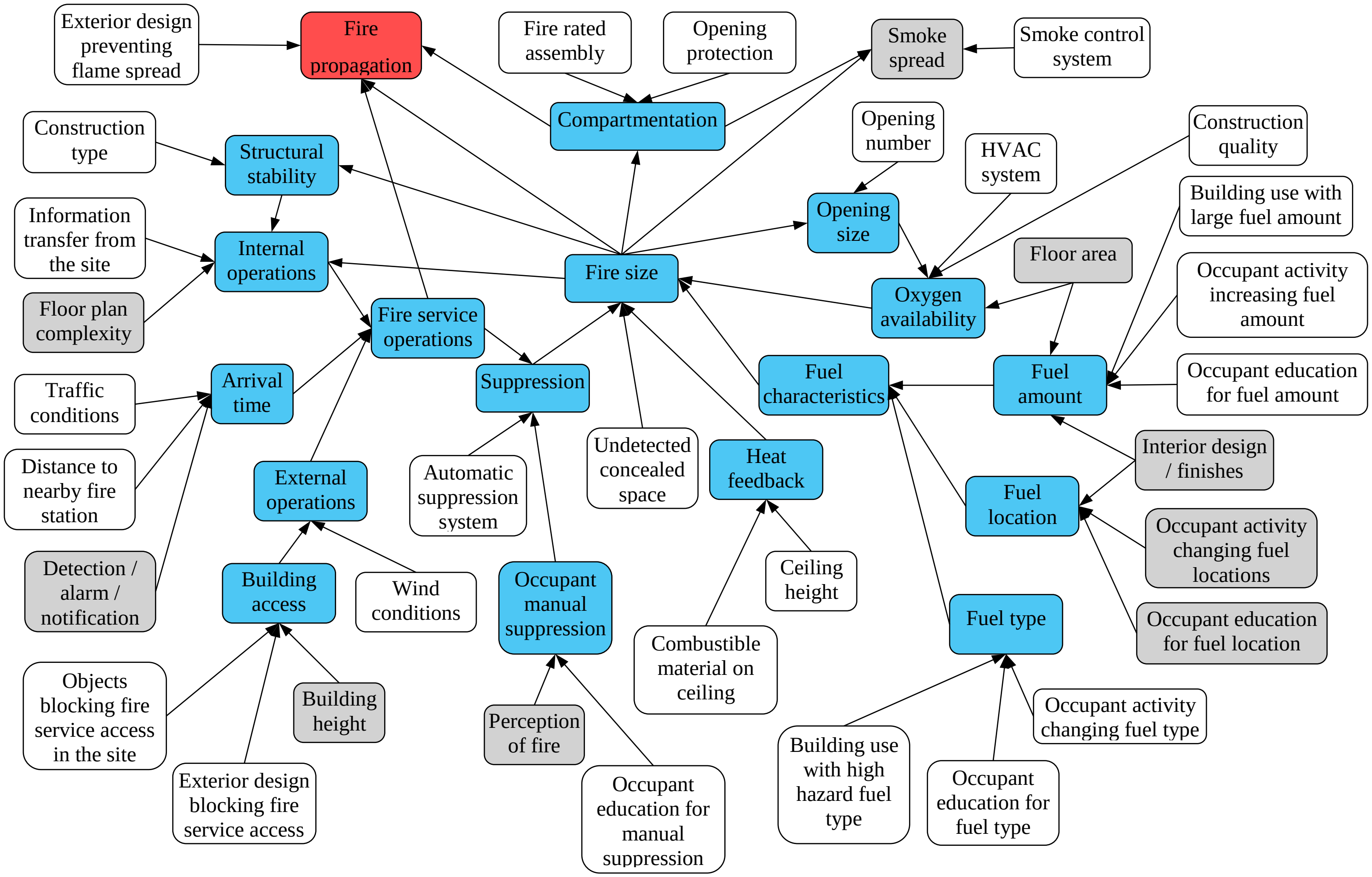

Figure 19. Hierarchy of attributes for property protection performance

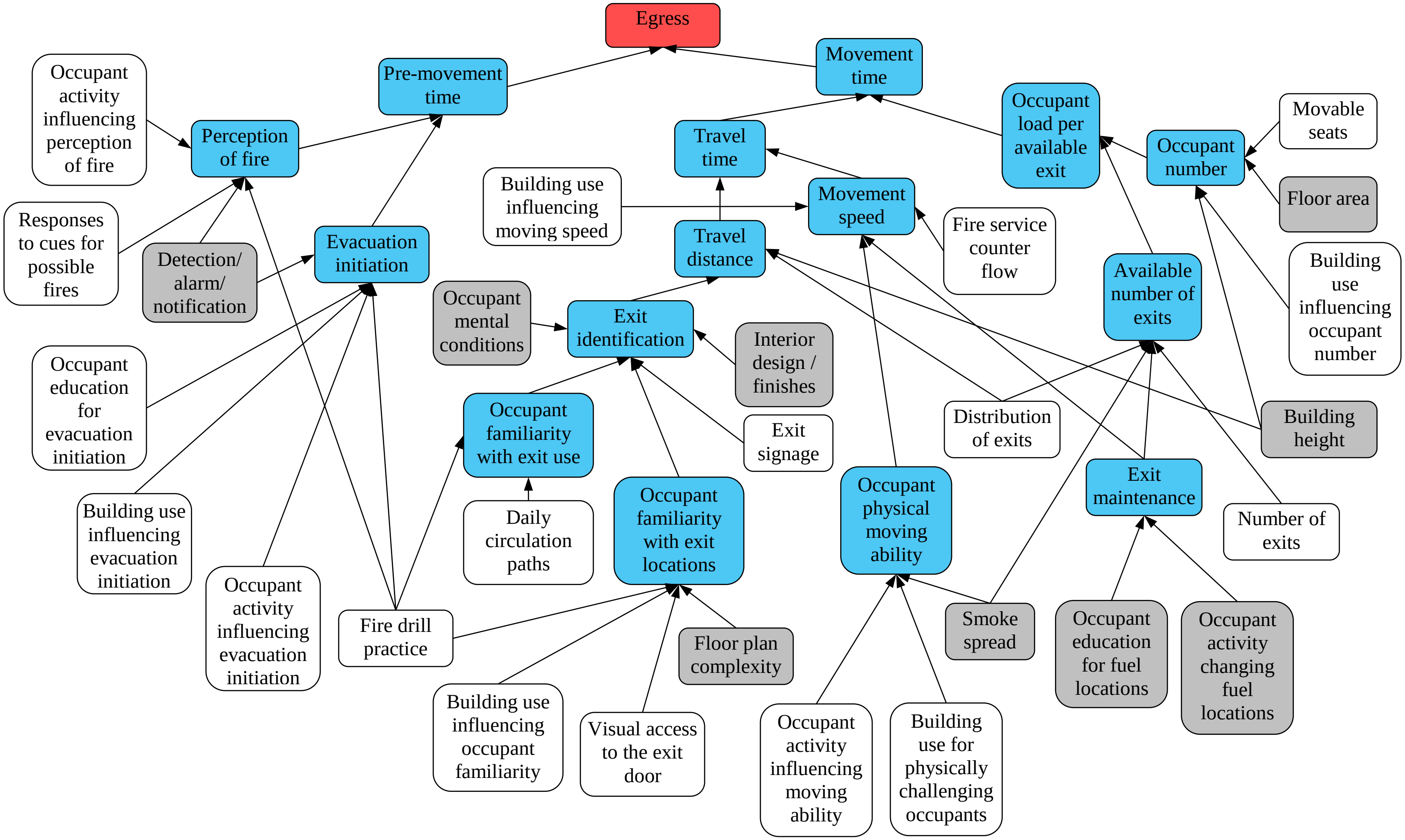

Figure 20. Hierarchy of attributes for life safety performance

In the quantitative models shown in Figure 19 and Figure 20, two different types of influence relationships are defined: static and dynamic. Static relationships indicate that upper level characteristics are influenced by lower level characteristics while dynamic relationships represent mutual influences. Most of the interactions shown in Figure 19 and Figure 20 are static relationships, but the relationship among the fire size, structural stability, internal operation, fire service operations, and suppression and the relationship among the fire size, opening size and oxygen availability are dynamic. This is because fire service suppression operations are influenced by structural stability as fire fighters are pulled out of the building in case that structural stability is decreased by large fire sizes. Once fire service stops suppression activity within the building, fire size tends to become larger. In the same way, a large fire size can break windows, which in turn provides more oxygen from which fire can be larger. A different quantification method is used for the relationship of dynamic influence, which will be explained in the section of application of the quantitative ICIM.

3.4.2 Quantification method

To reflect the relative importance of characteristics within the hierarchy illustrated in Figure 19 and Figure 20, the analytical hierarchy process (AHP) is used. AHP is a decision-making procedure for multi-attribute problems developed by Saaty [20]. By assessing relative importance of lower level attributes in the hierarchy, upper level attributes are quantified by weighted sum method. The relative importance is calculated based on the eigenvalue/eigenvector of reciprocal matrix. This approach is appropriate for the quantitative model of the ICIM as applied to a specific building as the weights of influencing factors will be a function of specific designs, building uses, occupants, site conditions, etc. In the first instance, judgments of the fire engineer can be used to assign weights and values can also be determined jointly between stakeholders. Judgments are influenced by data and analysis. This approach has been used in other fire safety performance evaluation approaches [21, 22].

To illustrate the mathematical formulation and calculation procedure, an example, for the building access characteristic, is provided below.

According to the diagram in Figure 19, building access for the external fire service operations is influenced by three attributes (or characteristics): building height, objects blocking fir eservice access in the site, and exterior design blocking fire service access. Let’s assume that each attribute has an absolute importance value to building access as listed in Table 2. Per this assumption, “building height” is $\frac{w_1}{w_2}$

times more important than “objects blocking fire service access in the site”, and $\frac{w_1}{w_3}$ time more important than “exterior design blocking fire service access.”

Table 2. Assumed influencing variables for building access

Attributes	Absolute importance
Building height	w_1
Objects blocking fire service access in the site	w_2
Exterior design blocking fire service access	w_3

The reciprocal matrix which shows the relative importance of the attributes is written as:

$$\mathbf{A} = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \frac{w_1}{w_3} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \frac{w_2}{w_3} \\ \frac{w_3}{w_1} & \frac{w_3}{w_2} & \frac{w_3}{w_3} \end{bmatrix}$$

Multiplying the reciprocal matrix, **A,** with the importance vector, **w**,

$$\mathbf{Aw} = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \frac{w_1}{w_3} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \frac{w_2}{w_3} \\ \frac{w_3}{w_1} & \frac{w_3}{w_2} & \frac{w_3}{w_3} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = \begin{bmatrix} w_1 + w_1 + w_1 \\ w_2 + w_2 + w_2 \\ w_3 + w_3 + w_3 \end{bmatrix} = 3 \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = n\,\mathbf{w}$$

Where n = the number of attributes

The form, $\mathbf{Aw} = n\mathbf{w}$, has similarity with the eigenvalue/eigenvector format in linear algebra, which is $\mathbf{Aw} = \lambda\mathbf{w}$, where λ is the eigenvalue and **w** is the eigenvector. From this relationship, it is found that once the reciprocal matrix, **A**, is determined, eigenvector, **w**, which indicates the relative importance of each attribute can be calculated.

Matrix A is formulated by pair-wise comparisons of the attributes which typically uses values from 1 to 9 and their reciprocals as proposed by Saaty. The scale of relative importance is shown in Table 3.

Table 3. Scale of relative importance [23]

Intensity of relative importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slight favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgment	When compromise is needed
Reciprocals of above non-zero numbers	If an activity has one of the above numbers assigned to it when compared with a second activity, then the second activity has the reciprocal value when compared to the first.	

The number of pair-wise comparisons of the attributes is determined by the total number of the attributes. Generally, when more attributes are involved, the consistency of the pair-wise comparison becomes decreased, and the actual reciprocal matrix becomes prone to having some deviations in their components from the exact reciprocal matrix components. Such that, λ is not always the same value with '*n*', but the eigenvalue which is close to '*n*,' is selected and its corresponding eigenvectors become the relative importance of the attributes. This relationship can be written as:

$$\mathbf{A}'\mathbf{w}' = \lambda_{\max}\mathbf{w}'$$

Where $\mathbf{A}'$: Actual reciprocal matrix (commonly non-consistent) obtained from subjective pairwise comparison

$\mathbf{w}'$: Estimated eigenvector corresponding to $\lambda_{\max}$

$\lambda_{\max}$: The maximum eigenvalue which is close to the number of variable, *n*.

For the building access attribute for external fire service operations, the reciprocal matrix is formulated in Table 4 followed by the rationales for the relative importance. Note that the justification represents the authors' views, and that rationale and weighting could change by project and user, and that over time, consensus values and rationale could be developed and codified.

Table 4. Reciprocal matrix for building access

	Building height	Objects blocking fire service access in the site	Exterior design blocking fire service access
Building height	1	2	5
Objects blocking fire service access in the site	1/2	1	2
Exterior design blocking fire service access	1/5	1/2	1

a. Building height vs. objects blocking fire service access in the site

Both a large building height and objects blocking fire service access such as tall trees, water ponds, and limited access road in the site significantly hinder fire service's access to the building. However, it is possible to compromise the hindrance caused by blocking objects in the site to some extent using various fire service equipment or attempting different directions of access route to the building while it is practically impossible to conduct external suppression mission if building is too tall for fire service to reach. Therefore, it is concluded that building height is 2 times more important than the objects blocking fire service access in the site.

b. Exterior design blocking fire service access vs. building height

Compared to the exterior design blocking fire service access such as roofs with vegetation or solar panels, no or a small number of opening on the façade facing to the direction of fire service access, or multi-layer façade by which water stream may not effectively reach the internal space of a building., building height is a more critical factor for fire service. If the equipment of fire service is not sufficient to reach upper floors of a tall building, suppression mission outside the building for those floors is impossible while exterior design blocking fire service access is obstructive, but do not make it impossible. For this reason, it is concluded that building height is 5 times more important than the exterior design blocking fire service access.

c. Objects blocking fire service access in the site vs. exterior design blocking fire service access

Compared to the exterior design features blocking fire service access, objects in the site tend to be generally large-scale and more difficult to cope through to access the building. Therefore, from the perspective of the effectiveness of fire service operation, it is concluded that objects blocking fire service access to the building in the site is 2 times more important than exterior design blocking fire service access.

The reciprocal matrix for the building access attribute has three eigenvalues, which are 3.0385, -0.0193+0.3415i, and -0.0193-0.3415i. Among this, the first eigenvalue is close to the number of matrix components which is 3. Corresponding eigenvectors to this eigenvalue are -0.8902, -0.4132, and -0.1918. Normalizing these values being divided by their sum, the importance factors ($\mathbf{w}'$) are calculated as shown in Table 5.

Table 5. Importance factor for the attributes of fire service operation

	Building height	Objects blocking fire service access in the site	Exterior design blocking fire service access
Importance factors	0.5954	0.2764	0.1283

It is recognized that this example uses importance factors as generalized by the author for example. However, consensus on scales and important factors can be developed for specific projects with key stakeholders, as well as over time by committees or others working on consensus, much in the way the weighting in the FSES was developed. This not only would help engineers in the application of this assessment approach, but would address a concern identified by several building regulatory entities wherein the lack of consistency in performance assessments and design solutions have pushed the regulators to 'prescribe' various performance design factors [19]. A tool such as outlined above could be beneficial in facilitating broad agreement within a jurisdiction on key performance parameters and their importance for being addressed within fire safety design development.

Along with the importance factor, each attribute has its own performance value. As the importance factors are normalized between 0 and 1, attribute performance values are also scaled between 0 and 1 such that upper and lower level attributes are in the same scale consistently. In the current study, three different values of performance scale are used: high, medium, and low with high being good for fire safety and low being unfavorable. Numerical values of 1, 0.5, and 0.01 are assigned to them, respectively. It should be noted that these values do not represent absolute performance. In other words, 'high' does not mean 100 times as effective as 'low'. Rather, it indicates relative contributions with respect to the performance of upper attributes. Poor performance (0.01) is almost neglected due to its small value regardless of the importance factor, while good performance (1) is fully reflected in the calculation of upper attributes in the scale of 0 to 1. Medium performance (0.5) may be used for the attributes whose performance is not clearly identified as low or as high. A similar scale system has been conventionally used in other areas such as geotechnical or psychological probability assessment to transform qualitative (or verbal) degrees of belief to numerical values [24]. Using weighted sum method, the quantified value for an upper level attribute becomes as:

$$\text{Quantified performance value of an upper level attribute} = \sum_{i=1}^{n} w_i x_i = w_1 x_1 + w_2 x_2 + w_3 x_3 + w_4 x_4$$

Where x_i = i^{th} attribute performance value in a given building (1, 0.5, or 0.01)

Assuming a tall high-rise building with the existence of objects blocking fire service access in the site (or around the building), the attribute performance value for the building access is calculated in Table 6.

Table 6. Attribute performance calculation for building access for external fire service operations

lower level attributes	Importance factor	Performance value	Weighted value	Upper level attributes
Building height	0.5954	0.01	0.0595	Building access = 0.1371
Objects blocking fire service access in the site	0.2764	0.01	0.0028	
Exterior design blocking fire service access	0.1283	1	0.1283	

3.4.3 Application of the quantitative model

To provide a more concrete illustration of the application of this process, a simplified version of quantitative model which can represent the full model is established in Figure 21 and applied to an actual building where a fire incident occurred. More detailed analysis is provided in chapter 4. The result of evaluation analysis is compared to the fire incident outcome and used to explore alternative fire safety design solutions.

The simplified model is formulated by mostly extracting intermediate level attributes from the full model shown in Figure 19 and Figure 20. Note that intermediate level attributes in Figure 19 and Figure 20 become the bottom level attributes in the simplified model in Figure 21 which can be expanded further consisting of lower level attributes.

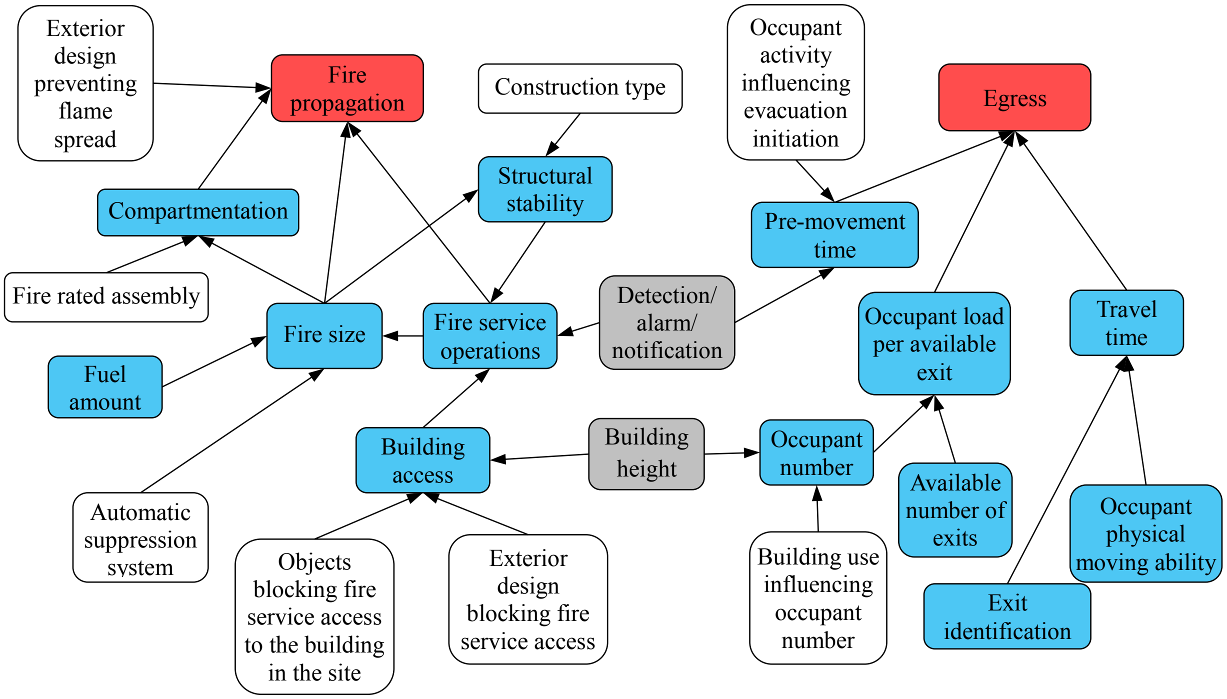

Figure 21. Hierarchy of the simplified model

The fire incident which occurred in 2008 at the Faculty of Architecture Building (Bouwkunde) of Delft University of Technology in Delft, the Netherlands [25, 26] is selected as a target building of analysis. A brief description of the building features including building design and fire protection measures and occupant characteristics are as follows:

> The Bouwkunde was a reinforced concrete, 13 story building consisting of a 3 story base and a 13 story tower structure. The tower was approximately 108 m long and 22 m wide. The floor plan of the tower section is divided into three areas: two large open design studios and office area at both ends and service area in the middle separated by 30 minute rated fire barrier. An exit stairwell was provided in each compartmented area. The architectural design studio had two different ceiling heights: a single story high ceiling where a mezzanine floor being hung from the floor above and two story high ceiling for the rest area of the design studio. Combustible acoustic panel was installed on the bottom of the mezzanine floor (or on the ceiling of single story high area). An automatic suppression system was not installed, but manual fire extinguishers were equipped in the building. External escape stairs connected from the fourth floor to the ground were installed. Automatic door closer and smoke alarm system were installed throughout the building. Most perimeter of the building was surrounded by water and large trees were located near the building. The building was side of the building was surrounded by water. Occupants were mainly students and faculty members who knew

the building layout well. The typical number of occupants is unknown, but could be significant considering the large floor area. Students were expected to bring more and possibly highly combustible fuel contents such as foam board and balsa wood to study architectural design.

Based on this description, attribute performance values are assigned. The weighted values are calculated as shown in Table 7 with the assigned performance values and the importance factors developed following the same method for the building access characteristics. In addition to the building access attributes in Table 4, the reciprocal matrices to calculate importance factors for fire service operations, fire size, fire propagation and egress attributes are include in Table 8. The performance value of fire size attribute which is dynamically linked with fire service operations is determined iteratively to satisfy that the values of fire size as lower level attribute and upper level attribute are identical.

Table 7. Calculated attribute values with the input of attribute performance values

No.	Lower level attributes	Importance factor	Performance value	Weighted value	Upper level attribute value	Upper level attributes
A1	building height	0.5954	0.01	0.006	0.1371	building access
A2	objects blocking fire service access in the site	0.2764	0.01	0.0028		
A3	exterior design blocking fire service access	0.1283	1	0.1283		
A4	construction type	0.4	1	0.4	0.4614	structural stability
A5	fire size	0.6	0.1024	0.0614		
A6	building access	0.5499	0.1371	0.0754	0.4124	fire service operations
A7	detection/alarm/notification	0.2402	1	0.2402		
A8	structural stability	0.2098	0.4614	0.0968		
A9	fire service operations	0.2297	0.4124	0.0947	0.1024	fire size
A10	automatic suppression system	0.6483	0.01	0.0065		
A11	fuel amount	0.122	0.01	0.0012		
A5	fire size	0.4	0.1024	0.041	0.047	compartmentation
A12	fire rated assembly	0.6	0.01	0.006		
A13	exterior design preventing flame spread	0.2	0.01	0.002	0.0728	**fire propagation**
A14	compartmentation	0.2	0.047	0.0094		
A5	fire size	0.6	0.1024	0.0614		
A1	building height	0.7	0.01	0.007	0.307	occupant number
A15	building use influencing occupant number	0.3	1	0.3		

A16	occupant number	0.5	0.307	0.1535	0.6535	occupant load per available exit
A17	available number of exits	0.5	1	0.5		
A18	exit identification	0.3	1	0.3	1	travel time
A19	occupant physical moving availability	0.7	1	0.7		
A7	detection/alarm/notification	0.6	1	0.6	0.8	pre-movement time
A20	occupant activity influencing evacuation initiation	0.4	0.5	0.2		
A21	occupant load per available exit	0.3108	0.6535	0.2031	0.7935	**egress**
A22	travel time	0.1958	1	0.1958		
A23	Pre-movement time	0.4933	0.8	0.3946		

Table 8. Reciprocal matrices for attributes consisting of more than two attributes

	A6	A7	A8
A6	1	2	3
A7	1/2	1	2
A8	1/3	1	1

	A9	A10	A11
A9	1	1/3	2
A10	3	1	5
A11	1/2	1/5	1

	A13	A14	A5
A13	1	1	1/3
A14	1	1	1/3
A5	3	3	1

	A21	A22	A23
A21	1	2	1/2
A22	1/2	1	1/2
A23	2	2	1

From the building fire safety evaluation, fire propagation attribute which represents property protection has a very low value while egress attribute which represents life safety has a relatively high value, which is actually in a good agreement with the major fire incident outcomes which is summarized as below.

> Fire occurred in the 6th floor of the north section of the tower structure and rapidly spread to upper floors through the exterior windows. The separation distance between exterior windows were not sufficient to prevent vertical flame spread. Fire also spread horizontally compromising the 30 minute fire barrier. A large fuel amount existed in the design studio area having a wide open space. Fire service arrived at the building, but did not effectively conduct suppression mission due to the objects blocking fire service access to the building and rapid fire spread within the building. A portion of building collapsed approximately 7 hours after the ignition. Fortunately, all occupants evacuated the building safely.

Despite the collapse, the fire safety performance of the Faculty of Architecture Building may be satisfactory if life safety was the only performance objective. However, for property protection which is also a common objective in performance-based fire safety designs, the current safety features need to be modified based on the agreement of relevant stakeholders. It should be noted that the relevant stakeholders include engineers, designers, and consultants who are related to both hard and soft characteristics, and do not indicate only fire engineers. With the purpose of improving property protection performance, the attribute performance value of fire propagation is compared for multiple candidate fire safety designs. By changing the attribute performance values of A2, A10, A11, A12, and A13 from 0.01 to 1 as shown in Table 9, fire propagation performance values are re-evaluated. Medium performance (0.5) is not considered in this example as the purpose is to show the performance variations per scenario, assuming only good or poor performance. It is found that automatic sprinkler system (A10) as a single attribute has the largest effect on improving the property protection performance. However, Design 8 in Table 9, a combination of allowing fire service access to the building (A2), controlling fuel amount (A11), and improved fire rated assembly (A12) and exterior design preventing flame spread (A13), can be also an effective fire safety solution for the Faculty of Architecture Building as shown in Figure 22.

Table 9. Fire propagation performance values for various fire safety design solutions

Design solution	A2	A10	A11	A12	A13	Fire propagation performance value	Summary
Current	0.01	0.01	0.01	0.01	0.01	0.0728	
Design 1	1	0.01	0.01	0.01	0.01	0.097	A2 only
Design 2	0.01	1	0.01	0.01	0.01	0.5223	A10 only
Design 3	0.01	0.01	1	0.01	0.01	0.1574	A11 only
Design 4	0.01	0.01	0.01	1	0.01	0.1916	A12 only
Design 5	0.01	0.01	0.01	0.01	1	0.2708	A13 only
Design 6	1	0.01	1	1	0.01	0.3766	A2 + A11+A12
Design 7	1	0.01	0.01	1	1	0.4138	A2 + A12+A13
Design 8	1	0.01	1	1	1	0.4984	A2 + A11 + A12 + A13

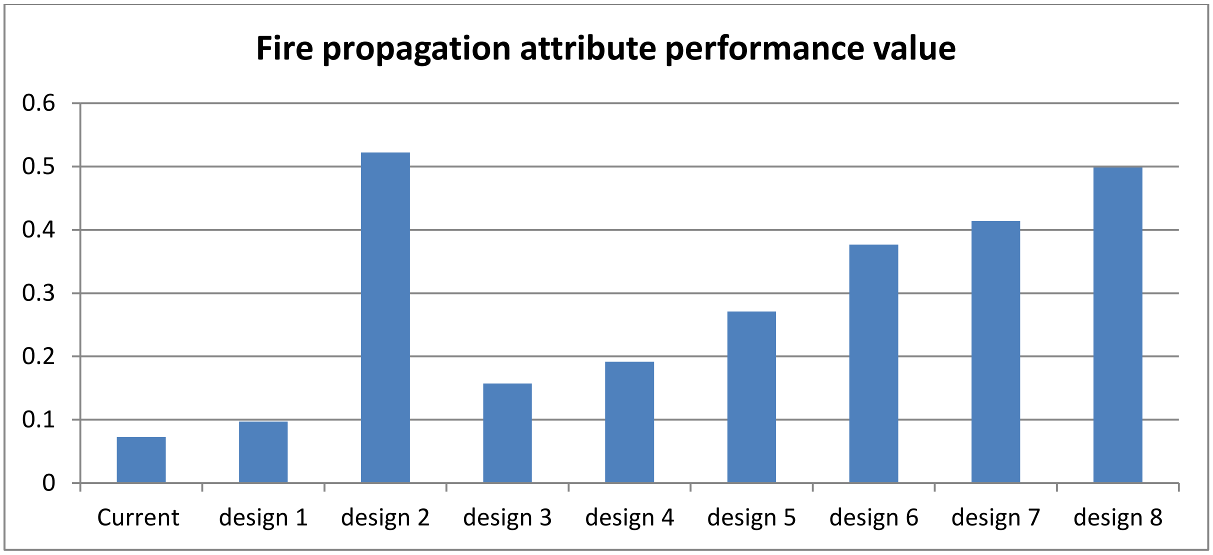

Figure 22. Comparisons of fire propagation attribute values for different fire safety designs

In a real fire safety evaluation project for a particular building, some of these attributes may be bounded by given conditions such as building site, project budget, or even stakeholders' preferences such that available attributes for design modification may be significantly reduced. In addition, it may be necessary to conduct more detailed analysis to determine the performance values for some attributes. For example, for the attribute of exterior design preventing flame spread, a sufficiently robust analysis method is recommended to calculate the extended flame height through openings and radiation effects on the materials on the floor above. The performance value of travel time attribute may be determined based on the computer simulation results of evacuation modeling programs. In this case, however, the user need to recognize whether the imbedded features of evacuation simulation programs for exit identification such as occupant familiarity, influence of interior design, exit signage, and visual access to the exit door and their effects on the simulation results are reasonable [14].

3.5 Conclusion

Building fire safety performance is a complex matter with various characteristics being involved from building, people, and fire components as a system. Utilizing the conceptual background in the systems approach in the 1970s, two qualitative models were developed: Generic Fire Response Model (GFRM) and Integrated Characteristic Interaction Model (ICIM). The GFRM reflects dynamic features of fire development, building responses, and people activities from a broad perspective to capture the generic phenomena of building fire safety. Chronological order and multiple fire safety strategies can be identified easily from this model compared to the FSCT. The ICIM is a more detailed version of the

GFRM including various hard and soft characteristics and their interactions which were identified from the 15 actual previous fire incidents. By extracting characteristics from actual fire incidents, the validity of characteristics became increased when compared to the identification method through survey among fire engineers. In addition to this, compared to the previous systems approach, the ICIM can be distinguished by incorporating more and clearer soft characteristics, specifically building design and occupant characteristics.

Based on the holistic understanding of the interactions of characteristics, a quantification method commonly used in Analytical Hierarchy Process (AHP) was utilized to evaluate fire safety performance. A simplified version of the quantitative ICIM was applied to the actual fire incident which occurred at the Faculty of Architecture Building of the Delft University of Technology, the Netherlands, to show the framework of the quantification method and the step by step application procedure. By collecting relevant stakeholders' pair-wise comparison of the attributes, the chronic criticism on the subjectivity of the quantified values can be reduced in the proposed method, although further research is still required to reduce the criticism by obtaining more objectivity via adjusting the importance factors and attribute performance values to match historical fire incident outcomes. Regardless of this subjectivity, relative comparisons among multiple fire safety designs can be a useful tool to identify alternative design solutions. The proposed AHP-based tool can also help identify when and where more in-depth analysis may be needed by highlighting issues which arise from the confluences of characteristics for any particular building.

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4 Incorporation of fire safety performance into building design process[3]

This chapter combines chapter 2 and chapter 3 into a single concept that fire safety performance needs to be included in building design process in more effective way. Detailed methodology is presented using an exemplary building being applied by the quantified fire safety performance evaluation method.

4.1 Introduction

Building design involves many decisions and actions of multiple stakeholders from various disciplines, including architects (the primary designers), structural, mechanical, electrical, and fire engineers. With so many stakeholders involved, a significant challenge exists with collaboration and communication, as a slight building design change in one discipline may impact multiple disciplines at various levels of decisions [1]. As such, a well-organized building design process is required to incorporate a variety of design needs of multiple disciplines in a manner that necessary information is provided to relevant stakeholders in order. However, this systematic planning is not fully practiced in many building projects [2, 3]. Due to the information generated after initial building design, or insufficient performance of selected design in some disciplines, rework is typically necessary, which makes the building design process inevitably iterative.

The iteration in building design process generally follows the four steps: analysis, synthesis, evaluation, and communication as shown in Figure 23 [4]. Depending on building design stage, detailed tasks of each step may be different, but generally speaking, problem identification, solutions development, evaluation of solutions' performance, and selection of optimal design are conducted in analysis, synthesis, evaluation, and communication, respectively. In the case that problems are complicated with a large number of stakeholders involved, more time and efforts are required to solve them, i.e., the design burden due to the iteration increases. To improve design efficiency, this burden needs to be decreased, which can be accomplished by two strategies: increasing the speed of iterations and / or decreasing the number of iterations [5]. Faster iteration can be achieved by improved design performance of each stakeholder with accelerated analysis and evaluation tools, and less iteration can be achieved by providing better collaborative environment among stakeholders. An example of the former strategy is development of more efficient design and analysis tools such as computer-aided design (CAD) or computer programs for performance simulation which accelerate individual design activities. An example of the latter strategy is the concept of integrated building design in which various project

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stakeholders gather together from early design stages to identify interrelated problems, discuss solutions, and make decisions based on mutual agreement.

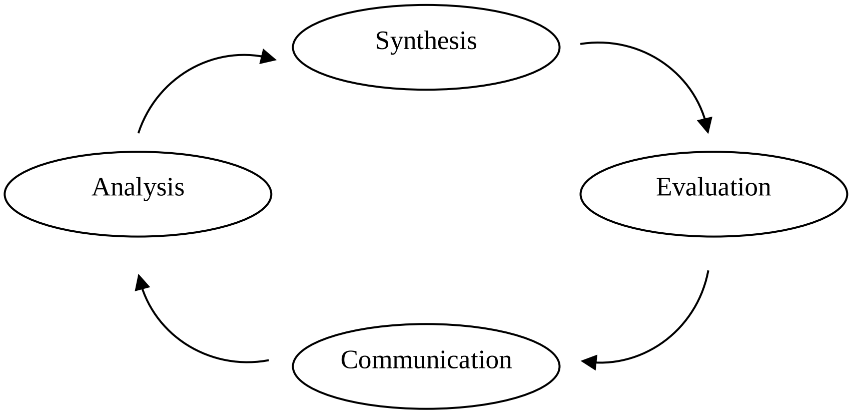

Figure 23. Iterative building design process

While pursuing the efficiency, building designs must comply with building and fire safety regulations (codes and standards), which provide minimum requirements for public health, safety, and general welfare of building users. Especially for fire safety, regulations are established to protect occupants, emergency responders, and properties in fire emergency operations. Building and fire safety regulations are generally categorized by two different types: prescriptive regulations and performance regulations. There are hybrid regulations in which both performance requirements and detailed prescriptive requirements co-exist, but they can independently fall into either one of the types. In prescriptive regulations, detailed requirements regarding fire safety features such as egress width, travel distance, and the number of exits, are prescribed whereas in performance regulations, requirements are prescribed only at the performance level and detailed means and methodology to achieve the performance are not generally included in regulations [6]. For example, per the International Building Code (IBC) published by International Code Council (ICC), the most widely used prescriptive building code in the USA, the maximum exit access travel distances are specified per occupancy and with/without sprinkler system, which ranges from 22.8 m (75 ft) to 121.9 m (400 ft). More specifically, for residential occupancy, the distance should not exceed 60.9 m (200 ft) with sprinkler system and 76.2 m (250 ft) without sprinkler system. On the other hand, as per the ICC Performance Code for Building and Facilities, exit access distance is not quantitatively specified, but addressed by the requirement that "the construction, arrangement and number of means of egress, exits and safe places for buildings shall be appropriate to the travel distance, number of occupants, occupant characteristics, building height and safety systems and features." This is similar to function- or performance-based building regulations in

Australia, England, New Zealand and elsewhere. The different levels of requirements included in the two regulation types can be illustrated as shown in Figure 24.

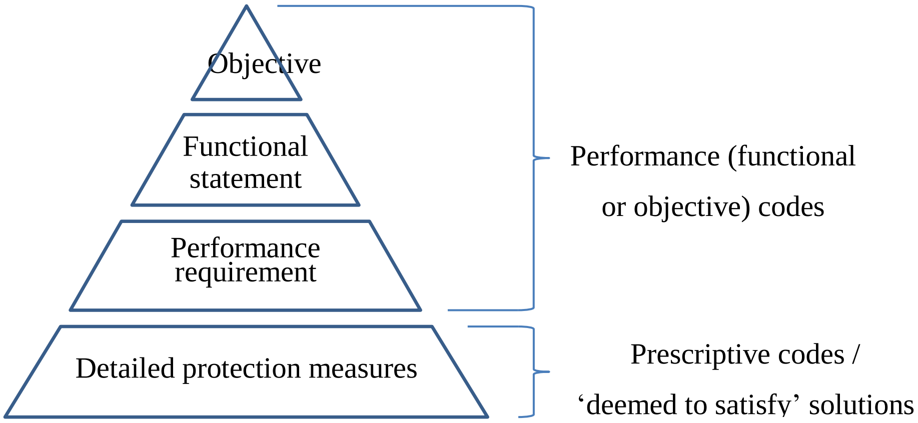

Figure 24. The level of requirements in prescriptive and performance-based regulations

Prescriptive regulations become widely used in the 20th century. However, by the last quarter of the century, concerns were raised as to whether the prescriptive requirements correctly reflect the fire safety performance that stakeholders want, whether they are flexible or updated fast enough to keep pace with fast-developing building technology, new materials, and innovative building designs, and whether they were cost-effective [7]. In response to these concerns, performance-based codes and design approaches emerged in the 1970s, and performance-based codes are currently implemented in more than 20 countries, with performance-based design used worldwide with continuous evolvements [8, 9]. Even in the US where prescriptive building regulations are implemented, performance-based design solutions are allowed under the clause of “104.11 alternative materials, design and methods of construction and equipment,” of the International Building Code [10]. Generally speaking, performance-based fire safety design solutions require more sophisticated approach based on fire science and engineering than prescriptive solutions and provides more flexibility and less restrictions to building design.

Along with innovation in regulations and fire safety design approaches, there has been development in computational tools and methods in building industry to increase building design efficiency. This includes CAD, computer programs for a variety of building performance analysis, e.g., structure, energy consumption, fire, air quality, and so forth. However, in the case of building regulations and CAD, there has been a disconnect. While regulations have moved to performance, tools to support regulation review thrive on the prescriptive approach. Since fire safety features and their designs are closely related with building design, there have been continuous efforts of incorporating building and fire safety regulations into CAD programs [11-13]. Some of them were developed in the BIM environment or as part of an electronic application for the approval of building authority [14, 15]. The format of incorporation was an automated feature of checking code compliancy of a given building design. This approach intends to save time and efforts by avoiding manual search of relevant code provisions and to prevent undue design modification in later building design phases caused by non-code-compliant building features. This is in accordance with the concept of more effective and efficient building design process as it can reduce the design burden from the iterations between primary designers and fire engineers. The efforts, however, have been made only for prescriptive regulations. Considering the global and increasing popularity of performance-based building and fire safety regulations and design practices, it is necessary to develop performance-based collaboration and tool development for building design and fire safety. In this context, the current study aims to develop a framework to better incorporate building fire safety performance into building design process.

4.2 Background

In this section, two topics are mainly discussed: the concept of building fire safety performance and design decisions in the building design process. Based on this discussion, conceptual framework about the methodology to incorporate building fire safety performance into building design process is presented.

4.2.1 Building fire safety performance

"Performance" indicates the level of accomplishment of mission measured against preset criteria of objectives. Since a building is designed with various objectives such as aesthetics, sustainability, cost-effectiveness, structural stability, fire safety, and human comfort as discussed in chapter 2, building performance can be viewed generally by two different perspectives: comprehensive building performance, which is the averaged accomplishment over various design objectives, and specific building performance, which is measured only for one objective. Depending on design priorities of core design team, more focus may be given to a specific building performance area such as aesthetics or sustainability, but well-performing buildings are expected to have good performance in both comprehensive and specific aspects. Building fire safety performance, in this sense, is specific building performance, which indicates the accomplishment level of mitigating fire impacts as well as a component factor for the comprehensive building performance.

The impacts of building fire incidents are typically considered in terms of four aspects: life safety, building property damage, business interruption, and environmental protection, for which quantitative criteria for building fire safety performance can be developed. For life safety, which is the most common goal for building fire safety, the objective of available safe egress time (ASET) must greater than the required safe egress time (RSET) is widely accepted as a criterion. This intends that all occupants in the building can move to a safe place inside or outside of the building before hazardous conditions are reached. For property protection, the performance objective may vary building by building, but it is generally considered successful if the fire is confined within the room of origin (or fire area), providing a measurable criterion in building area or volume. For business interruption and environmental impacts, the criteria vary since the acceptable monetary loss, fire risk perception level, and sensitivity to environmental protection vary depending on building (or business) owners and geographical and societal environments of buildings. In the current study, we focus on life safety and property protection.

Even with limiting discussion of building fire safety performance to life safety and property protection, it is very challenging to assess performance due to the level of complexity of attributes. At a high level, there are three well-known key components which determine building fire safety performance: building, people, and fire [16]. The building component represents fire safety measures installed in buildings such as active and passive fire protection systems and means of egress, building design (architectural) features, and site characteristics such as environmental conditions and infrastructures [17]. The people component includes occupant's physical and mental capability associated with evacuation phenomena and firefighters' suppression and rescue mission. The fire component indicates fuel type, amount, and location and burning characteristics such as heat release rate and smoke and toxic gas production rates. The complexity of building fire safety performance is involved with not only the variety of individual attributes, but also interactions among them. For example, proper exit signs as a building characteristic can increase occupants' capability to identify an exit route, which is a people characteristic. This people characteristic is influenced by occupants' physical conditions and their relative locations, which are also influenced by building use. Building use can also influence the fuel type and fire source. As such, due to the interactions among the characteristics, a holistic understanding of the effects of the characteristics of building, people, and fire and their interactions is required to assess building fire safety performance appropriately.

Some of the building characteristics are closely involved with building design features which have been considered mainly for other building aspects such as aesthetic, energy, and acoustical performance. These can affect building fire safety performance via changing human behavior in fire conditions, providing more fuels, accelerating fire and smoke development, and hindering rescue and suppression mission of fire fighters. For example, complex floor plans make it more difficult for occupants to identify a proper exit route than simple floor plans, which increases evacuation time [18]. Double-skin façade design which reduces energy consumption of buildings [19] and sandwich panels which provide benefits of constructability and insulation [20] can contribute to vertical fire and smoke spread. Natural ventilation for low-energy consumption raises concerns for fire and smoke control [21]. Acoustic tiles which improve sound legibility are often increase fuel amount and promote fast fire development within the compartment due to their typical locations on ceiling and walls [17]. Occupants also rely on their architectural space experience with buildings to plan the exit routs; exit signs can help occupants' exit route decisions, but the portion of occupants who rely on exit signs are not as high as expected [22, 23]. Therefore, building fire safety performance needs to be understood and assessed accounting for building design features which may be also related with other specific building performance.

Prescriptive building regulations and design, however, have limitations to comprehensively capture the interactive effects, especially regarding the attributes of building design features, people, and fire. Due to the nature of regulations which prescribes detailed requirements, only physical building systems and components are generally included as target objects of requirements, by which code compliancy can be clearly confirmed. This does not mean that prescriptive regulations ignore the effects of building design features, people characteristics, and fire characteristics on the fire safety performance, but rather implies that comprehensive fire safety performance is not fully captured via prescriptive requirements. In addition, design solutions of fire safety measures in prescriptive regulations are typically dependent on occupancy classification, construction type, building height and area, and sprinkler system existence, but these criteria are not fine enough to consider the variability of numerous building designs and to provide a consistent level of fire safety performance. This is why some building fire incidents results in unacceptable damage and loss, from which more restrictive updates of prescriptive requirements are continuously made.

4.2.2 Building design

Building design can be described as a continuous series of actions of project stakeholders, but often broken into four phases: predesign (PD), schematic design (SD), design development (DD) and construction documents (CD) [24]. Following these phases, either different tasks are conducted or the level of detail of the same task is increased. A list of generic tasks and design decisions is introduced in the Architect's Handbook of Professional Practice published by American Institute of Building designers and part of them is included in Table 10 to understand building design progress.

Table 10. Design decisions in each building design phase

Phase 1: PD	Phase 2: Early SD	Phase 3: Later SD or early DD	Phase 4: DD or early CD
General			
Project objectives Project scope Program code and regulations	Program interpretation Basic design concepts Sitting	Design concept elaboration Schematic floor plan Schematic sections	Floor plans Sections Typical details

Project budget Project schedule Delivery approach	Building massing Access and circulation sustainability		
Site			
Site development criteria Requirements for access, circulation, parking, utilities, and lighting	Access and circulation Views to/from buildings Acoustics and other site issues	Design concept elaboration Initial site plan Schematic grading, planting, paving plans	Site plan Planting plan Typical site details Outline specifications
Superstructure			
Performance requirements for floor, roof, stair, other structural elements	Relation of structure to spatial organization, elevation, etc. Basic structural module Initial system selection	Structural system selection Outline framing plan	Floor framing plans Roof framing plans Sizing of elements Important details Outline specifications
Exterior closure			
Restrictions on exterior design, materials, etc. Performance requirements for walls, doors, windows, etc.	Approach to elevations, Views to/from building Initial envelope elements sizing and selection	Design concept elaboration Selection of wall systems, materials Schematic elevations	Elevations Key exterior details Outline specifications
Interior construction			
Performance requirements for partitions, finishes, specialties Flexibility requirements	Approach to partitioning built-in furnishings Interior design vocabulary Layout of key spaces	Room designs Selection of partition systems, finishes Important fixtures or theme elements	Input to plans and elevations Key interior elevations Initial finish schedules Outline specifications
Mechanical systems			
Performance requirements for plumbing, fire protection Need for special mechanical systems	Impact of mechanical concepts on building planning Initial systems selection Initial distribution ideas Space allocation for mechanical areas	Mechanical systems selection Refinement of service, distribution concepts Input to plans, sections, and elevations	Initial system drawings and key details Input to floor plans, framing plans, sections, elevations Initial equipment list

Design progress in each design phase can be accomplished differently depending on project scale and project delivery system, but largely divided into two schemes: conventional linear design and integrated design. In the former design scheme, architects mainly lead design progress and once the design is much developed, other engineers and consultants are requested to participate in the project [25]. This can be efficient for small-size building projects which only a few stakeholders are involved with and the expected performance of the building is not high with a relatively small amount of project budget. The design objectives and criteria are relatively simple and sophisticated analysis and evaluation for building performance is not generally necessary. As such, architects can develop building design alone until when inputs from other engineers and consultants are necessary; sometimes this is as late as building design is almost completed.

Integrated building design [26], on the other hand, provides a more ideal building design environment. Project stakeholders including the owner, project manager, architects, and design consultants, gather together from early design phases and share information afterwards as design progresses. Although architects may have vast experiences of building design, it is limited to understand and to be updated with new technology, materials, and regulation changes in various fields such as mechanical, electrical, and fire engineering. By involving experts from early design phases, the target building performance can be better identified and the possibility of conflicts in later building design phases can be decreased. For this reason, the design scheme is often adopted for large-size building projects or projects in which high building performance is required. Being accompanied by the global green building design trend and increased understanding of designers on the benefit of early involvement of engineering experts, integrated building design gains more popularity.

The relationship of effects and effort in the two building design schemes are well explained in MacLeamy curve as shown in Figure 25. By assigning more efforts of stakeholders in early design phases such as PD and SD, more opportunities for cost reduction and better functional capabilities are allowed and the cost of design changes are minimized.

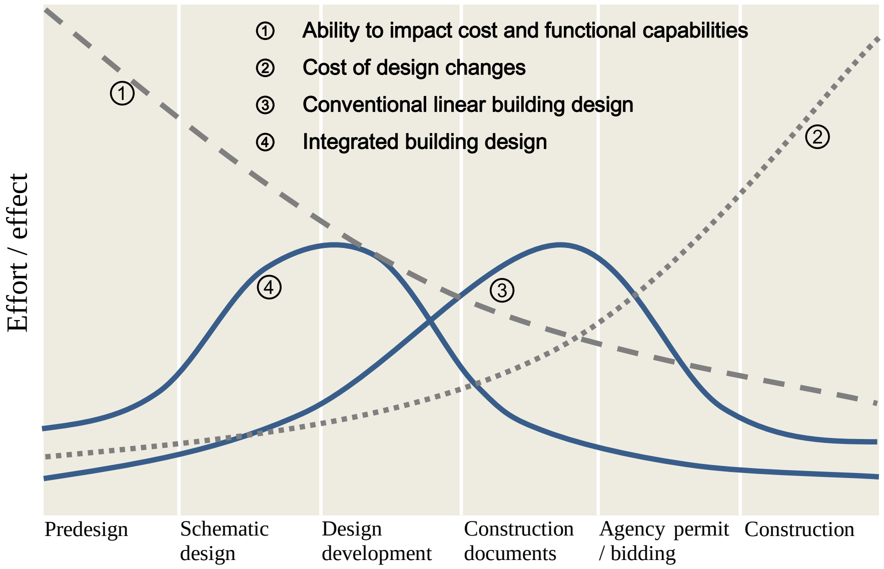

Figure 25. Macleamy Curve [27]

It should be noted that the design decisions in the four design phases do not disappear in integrated building design process, but the way that necessary decisions made in each design phase become more integrated across multiple disciplines [28].

4.3 Development of conceptual framework

The relationship between building design progress led by primary architect and the role of fire engineers can be summarized as shown in Figure 26 considering the iterative building design nature and the two building design schemes, conventional linear design and integrated design.

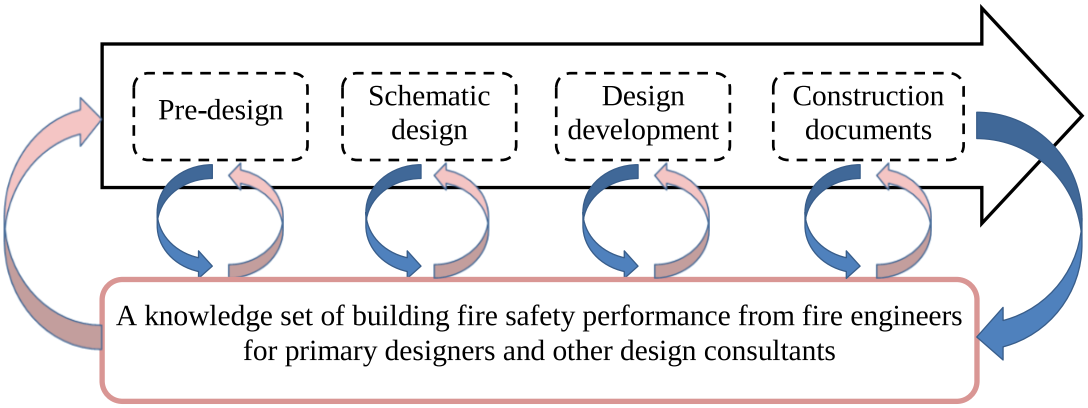

Figure 26. Collaboration of primary designers and design consultants

Arrows indicate the information flow such that the loops formed by two counter-directional arrows represent collaborations between primary designers and fire engineers. There exist two different sizes of collaborations represented by multiple small loops and one large loop. Small loops connected to each building design phase in Figure 26 represent ongoing collaborations among design participants as needed as building design progresses. The large loop represents the collaboration in later building design phases when the building design features are almost determined. In this sense, the small loops and the large loop represent the collaboration concepts in the integrated building design scheme and conventional linear building design scheme, respectively.

Although integrated building design scheme provides more ideal design environment for better performing buildings as shown in the Macleamy curve in Figure 25, it is more difficult to reflect fire safety performance into building design process. To evaluate the performance, fire engineers need building design details from primary designers, but in early design phases, it is impossible to obtain necessary information as design is still in the incubation. In this design scheme, therefore, fire engineers need to provide architects with timely and necessary information regarding fire safety concerns originated from the building design features. Some information may be accepted by the designer and reflected in the development of building design, but others may not. When the information is not accepted, fire engineers need to reflect the effects of the rejected information on the fire safety performance for the next information delivery developing alternative solutions.

On the other hand, in the conventional linear building design scheme, a good amount of building design details can be provided to fire engineers, which promotes sophisticated simulation programs for fire and evacuation phenomena. Computer simulation programs have been developed significantly for the last quarter century and continuously updated. They also generally provide better visual representation which is beneficial in communicating with stakeholders. However, limitations still exist such as the lack of consideration on interactive effects of attributes among the building, people, and fire components. For example, most simulation programs for egress phenomena have limited capability in modeling evacuation initiation, exit identification, and exit route selection of occupants, although all of these can significantly influence egress time. In addition, abundant building information can disorient fire engineers (or modelers) such that even unnecessary simulation can be executed, which decreases the efficiency and effectiveness of analysis as well. To assist fire engineers to overcome these drawbacks and to interpret the simulation results appropriately, fire engineers need to possess a holistic perspective of building fire safety performance taking into account the effects of building design features, from which a big picture of fire phenomena can be captured.

To accommodate these needs, a model is planned to be developed, which shows the big picture of fire phenomena, i.e., how fire safety performance is influenced by what attributes including building design features. It is also expected to support a quick and flexible performance evaluation from which timely communication between architects and fire engineers is made with little details of building design available (or with potential diverse design options). To provide consistent fire safety performance, a quantitative approach is preferred for performance evaluation.

4.4 Quantitative approach to incorporate fire safety performance into building design process

Following the same quantification method introduced in chapter 3, weighting factors for complete attributes in Figure 19 and Figure 20 are presented in Table 11 and Table 12. Attributes with higher weighting factors represent more importance to the performance of upper level attributes. Note that the sum of weighting factors of lower level attributes for an upper level attribute equals to one.

Table 11. Weighting factors for the sub-attributes of fire propagation

Lower level attributes	Weighting factors	Upper level attributes
building use with high hazard fuel type	0.4286	fuel type
occupant education for fuel type control	0.4286	
occupant activity changing fuel type	0.1429	
occupant education for fuel location control	0.1634	fuel location
occupant activity changing fuel locations	0.2970	
interior design / finishes	0.5396	
occupant education for fuel amount control	0.1038	fuel amount

occupant activity increasing fuel amount	0.2087	
building use with large fuel amount	0.1809	
floor area	0.3689	
interior design / finishes	0.1376	
fuel type	0.4000	fuel characteristics
fuel locations	0.2000	
fuel amount	0.4000	
the number of openings	0.4000	opening size
fire size	0.6000	
opening size	0.3683	oxygen availability
HVAC system interlocking features	0.3683	
construction quality	0.0704	
floor area	0.1929	
construction type	0.3000	structural stability
fire size	0.7000	
traffic conditions	0.1958	arrival time
distance to nearby fire station	0.4933	
detection / alarm / notification	0.3108	
building height	0.6483	building access
objects blocking access in the site	0.2297	
exterior design blocking fire service access	0.1220	
wind condition	0.3333	external operations
building access	0.6667	
structural stability	0.2825	internal operations
information transfer from the site	0.0674	
floor plan complexity	0.0674	
Fire size	0.5826	
internal operations	0.1958	fire service operations
arrival time	0.3108	
external operations	0.4933	
perception of fire	0.3000	occupant manual suppression
occupant education for manual suppression	0.7000	
fire service operations	0.1576	suppression
automatic suppression system	0.7608	
occupant manual suppression	0.0816	
combustible material on ceiling	0.7000	heat feedback
ceiling height	0.3000	
suppression	0.4790	fire size
undetected concealed space	0.0890	
heat feedback	0.0890	
fuel characteristics	0.1715	
oxygen availability	0.1715	
fire rated assembly	0.2500	compartmentation
fire size	0.5000	
opening protection	0.2500	
compartmentation	0.2500	smoke spread
fire size	0.5000	
smoke control system	0.2500	
fire service operations	0.3333	fire propagation
fire size	0.3333	
compartmentation	0.1667	
exterior design preventing flame spread	0.1667	

Table 12. Weighting factors for the sub-attributes of egress

Lower level attributes	Weighting factors	Upper level attributes
occupant activity influencing perception of fire	0.4545	perception of fire
responses to cues for possible fires	0.0909	
detection / alarm / notification	0.4545	
detection / alarm / notification	0.2738	evacuation initiation
occupant education for evacuation initiation	0.1428	
building use influencing evacuation initiation	0.0595	
occupant activity influencing evacuation initiation	0.2502	
fire drill practice	0.2738	
perception of fire	0.4000	premovement time
evacuation initiation	0.6000	
fire drill practice	0.3750	occupant familiarity with exit locations
building use influencing occupant familiarity	0.3750	
floor plan complexity	0.1250	
visual access to exit doors	0.1250	
fire drill practice	0.3750	
occupant mental conditions	0.0721	exit identification
occupant familiarity with exit locations	0.1913	
occupant familiarity with exit use	0.3683	
exit signage	0.1913	
interior design / finishes	0.1770	
exit identification	0.1634	travel distance
building height	0.5396	
distribution of exits	0.2970	
occupant activity influencing moving ability	0.1429	occupant physical moving ability
building use for physically challenging occupants	0.4286	
smoke spread	0.4286	
occupant activity changing fuel locations	0.6000	exit maintenance
occupant education for fuel locations	0.4000	
occupant physical moving ability	0.4554	movement speed
exit maintenance	0.1409	
fire service counterflow	0.2628	
building use influencing moving speed	0.1409	
travel distance	0.5000	travel time
movement speed	0.5000	
smoke spread	0.0973	available number of exits
exit maintenance	0.1640	
distribution of exits	0.3370	
the number of exits	0.4018	
building height	0.3789	occupant number
movable seats	0.0836	
floor area	0.3376	
building use influencing occupant number	0.1998	
available number of exits	0.5000	occupant load per available exit
occupant number	0.5000	

travel time	0.4000	movement time
occupant load per available exit	0.6000	
premovement time	0.5000	egress
movement time	0.5000	

4.4.1 Application of the fire safety performance evaluation model to building design

Application of the performance evaluation model within the building design process can be illustrated using an actual building where a fire incident occurred [29, 30]. The building description is included in chapter 3, but for more detailed analysis accounting for the entire attributes, design details are provided below.

> A 16-story, reinforced concrete building is designed for the Department of Architecture in a university. It houses offices for professors, multiple classrooms, several service spaces, and design studios where design activities such as making study models and drawing floor plans are conducted by students. The first 3 floors are used for assembly purposes housing service spaces such as cafeteria, convention halls. The rest 13 floors are composed of 2-story high design studios and office areas with each floor being approximately 100 m long and 20 m wide. Floor plan is not complex and there is no undetected concealed space in the building. Two design studios are located in each floor at both ends having service area in the middle. In the perimeter of the design studios, 5 m high exterior windows made of regular glasses are installed. Between windows, 2 m high vertical separation is provided. A total of 3 exits are provided in each floor and design studios have movable seats and can be flexibly used for other purposes such as a regular classroom. Combustible interior finishes such as wood panel and additional paper works are located in the walls of corridors and combustible acoustic panel is planned on the ceiling to compensate the negative effects of the large room size of design studio on sound quality. Detection and alarm systems are designed throughout the building. There is no duct work and smoke control system above the ceiling such that interlocking feature with building alarm system is not necessary. Two 30 minute fire-rated barriers are designed to separate the service area from the design studios. Exit signs are well installed along with a good visual access to the exit doors. Exits are well distributed considering the locations of occupants. A nearby fire station is located about 3 km away from this site and traffic conditions on the route are generally satisfactory. A consistent wind direction and strong wind are not expected in the site. Fire drills are expected to be conducted twice a year, but other occupant educations for fuel control and fire emergency conditions are not planned. Trees and a water pond are included in the site design which may block the access of fire fighters to the building, although there is no exterior design blocking fire service access.

Based on these original building design features, performance values of the bottom level attributes are determined following the same method described in chapter 3. From these, the top two attributes of fire propagation, used here to represent property protection, and egress, which reflects occupant life safety, are calculated. The connection between attributes, initial assigned performance values (i.e., numerical values beside white boxes), calculated intermediate-level attribute performance values (numerical values beside blue boxes), and top-level attribute performance values (numerical values beside red boxes) are shown in Figure 27 and Figure 28.

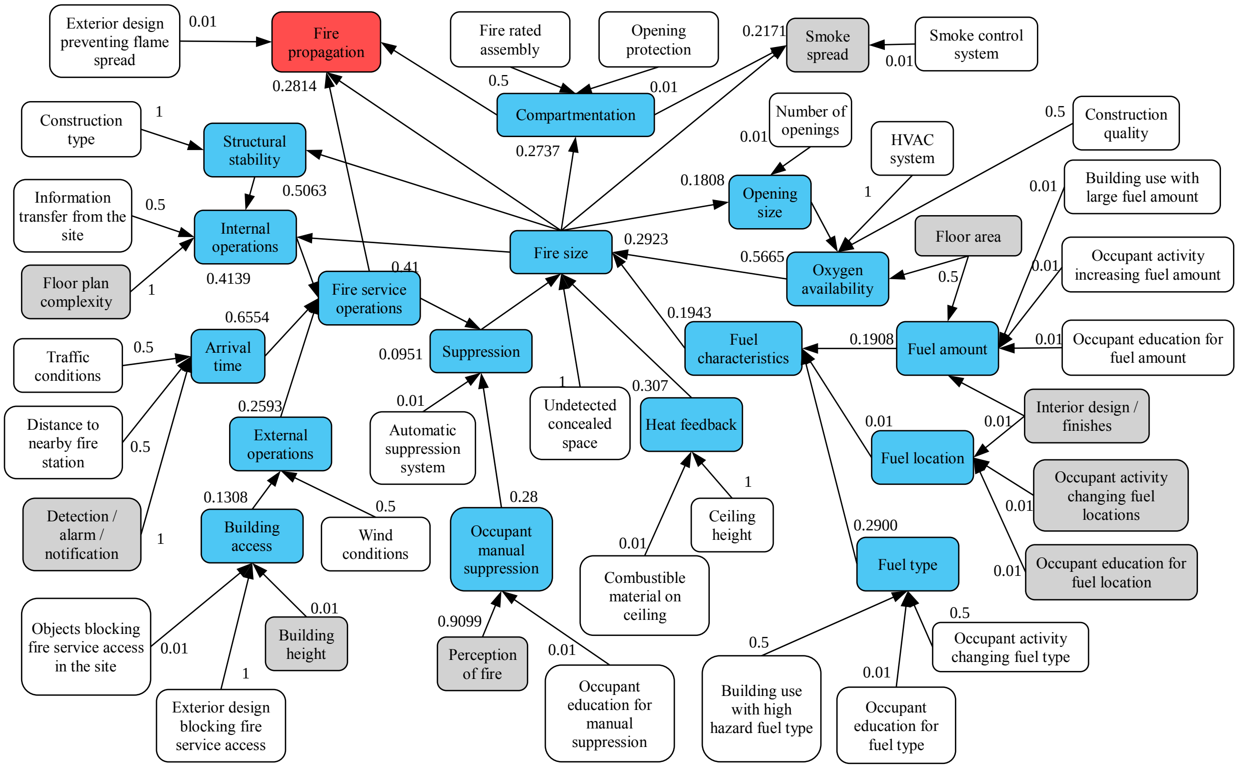

Figure 27. Performance values of the attributes for property protection

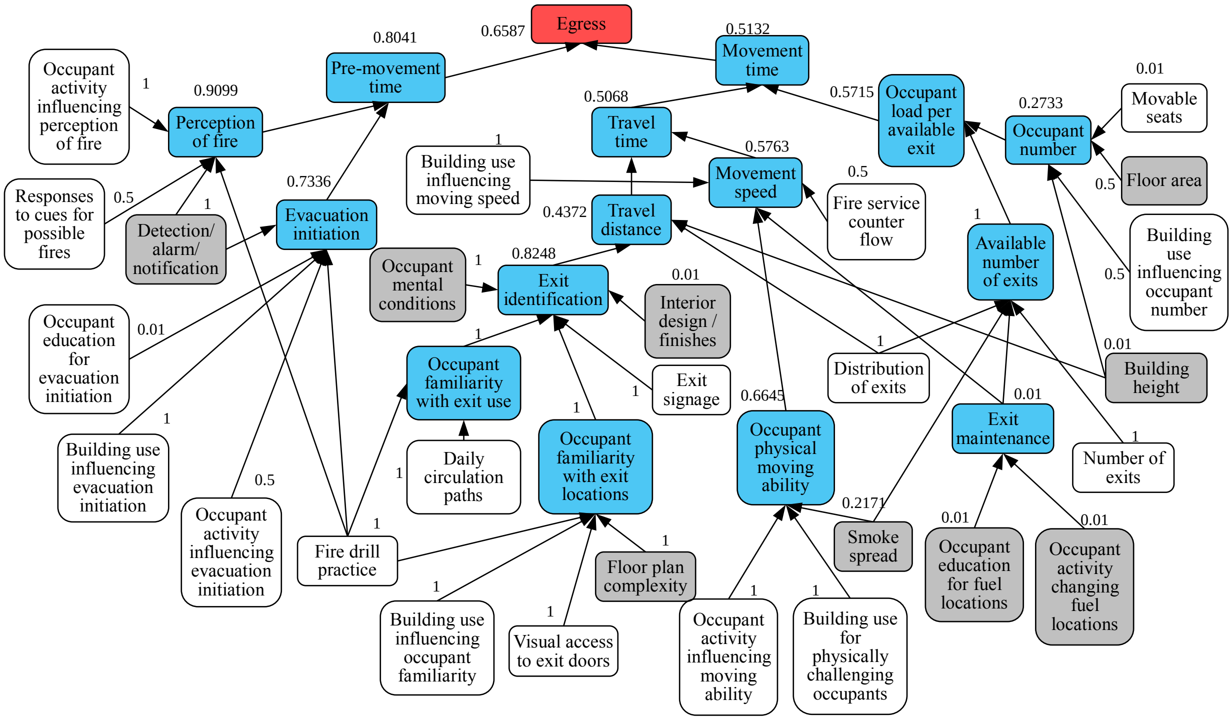

Figure 28. Performance values of the attributes for life safety

Based on the application of the performance evaluation model, the performance values of the fire propagation attribute and of the egress attributes are 0.2814 and 0.6587, respectively, for the original design. This can be interpreted as the original building design facilitates life safety well (high value), but most likely does not provide enough safety features for property protection (low value), which is in good agreement with the actual outcome of the fire incident: partial building collapse.

Although the model comprehensively captures the interrelationships among various performance attributes such that it can be effectively used for comparative purposes, it does not represent absolute fire safety performance due to the uncertainty involved with subjective weighting factors and the performance values of the bottom attributes. Once this model is applied to a large number of building and fire safety design cases and a database for the analysis is formed, the model can be used for absolute performance analysis.

Utilizing the performance evaluation model, the fire safety performance of this building can be improved by identifying fire safety concerns to architects and providing a mechanism to assess the relative performance of mitigation option. This can occur at any phase of the design process. Since different information is available at each stage of the design process, the attributes which can most effectively be assessed change over the course of the project (e.g., specific interior layouts might not be known at the preliminary design phase, but the site layout may well be). To help engineers and designers understand which attributes can be most readily affected, based on the phase of design, a matrix of attributes and building design process phases can be constructed. This is illustrated in Table 13, where gray boxes indicate in which design process phase (column) the attribute (row) has the largest relative influence. Relative fire safety concerns in each design phase are determined based on the design decisions decribed in Table 10. However, it should be noted that the design phases are determined in the design environment of a comprehensive performance-based fire safety design approach, and can vary depending on the primary architects' design methodology and the project scale.

Table 13. Building design phases when the performance of fire safety attributes are determined

No.	Bottom level attributes	PD	SD	DD & CD	During operation (DO)
A1	building use with high hazard fuel type	▨			
A2	occupant education for fuel type control				▨
A3	occupant activity changing fuel type	▨			
A4	occupant education for fuel location control				▨
A5	occupant activity changing fuel locations	▨			
A6	interior design / finishes			▨	
A7	occupant education for fuel amount control				▨
A8	occupant activity increasing fuel amount	▨			
A9	building use with large fuel amount	▨			
A10	floor area		▨		
A11	the number of openings		▨		
A12	HVAC system interlocking features			▨	
A13	construction quality				▨
A14	construction type		▨		
A15	traffic conditions	▨			
A16	distance to nearby fire station	▨			
A17	detection / alarm / notification			▨	
A18	building height		▨		
A19	objects blocking access in the site			▨	
A20	exterior design blocking fire service access			▨	
A21	wind condition	▨			
A22	information transfer from the site				▨
A23	floor plan complexity			▨	
A24	occupant education for manual suppression				▨
A25	automatic suppression system			▨	
A26	combustible material on ceiling			▨	
A27	ceiling height		▨		
A28	undetected concealed space			▨	
A29	fire rated assembly			▨	
A30	opening protection			▨	
A31	smoke control system			▨	

A32	exterior design preventing flame spread		▨		
A33	occupant activity influencing perception of fire	▨			
A34	responses to cues for possible fires				▨
A35	occupant education for evacuation initiation				▨
A36	building use influencing evacuation initiation	▨			
A37	occupant activity influencing evacuation initiation	▨			
A38	fire drill practice				▨
A39	building use influencing occupant familiarity	▨			
A40	visual access to exit doors			▨	
A41	daily circulation paths			▨	
A42	occupant mental conditions	▨			
A43	exit signage			▨	
A44	distribution of exits			▨	
A45	occupant activity influencing moving ability	▨			
A46	building use for physically challenging occupants	▨			
A47	occupant activity changing fuel locations	▨			
A48	occupant education for fuel locations				▨
A49	fire service counter-flow			▨	
A50	building use influencing moving speed	▨			
A51	The number of exits		▨		
A52	movable seats		▨		
A53	building use influencing occupant number	▨			

Relevant fire safety concerns in each design phase are determined based on the design decisions described in Table 10.

As a building design becomes more developed (i.e., the process moves from PD to SD to …), the performance values of the bottom attributes in Table 13 become better defined. This means that the performance values of the top two attributes are gradually narrowed down to final values. The attributes in PD are somewhat fixed by building site and use and the ones in during operation (DO) are more influenced by building manager while the attributes in the columns of SD and DD & CD are mainly controlled by primary designers and fire engineers. Therefore, the relevant attributes to incorporate fire safety performance into building design process mainly belong to the columns of SD and DD & CD.

With this categorization of attributes into different design phases, the performance values of the top two attributes can be estimated even in early design stages. . For example, if the building design is in the PD, attributes in the SD and DD & CD are undetermined, but by assuming poor performance (0.01) of those, the minimum fire safety performance in PD can be calculated. In the same way, as more attributes are defined along with design development, what attribute values need to be increased or can be decreased to satisfy the expected fire safety performance can be identified.

Assuming that the current building design is in SD as an example, the performance values of the top attributes are estimated as shown in Figure 29 and Figure 30. All undetermined performance values of the attributes in DD & CD are fixed at 0.01; as the existence of HVAC system will be determined by SD, the performance value of the HVAC interlocking feature is determined to be 1. The connection between attributes, initial assigned performance values (i.e., numerical values beside white boxes), calculated intermediate-level attribute performance values (numerical values beside blue boxes), assumed poor performance values (numerical values of 0.01 beside the boxes of attributes in red color) and top-level attribute performance values (numerical values beside red boxes) are shown in Figure 29 and Figure 30.

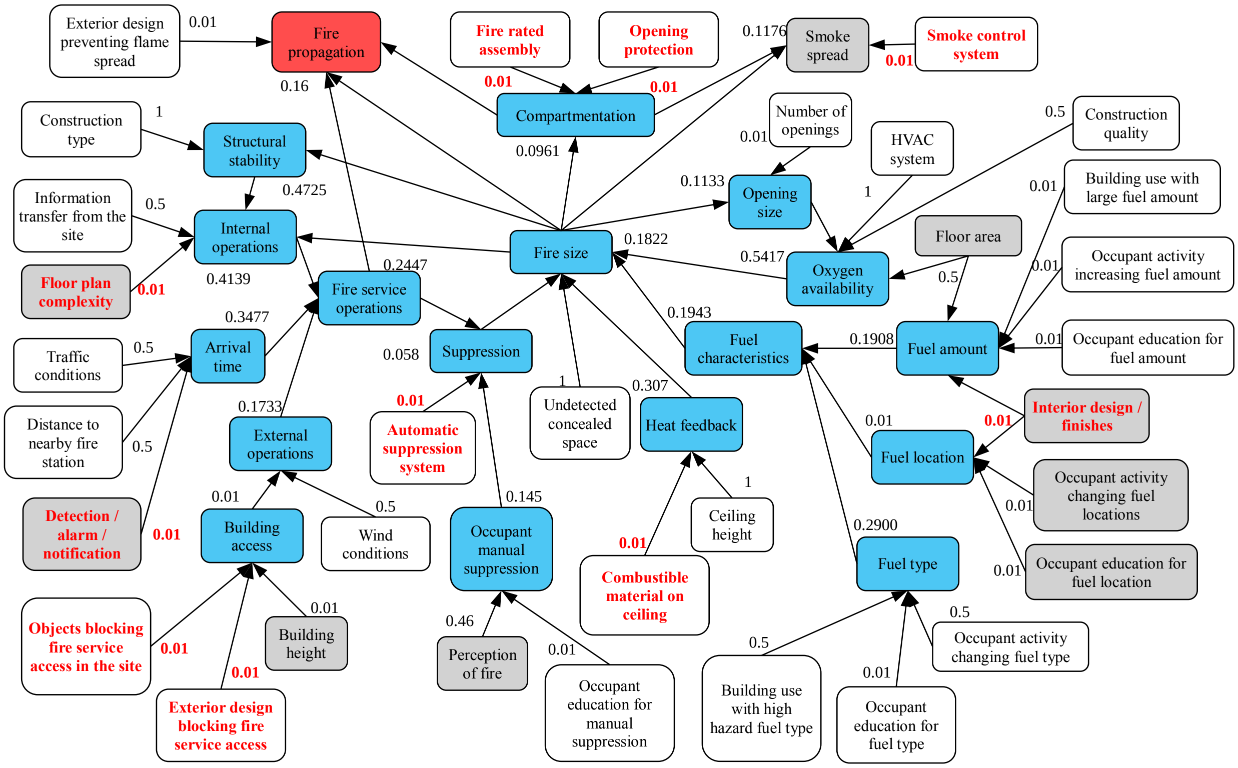

Figure 29. Performance values of the attributes for property protection in the SD phase

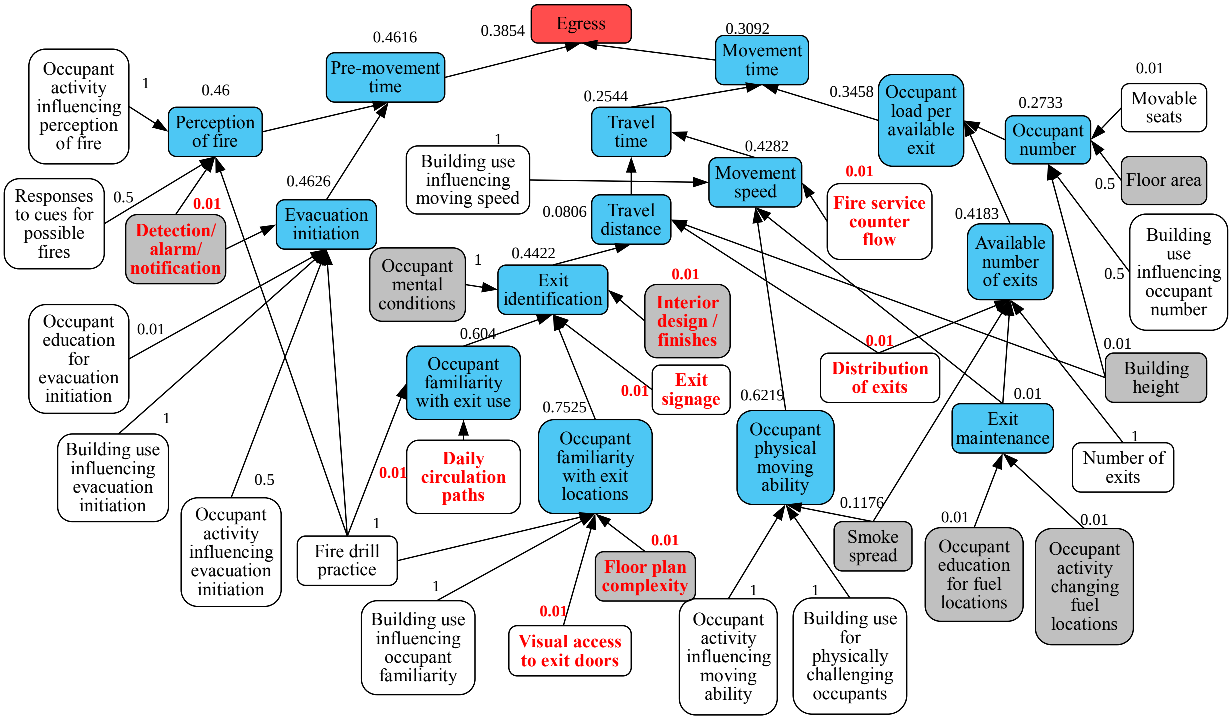

Figure 30. Performance values of the attributes for life safety in the SD phase

Although the actual building fire safety design is primarily focused on life safety, property protection is also a common building fire safety performance concern. In this example, the performance values of fire propagation are low indicating fire safety for property protection needs to be increased. Using this approach, various building designs, fire safety designs, and combinations of these are possible to evaluate in terms of achieving life safety and property protection goals. This can be illustrated by example. Using the performance values in Figure 29 and Figure 30 as the base case, several building and fire safety design scenarios are considered and evaluated as described below.

Scenario 1 reflects a high degree of design freedom for architects, or in other words, minimal constraints. As such, the performance values for several attributes are set to the lowest value (0.01), meaning that the design decisions could be good for design but not so for fire safety. These include floor plan complexity, objects blocking fire service access in the site, exterior design blocking fire service access, combustible material on ceiling, the fire rated assembly, opening protection, interior design / finishes, visual access to exit door, daily circulation path, distribution of exits and fire service counterflow. To achieve flexibility with these 'passive' attributes, a strong focus is placed on active systems, including detection / alarm / notification, automatic suppression and smoke control systems, which are to be included (meaning their numerical value is 1.0). In addition, the value of exit signage is set to 1.0.

Scenario 2 assumes that an automatic sprinkler system is not a desired option. Instead, compartmentation and fire service operations are to be improved over the base case, along with the increased performance of combustible material on ceiling and interior design / finishes. In addition to this improvement, the values of exit signage and distribution of exits are increased as they are required by most prescriptive fire safety codes for egress. As such, values for these parameters are set to 1.0.

Scenario 3 assumes that performance associated with occupant evacuation, fire service operations and fuel characteristics are increased (values of 1.0) while compartmentation and suppression performance remain low (values of 0.01). This scenario represents a case in which more reliance is placed on fire service operations than in-house building fire safety measures.

The scenario 4 is intended to maximize fire safety using all available attributes.

Table 14. Building and fire safety design scenarios before DD & CD

Attributes	Base case	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Original design
Floor plan complexity	0.01	0.01	1	1	1	1
Detection/ alarm / notification	0.01	1	1	1	1	1
Objects blocking fire service access in the site	0.01	0.01	1	1	1	0.01
Exterior design blocking fire service access	0.01	0.01	1	1	1	1
Automatic suppression system	0.01	1	0.01	0.01	1	0.01
Combustible material on ceiling	0.01	0.01	1	0.01	1	0.01
Interior design / finishes	0.01	0.01	1	0.01	1	0.01
Fire rated assembly	0.01	0.01	1	0.01	1	0.5
Opening protection	0.01	0.01	1	0.01	1	0.01
Smoke control system	0.01	1	0.01	0.01	1	0.01
Daily circulation paths	0.01	0.01	0.01	1	1	1
Visual access to exit doors	0.01	0.01	0.01	1	1	1
Exit signage	0.01	1	1	1	1	1
Fire service counter flow	0.01	0.01	0.01	1	1	0.5
Distribution of exits	0.01	0.01	1	1	1	1

Using the attribute assignments that correspond to the base case (low performance in all areas), the four postulated scenarios, and the original building design features, as reflected in Table 7 performance values related to fire propagation and egress are calculated and presented in Figure 31 for each building state.

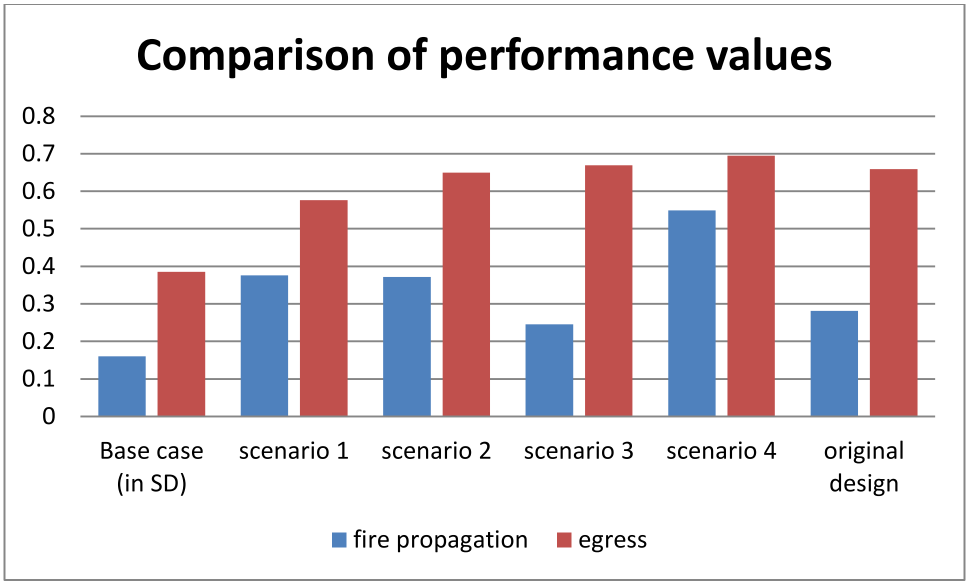

Figure 31. Performance values of fire propagation and egress for various building and fire safety design scenarios

Starting with the Base Case (low performance values in all areas), it can be observed that the fire propagation and egress performance are lowest when compared to all other options. As various design options are considered (based on the four scenarios described above), various impacts on fire propagation and egress are observed, illustrating marked improvement in fire propagation and egress performance with every option, and significant differences in fire propagation and egress performance between options. Comparing the four scenarios to the original design, the performance values for egress are not significantly different indicating that the design was adequate for life safety, but vary significantly with respect to fire propagation, both in the positive and negative direction. However, even for Scenario 4 which reflects the largest performance increase, the performance value is only slightly higher than 0.5. This indicates that the range of available options for decreasing fire propagation (increasing property protection) is limited due to previous design decisions (e.g., site access, façade design, etc.). To increase the fire propagation performance more in this building, fire engineers would have needed to become involved in an earlier design stage in order to address exterior design issues with allow for external flame spread. If the exterior system (façade, nosing, etc.) was designed to prevent flame spread, for example., the performance value of the 'exterior design preventing flame spread' would be 1.0, and the final the fire propagation value would become 0.7143 in the case of attribute values identified in Scenario 4. This is a much larger value than the current fire propagation value given for Scenario 4 in Figure 31 (about 0.55). It is also observed that similar performance improvements can be achieved by different combinations of building and fire safety design as can be seen in the comparison of Scenario 2 and 3 for the egress attribute and of Scenario 1 and 2 for the fire propagation attribute. This further illustrates that the intended fire propagation performance can be achieved in multiple ways since some building design features have similar influences on fire safety performance with some fire safety measures as discussed in chapter 3. Note that this example is different from identifying alternative solutions in that relevant attributes are identified along with building design development.

Although the analysis and exemplary scenarios are based on the assumption that the building design in the SD phase, fire engineers can present multiple fire safety strategies to architects in the PD phase such that more flexible building design and fire safety design solutions can be achieved. Various fire safety design scenarios can be provided to architects and other project stakeholders by fire engineers and the most appropriate (economic, aesthetic, or easily constructible) building design solutions with fire safety performance being incorporated can be developed using the proposed method.

It should also be noted again that while the selection of attribute performance values shown here is subjective and based on a system of low = 0.01, medium = 0.5 and high = 1.0, these values would be expected to become refined over time with use and consideration by more fire engineering practitioners. Also, they can be refined as data on the performance relationships between attributes is better understood. In the future, one could even envision connection between the attribute values and databases and perhaps even computational tools (models) that predict component performance. The main point here is that the performance evaluation model provides a usable framework to assess different fire safety options at different stages of the building design process, in a way that is transparent to fire engineers, architects and others who are involved in design decisions.

4.5 Conclusion

For more than a century, prescriptive regulatory requirements were applied to the details of building systems and components in many countries with the objective of providing a minimum level of acceptable fire safety performance. However, with the development of fire safety science and engineering, several countries have now implemented performance-based codes, and these (and countries with prescriptive systems) now more readily accept or allow performance-based fire safety design solutions. Despite this paradigm shift, many building designers – who have a significant influence on building fire safety performance – are not fully of the benefit of performance-based fire safety design. Fire safety engineers also need a quick, but comprehensive fire safety assessment tool to provide timely feedback on building design to building designers.

In this context, the suggested framework using the fire safety performance model is beneficial for both building designer and fire safety engineers. From an early building design stage, fire safety engineers can provide building designers with potential fire safety concerns regarding site location, space layout, and building design features based on the estimated performance value. In addition by suggesting alternative solutions which result in a comparable performance value, more desirable (cost-effective, reliable, and aesthetic) building and fire safety design solutions can be selected without sacrificing fire safety performance.

It should also be noted again that while the selection of attribute performance values based on a system of low = 0.01, medium = 0.5 and high = 1.0 and the relative importance in pairwise comparison shown here are subjective, these values would be expected to become refined over time with use and consideration by more fire engineering practitioners. Also, they can be refined as data on the performance relationships between attributes is better understood. In the future, one could even envision connection between the attribute values and databases and perhaps even computational tools that predict component performance. The main point here is that the performance evaluation model provides a usable framework to assess different fire safety options at different stages of the building design process, in a way that is transparent to fire safety engineers, architects and others who are involved in design decisions.

Although the quantified values in the current study were appropriate to predict the outcome of actual fire incident, those were determined by authors. Due to this subjectivity, they may be limited to be widely accepted among various schools of researchers and practitioners in many countries. However, better and hopefully more accurate values can be developed by comparing the proposed evaluation model with more fire incident data (both success and failure), by eliciting a broader sample of input from experts and project stakeholders, and by linking analytical and computational analyses to the establishment of performance values. Through these, the quantified values can achieve more objectivity and possibly used as a verification method to determine whether proposed building and fire safety design can meet the performance requirements.

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5 Conclusions and Main Outcomes

Building fire safety performance is significantly influenced by building design features and naturally, architects (primary decision-maker for building design features). However, there have been discrepancies that fire engineers have not comprehensively consider building design effects on fire safety performance and architects have not considered fire safety performance in the building design process. This may have been acceptable in the prescriptive building and fire safety regulations and conventional building design process in which building design and fire safety design are understood as separate (or not closely related) subjects. However, in the current conditions that performance-based fire safety design approach is practiced in more than 20 countries and the integrated building design process gains more popularity in AEC industry, it becomes necessary to understand the effects of building design features on fire safety performance and to holistically practice building design process for design efficiency as well as improved fire safety performance.

In this context mainly three tasks were conducted:

- Identifying the significant influence of building design features on building fire safety and current fire engineering's incomprehensive approach for fire safety performance assessment.
- Developing holistic fire safety performance evaluation models which consider building design effects
- Utilizing the performance evaluation models to increase building fire safety

Fundamental differences between architects and fire engineers and historical aspects which led to the current relationship between them were explored in the first task. Architects have long maintained the project manager position as well as primary architect position since ancient times, which led the activity of building design being more focused on architects' perspectives. Naturally architects' interests on which aesthetics, exterior shape and spatial organization are more focused. This trend still exists, but became weak since building technology, new building materials, expected building performance level cannot be handled by architects alone. This requires involvement of design consultants including various engineering experts such as mechanical, electrical, and fire engineers in the building design process. Compared to mechanical, electrical engineering field, fire engineering is relatively young, and has experienced significant developments in the past few decades utilizing pre-existing and validated knowledge in other fields and still in the fast development process which may include fire modeling, evacuation modeling, fire safety measures, and design paradigm shift from prescriptive-based to performance-based. In this transitional period, it is identified that building design led by architects as building design experts sometimes can generate unsafe buildings due to the differences of perspectives of architects and fire engineers on buildings and approaches in the still-developing fire engineering approaches. To overcome this limitation, collaborations between fire engineers and architects are critically required.

These issues led to the second task which is developing performance evaluation models accounting for building design effects on fire safety performance as a medium of collaborations. There have been various approaches to evaluate fire safety levels of buildings. Most of these models generally determine the level based on what fire safety measures are installed in buildings. Some of them consider occupant characteristics, but the interactions between built environment and occupants and fire services are not comprehensively included. Even in the most common life safety criterion, ASET > RSET, the building design effects is not fully considered as these are generally based on the verification methods and engineering tools which do not holistically take into account the building design effects. To develop the models, attributes of fire safety performance were identified from actual fire incidents and the cause-effect relationships among them were established first. Then, by organizing the attributes with a focus on two common fire safety objectives, life safety and property protection, two conceptual fire safety performance models were developed. Each model has a tree structure of attributes connected with cause-effect relationships such that a change of lower level attribute's performance can change connected upper level attribute performance. For this, two quantitative values are assigned to each attribute: performance value and importance factor. The performance value implies the performance level with respect to an upper attribute, and the importance factor represents a relative contribution to an upper attribute. This feature enables quantitative comparison of fire safety performance between different building designs and fire safety measures. In addition, thanks to the network of various cause-effect relationships, multiple methods (or combinations of different performance values of attributes) to achieve the equivalent life safety and property protection performance can be identified, which results in identifying alternative solutions.

The models can be also utilized in the building design process. To holistically evaluate fire safety performance, the information about design details from architects are necessary, but the information can be frequently change reflecting various objectives (needs and wants) of clients and other stakeholders and gradually available following building design progress. This implies that fire safety performance estimation in early building design stage can be different from the one at later building design phase due to design detail change. However, it is necessary for fire engineer to provide fire safety concerns as early as possible to architects to avoid further conflicts of design details with other stakeholders. Since quick assessment is possible from the models with assumed performance values of attributes, the fire safety performance can be estimated in early design stage accounting for the effects of future building design features in advance. This can ultimately decrease possible design conflicts and form a basis of collaboration between architects and fire engineers.

It should be noted that the fire safety performance evaluation models are intended to be applied to general buildings and occupancies such that it is more or less generic, flexible, and prototypical. Therefore, fire engineers who use the models should have a good understanding of holistic fire safety performance as a prerequisite. For those who have holistic perspectives, the presented models can be expanded and shortened for different buildings and occupancies.

6 Future Work

The current study underscore the importance of holistic approach for fire safety measures and building design features for improved fire safety performance and more efficient building design process. As part of this objective, fire safety performance models accounting for building design effects were developed based on the interactions among the attributes. In the current study:

- These interactions were defined only at a high level (macro-interaction). For example, a stair pressurization system is considered as part of a smoke control system which influences smoke spread. Then smoke spread influences occupant's physical moving ability and limits the available number of exits. If the performance goes into a micro-interaction level, the performance of stair pressurization system can be influenced of reliability of system components and connected parts, which increase the level of complexity. In the current study, this work is not included and is expected to be conducted by each system designer and engineers in the future.
- In the quantification method applied in the performance evaluation models, subjective expert opinions are included. This means that the analysis results may not be reasonable if fire engineers' expertise is irrelevant to holistic fire safety performance. To reflect this limitation, it is necessary to look into a variety of fire incident data from which more reliable data for the quantified values can be identified. Another way to mitigate this subjectivity issue may be conducting surveys through which well-experienced fire engineers with holistic perspectives provide good subjective expertise pursuing more objectivity.
- In relation with the quantification, the criteria for the quantified performance values are not proposed. In other words, the values to pass/fail (or accept/reject) building design features and fire safety measures have not been included in this research. For the regulatory purposes, expected fire safety performance needs to be quantified for verification and validation if quantification is acceptable as a way of verifying performance. However, with limited data of success of failure from fire incidents, it is quite difficult to obtain objectivity of the quantified values. Rather the performance evaluation tools can be utilized to comparatively evaluate currently existing buildings and find optimum values by considering that the current code-compliant buildings (both in prescriptive-based and performance-based regulations) satisfy the expected performance from the society.

In addition to the current model development with the introduced future works, the next version of fire safety performance models need to be developed in the context of building information modeling (BIM). BIM-based building design tools have gained popularity and will be applied to more buildings in the future along with the integrated building design process. This means that more integrated building design encompassing various design consultants and engineers will be achieved. It has been also observed that design tools contain a basic level of performance evaluation features. For example, building design tools calculate structural loads and necessary duct size for appropriate HVAC performance. In the same way, fire safety performance can be estimated in building design tools, which enable architects can automatically check the fire safety performance in the building design process. Inputs from fire engineers such as fire size and analysis may be still required as input data, but holistic fire safety performance can be analyzed in building design environment without additional and separate fire safety performance analysis tools. This certainly can decrease misconceptions and miscommunications between architects and fire engineers. A structure of BIM-based fire safety evaluation model is proposed in Appendix B.

Appendix A

Increasing Building Fire Safety by Bridging the Gap between Architects and Fire Safety Engineers

Increasing Building Fire Safety by Bridging the Gap between Architects and Fire Safety Engineers

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Abstract

Fire safety engineers are often viewed as driving the level of fire safety of buildings as they design and review the fire safety and egress systems. However, the design and review missions are generally conducted based on a given building design, including spatial layout, material use and site plan, which are mostly determined by architects. Therefore, architects have a significant influence on the fire safety design of buildings, even if fire safety engineers are seen as having final responsibility. As such, a building design that takes fire safety into account at early stages of architect involvement becomes more ideal, and can yield better a performing building in a possible fire incident. However, little research has been conducted into what aspects of fire safety of buildings architects should consider in the building design process, and on how effective fire safety engineers are at delivering fire safety guidance to architects to improve the building fire safety performance. A better understanding of these is beneficial to increase the actual fire performance of buildings. This research aims to develop a method to increase building fire safety performance by decreasing the gap between architects and fire safety engineers in the context of *building, people and fire,* well-known key components in building fire safety. To gain insight into the actual fire performance of buildings, and the interaction of *building, people and fire* with respect to building design and fire safety systems employed, fire incidents which resulted in a large number of casualties are analyzed. One of the fire incidents is exemplified to illustrate how the proposed method can address shortcomings in building design that were identified.

Introduction

A building is a complex system comprising multiple inter-related sub-systems. These sub-systems can be largely divided into two categories: functional needs and design features. The functional needs may include air quality, thermal comfort, sanitation, safety, acoustical quality, and lighting, which experts in each field design and install proper equipment in the building. The design features indicate space organization, interior finishes, exterior shape, and material use, etc., which are mostly determined by architects. These two categories are seemingly completely different regimes, but in fact are closely linked as one system influencing each other. For instance, large exterior windows allow more sunlight into the interior space which helps the occupant feel more comfortable, but generally require a larger demand of heating system in the winter season. In this example, the design features affects the functional needs requiring more capacity of heating system. Many other inter-relationships are possible and these links make the building design is a very complicated process requiring the optimization of the inter-relationships in various fields. The complexity of building design becomes ever more serious when the inter-relationships compete against one another [1, 2].

As such, sharing knowledge and information, and arranging priorities among the inter-relationships is critical to improve the performance of the building. Architects and engineers (including fire safety engineers) are, however, intrinsically different in many aspects, which undermines effective cooperation. Some statements regarding the inherent differences are introduced as below.

- Architects and engineers have different perception modes [3]. Architects develop a project from conceptual diagrams and end with detailed drawings. In other words, pictorial expressions and descriptive words to describe their work are often used among architects. However, engineers are accustomed to mathematical figure and quantitative terms which are more deterministic expressions. Therefore, when engineers communicate with architects, they may think architects' expressions are not exact enough, or even vague.
- Architects and engineers have different interpretations for the same language [4]. As "being safe" is a different concept to prisoners and people outside the prison, the same language can be interpreted differently in terms of precision, amount, and level to architects and fire safety engineers.
- Architects and engineers have different objectives and values [5]. As artists do not often compromise their artistic desire with worldly value, architects have a passion for artistic expression, which sometimes surpass the basic functionality of buildings and make cooperation difficult with engineers.

In addition, some architects do not have significant formal education regarding functional needs, instead being instilled with a focus on design values (form versus function), and some engineers do not appreciate the effect of design features on the functional aspects [6]. Parallels can be drawn to building fire safety design. Some architects believe that fire engineers are trying to destroy their vision by adding fire safety measures, while some fire safety engineers believe that building drawings are completed by architects first, and that the role of fire safety engineers does not need to extend beyond checking code compliance in code-based design, or designing fire safety systems based on the given drawings in performance-based design. In such cases there is a lack of understanding about the role of architects in influencing the fire safety level, and consequently, knowledge from fire safety engineers is hardly reflected on the final building design. Although architects, of course, do not need to be as knowledgeable as fire safety engineers in the field of fire safety engineering, and vice versa, a better understanding of both architects and fire safety engineers about how fire safety of buildings is affected by building design features is certainly beneficial to improve the actual fire performance of buildings.

The objective of this study, therefore, is to develop a method in which architects and fire safety engineers understand the inter-relationship of their works in terms of fire performance of buildings despite the complexity of building design and inherent differences. For this, how architects and fire safety engineers view the fire and associated phenomena in their mission needs to be investigated first as this is the root of differences and the gap is originated from.

The gap between architects and fire engineers

It is very common to explain fire and associated phenomena by drawing three components, building, people, and fire as shown in Figure 32 [7]. Each component has sub-components, the characteristics, and some of them are shown in Figure 33. The characteristics can be as various as possible: measureable quantities such as building height and area, occupant number, and not-readily-known values including human sensitivity and architectural design features. Figure 32 also shows intersection areas between the components, indicating that the three components influence each other: the interactions among the characteristics of each component.

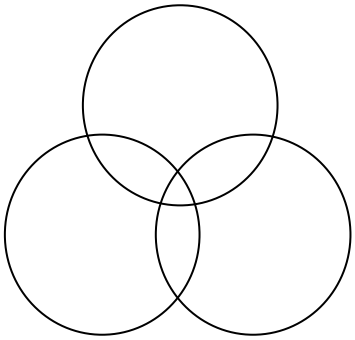

Figure 32: Components in building fire incidents

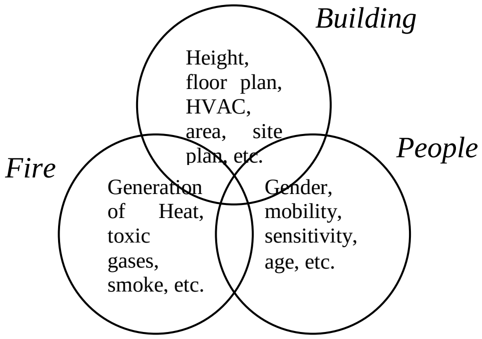

Figure 33: Characteristics of each component

These diagrams effectively explain the relationship of the three components in fire incidents, but do not reflect how architects and fire safety engineers actually perceive them. Although both architects and fire safety engineers work in the same project, want to minimize the probability of fire incidents, and the life loss and property damage from fire incidents, the perception of the relative importance of the three components can be quite different. For example, if assumes that the area of each circle in Figure 32 can be changed to reflect the relative number of concerns associated with the component, and a color can be used to reflect the relative magnitude of the importance of the component, the diagram may look like Figure 34 and Figure 35 when viewed from a fire safety engineer and architect perspective respectively.

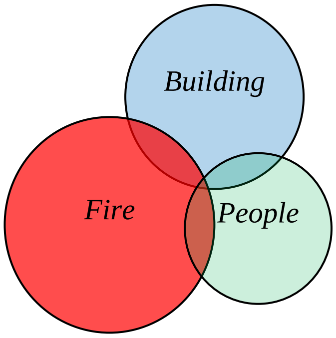

Figure 34: Relationship to fire safety engineers

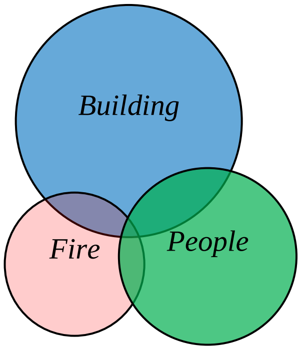

Figure 35: Relationship to architects

In terms of the characteristics that may influence the perceptions, architects may consider more about artistic expression, or even functional needs for occupants' daily comfort for the *building* component, but means of egress and passive fire protection systems are more important to fire safety engineers. For the *people* component, architects want to attract people to the building by emphasizing the environment and atmosphere people want within the building, but fire safety engineers are more interested in safely and efficiently evacuating people from the building in a fire situation. For the *fire* component, fire safety engineers look at the building contents as a fuel load, and investigate such issues as possible ignition sources, fire spread probability and secondary fuel distribution, but architects may not think at all about how the contents might relate to fire, thinking they are relieved from fire issues by complying with code requirements (or relying on fire safety engineers). In terms of the interactions, architects may be more interested in *people's* behavioral responses as a function of changes in the *building's* thermal capacity [8, 9], lighting [10], and interior design [11] whereas fire safety engineers focus more on how the *fire* is controlled and kept within the *building*, how the *building* promotes the evacuation process, or suppression activity of *people*. As the viewpoints of architects and fire safety engineers are reflected in the building design as well as fire safety design, incongruent perspectives decrease the actual fire performance of buildings. Therefore, it is critical to recognize the characteristics and interactions of the three components correctly. Failure to do so can help explains what actually can happen in fire incidents where intended performance is not achieved.

Identification of characteristics and interactions

Until now, there is no formalized method to extract the characteristics and the interactions discussed above, and various means may be possible. In the current study, two criteria are used: dependency on interrelated components, and sequence of events as observed in general fire incidents. Dependency on other components indicates the direction of influence among the characteristics, which clarifies the cause and effect relationship. For example, in a scenario where an occupant first leaving the fire floor activates a manual alarm, and the building alarm system notifies other occupants or building management personnel (sequence), the *building* (the alarm system) is affected by *people* (an occupant), in addition to affecting *people* (other occupants, or building management personnel) (dependency). Further, this approach allows the characteristics to be identified by two attributes: intrinsic and influenced. Intrinsic attributes describe the inherent characteristics that are associated with the component, often regardless of fire, whereas influenced attributes describe the characteristics being affected by, or closely associated with, the interaction of components in fire incidents. In this taxonomy, floor plans and façade design are intrinsic characteristics, and smoke control systems and a means of egress are influenced characteristics for the *building* in interaction with *fire*. The event sequence as the second criterion is used especially for *fire* and *people* components. Most fire events are summarized as an ignition, continuous burning without self-extinction, the generation of combustion products, and the propagation. The characteristics are expanded at the level of physical variables such as ignition source for ignition, oxygen, fuel, and required heat energy for continuous burning, and heat release, toxic gases, and smoke for combustion products. For the *people* component, following the order of egress events, perception of fire, evacuation initiation, exit route selection and movement, and fire service activities which are suppression and search and rescue mission are derived.

As stated above, interactions are critical as they can explain what actually happens in building fires. Therefore, the best source to identify the interactions is to review historical fire incidents. For this study, a 15 fire investigation reports, which contain detailed floor plans or pictures from which design features are informed, have been reviewed: 14 from the National Fire Protection Association and one additional fire analysis that the authors recently conducted [12]. Taking into account the building code updates and development of building construction technology, relatively recent fire incidents were targeted. The fires studied were:

a. 5 assembly buildings
    1. Dance hall fire, Gothenburg, Sweden, Oct 28, 1998, 63 fatalities
    2. Beverly Hills supper club fire, Southgate, KY, USA, May 28, 1977, 165 fatalities
    3. Cocoanut Grove night club fire, Boston, MA, USA, Nov 28, 1942, 492 fatalities
    4. Indianapolis athletic club, Indianapolis, Indiana, USA, 1992, 2 fatalities

    5. Station night club fire, West Warwick, RI, USA, 2003, 100 fatalities
  b. 4 health care buildings
    1. Arlington, Washington, USA, April 27, 1998, 8 fatalities
    2. Hospital Petersburg, VA, USA, Dec 31, 1994, 5 fatalities
    3. Health Care Center Memphis, TN, USA, Mar 21, 1988, 3 fatalities
    4. Nursing home fire Dardanelle, ARK, USA, Mar 13, 1990, 4 fatalities
  c. 2 non-residential high-rise buildings
    1. One meridian plaza, Philadelphia, PA, USA, Feb 23, 1991, 3 fatalities (fire fighters)
    2. Bouwkunde, Delft University of technology, Netherlands, May 13, 2008
  d. 1 residential high-rise building
    1. High-rise apartment, North York, ON, Jan 6, 1995, 6 fatalities
  e. 1 dormitory
    1. Fraternity house fire, Chapel Hill, NC, May 12, 1996, 5 fatalities
  f. 2 hotels
    1. Residential hotel, Reno NV, Oct 31, 2006, 12 fatalities
    2. Paxton hotel, Chicago IL, Mar 16, 1993, 20 fatalities

Identified characteristics and interactions are drawn to show the directional influence between two components as shown in Figure 36, Figure 37, and Figure 38. Arrow with solid line indicates cause and effect relationship, and dotted one implies that one characteristic is considered as a sub-component of the other characteristic. An overview of the interactions is provided with explanations of some characteristics in each section, and a historical fire incident is exemplified to explain the interactions among the three components.

Between building and people

In fire incidents, occupants tend to leave their current locations for a safe location. This sometimes becomes a massive evacuation depending on the number of occupants and the emergency plan of the building. Buildings facilitating evacuation movement effectively reduce the risk of life loss by decreasing the time to evacuation. The relevant characteristics may include a floor plan which improves occupants' space familiarity, a fire drill by building management, the proper location and design of means of egress relative to the building site plan. Another *people* group is the fire fighter who enters the building sometime after the ignition often while everyone else leaves. Therefore, securing the fire fighter's moving path, the building's structural integrity, and facility equipment helping the fire fighter's activity are the main concerns of the *building* component. Concealed space where a fire can be well developed can be detrimental to the life safety of fire fighters. Improper exterior design such as small windows and over-designed security systems can hinder the fire fighter's access to the space inside the building. Occupants also influence the building's response to the fire. Occupants with past fire experience can perceive the cues for possible fires and be more cautious about fire ignition. Keeping exit doors open using door latches for daily convenience can lead to a fast smoke spread. Activating manual pull alarm can notify others and help them be ready for evacuation, and closing the door of the room of origin prevents or delays further fire and smoke spread. Among the intrinsic *building* characteristics, "cues for possible fires" implies any types of sign observed before fire incidents. This may include water leaks, abnormal mechanical sound, or electrical instability. Occupants' frequent travel route, and space relationship with adjacent buildings or spaces which influences the evacuation path are included in "site plan". In the *people* component, "non-adaptive behavior" indicates any actions people take adverse to fire safety. This may include not closing door during evacuation, fleeing from the fire without notifying other occupants, or pushing other evacuees aside to move out quickly.

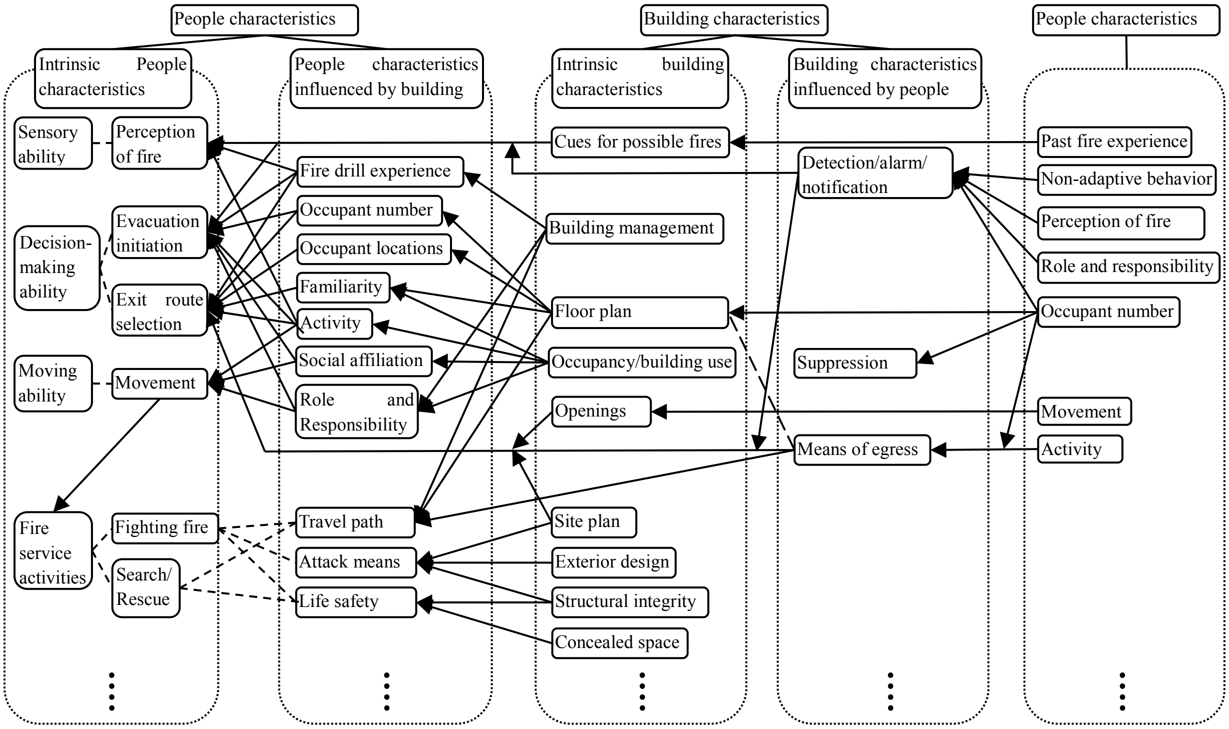

Figure 36: Interactions between *building* and *people*

Between building and fire

The building minimizes the fire effects on the building and the occupant by suppressing or controlling the fire with active and passive fire protection systems. The mechanism of these systems is to restrict fuel, oxygen, and heat feedback to fuel surface that prevent the continuity of fire and to block the spread path of combustion products. The components of the building components affect the fire development using this mechanism. Room size can determine the initial amount of oxygen as well as general fuel amount. Airtightness of the room can influence the fire development as well. A lower ceiling height can increase a radiant heat feedback to the fuel and combustible acoustical ceiling tiles can exacerbate the condition. On the other hand, smoke layer height can decrease faster in a smaller room with lower ceiling height, which is not favorable to fire safety. Oxygen may be provided to the room of origin by non-stopping HVAC system. Concealed space is a good place for a fire to well develop without detection devices. The use of unrated materials inside and outside the building can help fire spread. The fire also influences the building. It can activate fire detection/alarm system and suppression system, but at the same time possibly disarm the systems by damaging associated electrical systems and backup power source. Existing structures can be ignited by adjacent building fires. The egress capacity can be decreased if a fire occurs in the path to or within the means of egress. Even ignition itself can undermine the reputation of the building. In the intrinsic characteristics, value loss implies the historical, communal, reputational, and monetary value loss.

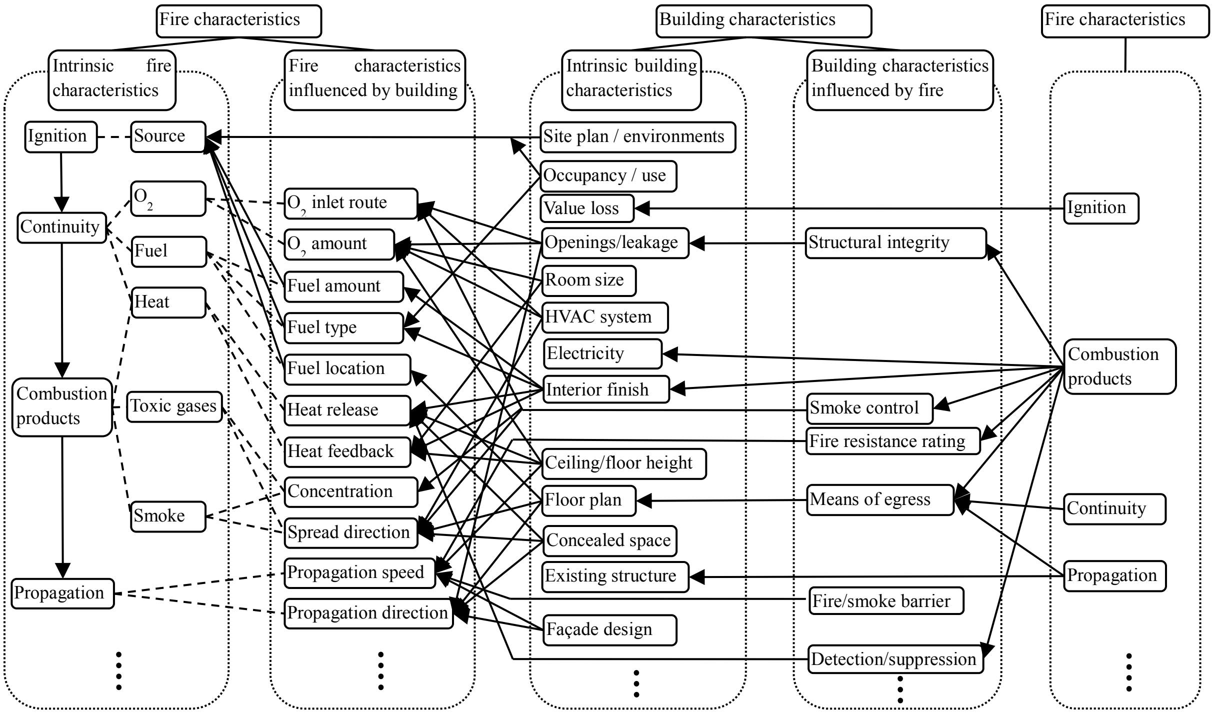

Figure 37: Interactions between *building* and *fire*

Between people and fire

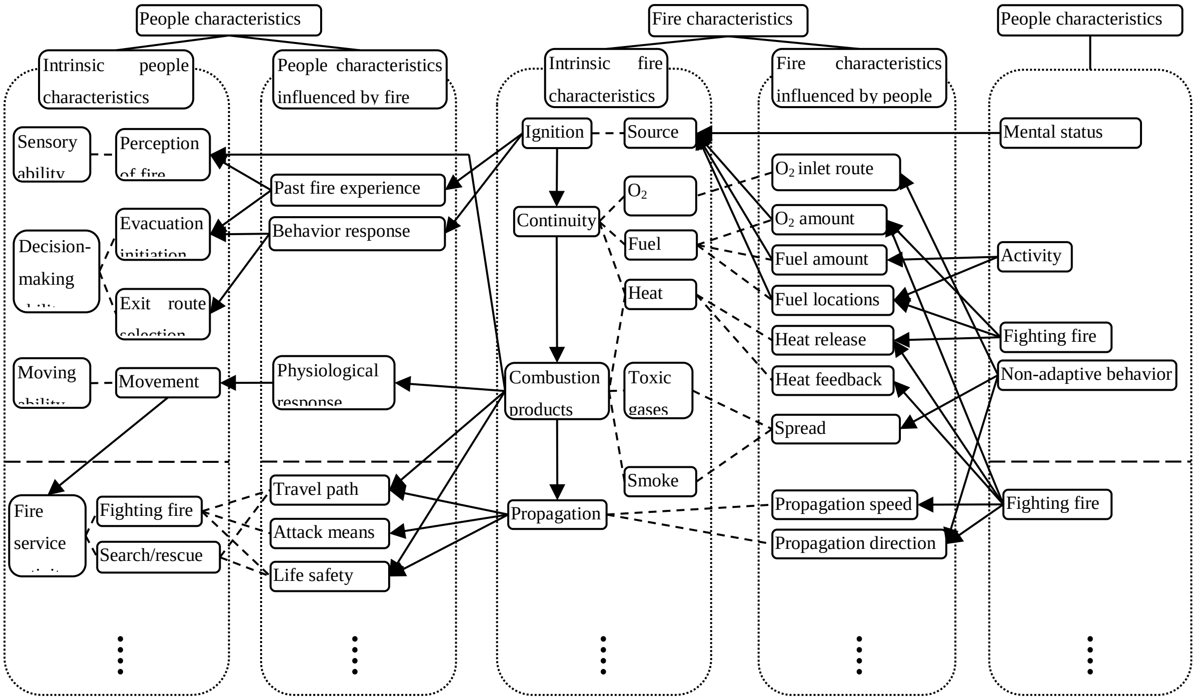

Figure 38: Interactions between *people* and *fire*

The effects of fire on people can be largely divided into two things: behavioral and physiological responses. Behavioral response includes notifying others, getting dressed or collecting personal items, checking pets, or fighting fires, which usually delay the initiation of evacuation [13]. Physiological response to the combustion products deteriorates moving ability such that evacuation may not be completed. Fire fighters are naturally influenced by the fire but they are professionally trained to cope with the fire situation. People in an unstable mental condition whether or not it is chronic or acute, or serious or trivial can set a fire intentionally or unintentionally. For example, even a seriously wounded patient can cause a fire in a hospital bed with cigarette if the person is a chronic smoker and cannot overcome the desire. Activity of people such as partying can increase the fuel amount, and change the location of fuels even to the means of egress. Firefighting as a behavioral response may extinguish the fire or at least decrease heat release rate, although it is not generally recommended in the U.S.

Integrated model development

The characteristics of the three components and the interactions among them are separately formed in the previous sections. The three figures do not explain all possible situations as they are extracted only from 15 fire incidents such that the characteristics and interactions need to be extended as more researches are further conducted. However, the figures certainly inform how the three components are inter-related in fire incidents, and the actual fire performance of the building is determined by the interactions among the components. To see the inter-relationship more clearly, some of the characteristics and interactions are selected from Figure 36, Figure 37, and Figure 38, and integrated as shown in Figure 39. Each component has its own color code applying to the characteristics and solid arrow lines. A solid line connecting two relevant characteristics indicates the cause and effect relationship. The black lines, however, indicate the interactions in both directions. Interactions with thick solid lines are used to explain what actually happened in the Fraternity house fire, Chapel Hill, NC, May 12, 1996. This fire is exemplified to compare the building's fire safety strategy with the actual fire performance of the building.

On May 12, 1996, a fire occurred at a 4-story university fraternity house in the U.S. which claimed 5 occupants' lives, and injured 3 others. A graduation party was held in the building from the evening of May 11 and a fire appeared to be caused by smoke materials in the basement at about 6 AM the next morning. The building was designed as a fraternity house with masonry exterior walls (2-hr rating), and wooden interior structural components (1-hr rating). The building had a mixed occupancy with the basement for assembly and 1 to 3 stories for residential purposes. One open stairway from the basement to the 3rd floor was located in the center of the building. Two exterior metal escape ladders were located on both ends of the building connecting 2nd and 3rd floor to the ground level. Battery powered smoke detectors were installed in the corridors, but the building did not have a fire alarm system and an automatic sprinkler system. One male occupant in the 2nd floor heard the smoke detector sound and confirmed smoke and fire in the 1st floor. Then, he notified his companion and left through the escape ladder. He tried to get back to the room as his companion did not join, but could not but leave the building due to the high heat and smoke from the open center stairway. Among the 5 casualties, 4 of them were found in bedrooms with high blood alcohol level, and one found in the doorway with no blood alcohol.

The intended fire safety strategy based on the installation of fire safety systems and building design appears to be as below.

- Fire is detected by smoke detectors located in the corridor and the detector sound notifies the occupants.
- Two escape ladders at both ends of the corridor are provided as a means of egress in case the central stairway is not available.

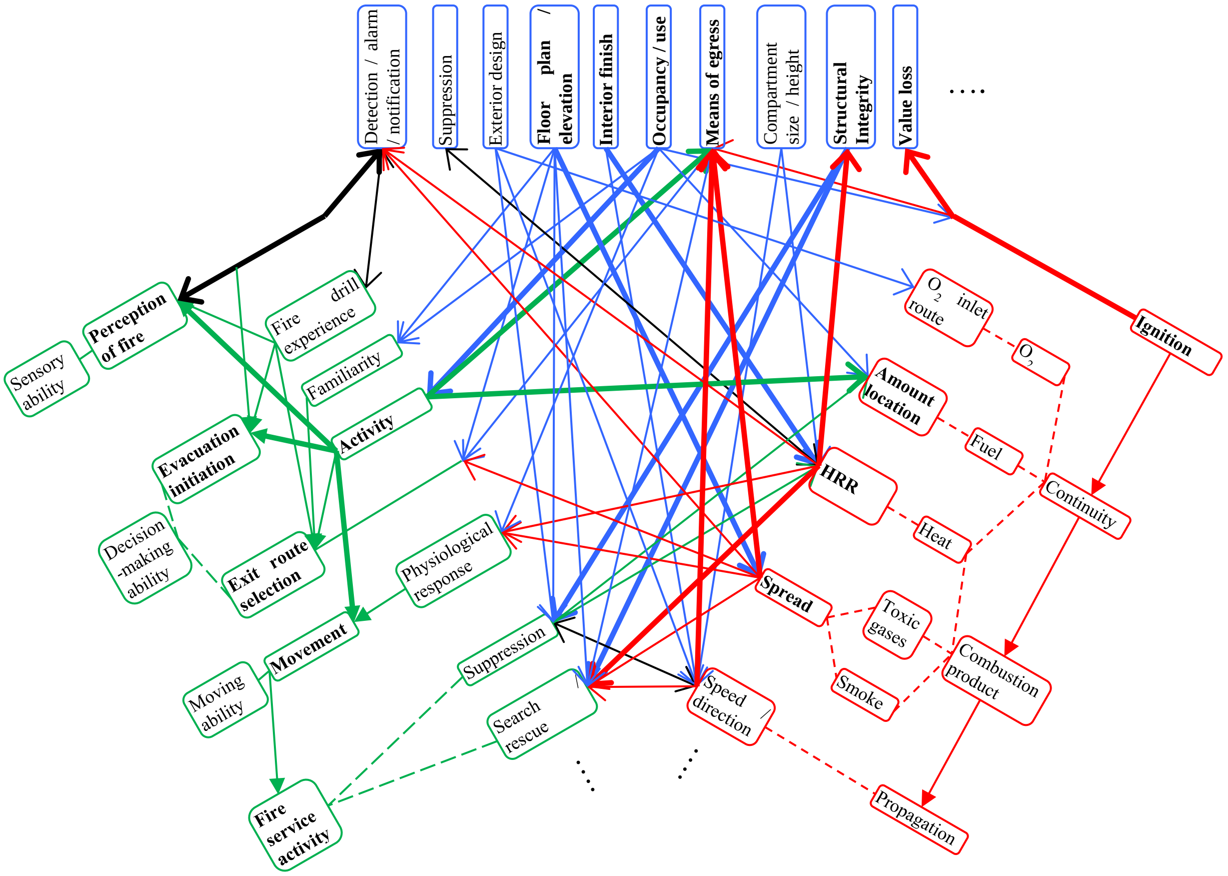

Figure 39: Integrated model of interactions of the three components

However, this fire strategy worked well only for one occupant who survived and did not for the 5 casualties. This raises a very critical question "What was wrong with the intended fire strategy?" Using Figure 39, additional points which should have been understood by both fire safety engineers and architects are found as below.

- As this building is designed to be a fraternity house, it is expected that parties will be often held in the space. During parties, the space can be overcrowded, and party attendees are often under the influence of alcohol (occupancy → activity).
- Alcohol impedes the occupant's sensory, decision-making, and moving abilities such that late perception of the fire delays the notification to others (activity → perception of fire → notification) and the evacuation initiation (activity → evacuation initiation) with less agility (activity → movement).
- Overpopulation requires more means of egress (activity → means of egress).

- Alcohol and disposables for parties such as plastic cups and paper towels increase the fuel amount of the space (activity → fuel amount) and often they are stored in a specific place (activity → fuel location). In a fire incident, increased fuel leads to higher HRR (fuel amount/location →HRR)
- Combustible interior finishes increase HRR in the basement (interior finish → HRR). Fire spreads through the open stairway throughout the building (floor plan → fire and smoke spread).
- Fire services could not perform active suppression and search/rescue mission as high heat release rate and fast fire spread through the open stairways deteriorate the structural integrity of the building (HRR → structural integrity → fire service activity)
- The fire incident in the fraternity house can degrade the reputation of the university in terms of fire safety and student management (ignition → value loss).

Therefore, the integrated interaction model can explain what actually happened for this fire incident in more detail. The model also leads to other possible or worse conditions which could have occurred. For instance, the one surviving student could have been injured as the exterior escape ladder is not safe enough for the student to use under the influence of alcohol (activity → moving ability). The corridor, a path to the escape ladder, could have been unavailable if the furniture were moved to the corridor, not the outside, which actually happened in Dance hall fire, Gothenburg, Sweden disabling one of the two means of egress (activity →means of egress).

Application of integrated model

Not only can the integrated model be used to analyze the actual fire incident as in the previous section, but can also be used to increase the building fire safety design, which is the main purpose of the integrated model. The method is to compensate the interactions by implementing counter effective characteristics to identified key characteristics of each component or improving the key characteristics. For example, the key characteristics in the exemplified fire incident are identified in the *people* component (occupant activity), in the *fire* component (fuel location, HRR, and fire and smoke spread), and in the *building* component (means of egress, detection / alarm / notification system, floor plan along with means of egress, occupancy/use, interior finish, structural integrity, value loss). Among these, occupancy/use cannot be changed as this activity is an inherent characteristic of the fraternity house. Likewise, weakened moving ability under the influence of alcohol is also expected along with it. Then the only strategy in the *people* component based on Figure 39 is to increase the level of sensory ability such that occupants perceive the fire earlier. This can be achieved by strengthening the fire drill experience, and the detection / alarm / notification system both of which are expected to decrease pre-movement time. For the *fire* component, the fuel amount and location as well as ignition are not easily controlled as they vary on occupants’ perception of fire safety and the level of caution. As fire incidents, however, are related to the university's reputation, it may be reasonable for the university or fraternity association to regularly dispatch check-up personnel to ensure the amount/location of fuel and train the fraternity members to be more cautious about fire safety. Although HRR is a subsequent result of fuel amounts, it can be controlled by installing an automatic suppression system and non-combustible interior finishes. By dividing a large space into small spaces, maximum HRR can be decreased, but space use along with "room size" should first be discussed with architects. Fire spread speed can be controlled by using fire-rated materials, but the spread direction is not readily known as the fuel distribution can change. Therefore, the only strategy of the *fire* component is to cope with the characteristics of ignition, HRR, and spread speed. For the *building* component, floor plans need to be simple enough with clear exit signs for visitors who do not know about the building layout to evacuate without disorientation, and non-combustible interior finishes need to be selected at least along the path to the means of egress. A fraternity house requires the means of egress to be even safer than regular residential building as the occupants may lack mobility and decision-making abilities. This may include more remote exits with unobstructed paths to reach a safe point, and fire and smoke rated doors on each level with automatic door closure into fire rated exit enclosure.

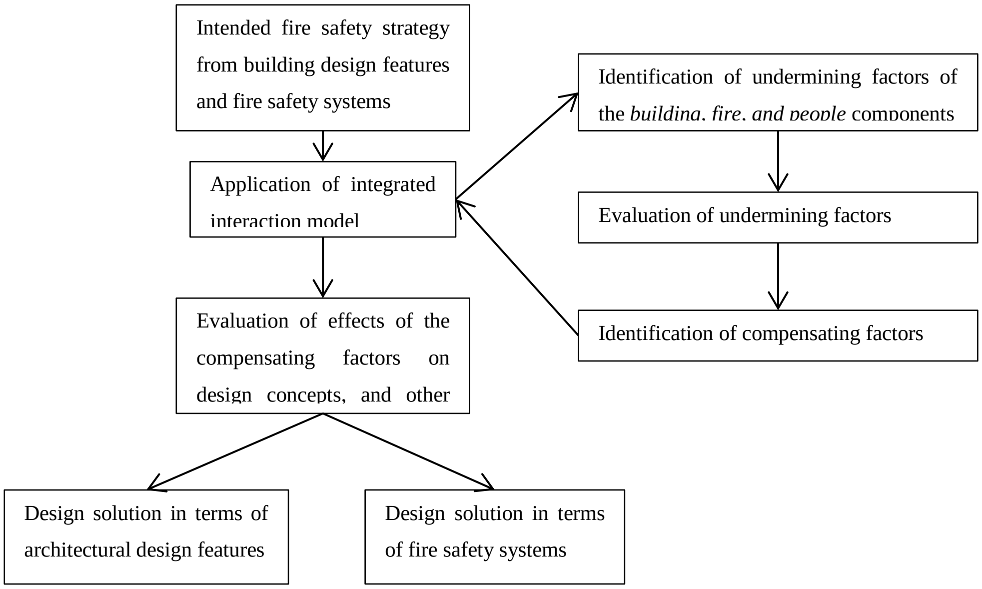

Figure 40: A flowchart of application of integrated interaction model

Summarizing the compensating method for this fire based on Figure 39, it is recommended that regular checkup by university authorities on the fraternity house and its members in terms of fire safety be conducted, and non-combustible interior finishes, automatic suppression systems, improved detection /

alarm / notification systems, and simple floor plans with safer means of egress be installed. Among these, architects should recognize the need for simple floor plans, an upgraded means of egress, and the use of non-combustible interior finishes to improve the actual fire performance of the building. Hiding exit doors behind walls and coloring exit doors with the same color as the background, and complex floor plan features such as angled corridors may be aesthetically attractive, but detrimental to fire safety. A flowchart for using the integrated interaction model is introduced in Figure 40.

Conclusion

A study has been conducted aiming at developing a method to increase the building fire safety by bridging the gap between architects and fire safety engineers. To investigate the role of architects in terms of fire safety, what happened in actual fire incidents were investigated via the 15 fire incidents. Key characteristics were identified and arranged along with the three components: *building*, *fire,* and *people*. By connecting the characteristics based on the cause and effect relationship and integrating the relationship, it not only became clear that architects' missions were closely linked to the actual fire performance of the building, and but also that the available solutions to improve the fire safety could be revealed. The current study forms a basis to help the design and evaluation of fire performance of buildings. In future studies, further investigation of fire incidents, the interactions within each component and with other functional systems, and the incorporation of building design process into the model with input from architects will be employed.

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Appendix B

Improved incorporation fire safety performance into building design environment using BIM tools

Improved incorporation fire safety performance into building design environment using BIM tools

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Abstract

This research aims to develop methods to incorporate building fire safety performance into building design process. Two different methods are proposed being developed based on theoretical iterative building design process, two different project delivery schemes: conventional linear building design and integrated building design, and the generic design decisions in each design phase. First, a knowledge set is developed which provides design participants with the effects of building design decisions on fire safety performance. This knowledge set intends to minimize design conflicts in later building design phases by providing necessary concerns in advance, which allows design participants to have opportunities of considering fire safety performance in their decision-making process. Second, a framework of necessary features of building fire safety performance evaluation kit is developed assuming smart objects in BIM tools contain information for fire safety simulations. With this evaluation kit, design participants can assess building fire safety performance more holistically in a consolidated form, not as an assembled evaluation of individual simulation results.

Keywords: Building performance, fire safety strategy, fire incidents, interactions

Introduction

Building design consists of many decisions and actions of multiple stakeholders from various disciplines. In addition to architects, the primary designers, and other design consultants such as mechanical, electrical, structural, environmental, and fire safety engineers are also closely involved in building design projects. A big challenge in building design lies in collaboration and communication among the stakeholders as a slight building design change in one discipline may impact multiple disciplines at various levels of decisions [1]. As such, a well-organized building design process is required to incorporate a variety of design needs of multiple disciplines in a manner that necessary information is provided to relevant stakeholders in order. However, this systematic planning is not fully practiced in many building projects [2, 3]. Due to the information generated after building design is determined or insufficient performance of selected design in some disciplines, rework is typically necessary, which makes building design process be inevitably iterative.

The iteration in building design generally follows the four steps: analysis, synthesis, evaluation, and communication as shown in Figure 23 [4]. Depending on building design stage, detailed tasks of each step may be different, but generally speaking, problem identification, solutions development, evaluation of solutions' performance, and selection of optimal design are conducted in analysis, synthesis, evaluation, and communication, respectively. In the case that problems are complicated with a large number of stakeholders involved, more time and efforts are required to solve them, i.e., the design burden due to the iteration increases. To improve design efficiency, this burden needs to be decreased which can be accomplished by two strategies: increasing the speed of iterations and decreasing the number of iterations [5]. Faster iteration can be achieved by improved design performance of each stakeholder with accelerated analysis and evaluation tools, and less iteration can be achieved by providing better collaborative environment among stakeholders. An example of the former strategy may be development of design tools such as computer-aided design (CAD) programs which accelerate individual design activities. An example of the latter strategy may be the concept of integrated building design in which various project stakeholders gather together from early design stages to identify interrelated problems, discuss solutions, and make decisions based on mutual agreement. In this context, building information modeling (BIM) tools have a great potential for both strategies as they provide more convenient design environments and a shared format of design data for improved communication among stakeholders.

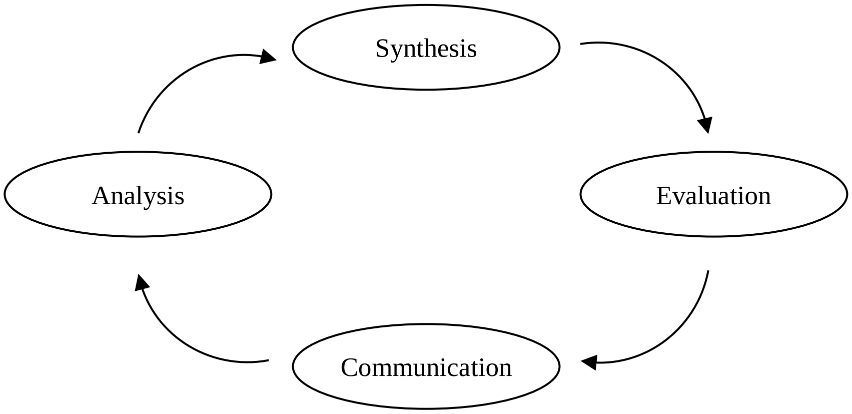

Figure 41. Iterative building design process

Buildings are designed abiding by building regulations (codes and standards) to provide the minimum requirements for public health, safety, general welfare to building users. Especially for fire safety, they are established to protect occupants, emergency responders, and properties in fire emergency operations. Building and fire safety regulations are generally categorized by two different types: prescriptive regulations and performance regulations. In prescriptive regulations, detailed requirements regarding fire safety features such as egress width, travel distance, and the number of exits, are prescribed whereas in performance regulations, requirements are prescribed only at the performance level and detailed means and methodology to achieve the performance are not included in regulations [6]. For example, per International Building Code (IBC) published by International Code Council (ICC), the most widely used prescriptive building codes in the US, the maximum exit access travel distances are specified per occupancy and with/without sprinkler system, which ranges from 22.8 m (75 ft) to 121.9 m (400 ft). More specifically, for residential occupancy, the distance should not exceed 60.9 m (200 ft) with sprinkler system and 76.2 m (250 ft) without sprinkler system. On the other hand, per ICC Performance Code for Building and Facilities, exit access distance is not quantitatively specified, but rather included as “the construction, arrangement and number of means of egress, exits and safe places for buildings shall be appropriate to the travel distance, number of occupants, occupant characteristics, building height and safety systems and features,” under performance requirements. The different levels of requirements included in the two regulation types can be illustrated as shown in Figure 24.

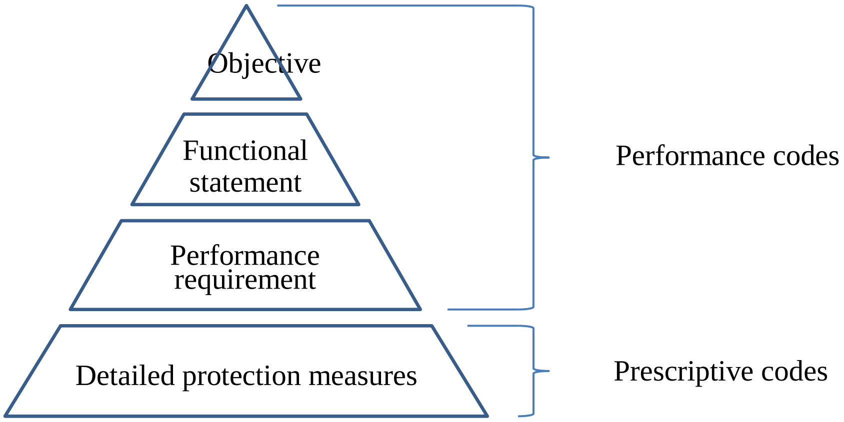

Figure 42. The level of requirements in prescriptive and performance-based regulations

Prescriptive regulations have been implemented for about a century, but raised concerns such as whether the prescriptive requirements correctly reflect the fire safety performance that stakeholders want and whether they are flexible or updated fast enough to keep pace with fast-developing building technology, new materials, and innovative building designs [7]. In response to these concerns, performance-based regulations emerged in the 1970s and they are currently implemented in more than 20 countries which are mostly developed countries and used prescriptive regulations. Even in the US where prescriptive building regulations are implemented, performance-based design solutions are allowed under the clause of "104.11 alternative materials, design and methods of construction and equipment," in International Building Code [8]. Generally speaking, performance-based fire safety design solutions require more sophisticated approach based on fire science and engineering than prescriptive solutions and provides more flexibility and less restrictions to building design.

Since fire safety features and their designs are closely related with building design, there have been continuous efforts of incorporating building and fire safety regulations into CAD programs [9-11]. The format of incorporation was an automated feature of checking code compliancy of a given building design. This approach intends to save time and efforts by avoiding manual search of relevant code provisions and to prevent undue design modification in later building design phases caused by non-code-compliant building features. This is in accordance with the concept of more effective and efficient building design process as it can reduce the design burden from the iterations between primary designers and fire safety engineers. The efforts, however, have been made only considering prescriptive regulations. Thanks to the nature of detailed requirements at the level of systems and components, the feature to check the code compliancy automatically is possible. For example, the exit access travel distance to a nearest exit can be measured in CAD programs and compared to the prescribed values in codes. However, little research has been conducted on how to incorporate "building fire safety performance" into building design process improving the design efficiency and effectiveness. In the current study, two approaches are introduced considering building design environment using BIM tools.

Background

In this section, three topics are discussed: building fire safety performance, building design phases and design scheme, and application of BIM tools in building design. Based on this discussion, conceptual framework about the methodology to incorporate building fire safety performance into building design is developed.

Building fire safety performance

"Performance" indicates the level of accomplishment of mission measured against preset criteria of objectives. Since a building is designed with many objectives such as aesthetics, sustainability, cost-effectiveness, structural stability, fire safety, human comfort and many more, building performance can be viewed by two different perspectives: comprehensive building performance which is the averaged accomplishment over various design objectives and specific building performance which is measured only for one objective. Depending on design priorities of core design team, more focus may be given to specific building performance such as aesthetics or sustainability, but well-performing buildings are expected to have good performance in both comprehensive and specific aspects. Building fire safety performance, in this sense, is specific building performance which indicates the accomplishment level of mitigating fire impacts as well as a factor to determine comprehensive building performance.

The impacts of building fire incidents are typically considered in terms of four aspects: life safety, building property damage, business interruption, and environmental protection which can be used as criteria for building fire safety performance. For life safety which is the most common criteria for building fire safety, available safe egress time (ASET) > required safe egress time (RSET) is widely accepted, which intends that all occupants in the building can move to a safe place in and out of the building before hazardous conditions are reached. However, for direct property damage, business interruption, and environmental impacts, there is no widely used quantified criteria as the acceptable monetary loss, fire risk perception level, and sensitivity to environmental protection vary depending on building (or business) owners and geographical and societal environments of buildings. In the current study, therefore, life safety is mainly considered for building fire safety performance to avoid any further assumptions.

With the limited definition of building fire safety performance to life safety, it is very challenging to assess it due to the level of complexity of various performance attributes. There are three well-known key components which determine building fire safety performance: building, people, and fire [12. Building component represents fire safety features installed in buildings such as active and passive fire protection systems and means of egress, architectural building design features, and building site characteristics such as environmental conditions and infrastructures [13]. People component includes occupant response to fire and their physical and mental capability associated with evacuation phenomena and firefighters' suppression and rescue mission. Fire component indicates fuel type, amount, and location and burning characteristics such as heat release rate and smoke and toxic gas production rates. The complexity of building fire safety performance is involved with not only the variety of individual characteristics, but also interactions among the characteristics. For example, proper exit signs as a building characteristic can increase occupants' capability to identify an exit route, which is a people characteristic. This people characteristic is influenced by occupants' physical conditions and their relative locations, which are also influenced by building occupancy. Building occupancy can also influence the fuel type and fire source. As such, due to the interactions among the characteristics of the three key components, a holistic understanding of the effects of building characteristics, occupant characteristics, fire characteristics, and their interactions is required to assess building fire safety performance appropriately.

Some of the building characteristics are closely involved with building design features which have been considered mainly for other building aspects such as aesthetical, energy, acoustical performance. These can affect building fire safety performance via changing human behavior in fire conditions, providing more fuels, accelerating fire and smoke development, and hindering rescue and suppression mission of fire fighters. For example, complex floor plans make it more difficult for occupants to identify a proper exit route than simple floor plans, which increases evacuation time [14]. Double-skin façade design which is good for energy conservation can contribute to vertical fire and smoke spread [15]. Acoustic tiles are often increase fuel amount and due to its typical locations on ceiling and walls, it promotes fast fire development within the compartment [13]. Occupants also rely on their architectural space experience with buildings to plan the exit routs; exit signs can help occupants' exit route decisions, but the portion of occupants who rely on exit signs are not as high as expected [16, 17]. Therefore, building fire safety performance needs to be understood and assessed accounting for building design features which may be also related with other specific building performance.

Prescriptive building regulations, however, have limitations to comprehensively capture the interactive effects, especially regarding the characteristics of building design features, people, and fire. Due to the nature of regulations which prescribes detailed requirements, only physical building systems and components are generally included as target objects of requirements, by which code compliancy can be clearly confirmed. This does not mean that prescriptive regulations ignore the effects of building design features, people characteristics, and fire characteristics on the fire safety performance, but rather implies that comprehensive fire safety performance is not fully captured via prescriptive requirements. In addition, design solutions of fire safety measures in prescriptive regulations are typically dependent on occupancy classification, construction type, building height and area, and sprinkler system existence, but these criteria are not fine enough to consider the variability of numerous building designs and to provide a consistent level of fire safety performance. This is why some building fire incidents results in unacceptable damage and loss, from which more restrictive updates of prescriptive requirements are continuously made.

Building design

Building design can be described as a continuous series of actions of project stakeholders, but often broken into four phases: predesign (PD), schematic design (SD), design development (DD) and construction documents (CD) [18]. Following these phases, either different tasks are conducted or the level of detail of the same task is increased. A list of generic tasks and design decisions is introduced in the Architect’s Handbook of Professional Practice published by American Institute of Architects and part of them is included in Table 10 to understand building design progress.

Table 15. Design decisions in each building design phase

Phase 1: PD	Phase 2: Early SD	Phase 3: Later SD or early DD	Phase 4: DD or early CD
General			
Project objectives Project scope Program code and regulations Project budget Project schedule Delivery approach	Program interpretation Basic design concepts Sitting Building massing Access and circulation sustainability	Design concept elaboration Schematic floor plan Schematic sections	Floor plans Sections Typical details
Site			
Site development criteria Requirements for access, circulation, parking, utilities, and lighting	Access and circulation Views to/from buildings Acoustics and other site issues	Design concept elaboration Initial site plan Schematic grading, planting, paving plans	Site plan Planting plan Typical site details Outline specifications
Superstructure			
Performance requirements for floor, roof, stair, other structural elements	Relation of structure to spatial organization, elevation, etc. Basic structural module Initial system selection	Structural system selection Outline framing plan	Floor framing plans Roof framing plans Sizing of elements Important details Outline specifications
Exterior closure			
Restrictions on exterior design, materials, etc. Performance requirements for walls, doors, windows, etc.	Approach to elevations, Views to/from building Initial envelope elements sizing and selection	Design concept elaboration Selection of wall systems, materials Schematic elevations	Elevations Key exterior details Outline specifications
Roofing			
Performance requirements for roofing elements	Roof type Initial system selection	Selection of roof system, materials	Outline specifications
Interior construction			
Performance requirements for partitions, finishes,	Approach to partitioning built-in furnishings	Room designs Selection of partition	Input to plans and elevations Key interior elevations

specialties Flexibility requirements	Interior design vocabulary Layout of key spaces	systems, finishes Important fixtures or theme elements	Initial finish schedules Outline specifications
Mechanical systems			
Performance requirements for plumbing, fire protection Need for special mechanical systems	Impact of mechanical concepts on building planning Initial systems selection Initial distribution ideas Space allocation for mechanical areas	Mechanical systems selection Refinement of service, distribution concepts Input to plans, sections, and elevations	Initial system drawings and key details Input to floor plans, framing plans, sections, elevations Initial equipment list

Design progress in each design phase can be accomplished differently depending on project scale and project delivery system, but largely divided into two schemes: conventional linear design and integrated design. In the former design scheme, architects mainly lead design progress and once the design is much developed, other engineers and consultants are requested to participate in the project [19]. This can be efficient for small-size building projects in which only a few stakeholders are involved with a relatively small amount of project budget and the expected performance of the building is not high. The design objectives and criteria are relatively simple and sophisticated analysis and evaluation for building performance is not generally necessary. As such, architects can develop building design alone until when inputs from other engineers and consultants are necessary; sometimes this is as late as building design is almost completed.

Integrated building design [20], on the other hand, provides a more ideal building design environment. Project stakeholders including the owner, project manager, architects, and design consultants, gather together from early design phases and share information afterwards as design progresses. Although architects may have vast experiences of building design, it is limited to understand and to be updated with new technology, materials, and regulation changes in various fields such as mechanical, electrical, and fire safety engineering. By involving experts from early design phases, the target building performance can be better identified and the possibility of conflicts in later building design phases can be decreased. For this reason, the design scheme are often adopted for large-size building projects or projects in which high building performance is required. Being accompanied by the global green building design trend and increased understanding of designers on the benefit of early involvement of engineering experts, integrated building design gains more popularity.

The relationship of effects and effort in the two building design schemes are well explained in MacLeamy curve as shown in Figure 25. By assigning more efforts of stakeholders in early design phases such as PD and SD, more opportunities for cost reduction and better functional capabilities are allowed and the cost of design changes are minimized.

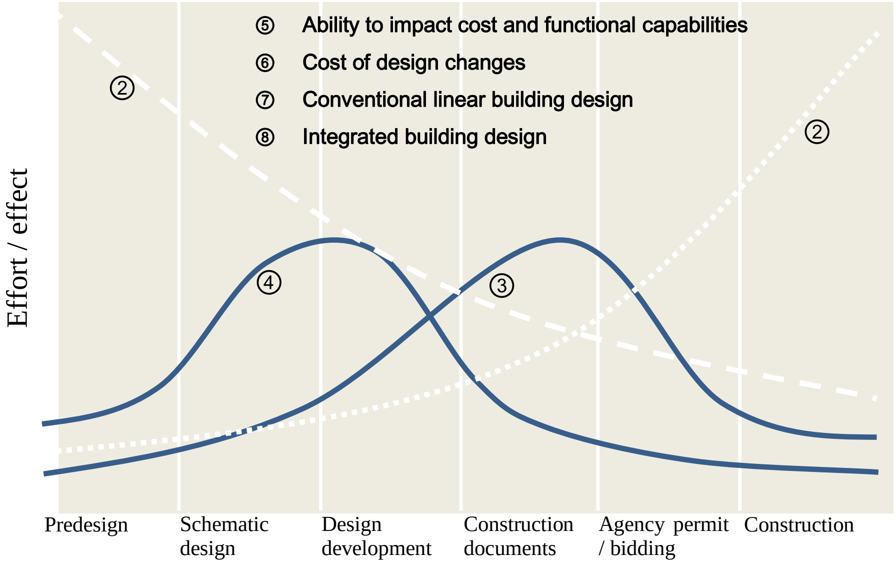

Figure 43. Macleamy Curve [21]

It should be noted that the design decisions in the four design phases do not disappear in integrated building design process, but the way that necessary decisions made in each design phase become more integrated across multiple disciplines [22].

Application of BIM tools in building design

BIM may be defined as "modeling technology and associated set of processes to produce, communicate, and analyze building models [23]," which can be applied to support various aspects of building projects during its life cycle from design stage to building use. In the current study, the discussion is limited to the use of BIM tools in the building design such that the benefits of BIM beyond the design stage are not included.

Both BIM design tools and conventional computer-aided design (CAD) tools provide electronic file format of building design and can be sharable among the building design team. The major difference between them, however, are originated from so-called smart objects or parametric objects [24] and advanced support for the collaboration of project participants. Smart objects represent physical building elements which contain not only dimensions which is also delivered by CAD files, but also other associated information such as material, acoustic, and energy data although the level of information may vary depending on the maturity of BIM tool use. With the use of smart objects, any information change is automatically updated among design team participants. For example, architects change a portion of building design, its influence on mechanical and structural components are easily identified by relevant design consultants and discussion to develop a new design solution can be initiated. Without this feature, the design conflict may have been identified even in construction stage.

Another benefit of BIM tools is a great potential for combining design and evaluation feature across multidisciplinary fields. Since design is naturally a trial and error approach to find an optimal solution, it is critical to evaluate the expected performance of candidate designs. Traditionally, design and evaluation tools are separated such that design is completed in one tool and performance analysis is conducted in other tools. This segregation may be due to various reasons: different knowledge and skill sets required for design and performance analysis tasks, features of design tools which do not have enough information for performance analysis, and lack of interoperable file formats between design tools and analysis tools. This condition practically results in additional steps such as conversion of file format and modification (addition or subtraction) of the information of imported files to be used for analysis tools.

In addition, since different disciplines have used different evaluation tools, only specific building performance has been assessed without comprehensive consideration of interactive effects of building features on other building performance. For example, a certain design of structural components is more efficient and economical and has better constructability, but may have poor thermal resistance performance in fire conditions, but not all structural components are evaluated for fire conditions. Once BIM tools contain necessary object information for a wide range of building performance simulations, comprehensive building performance can be evaluated within BIM tools as well as specific building performance. The smart objects and a shared platform in BIM tools can provide a great potential for more consolidated building design approaches.

Development of conceptual framework

Since building fire safety performance is influenced by building design features and BIM tools can provide better collaboration environment for architects and design consultants, opportunities for fire safety performance to be incorporated into building design using BIM tools are promising. The relationship between building design progress and the role of design consultants can be summarized as shown in Figure 26 considering the two building design schemes: conventional linear design and integrated design and the iterative building design process.

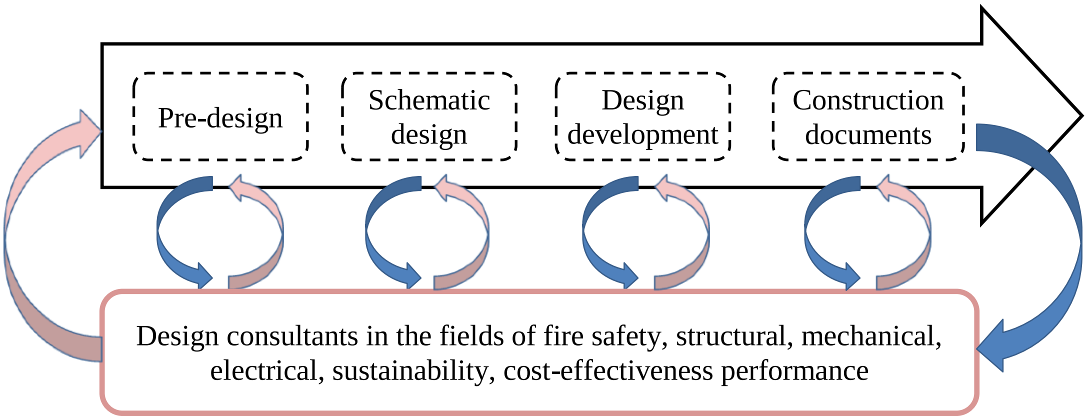

Figure 44. Collaboration of primary designers and design consultants

Arrows indicate the information flow such that the loops formed by two counter-directional arrows represent collaborations between primary designers and design consultants. There exist two different sizes of collaborations represented by one large loop and multiple small loops. Although there are four small loops connected to each building design phase in Figure 26, this does not mean four times of collaboration, but ongoing collaborations as needed as building design progresses. The large loop also did not mean the collaboration after construction documents are completed, but rather implies the collaboration in later building design phases when the building design features are almost determined. Therefore, the small loops and the large loop represent the integrated building design scheme and conventional linear building design scheme, respectively.

Although integrated building design scheme provides more ideal design environment for better performing buildings as shown in Macleamy curve in Figure 25, it is more difficult to reflect building performance into building design process. To evaluate building performance, relevant design consultants need building design information from primary designers, but in early design phases, it is impossible to obtain necessary information as design is still in the incubation. The integrated building design, however, can be a truly effective when the design consultants are capable of understanding and estimating the possible effects of building design on the specific building performance in advance even at building design phases of little building design accomplished. For this, a knowledge set in terms of the relationship between building design attributes and their effects on specific building performance needs to be developed. Based on the knowledge set, design consultants in each discipline can provide proactive information to other design participants as well. On the other hand, conventional linear building design scheme may provide more information about the building design details to design consultants for building performance analysis as building design is much developed when they are requested to participate in the project; interactive effects among building design features, components, and systems can be also included in analysis. However, the current conditions of separated building design and performance analysis tools across various disciplines do not support a proper interface for this benefit.

In this context, the current study proposes two strategies to incorporate building fire safety performance in both building design schemes which also contribute to the efficiency of building design process. Modifying Figure 26, the two strategies may be conceptualized as shown in Figure 45. First, for small size loops, fire safety performance knowledge set needs to be developed as a reference material based on which fire safety engineers provides timely and necessary information in advance to primary designers and other design consultants. Second, for a large size loop, a framework of a consolidated building fire safety performance evaluation kit within BIM design tools needs to be established. In the current study, the influence of building design decisions on the fire safety performance is identified in each building design phase for the first strategy and necessary features and functionalities of fire safety evaluation tools are identified assuming future development of BIM design tools for the second strategy.

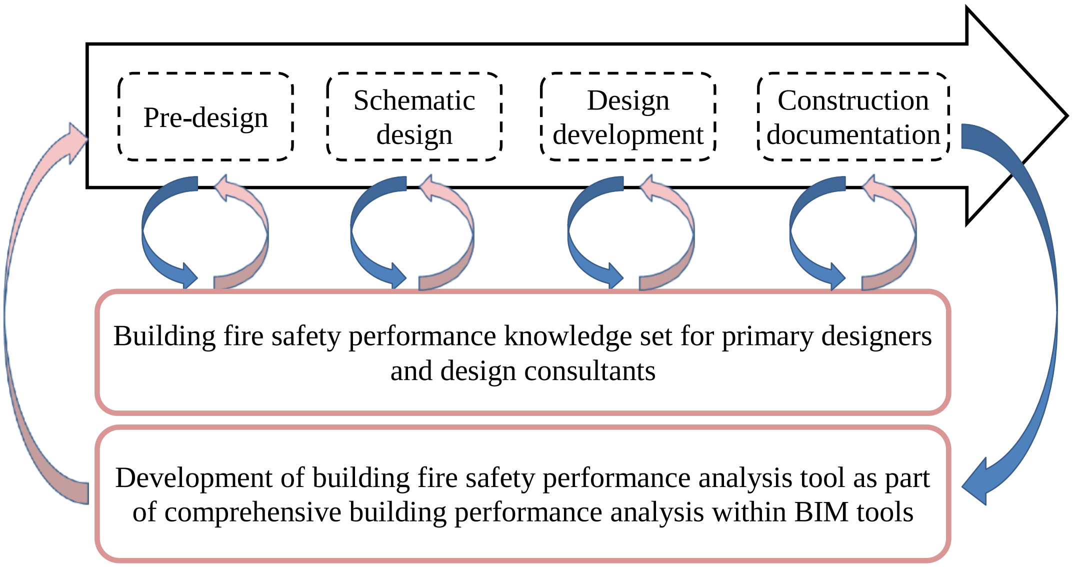

Figure 45. Two strategies to incorporate building fire safety performance

Knowledge set for building fire safety performance

Before identifying relevant building design decisions, it is necessary to define the attributes which influence building fire safety performance comprehensively; some may be related to building design decisions and others may not. One of the best data sources for the attributes may be building fire incidents reports, which generally include building descriptions, fire fuel conditions, ignition and fire development process, firefighter's and occupants' response. A total of 15 fire incidents were analyzed and relevant attributes are already extracted in terms of building, people, and fire components [25]. Among them, ones related with building design decisions are extracted for the three design phases during which most building design details are determined.

Phase 1: Predesign

- Building regulations and regulatory system

Since buildings are to be designed in accordance with building regulations, available or mandatory regulations should be checked in the first place. In addition, primary designers may not know about the availability of performance-based comprehensive fire engineering design solutions. In this case, fire safety engineers need to update the designers. The perspective of building officials who commission buildings is also critical; some may prefer prescriptive regulations which may limit or even prohibit the performance-based fire safety design solutions. Therefore, it is very important for designers, fire safety engineers, and building officials to agree with the fire safety design approach before initiating building design, and to be updated about any changes and issues regarding the design method.

- Occupancy and overall building floor area and height

Occupancy or building use is very critical in terms of fire safety performance as it most defines the characteristics of occupants, building and fire. Therefore, once the occupancy is determined, architects need to be informed about the concerning characteristics from the perspectives of fire safety engineers.

- Environmental conditions (temperature, wind, humidity, flood, hurricane, vegetation, soil, hydrology, seismic zone)

The influence of environmental conditions on building fire safety performance is significant. Wind direction affects the direction of smoke and flame spread within a building. As occupants' egress path and firefighters' attack route can be affected by the wind direction, designers may need to take it into account, especially for the buildings located near a large lake or the ocean where consistent wind directions are often expected. Egress path in the leeward direction and fire attack route of firefighters in the windward direction may not be preferable. The wildland-urban-interface (WUI) fire and its propagation to buildings may be possible in the dry season. Vegetation or water ponds next to buildings can hinder fire engine's approach and firefighting activities. Buildings in a seismic zone can have a higher probability of fire incidents as fire often occurs after earthquakes and firefighters' rescue and suppression mission can be easily limited due to earthquakes.

- Communal environment (rural, urban, tourism, large city, existing structure)

The close proximity of fire departments can be beneficial to building fire safety. If it is difficult to expect full firefighting and rescue services from fire departments due to the limited capability of man power and equipment, the building may need to have more stringent fire protection systems. The possibility of fire propagation from adjacent buildings also needs to be investigated if the building is located in a city area. The building envelope materials, the separation distance, the locations of openings and occupancies of nearby buildings are also important.

- Infrastructures (traffic, gas, electricity, water)

If water resources are limited, or stable city water is not expected, a separate source of water may be prepared for sprinkler systems and firefighting activities. Electricity is very important for all active fire protection measures and if poorly managed, it can be an ignition source. If heavy traffic conditions are often expected near the building of concern or in the path from fire departments or hospitals to the building, the time to reach to the building of emergency crews can be increased, which proposes more stringent building fire safety measures.

- Site history and its historical value

Sites having historical values may not provide proper access routes to emergency crews as the development of road or nearby land may have been restrained. To be in harmony with historical value, the same building materials with existing structures may be selected, but they may not have as good flame resistance performance as modern materials.

Phase 2: Schematic design

- Project objectives and design concept

The design approaches to materialize project objectives are determined in schematic design phase. For example, the approaches such as using eco-friendly materials, vegetation or solar energy panels on the roof, double façade systems, and rain water harvesting systems are developed for the objective of green building design. Fire hazards or safety issues from these need to be consulted with fire safety engineers (Meacham NFPA report).

- Building orientation and schematic site design

Views from/to the building, daylight conditions, and access routes to the site, site topology, and background noise often affect the building orientation and site design. In fire conditions, the relative direction of the main entrance door with the existing buildings, parking lot, and expected firefighter’s access route are important attributes for fire safety performance as they can determine the occupants’ evacuation direction and the effectiveness of firefighter’s activities. A designated space outside the building may be helpful for a meeting location of evacuating occupants or for a temporary space for urgent medical care. The area needs to be sized considering the number of occupants as more people need more space, and the capacity of local hospitals.

- Occupant flow or circulation (parking, elevators, escalators, stairs)

Occupant flow in normal building operations is very important as occupants tend to evacuate the building following the same paths in fire conditions. Occupants may go to elevators in fire conditions and find they may not be operational. Therefore, secondary egress routes from the elevator should be easily found architecturally. Relying on exit signs is not wise enough as exit signs are not as effective as they are expected in guiding occupants.

- Programing and schematic space allocation

For spaces in which a large or fast developing fire is expected, a small space area is preferable. Generally fuel amount is proportional to the space size, higher HRR is obtained in a large space in a short time, especially with a low ceiling height. Ignition probability varies depending on space use; kitchens have a higher ignition probability than living room. Unoccupied spaces with higher ignition probability would be better if located in upper stories. As flame tends to spread upward or horizontally, by locating more dangerous areas in upper stories, floors below them can be less susceptible to fire spread. Rooms for a large number of people may be better located in the ground level where direct exits to the outside can be provided.

Stage 3: Design development

- Site plan and landscaping

More details of site plan and landscaping are determined. Candidate locations of hydrant and fire engines in fire conditions, firefighter's access routes, police control lines, and any possible blockages for these need to be determined. Any building ornaments, sculptures, and vegetation would not increase fuel amount, possibility of ignition, occupant evacuation time and the difficulties of firefighter's access and activities.

- Floor plans and sections

The locations of exit need be determined based on the actual locations of occupants in the building and occupant characteristics. Two or more exits located far from each other are recommended assuming the condition that at least one exit is unavailable, but actual exit selection of occupants in fire conditions is more important than the number of exits. If only one exit is expected to be mainly used out of two in fire conditions, the floor plan may need to be revised. In addition, the total number of exits and the locations of them need to be evaluated with other fire protection systems and the characteristics of the space.

Simply one exit may suffice for specific buildings and spaces. Rooms housing a large number of people such as a large conference room, or a theater may need to be provided with their own exits directly discharged to a safe place. People tend to have a low familiarity in hotels, shopping malls, airports, and ambulatory buildings where it is often expected that occupants stay in the building for a short period of time and do not have enough opportunities to perceive the entire structure. In these occupancies, exit doors need to be clearly and easily recognized by the occupants from most of the corridor areas. Hiding doors from the lines of sight of occupants can cause delay in finding the right exit route.

- Structural system and roof system

Structural integrity has been emphasized for the firefighter's life safety since structural failure generally occurs when firefighters conduct their mission in the building. If an innovative structural system is adopted in the building design, not only its structural performance in normal building operation but also the performance in fire conditions should be considered including the effects on the fire fighter's activities. For example, roof structures having vegetation or solar panels would be difficult for fire fighters to attack the fire via roof access.

- Building envelope design

Flame spread issues through the exterior envelope would be one of the biggest concerns in building fire incidents. Adjacent openings need to be provided with enough vertical separation distance or long enough spandrels such that vertical flame spread is less probable along the building envelope. Outwardly slanted envelop surface as height increases can promote flame extension on the exterior wall surface. The separation distance is calculated based on the expected flame extension based on the fuel characteristics and opening size, not a fixed value (IBC prescribed the minimum 0.9m separation for unsprinklered buildings). Exterior equipment located on top of buildings such as a large advertising panel, or Heating, Ventilation, and Air Conditioning (HVAC) unit may be more susceptible to fire or electric short circuit and hard to detect in early fire development stage. Fire can also spread downwards by falling objects engulfed with flame.

- Interior finishes

It is definitely better to use non-combustible materials for interior finishes. However, interior finishes actually mean more than combustibility characteristic. Textures and colors of interior finishes influence occupants' space perception and can help them recognize their relative locations within the building and find the exit routes with a better sense of orientation.

Fire safety performance suite in BIM design tools

BIM design tools significantly improve the communication among primary designers and design consultants by allowing a shared platform across multidiscipline. Primary designers design building envelope and interior layout and structural engineers design appropriate structural systems. On the same design file, mechanical, electrical and fire safety engineers add relevant systems and components. This is the same as actual construction process, except for the fact that things are done virtually. In this process, design consultants in each discipline need to determine necessary capacity of the systems and components based on preliminary analysis. For example, structural engineers calculate structural loads to select appropriate sizes of beams and columns. Mechanical engineers calculate thermal loads based on space size to select proper HVAC systems and ductwork. For this reason, some BIM tools provide preliminary structural and thermal performance analysis tools to support the design process. The benefit of this design / analysis suite for structural and thermal performance is to reduce the work load associated with file conversion and additional file information modification such as adding necessary input properties for separate evaluation programs.

BIM design tools, however, do not provide analysis features for fire safety systems yet. Although system manufacturers provide modules for sprinkler and alarm systems compatible with BIM design tools, these are still for design purposes, not for analysis. Therefore, fire safety engineers use external programs to conduct necessary analysis such as hydraulic calculations for sprinkler system design and electrical current analysis for alarm system selection, and based on the analysis, separately draw them in BIM design tools for the purpose of communication with other design participants. Since objects in BIM already contain property information such as pipe size and voltage capacity, hydraulic calculation and electrical current calculation can be added without great modification, which allows fire safety engineers to evaluate sprinkler systems and fire alarm systems and design them within BIM tools.

In performance-based fire safety approach, BIM tools provide 3D building geometry which can be imported to separate fire and smoke modeling, evacuation, and structural analysis programs. Without much change of the imported building geometry, information such as fire fuels and their material properties, occupant number and locations, and external gas temperature profile are added in the analysis programs and relevant phenomena are simulated. This is a much developed feature when compared to previous 2D-based building design tools, which required manual user input of 3D building geometry, not to mention necessary input information to performance analysis tools. However, the current advanced features do not fully take advantage of smart objects of BIM tools yet. The full benefit of incorporating fire safety performance into BIM design tools may require a little bit of imagination and futuristic perspectives. If smart objects have necessary information such as thermal, mechanical, and kinetic material property data and occupant characteristic data, fire safety engineers do not additionally type in the necessary information for external analysis programs. If foreseen several decades later when computer processing power and simulation capability of various architecture and relevant engineering fields are much developed, building design programs will have more consolidated features of design and performance analysis over a variety of relevant disciplines. It may be possible to complete building design without the use of any external analysis programs. The importance of this in-house fire safety evaluation kit is due to the holistic nature of building fire safety performance which is a function of building design features, people, and fire characteristics as well as fire safety systems and components [13].

Assuming the future capability of BIM tools, the current study proposes building fire safety performance evaluation kit as shown in Figure 46 which include five sub-modeling modules with regard to structural and non-structural building components and systems, occupant's egress and fire service activities, and fire and smoke development which corresponds respectively to the three key components: building, people, and fire. There are multiple programs currently available for the three modules such as SAFIR, ANSYS and ABAQUS for structural response modeling in fire conditions, FDS, SMARTFIRE, and FLUENT for fire and smoke modeling, and STEPS, PATHFINDER, and EXODUS for occupant's egress modeling. The three available modeling tools communicate together to a certain extent such that fire temperature curve obtained from the fire and smoke development model can be used for structural analysis tools and evacuation analysis tools. Although FDS and occupant evacuation phenomena were combined together into the FDS+EVAC program, this may be the only effort to pursue more consolidated fire safety analysis program. However, little efforts have been made for the other two modules: non-structural components and systems and fire service activities, with respect to building fire safety performance.

Non-structural building components and systems includes MEP systems such as HVAC and ductwork, electrical equipment, and gas and water pipes, compartmentalization components, façade systems, occupant circulation systems, and active and passive fire safety systems. Among these, means of egress and elevators are generally included in egress modeling tools and active fire safety systems are included in fire and smoke modeling tools. However, these features are exclusively included only for those phenomena and their interactive features with other non-structural systems in fire conditions are not included. For example, HVAC unit and fire and smoke dampers can be included for fire and smoke modeling, but their effects are limited in the modeling space domain which is determined by users such that the effects on other building spaces and equipment are unknown.

Modeling firefighters' suppression and rescue mission is very critical in determining building fire safety performance as it may be the only way to control the fire size. It is, however, very difficult to model due to its dynamic performance features which depend on the local fire conditions in buildings and the decisions of the firefighter chief present at the scene. Although precise evaluation based on activity simulation may not be achieved anytime soon, other attributes such as the distance to the target building from the nearest fire station and the time to arrive at the target building, equipment capability and the number of available firefighters of the station, protocol of conducting the mission can be readily known and can be included in the evaluation program. Based on this, fire safety engineers can make expert decision on how much support from fire services can be expected, which help design in-house fire safety features of buildings.

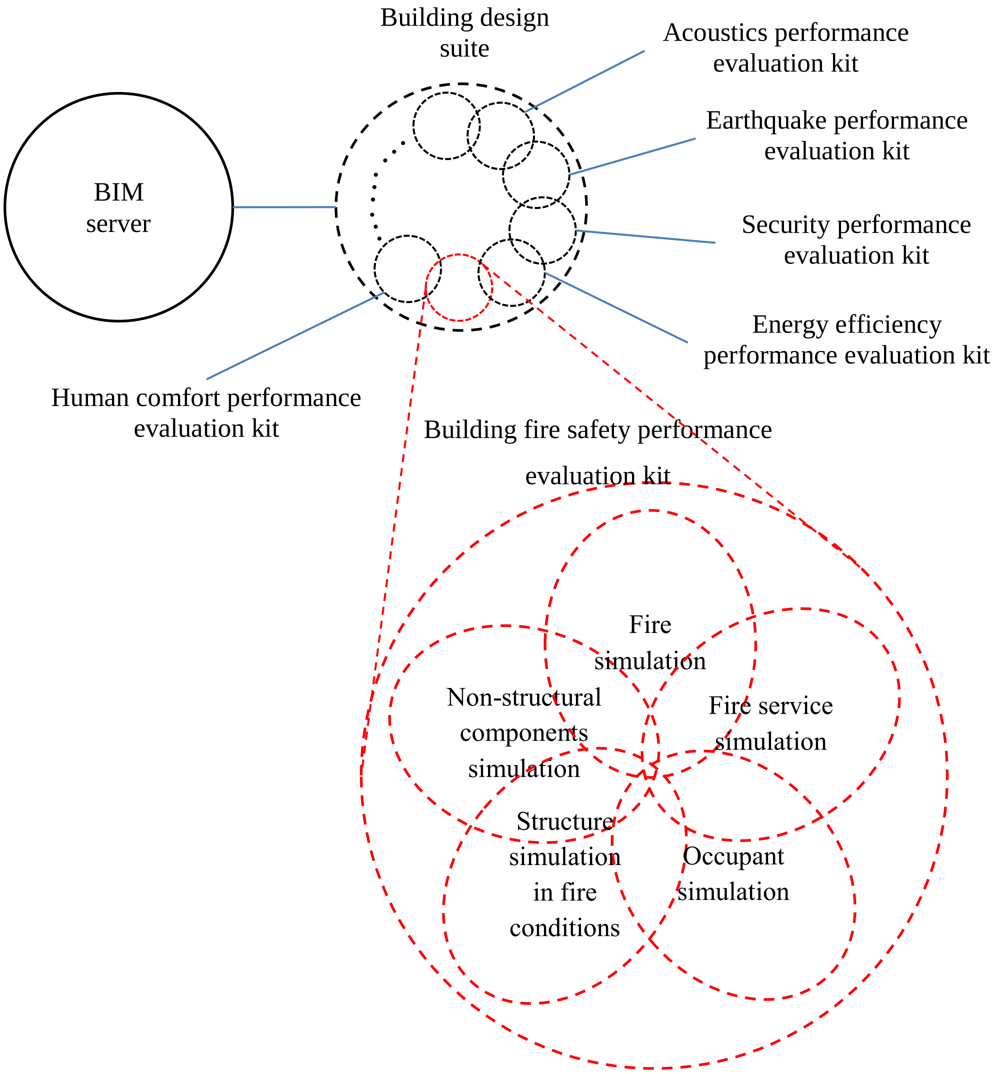

Figure 46. Expected Building design suite and fire safety performance evaluation kit

The five sub-modules are not separate simulation programs: they are included in one building fire safety performance evaluation kit and need to be run concurrently as these phenomena occur in actual fire conditions. Since building fire safety performance are holistically determined by interactions among the three key components, separated simulations and combining the results may not represent actual performance.

Although this evaluation kit can help building design development and design decisions of primary designers and design consultants, to capture the holistic fire safety performance, other building systems and components should be designed as input data information. This implies that the benefit of the holistic performance evaluation is only provided in later building design phases. This is analogous to conventional linear building design scheme. To compromise this disadvantage, fast computing power for simulation is mandatory to maintain the efficiency and effectiveness of building design process and to be in accordance with the fast iteration strategy in Figure 23. In addition, the knowledge set for building fire safety performance needs to be actively utilized in design phases which can contribute to the less number of iteration strategy.

Conclusion

Building fire safety is more governed by the regulatory requirements than market decisions since it is considered as a public good. For more than a century, the prescriptive regulatory requirements were applied to the details of building systems and components with the objectives of providing the minimum acceptable fire safety performance. However, without directly checking actual performance provided by the detailed requirements, the performance proven from fire incident results, unless the life loss and property damages are extremely significant, have been considered as minimum acceptable performance. With the development of fire science and engineering, fire safety performance can be measurable, and most developed countries which have used prescriptive regulations nowadays accepted or allowed performance-based fire safety design solutions. Despite this paradigm transition, primary architects are not fully updated with the benefit of performance-based fire safety design yet as is shown in the efforts to incorporate prescriptive building regulations into BIM design tools, not building fire safety performance. In the current study, two approaches to incorporate fire safety performance into building design are considered: proactive design information to primary designers and other design consultants in terms of the effects of building design decisions on fire safety performance and framework of building fire safety evaluation program within BIM design tools. Each strategy was derived from the close observation of iterative conceptual building design process, building design phases and design scheme, and finally a great potential of BIM design tools.

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