Enhancing Building Fire Safety Performance by Reducing Miscommunication and Misconceptions

Fire Technology, 50, 183–203, 2014

DOI: 10.1007/s10694-013-0365-2

Enhancing Building Fire Safety Performance by Reducing Miscommunication and Misconceptions

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Abstract. Building fire safety is driven by regulations and technical building codes, at least as a minimum requirement. As fire protection engineers (FPEs) design fire safety measures based on requirements in 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. The only exception is where the FPE is invited to assist in the project planning, feasibility and early concept design stages of a project. Regardless, architects also can influence building fire safety performance, whether or not they explicitly acknowledge or understand this. Although architects design buildings within the boundaries of the regulatory requirements, the architect's focus is often related to the visual and spatial aesthetics of buildings linked to building form and functionality, which are not subject to the regulations. These aesthetics can sometimes compete with fire safety objectives. As such, buildings can be unsafe in certain situations due to unintended effects of building design features on actual fire safety performance. This research describes the relationship between architecturally conceived building design features, design expectations for fire safety systems, and the actual or conceivable fire safety performance of the building. Steps are proposed that FPEs can take to identify and address potentially competing objectives and deliver increased fire safety performance.

Keywords: Architects, Fire protection engineers (FPEs), Building design, Building fire safety performance

1. Introduction

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 space design. 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. In a

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traditional linear building design process which is often applied to small-scale building projects, architects may play the role of project manager, overseeing the entire project from the design stage to the stage of building occupation. In an integrated building design process, however, in which architects and engineers develop building specifications together from an early stage of the project [1, 2], 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 article, represents entities who determine the details of building design features such as site plan, exterior shape, space layout, landscaping and interior design.

Architects make numerous design decisions which take into account available budget, various functional and aesthetic features to satisfy the needs of clients and stakeholders as well as compliance with building codes and regulations. 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. Key design objectives identified in a variety of sources are summarized in Figure 1 [3–6].

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. 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 [7]—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 [8, 9].

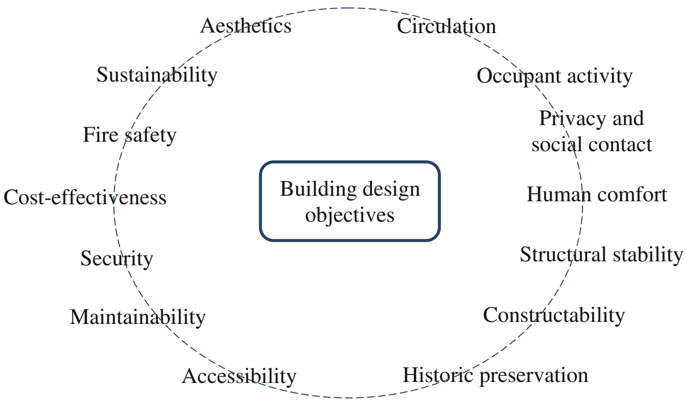


Figure 1. Various design objectives of architects.

There are largely two forms of building and fire codes: prescriptive-based and performance-based. Fire safety design based on prescriptive codes has been conducted for about a century, but there has been criticism that such codes lack a scientific basis for several of the requirements and 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 [10]. This form of regulation was intended to facilitate innovation, while at the same time reducing regulatory burden and unnecessary costs. At present, many developed European and Asian countries have adopted or are in the process of adopting performance-based codes and design for fire [11]. Performance-based design (PBD) for fire is also seen 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 [12].

With this paradigm transition from prescriptive-based to performance-based fire safety and from the linear to integrated building design process, 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 and the collaboration between architects and FPEs becomes more probable, innovative, creative, and challenging building designs, systems and features is possible. 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 by examining the following items:

- The gap between the way architects and FPEs think and communicate
- Effects of building design features on actual fire safety performance
- More comprehensive fire safety performance evaluation by FPEs

2. Gap Between Architects and Fire Protection Engineers

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. It should be noted that these differences are broadly generalized and do not apply to all architects and FPEs. However, realizing the general tendency of the difference between these professions is helpful in understanding each other.

(a) Communication style [13]

Generally speaking, architects are creative people. They are visually- and spatially-oriented, turning even scientific or engineering concepts articulated by engineers into shapes or spatial forms. 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 analytically oriented. They 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 meaning [14]

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." [15]

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 meaning to building design in relation to other buildings and environments.

The differences mentioned above are applicable to how architects and FPEs may view their roles in building projects. This can be illustrated using the diagram in Figure 2, which is often used in the FPE community. 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.

While the diagram generally is not used to represent an individual's 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, the perspective of FPEs and architects may be postulated as Figure 3. The larger the circle size is, the more emphasis is assigned.

From the perspective of FPEs, the fire component may have a larger area than the building or people component as shown in Figure 3a. This does not mean that FPEs consider building or people components less important 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 building designers, are focused mostly on the building component as they are largely in charge of determining exterior

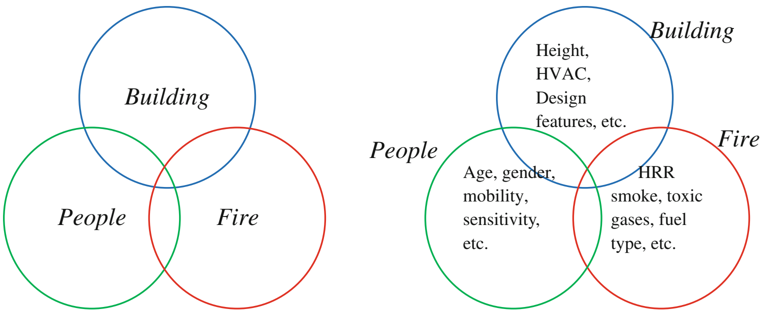


Figure 2. Common components in building fire incidents.

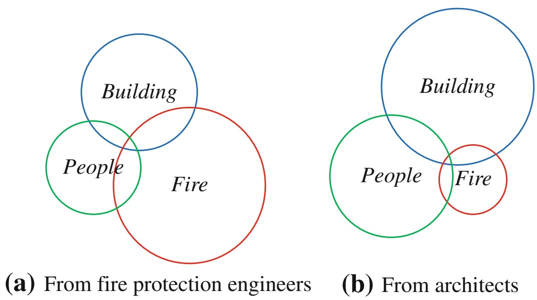


Figure 3. Different perspectives of fire protection engineers (a) and architects (b) on the well-known key components in building fire safety.

Figure 4. Fire origin (*red circle*) and collapsed portion of the building (*blue dotted* lines) [19, 20] (Color figure online).

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 that shown in Figure 4.

The different perspectives of architects and FPEs can be also found from the categorization of building use. In the international building code (IBC) [16], the most widely used prescriptive building code in the U.S., mainly 10 occupancies are defined, and some of these occupancies 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 or installation of an automatic sprinkler system. As different requirements represents different level of fire hazard perception, it may be said that the 10 building occupancies in IBC suffice the need for fire hazard categorization in terms of building use. The Architects' Handbook [17], however, lists 30 building uses referring to them as "most building types likely to be encountered by architects", and states various considerations 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.

3. 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. If it is assumed 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.

3.1. 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 [18]. 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 h 40 min after the ignition. The relative location of the fire origin and collapsed portion of the building are shown in Figures 4 and 5.

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

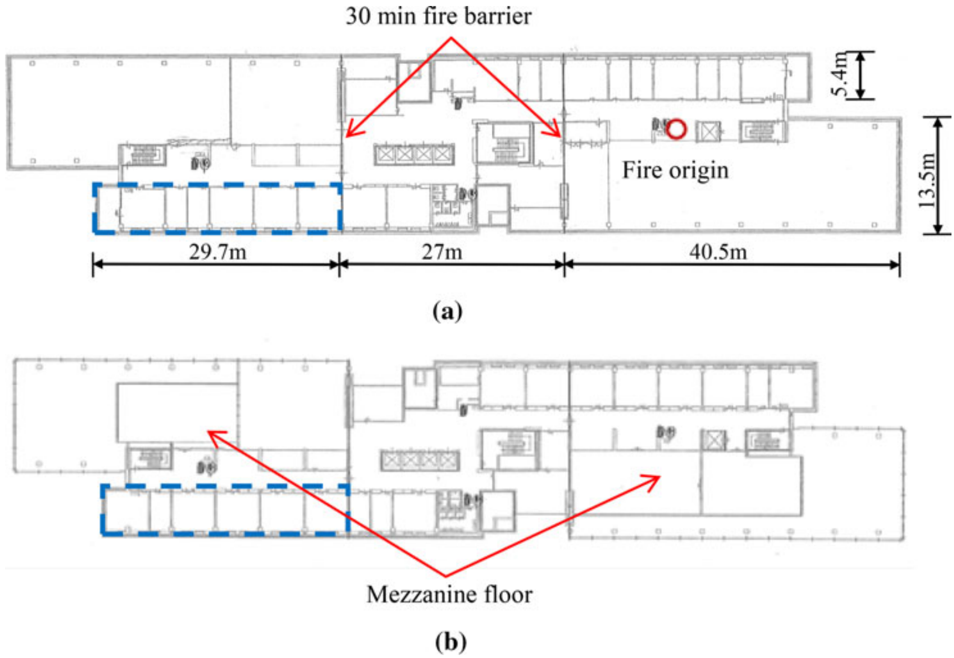


Figure 5. Typical floor plans of even floors (a) and odd floors (b) [20].

had a single story height. This was due to the mezzanine floor being hung from the floor above as shown in Figures 5 and 6. 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 drawn the attention of fire and structural experts, as this building was basically made of steel and concrete, excellent fire resistant materials and complied with the building code for existing structures in The Netherlands. Vertical fire spread was not expected to the extent that occurred, and horizontal 30 min 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.

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. The massive tower section and the design studio area was one large space that 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 40 years [21]. Recalling the diagram with three circles in Figure 3, the Bouwkunde must have been a good design from the architects' viewpoint.

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

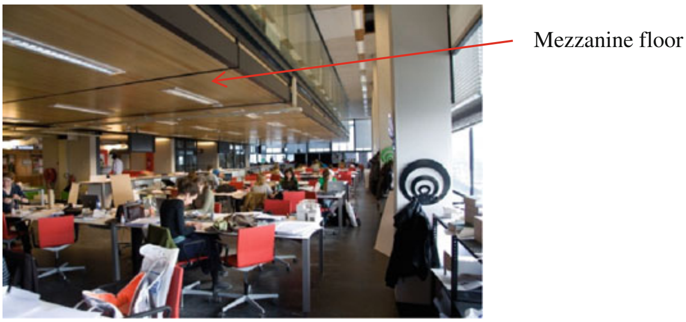


Figure 6. Internal space layout of studio area and mezzanine floor [20].

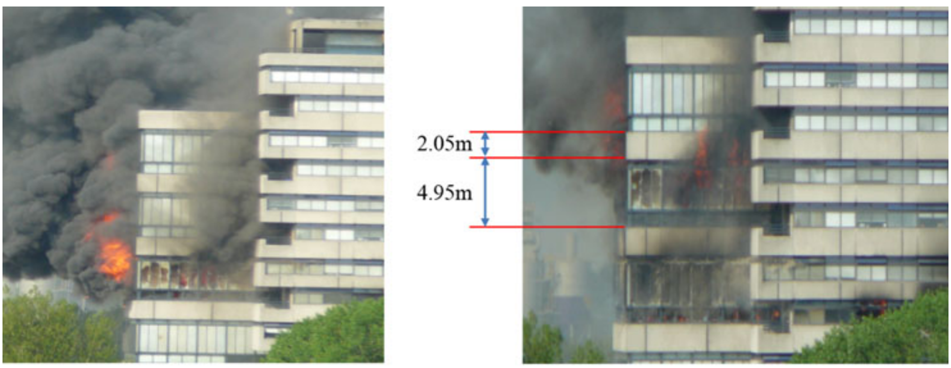
simulations. The acoustic material itself worked as an additional burner located on the ceiling.

- The 30 min fire barrier was not good enough to contain the fire in the room of origin as the fire developed very quickly, which did not allow fire service to conduct a 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 a large flame extension which could cancel the 2.05 m vertical separation. The extended flame height out of the opening reached more than 7 m as shown in Figure 7. This vertical separation distance incidentally complied with the IBC requirement, and therefore the same design features would also satisfy prescriptive requirements in the U.S. and could result in the same vertical flame propagation.
- Horizontally continuous exterior windows became the channel of horizontal fire propagation allowing the fire to spread around the fire barriers.

3.2. The Effects of Building Design on Human Behavior

Full scale experiments to measure fire brigade intervention times were conducted at the Crowne Plaza Hotel in Copenhagen, Denmark [22]. The building is 25-stories 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



(a) Extended flame via openings **(b)** Fast vertical fire spread

Figure 7. Extended flame over two-stories high (a) and fast fire spread (b) which was taken 12 min after the picture in (a) [20].

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 8.

The activities of firefighters were divided into 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,

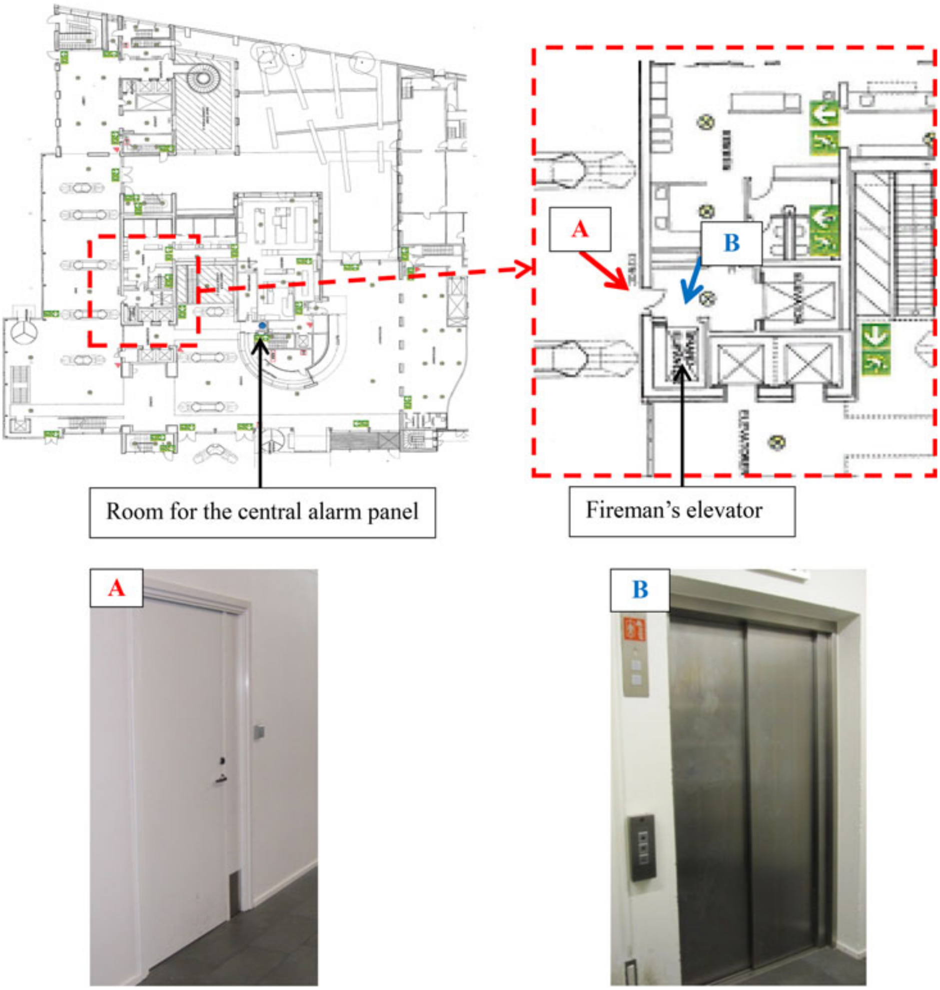


Figure 8. Floor plan of ground floor and actual view of doors to reach fireman's elevator [22].

the time to locate the door of the room (marked as 'A' in Figure 8) 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 min 26 s to 9 min 12 s with the average of 8 min 16 s. This means that firefighters spent over 8 min just to 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 min is not a trivial duration. It can dramatically change the incident outcome.

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 8. First there is no sign to identify the fireman's elevator, and the color of the door is identical to its background color, which makes 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 paper products 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 only by hotel staff 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 rescue and suppression activities. Clear signage for the fireman's elevator or space design allowing visual access to the fireman's elevator could have decreased the delay time. Such a improvement could have been achieved by proper collaboration between architects and FPEs with a good understanding of fire safety performance.

3.3. 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 FPEs, a structure for building fire safety performance is established in the context of architects, FPEs, and their mission as shown in Figure 9.

Architects and FPEs 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 FPEs 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 9. 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 were both fire safety and building design are entwined. Fire

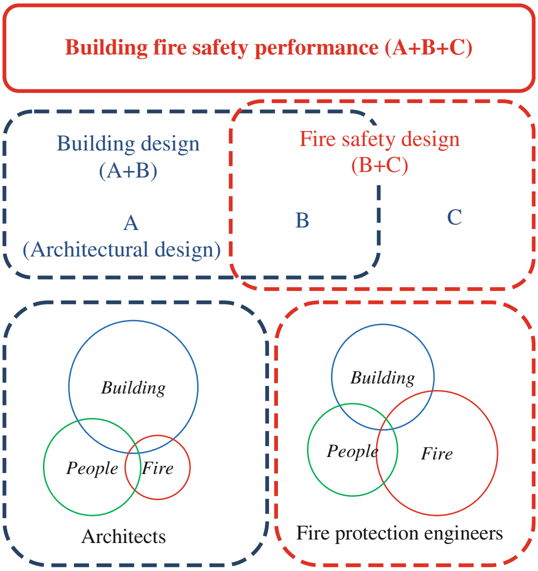


Figure 9. Structure of fire safety performance from the perspective of architects and fire protection engineers.

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 FPEs mostly govern. These may include various fire suppression systems, smoke control, detection/alarm/notification systems, and fire emergency plans. Traditionally, the mission of FPEs has 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 below in order to improve fire safety practices associated with building design.

1. The area, A (hereafter '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 the 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 unimportant 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 the Bouwkunde fire incident, building features such as exterior shape, space layout and acoustic tiles in the design studio are associated with fire safety features such as vertical separation distance, 30 min fire resistance barrier, and additional ceiling fire spread via the tiles, respectively, and affect actual fire safety performance inadvertently. In the Copenhagen fire brigade experiment, proper signage to indicate the fireman's elevator, which is an approach taken by the 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.

4. Performance Evaluation by Fire Protection Engineers

FPEs 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 for PBFSD, which is:σ_{β}^2. The variance of $e[n]$ for a modulator with an N-bit quantizer due to the clock jitter is given by:

$$\text{available safe egress time (ASET)} > \text{required safe egress time (RSET)},$$

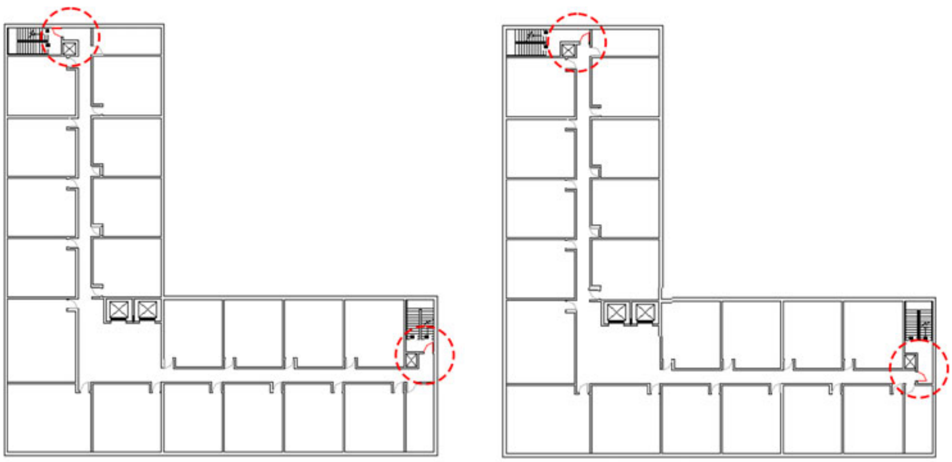
the role and use of computer models has increased significantly. However, an excessive emphasis on using computer models without the correct problem definition in the beginning and without taking into consideration limitations of the models can mislead FPEs and lead to errant designs. Most computer models 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 [23] but also architectural design features [24]. Human factors including fire drill experience, activity, role and responsibility, and learned irrelevance [25], and architectural design features such as floor plan complexity [26, 27], visibility and noticeability of exit doors and exit signs [28] 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 10: 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 10. The floor plan Figure 10a 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 10b is slightly modified by changing the exit door locations from Figure 10a.

Before seeing the results of egress models, it might be expected that the evacuation time of Figure 10a would be generally longer than that of Figure 10b, 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 during fire conditions [26, 29, 30], 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



(a) Floor plan with hidden exit doors **(b)** Floor plan with exposed exit doors

Figure 10. Floor plans for egress modeling.

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 s more in Figure 10a than Figure 10b which is only due to the extended travel distance of about 2 m in Figure 10a. 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 s and 38 s for both floor plans. The evacuation times in Table 1 were obtained from five different runs.

From the simulations, it is found that the total evacuation times and occupant 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 initial locations, but move toward exit coordinates 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 [31]. Therefore, without a correct understanding of the capability and limitation of egress models, FPEs may estimate the total evacuation time unrealistically, which also affects the results of the ASET/RSET analysis.

It should be noted, however, that authors do not judge that the floor plan in Figure 10b is better than that in Figure 10a. The floor plan in Figure 10a can accommodate windows on the exterior walls, which provide natural light and ventilation whereas the one in Figure 10b can be more helpful for occupants to identify the exit door locations in fire conditions. The final building design will be determined by the core design team based on site conditions, design concept for building envelope, the design objective of the exit stairwells, etc. What matters to fire protection engineers (FPEs) is to recognize the effects of hidden exit doors on occupant exit route selection, to discuss the effects with the core design team and to develop the fire safety design solution accounting for the effects. For example, when the floor plan in Figure 10a is chosen as the advantage of windows are more valued, FPEs need to develop more effective measures to guide occupants better to the exit doors such as green flashing lights in the exit signs [32] or to include larger evacuation time in the RSET analysis.

The number of practically available exits and occupant distribution for each exit also requires a critical analysis by FPEs as these are influenced by the floor

Table 1
Egress Modeling Input and Results

		Total evacuation time (s)	
Models	Occupant number	Figure 10a	Figure 10b
Model 1	57	37.3	35.3
Model 2	57	35–38	35–38

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 [33]. This phenomenon was reflected in the recent IBC update by requiring that the main exit should handle at least half of total occupant loads. However, there are various situations in which more than half of occupants try to use the main exit as proven by the Station Night Club fire incident, 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 11a. This type of warning sign is to make occupants refrain from using the emergency exit under normal conditions, 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 into a storage space as shown in Figure 11b. The items in this space decrease egress capacity or even make the door unavailable. Considering the fact that visually hidden exit doors and emergency exit doors are common design features and that exit capacity decreases often due to poorly located items in the egress path, critical analysis by FPEs is necessary in estimating the evacuation time more realistically.

5. 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 each often 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, the capability of FPEs 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

(a) Typical emergency exit doors **(b)** Nearby space of an exit door

Figure 11. Emergency exit door (a) and nearby space (b).

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 large shopping malls. Designing exit stairwells used more frequently in normal building operations can increase familiarity with exits, thereby decreasing the perception of learned irrelevance.

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

FPEs 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 proper part in it. For about a century, FPEs 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. Architectural design features which are not even subject to regulations 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 normal building operations. The space 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 fire safety performance and to design fire safety 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 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 article.

6. 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 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.

Work presented here reflects an initial step in a larger effort to improve building fire safety by bridging the gap between architects and FPEs. In the near future, more practical methodologies and a framework for analysis will be presented. For FPEs, 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 incidents 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 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 FPEs 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.

Acknowledgements

The authors thank Peter Johnson for reading the manuscripts and providing valuable comments.

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