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# Fire risk of high-rise buildings based on human behavior in fires

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**Abstract**
This paper describes the fire risk of high-rise buildings related to evacuation in case of fire. The fire risk is based on human behavior and on the determinants of a safe evacuation of occupants during a fire. An extensive review of literature on human behavior in fires revealed the determinants for fire safety engineering with regard to the survival of occupants. In this paper the determinants are set out for the assessment of fire risk of in particular high-rise buildings.

**Keywords:**
Fire risk, evacuation, human behavior, high-rise buildings

## 1. Introduction

Many fires in buildings have shown that the behavior of occupants is important for the survival of a building fire [Kobes, 2008]. Therefore it is reasonable to characterize the fire risk of buildings based on human behavior in fires. The concept of fire risk can be defined as the probability of a fire causing a loss of life (or injury) and/or damage to property [Tillander, 2004].

Human behavior is defined as actions that people take, based on the perception of the situation, the intentions for actions and the considerations before the actions are carried out. Occupants are in the first stage of a fire primarily thrown on their own resources or on those of surrounding people. The behavior of people in the first stage of a fire is the most determining factor for survival. An additional significant factor is the availability of fire safety measures, for example fire extinguishers and accessible escape routes. The assistance of professional emergency services, such as rescue operations conducted by firefighters and emergency treatment by paramedics, can only be provided just after the first, and most important, period of a fire. Therefore, the possibility of surviving a fire is determined on the fire response performance of people.

## 2. Human behavior in fires

### 2.1 Fire response performance

Fire response performance is the ability of an individual to perceive and validate signals of danger and to make and carry out decisions that are effective relating to survive a fire situation with none or little health complications afterwards. The fire response performance of humans is influenced by [O'Connor, 2005; Gwynne et al., 1999] (the behaviour of surrounding) people, (the design of) the building and (the effects of) the fire. To survive a fire there are three distinct strategies [Tong & Canter, 1985]. The first strategy is to (try to) extinguish the fire. The second strategy is to shelter and to wait for rescue. The third strategy is to evacuate.

In the literature review [Kobes, 2008] very little information is found on the extinguishment of a fire by occupants. Barnett et al. (2007) found that in 78 % of the domestic fires in Great-Britain and in 75.2 % of the fires in Australia the fire brigade was not called. This suggests that about one third of the fires puts itself out or this is done through actions of occupants. With regard to the strategy of 'shelter and wait' it is found in several fires where people rather tend to walk through smoke or even choose to jump out of the building instead of shelter and wait for being rescued [Proulx, 2003; SFPE, 2002; Gwynne et al., 2001; Graham & Roberts, 2000]. On the other hand, the strategy to instruct occupants of hotel or residential buildings to stay in their rooms / apartments is likely to be effective for the survival of a fire [Demers, 1981; Bryan, 1992].

Evacuation is the process in which the people in a building notice a fire and whereupon they experience several mental processes and carry out several actions before and/or during the movement to a safe place in or outside the building [SFPE, 2002]. This evacuation process is characterised by three certain basic activities and phases [O'Connor, 2005; Frantzich, 1994; Purser & Bensilum, 2001]:

- Awareness of danger by external stimuli (cue validation period)
- Validation of, and response to danger indicators (decision-making period)
- Movement to / refuge in a safe place (movement period).

The phases of clue validation and decision-making together are the pre-movement period.

## 2.2 Main findings on human behavior in evacuation

*Cue validation phase*

Since decision-making during evacuation depends upon the clues that the occupants perceive and on the occupants' interpretation of these clues, clue validation is an important process in evacuation. The perception of danger determines the reaction on signs of danger [Graham & Roberts, 2000].

A fire alarm bell or a 'slow whoop' signal is hardly recognized as a sign of danger and thus usually ignored by the occupants present in a building [Proulx, 2000b; Proulx & Laroche, 2001]. In addition sleeping children, elderly, people with a sleep delay, people under the influence of narcotics, alcohol or drugs and people in environments with significant background noise are unlikely to be waken up by a fire alarm [Bruck, 2001]. A fire alarm using a spoken message, or a communication system using personnel directives, is taken most seriously by the occupants present in a building [Proulx, 2000b; Proulx & Laroche, 2001; Proulx & Richardson, 2002].

The sight and smell of fire and smoke are the clearest indications of a dangerous situation and the need for evacuation [Proulx, 2001a]. Nevertheless, even then people are found to continue their normal activities and wait for other people to respond first before they take actions [Fahy & Proulx, 2001; Sandberg, 1997]. Several accidents and experiments indicate that evacuation training of personnel has a positive influence on the reduction of the pre-movement time [Fahy & Proulx, 2001; Purser & Bensilum, 2001; Sandberg, 1997].

Indications and clues which generally lead to an exploration of the situation, in case of fire, are [Tong & Canter, 1985]:

- Hearing a strange sound
- Uncommon behaviour of other people in the surroundings
- Observing fire and smoke.

In many cases the degree of uncertainty concerning the danger of the situation delays the beginning of an evacuation. Therefore, eliminating uncertainty is an important factor on improving human behaviour in fires.

*Decision-making phase*
Occupants normally evacuate using familiar routes, mostly the main exit which is normally the entrance of a building [Graham & Roberts, 2000; Sandberg, 1997]. The choice of route depends upon the familiarity of the occupants with the building, the availability of exits, the accessibility of the route towards exits and upon the lay-out complexity [O'Connor, 2005; SFPE, 2002]. Furthermore affiliative behaviour is considered to effect route choices during an evacuation [Cornwell, 2003]. Not the actual length but how it is perceived determines the route choice [Graham & Roberts, 2000; Sandberg, 1997; Gwynne et al., 2001]. For example, corridors with several corners and unfamiliar routes are experienced to be longer than straight and familiar routes [Løvås, 1998].

Fire exits which are not regularly used tend to have a negative association [Benthorn & Frantzich, 1996]. Based upon evacuation experiments in a department store it is presumed that the fire exit will only be used if the door is open and additionally if the walking distance towards the main entrance is two times longer than the walking distance towards the fire exits. Besides, during a fire in an elderly care home 95% of the patients were evacuated through the main staircase and the other three available emergency staircases were not used at all. As a result the total evacuation time was longer than calculated by the architect. Experiments and incident evaluations appear to show that personnel directives on route choice have a positive effect on the utilization of fire exits [Graham & Roberts, 2000; Sandberg, 1997; Benthorn & Frantzich, 1996; Johnson, 2005].

*Movement phase*
Incident evaluations have shown that people are confronted with smoke during evacuation [Frantzich, 1994; Gwynne et al., 2001]. Several interviewed evacuees who have tried to evacuate through smoke, declared that they had to change direction or even had to return because of breathing problems, vision reduction, fear or other reasons [Gwynne et al., 2001]. The reduction of sight and the irritation of breadthways as a result of smoke development have both a negative influence on occupants' way finding performance.

Way finding covers the way how people orientate themselves within a building [Raubal & Egenhofer, 1998]. People need to have spatial knowledge and various cognitive abilities to succeed in way finding. Two aspects are crucial in way finding performance, namely cues and choices. The way finding performance is determined by the perception and prior knowledge of persons who have to find their way within a building. Furthermore, there are four classes of spatial variables that influence way finding performance [Raubal & Egenhofer, 1998]:

- Visual access
- The degree of architectural differentiation
- The use of signs and room numbers to provide identification or directional information
- Plan configuration.

Way finding is supposed to be more dependent on the lay-out of the building and seems to be barely dependent on (escape) route signs [Raubal & Egenhofer, 1998]. Incident evaluations indicate that evacuees are hardly aware of the presence of escape route signs at ceiling level or at least their route choice is not based upon them [Johnson, 2005; Ouelette, 1993]. Nevertheless, experiments show that photoluminescent low-level exit path markings are likely to be more effective during a fire evacuation compared to conventional escape route signs [Ouelette, 1993; Proulx et al., 2000].

## 3. Fire risk assessment of a building design

### 3.1 Fire risk assessment

The fire risk of a building design is the probability and the consequences of fire in a building. Fire risk assessment is the process of estimating the fire safety performance of a building design.

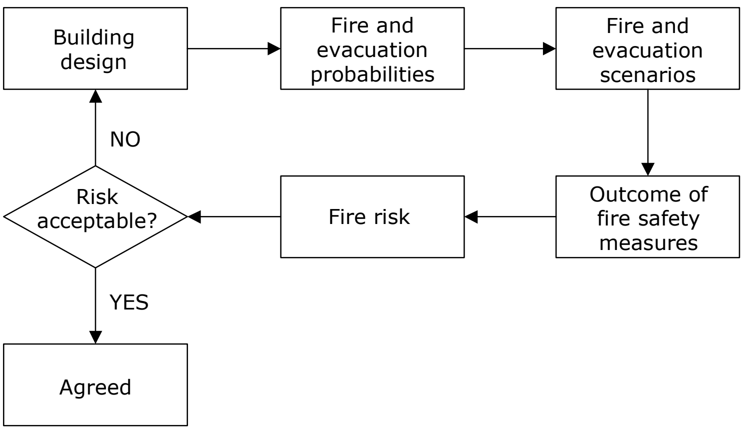


Figure 1: Fire risk assessment flow chart [Kobes, 2008]

The fire risk assessment starts with selecting the fire risk potentials of the building design. This selection of fire risk potentials can be based on the determinants for the fire safety performance of buildings (concerning human behavior).

Once the fire risk potentials of the building design are defined it is feasible to estimate the probability of fire originate in the specific building design and thereupon the consequences of fire in the specific building design. The estimation of the probabilities has to depend on data from statistics and casuistry on fires in comparable buildings. The required data to estimate the probability of fire originate can be:

- the amount of buildings with comparable features (i.e. occupancy)
- the amount of fires in a year

The amount of buildings with comparable features divided by the amount of fires in a year is the probability of fire originate in the specific building design. The required data to estimate the consequences of fire can be the following:

- characteristic fire causes
- characteristic fire development

- the amount of property damage
- characteristic human behavior in case of fire
- the amount of injuries and deaths in case of fire.

These distinctive consequences based on casuistry can be linked to fire scenarios and evacuation scenarios. By describing the scenarios basically the building fire safety performance is made qualified for a risk assessment.

### 3.2 Building fire safety performance

Based on the literature review [Kobes, 2008] three sets of determinants for the fire safety performance of buildings (relating to human behavior) are found. The range of human features are the first set of determinants, the range of building features are the second set and the range of fire features are the third set of determinants. The interactions between the (behaviour of) people, (the design of) the building and (the effects of) the fire take place during the clue validation period, the decision-making period as well as during the movement period.

The fire safety performance of a building is the degree in which on one side the fire threat has been reduced and on the other side the possibility of a rapid and save escape has been provided. By measuring the fire safety performance it is possible to predict the probability and extent of fire losses in terms of property damage, injuries and deaths.

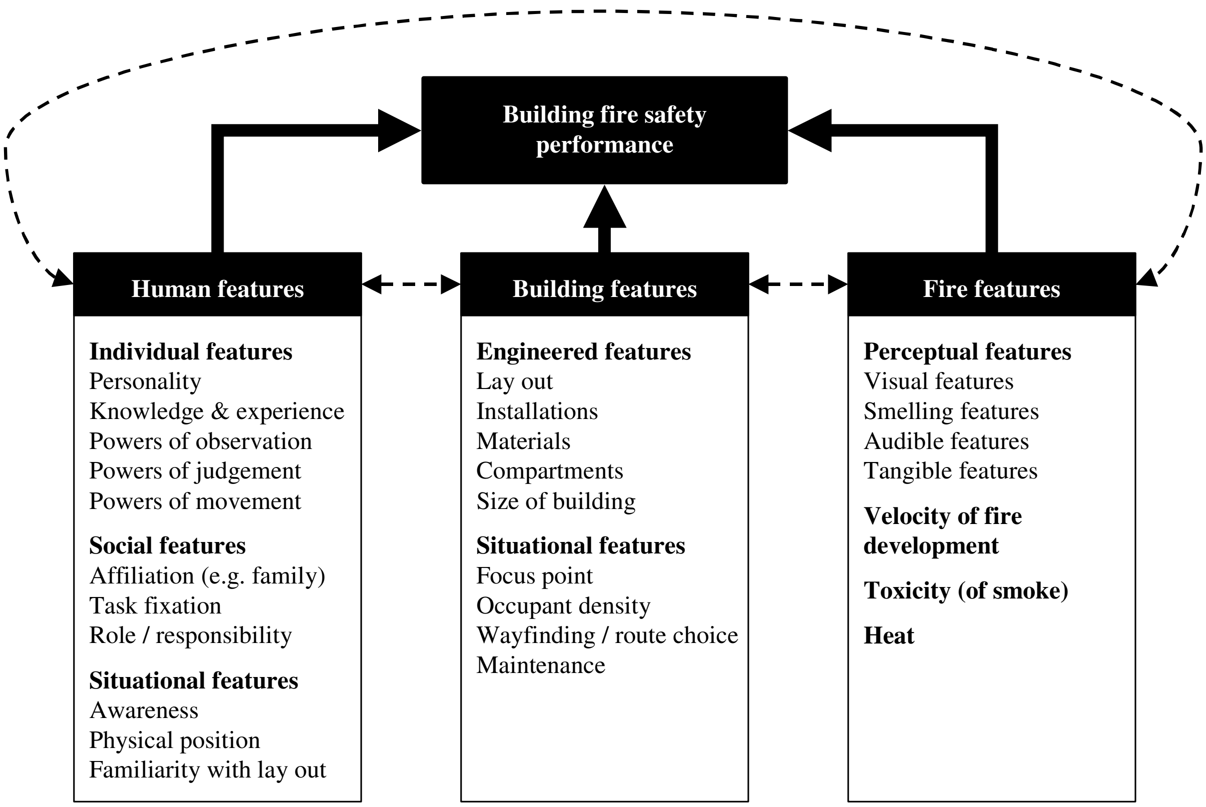


Figure 2: Determinants for building fire safety performance

The fire safety performance is historically measured in time [SFPE, 2002; BSI, 2004; BZK, 1995]. The fire threat is measured by the Available Safe Egress Time (ASET), which is based on fire scenarios and fire suppression scenarios. A fire scenario describes start or ignition, development and effects of a fire. A fire repression scenario describes the suppression and extinguishment of a fire. The possibility of a rapid and save escape is measured by the Required Safe Egress Time (RSET), which is based on evacuation scenarios. An evacuation scenario describes the human behavior in case of fire. Based on these three scenarios the required fire safety measures of a building design can be engineered.

### 3.3 Probability of fire fatality

Worldwide most of the fire fatalities occur at night in residential buildings in which occupants are asleep [Irvine et al., 2000; Bruck, 2001; Kobes, 2008]. In the Netherlands major fatal fires with more than five deaths per fire mostly occur in residential buildings and in public buildings [Kobes, 2008]. The major fires in public buildings have occurred in hotel accommodations (4 fires, 63 deaths), psychiatric institutions (3 fires, 31 deaths), homes for the elderly (2 fires, 14 deaths), a crowded pub (1 fire, 14 deaths), a night club (13 deaths) and a detention building (1 fire, 11 deaths).

In the Netherlands all the type of buildings mentioned above rarely have a sprinkler system. Statistical studies [NFPA, 2006a-c; NFPA, 2007] show that a automatic sprinkler will sharply decrease the fire damage and also the loss of lives (and injuries).

Almost in all major fatal fires an operational fire alarm system was lacking [Kobes, 2008]. Hence, most of these fires were noticed in a late stage. Consequently, survivors accounted a very rapid fire development as soon as they discovered the fire. Furthermore in most cases there was no trained Building Evacuation Team (BET) present. In all of the cases the main entrance was blocked by smoke and heat of the fire. Additionally, in half of the cases the fire exits were (or were assumed to be) locked and for that reason they could not be used. Therefore the occupants had to jump out of a window or had to wait to be rescued by bystanders, personnel and the fire brigade [Kobes, 2008].

In the USA most of the major fatal fires have occurred in assembly buildings with high occupant densities, specifically night clubs and theatres [Tubbs, 2004]. The determining factors for fatality in these fires are found to be the combustibility of the interior finishing, the existence of blocked, closed or hidden (fire) exits, the limited capacity of the exits and the high number of occupants present in the building during the fire [Tubbs, 2004].

## 4. Main findings on fires in high-rise buildings

Imperative for the understanding of human behaviour in high-rise building evacuation are the studies on the WTC evacuation (1993) and the WTC 9/11 disaster (2001) [Fahy & Proulx, 2005; Bukowski, 2005; Proulx, 2007; Averill et al., 2005, Averill et al., 2007; Galea, 2005; Galea et al., 2007]. The researchers found data about escape times, pre-movement times and actions, the flow in staircases, the use of elevators among other things. Data gathered from research on the WTC 9/11 disaster is incorporated in a database (HEED[1]) which is accessible for researchers internationally [Galea, 2005; Galea et al., 2007].

[1] High-rise Evacuation Evaluation Database (HEED).

## 4.1 Staircases

Fatal fires in more-storey buildings have shown that there is a high probability of fire and/or smoke in staircases. This finding suggests that the measurements for the fire safety in staircases needs extra attention. In response to the evacuation studies after the WTC 9/11 attack, the requirements for staircases in high-rise buildings have been changed. For the changes see [ASSE, 2007].

Recent studies on the evacuation of high-rise office building reveal that the movement velocity is generally slow if the building is completely occupied [Proulx, 2007]. People who are in the staircase commonly feel that they have priority and let only few persons enter the downward flow of evacuees in the staircase. The following aspects are of great influence on the (downward) evacuation velocity in the staircase [Proulx, 2007]:

- size of the staircase
- population density in the staircase
- simultaneous evacuation from several floors
- evacuees trying to join the downward flow of evacuees in the staircase
- small talks between evacuees
- the use of cell phones and blackberries (or other smart phones)
- evacuees with overweight, extreme long and short evacuees
- unsuitable footwear (squeezing shoes, high heels, etcetera)
- counter flow of firefighters.

Studies on the evacuation of the WTC towers (1993 and 2001) also show that more people are facing difficulties when walking down the stairs than was estimated [Bukowski, 2005; Proulx, 2007; Averill et al., 2007]. Especially when long distances have to be traversed downwards stairs the number of people that encounter difficulties are high [Bukowski, 2005; Averill et al., 2007]. Furthermore, occupants are often not familiar with the staircases in high-rise buildings. Averill et al. (2007) found that 51% of the survivors of WTC 9/11 had never used the WTC stairs before. Occupants are more familiar with the elevators they normally use.

## 4.2 Elevators

In case of fire evacuees routinely or usually use a escape route that they are familiar with [O'Connor, 2005; SFPE, 2002; Graham & Roberts, 2000; Sandberg, 1997]. Consequently, in high-rise buildings occupants tend to use the elevator for their escape. The idea of making the use of elevators suited for evacuation in case fire dates from the beginning of the 1980's [Proulx, 2001b]. Nevertheless there is little empirical data available on the effect of the use of elevators on the change of surviving a fire. The studies on the WTC 9/11 disaster are the most important so far.

Although it is not allowed to use elevators in case of fire currently, the use of elevators can accelerate the evacuation and save lives in high-rise buildings [Proulx, 2001b; Fahy & Proulx, 2005; Averill et al., 2007]. In the WTC 9/11 disaster 27% of 158 interviewed survivors of WTC-2 made use of elevators [Fahy & Proulx, 2005]. Based on another study, in which over 1000 survivors were interviewed, it is estimated that about 3000 lives in WTC-2 were saved because of the use of elevators during the first 16 minutes of the disaster [Averill et al., 2007].

Allowing the use of elevators in case of fire, it is necessary to warrant the fire safety of elevators though. For requirements see [ Proulx, 2001b] and [Black, 2002].

### 4.3 Strategy of shelter and wait for help

The strategy of fire departments and BETs to instruct occupants of hotel or residential buildings to stay in their rooms / apartments is likely to be effective for the survival of a fire in a high-rise building[Demers, 1981; Bryan, 1992]. This is one of the conclusions of two hotel fires in Las Vegas in 1980 and 1981. During the first fire in the 26-storey building MGM Grand Hotel [Bryan, 1992] 85 persons died and 785 persons were injured. Most of the people perished by smoke inhalation were found in staircases and corridors [Bryan, 1992]. Three months later eight persons died in a fire in the high-rise Hilton hotel in Las Vegas (1981) [Demers, 1981]. The new strategy of the Las Vegas Fire Department was to instruct the hotel guests to stay in their rooms and to take some actions to prevent that smoke would come into the room. The instructions were given through the hotel telephone system. More information about the fire development was given to the hotel guests using news reporters who rushed to the fire location to make their news item for their television network. This new strategy was likely the most important factor of the relatively small figure of deaths [Demers, 1981]. Nevertheless, this strategy is only suitable if it is certain that the fire and smoke will not extend to the adjacent rooms/apartments and that the building will not collapse before all the occupants are brought to a save place.

## 5. Conclusion

To prevent high fatality in case of fire in high-rise buildings there are four main observations to denote.

First of all, in buildings where vulnerable people are present, such as care homes and hospitals, and in buildings where the people can be asleep, such as residential buildings, it is vital to prevent a large fire and smoke development. In other words, it is essential to extinguish or suppress an initiated fire as soon as possible. For that reason it is necessary to fit a sprinkler system in high-rise buildings, especially in high-rise apartment buildings, hotels and other high risk occupancy with regard to fire fatality.

Additionally, in many fires it is found that occupants normally evacuate by using familiar routes, mostly the main exit which is normally the entrance of a building. In a high-rise building the familiar route to the main exit is the use of an elevator. Therefore it is essential to make fire safe elevators so it is safe to use lifts in case of fire.

Furthermore, there are some aspects pointed out by Proulx (2007) that have great influence on the (downward) evacuation velocity in staircases. For making a safe evacuation possible by the use of staircases it is crucial to make staircase in such a way that they redress the aspects that have a negative influence on the velocity, such as counter flows of fire fighters who want to enter the building by use of staircases. A feasible solution is to make extra staircases that are especially designed and only for fire fighters to make use of.

And last but not least, in many evacuations it is found that people hardly respond on signals of fire, such as a fire alarm. People mostly wait for others to take the first respond. In case of fire the very fast response is nevertheless very critical for the survival of the fire situation. Spoken messages and personnel directives are found to be effective for the direct start of an evacuation and for the use of fire exits. So for making a rapid evacuation possible it is recommended to make use of spoken messages and to educate and train key role employees in organizations in the coordination of an evacuation. These key role employees are for example staff managers, receptionists, waitresses and teachers. In high-rise buildings it is possibly more effective to shelter and wait in a safe place in stead of evacuate all the people inside. The strategy of shelter and wait is only reasonable if the building features support this strategy. Therefore it is necessary to have a sprinkler system active during the fire, to fence in the smoke spreading and there have to be measures taken that make it possible to rescue awaiting people in a safe manner and in a short time. For requirements see also [Proulx, 2001b].

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