A Probabilistic Risk Analysis Methodology for High-rise Buildings taking into Account Fire Department Intervention Time

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ABSTRACT

Fire safety regulations have a major impact on many aspects of the overall design of high-rise buildings, where complex and non-conventional architectural elements and designs can lead to fire environments diverging significantly from those used in the development of current codes and standards. Additionally, fire-fighting in high-rise buildings must be carried out from the inside of the building and fire-fighters must use stairwells or special fire-fighter lifts to access the floors which are on fire

One way of assessing fire risk in such complex buildings is to use the principles of quantitative risk analysis (QRA), where deterministic and probabilistic models are combined to quantify risk and compare different fire safety strategies. In order to do this in high-rise buildings, account must be taken of the fire department intervention time in the QRA methodology, but data on the various parts of fire department action time has been scarce..

This paper focuses on the effect of the fire department intervention in high-rise building fires and how information on fire department intervention can be accounted for when using quantitative risk analysis to compare different fire safety strategies in such buildings.

KEYWORDS: analysis, egress, performance-based design, reliability, risk assessment, statistics.

INTRODUCTION

The increase in the construction of high-rise buildings through the last decades has put the focus of authorities and designers on the fire risks associated with such buildings and hence the possibilities of successful intervention of the fire department, where the time it takes from ignition until the fire-fighters are at the site and can start to fight the fire is the most important factor.

In order to analyse the risk associated to high-rise buildings and the probability of successful fire-fighting, it is important to analyse in detail the time that comprises the total time, from ignition to when the extinguishing action starts, and in design, facilitate the fire-fighters approach in order to shorten the action time within the building. This time depends on fire technical "notification" systems as well as the distance from the fire station, information available and the means of which the fire-fighters enter the fire scene.

To do a successful risk analysis of a high-rise building, taking into account the total time from ignition until the fire brigade reaches the location of the fire, the analysis must incorporate the different segments of the total time and take into account the variety of what this time comprises. This can only be done by using a probabilistic approach to fully take into account the possibility of failure for technical systems and distributions of the various time segments.

For high-rise buildings, the consequences associated with failure of fire technical systems and increase in fire brigade intervention time, become more critical than in a conventional building. Hence, a more thorough risk analysis is necessary to ensure that every aspect of the risk is taken into account.

FIRE SAFETY SCIENCE–PROCEEDINGS OF THE NINTH INTERNATIONAL SYMPOSIUM, pp. 957-968

In an earlier paper [1], a case study was presented, where a similar methodology was used to assess the fire risk in a high-rise building and a model was used to compare the efficiency of various fire safety systems. In this paper we use additional data to expand the methodology and the model in order to widen the applicability of the method.

PROBABILISTIC APPROACH FOR FIRE DESIGN

General

Probabilistic models for fire safety can be combined in various ways with deterministic fire models, such procedures regard the fire as being deterministic once the fire is fully defined but some of the inputs are assumed to be probabilistic variables. In design, such methodologies have been termed risk based fire safety engineering but the methodology has also been used for other purposes, such as the analysis of uncertainties in deterministic models.

Probabilistic models have gained increased attention within the fire science community with the shift from prescriptive codes to performance based codes. Using active technical solutions for fire safety in a high-rise building, such as sprinklers, can greatly improve the fire safety level in the building, when these systems work. However, the reliability of these systems is never 100 % and thus the case when they fail also has to be considered. Using probabilistic methods provides the engineer with the possibility of taking these cases into consideration and calculating the overall fire safety level of the building.

Using Monte Carlo based simulations allows the failure of individual fire safety systems to be simulated, depending on their reliability, and facilitates the creation of a simple and general model that can take into account all installed fire safety equipment and their reliability. Since the simulation model is made up of several modules, it is easy to compare different fire safety solutions by running simulations with different fire safety equipment installed.

Time from ignition to fire department intervention

The total time it takes from the ignition of the fire until the fire department starts to fight the fire can be modelled as seen in Figure 1. Some of these times are made up of several modules, such as the detection time which can depend on either manual detection time, the fire alarm detection time or the sprinkler system actuation time, and the actual detection time will be the shortest of these three times in the case that all systems works and detects the fire.

The total time from alarm to the time the fire-fighters start attacking the fire has been divided into five main parts and a number of sub-modules depending on what kind of fire safety equipment that is used in the building studied. A partly new model has been created to simulate the unmitigated fire growth time, where the different parts consist of individual modules. These modules are e.g. the detection time of installed equipment or manual detection time, the time delay before the alarm central is called, the dispatch time, the turnout time, the response time and the on-site activation time. A special focus is put on the fire-fighter lifts and other high-rise fire-fighting measures and their effect of the unmitigated fire growth time.

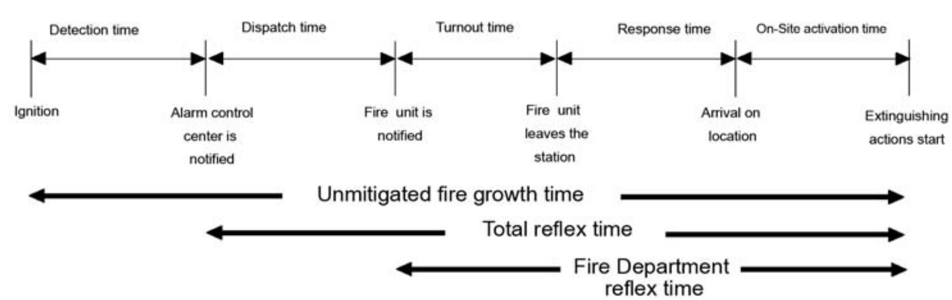

Fig. 1. Time line of the unmitigated fire growth time.

Taking the entire time from ignition to the start of extinguishing actions, it is important to be able to show how large impact a reduction of the total time will have. In some cases a reduction of a few minutes will not have any significant impact on the probability of the fire department's possibility to put out a fire where as in other cases a reduction of the time with 30 seconds will be crucial for the success of the fire-fighters. This can only be analyzed with probabilistic methods taking into the account the variation in the data samples and "all" possible combination of options.

Data samples

New research on fire department response and travel time for the Reykjavik Capital District Fire and Rescue Service (CDFRS) [2] is documented in this paper and incorporated into the model. This is done to create an as exact model as possible for the unmitigated fire growth time. It is also done to compare with the results of previous Finnish studies [5] of the reaction and travel time and whether the results can be generalized to other cities with similar size and infrastructure or not.

Data from the ambulance alarm database has been used for this report, while the less developed fire and rescue alarm database has been used to check how well the data is representing the fire and rescue part. This indicates that the dispatch time might be underestimated by 30 seconds, the turnout time by about 15 seconds, while the response time shows no significant difference. The data used in the results presented in this report is from January 2005 - October 2007.

Detection time

According to Icelandic regulations [11] all automatic fire alarms in high-rise buildings have to be connected to the fire department and therefore the time between detection and notification of the fire department is zero in the case that the fire alarm system works. Therefore no separate parameter considers the time between the detection of the fire and the time until the alarm control centre is notified. This time needs, however, to be taken into account in the case where the fire alarm fails to notify the fire department or in the case where there is no fire alarm available that automatically notifies the fire department.

The detection time depends on the mode of detection, the distance between detectors and the fire growth and the layout of the fire cell. Thus it is hard to set up a general model for the detection time, as the model has to be able to take into consideration a variation of these factors. With given information of the mode of detection (e.g. smoke detection system), floor height etc, the perimeter of the detection time can be minimized and thus increasing the accuracy of the model. If however, the system is not working, the detection relies on manual detection with far greater uncertainty in time. The distributions will have to be constructed for each building individually, taking all these factors into account.

Dispatch time

The dispatch time is the time from when the fire alarm control centre is notified until the fire unit is notified. The dispatch time is dependent on both the technology systems in the stations as well as the operation of the personnel, see Fig. 2.

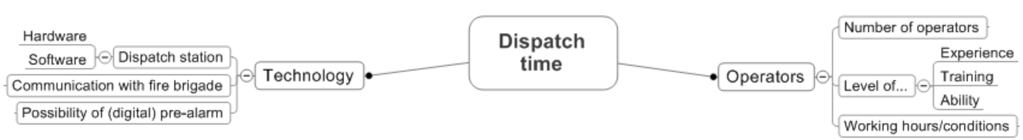

Fig. 2. Parameters affecting the dispatch time.

The technology has been evolving rapidly over the last decade, but with technology comes dependence on data (IT) systems and the complexity increases. This development has lead to a shortening of the dispatch time but it is questionable if the robustness has increased given the increased dependence on complex data systems. All the data systems are reliant on electricity and secure channels of communication, as well as highly trained personnel. Therefore, backup systems for electricity and computer servers are vital, as well as contingency plans for worst case scenarios.

As the operational procedures are constantly increasing in complexity, it is an important challenge to keep the well trained dispatch operators from changing jobs. The introduction of new operators is nevertheless a necessity, and this has to be handled with care. The dispatch time of the Icelandic emergency centre has been recorded for a number of years and displays a decreasing trend due to the above mentioned factors. Thus, as earlier mentioned, only data from 2005 to October 2007 was used when analyzing the distribution of the Icelandic dispatch time. The database does not only contain emergency alarms but also all kinds of other alarms and thus only alarms classified as priority alarms were considered when fitting a distribution to the data. This left a total of 6321 data samples of dispatch times that were used for fitting the distribution. The software BestFit 4.5 [6] was used to fit the distribution as presented in [1]. A lognormal distribution with μ= 58.7 and σ=47.8, which is presented in Fig. 3 described the dispatch time best.

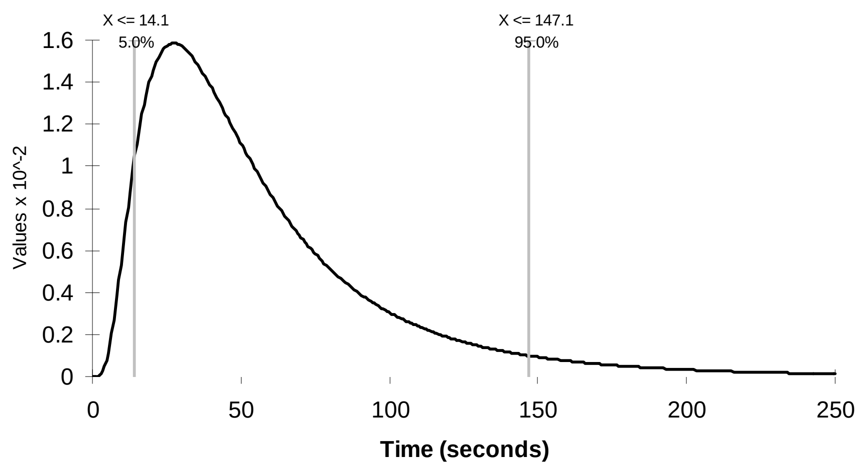

Fig. 3. The found distribution of the dispatch time, lognorm(58.7, 47.8).

Turnout time

The turnout time is the time from when the fire unit is notified until the unit is out of the station. The turnout time depends on the design of the fire station, internal communication and the availability of the fire-fighters, see Fig. 4.

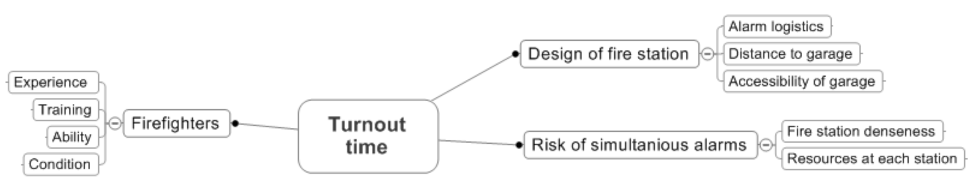

Fig. 4. Parameters affecting the turnout time.

Allowing the nightshift to sleep between alarms certainly lengthens the turnout time at night. At CDFRS this has been deemed acceptable as the response time is shorter at night but there is a potential here to improve the reflex time. A change in this aspect is very likely to affect morale though, and is perhaps not motivated considering the low number of alarms at night. This fact does, however, have an effect on the data analysis to some extent since at night it is expected that the turnout time is longer, but on the other hand the response time is shorter. We have, however, not taken this correlation into account in this study and therefore the spread of the total unmitigated fire growth time actually might be smaller than suggested by the findings of our study.

The highest potential for negatively affecting the turnout time is when simultaneous alarms occur. This could mean that there are two priority alarms for the same fire department station at the same time. The risk of simultaneous alarms is always present for any fire department. While the frequency is certainly higher for the big fire departments that serve a large number of people, the consequences are generally larger for smaller departments that have less resource to allocate. The CDFRS is a relatively small fire department in international comparison, serving about 190.000 inhabitants. The fact that the CDFRS also handles all ambulance transports in the capital area, and all the response personnel are educated and trained for both fire and ambulance, it has unusually good resource availability for its size.

The extent of these situations has not been analyzed particularly for the given data. However, the risk of simultaneous alarms has partly been taken into account by the use of extreme value distributions used for describing the turnout time. The turnout time of emergency vehicles in Reykjavik has been collected for the same period as the dispatch time, but does not show a significant trend. However, to keep the continuity in the data material, the same reference period used for calculating the dispatch time was used to calculate the distribution of the turnout time as presented in [1]. A lognormal distribution with the parameters μ= 88.4 and σ=41.1 as shown in Fig. 5 was found to be the best fit to the data.

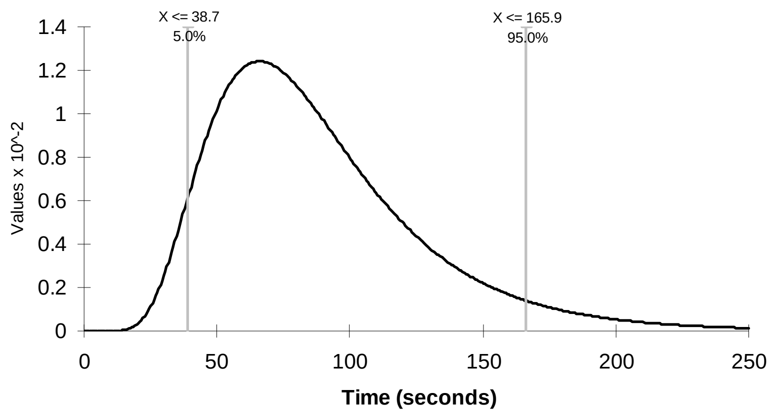

Fig. 5. The found distribution of the turnout time, lognorm(88.4, 41.1).

As can be seen in Fig. 5, 95 percent of the values in the found distribution are within a relatively small interval, but the long tail of the lognormal distribution takes into account the extreme values that might arise in the case of simultaneous alarms or other events that will increase the turnout time significantly.

Response time

The time that passes from the fire unit leaves the station until arrival on location is termed the response time. The response time is dependent on the distance from the fire station to the location of the fire as well as the traffic conditions and the driver and vehicle ability to cope with the situation, see Fig. 6.

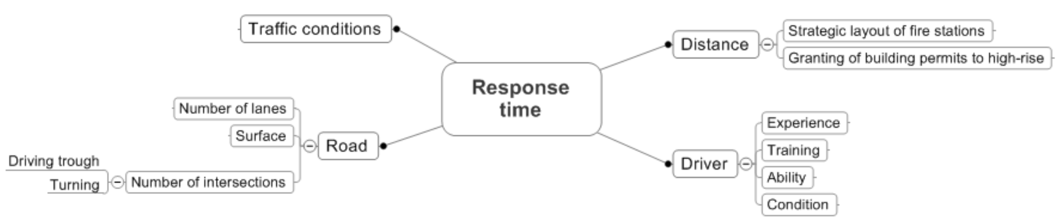

Fig. 6. Parameters affecting the response time

The most important parameter regarding the response time is, however, the distance and this parameter can not be manipulated since the placement of the fire department and a specific building are in most cases fixed. However, in the case that the fire station is relocated the validity of the made calculations can be shifted quite drastically and this is also an important parameter to take into account when doing a complete risk assessment. This is actually the case in Reykjavik, where in the near future, the operations at one of the fire stations is about to be terminated and instead two new stations will be created to better serve the entire capital area. As can be seen in Figs. 7 and 8, the coverage of the fire department will be significantly better both in general but also regarding high-rises.

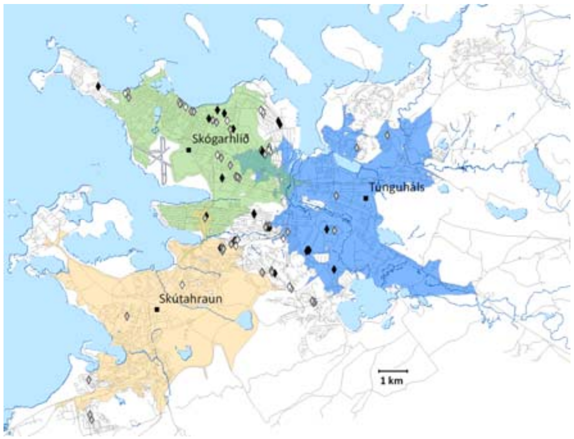

Fig. 7. Location of fire stations in Reykjavík 2008 and areas reached within 10 minutes. B

Fig. 8. Proposed locations of fire stations in Reykjavík 2009 and areas reached within 10 minutes.

In Figs. 7 and 8 the black diamonds represent 8 floor buildings, the grey diamonds 9-10 floor buildings and the white diamonds represent buildings that exceed 10 floors. The reason why the buildings are categorized this way is that the larger of the two hydraulic platforms that the CDFRS commands can possibly reach the ninth or even the tenth floor if wind conditions and other circumstances are perfect (34m). This rarely holds true though – Iceland is a windy place, and the platform usually has to work from an angle.

The black squares represent fire stations and the shaded area surrounding each station represents a modelled 5 minute response time. This is calculated using the assumption that the response vehicle drives at the maximum allowed speed for each stretch of road, ignoring delays like intersections and speed bumps. After calibrations using real data, this time has been shown to reflect quite accurately (on average) both the required 8 minute total reflex time for the ambulances and the 10 minute reflex time for fire engines. The reason that the 8 minute ambulance time coincides with the 10 minute fire engine time is threefold – the fire engine has longer turnout, response and onsite activation times.

Data analysis, GIS analysis and other input have been used over the last several years to convince the board of the CDFRS to close one station (Tunguháls) and replace it with two other stations (Skarhólabraut and Stekkjarbakki). The decision has been made and the stations are to be operational at the end of 2009, although the exact location of the Stekkjarbakki station was still being debated when this article was written (end of May 2008). The fact that several high-rise buildings are outside the required reflex time (as Fig. 7 shows) has been an important factor in the decision process, although several other factors have been considered as well.

The simple travel time model presented in Tillander [5] was used to set up equations for the expected travel time and the resulting curve and the measured values were presented in a previous paper [1]. The resulting equations of the travel time were:

$$t_a = \begin{cases} 174.6\sqrt{s}, s \le 4.6km \\ 40.7s + 187.2, s \ge 4.6km \end{cases}$$

The many parameters affecting the travel time make it impossible to use the fitted response time curve presented above in the proposed model since this model gives a deterministic value and the model is based on distributions. The data does for example show that there is a difference of the average speed of almost 2 km/h between summer (June – August) and winter (December – February), but since we are expecting that the fire frequency is constant over the year this difference have no practical impact since these differences are taken into account by describing the response time with a distribution of the average speed. Thus the travel time used in the model is instead calculated using the raw data and by fitting distributions to the average speeds of a number of data points around the sought distance. The advantages with this approach are that since there is such a large amount of data available it is possible to assume that the derivative is constant in the studied interval. This approach also allows us to take into account the scattering of the data. In the studies presented in this paper a total of 200 data points were used to create distributions of the expected average speed at a certain distance where we have taken 100 data points before and 100 after the studied distance.

For distances longer than 4.6 km this is also true based on the equation presented earlier and for shorter distances the number of data points is so high that the controlled interval was smaller than 0.3 km and for this interval, the assumption can be regarded as acceptable. However, for really short distances (< 1km) the number of data points was so low that it was impossible to fit a distribution and a different approach is needed in these cases. The disadvantage of this approach is that you need access to the complete data material and the generalization of the results is very limited. However, our fitted distributions had in most cases high p-values indicating that the fitted distributions were accurate. To have a consistent model it was decided to use the same distribution for all distances and since a log logistic distribution in most cases fitted the data best it was used for all distributions. In the case that the found distribution had a shift that was below zero it was assumed that the shift was at zero since it is not possible to use negative values for the speed. The expected values of the distributions constructed from the data were not continuously increasing as can be seen in Fig. 9, but the overall trend was increasing suggesting that the used method is acceptable.

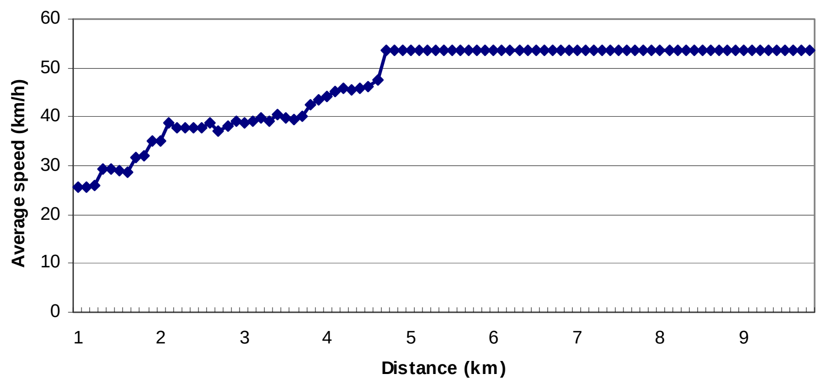

Fig. 9. Expected average speed based on the fitted distributions.

ON SITE ACTIVATION TIME IN HIGH-RISE BUILDINGS

General

The on site activation time is the time from when the fire unit arrives on location until the extinguishing action starts. The on site activation time is dependent on accessibility on the site, fire technical systems function and information as well as the location of the fire inside the building, see Fig. 10.

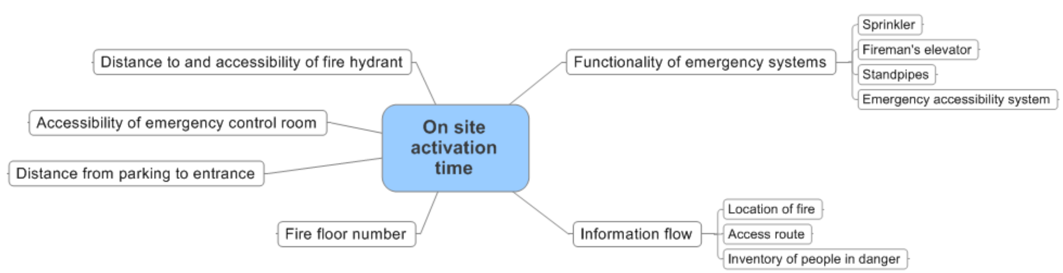

Fig. 10. Parameters affecting the “on site activation time”.

The on site activation time for the fire-fighters in high-rise buildings has some significant differences compared to regular buildings. Firstly, the possibility to attack the fire from the outside is very limited since the fire-fighters’ ladder trucks have a limited reach and thus the attack has to be performed from the inside. Secondly, with an increased height of the building the expected travel time for the fire-fighters within the building will increase.

Information on site is of great importance (e.g. the situation of the fire) as the time to obtain this information might be considerable, if the emergency systems are not functioning correctly due to the height of the building. There is also need to consider the placement of the "information central" as the risk of falling debris might influence the fire-fighting. In high-rises there are often requirements for additional fire safety measures such as fire alarm panels informing the fire-fighters where the fire was detected and fire elevators that can transport the fire-fighters rapidly to the originating floor.

Further, the egress of people might take a long time and may therefore influence the fire-fighting, especially the time to start the fire-fighting from the staircase. If the door needs to be open to facilitate fire-fighting operation, smoke is able to enter the staircase and contaminate it and the floors above the fire floor. Therefore it might be necessary to delay fire-fighting action until all occupants have been evacuated from the floors above the fire floor.

The fire-fighter elevator does not immediately solve the problem but with a well designed layout of the staircases and the installation of standpipes in the fire lobby provides possibilities to start fire-fighting activities even though the evacuation still takes place. Preferably the standpipes should have outlets within the staircase and also in the fire lobby, so as to avoid having to hold open the doors between the staircase and the fire floor. It is also of importance that the stairs have a connection to the fire-fighters lift through a fire lobby, to ensure that the attack can be performed fast, as suggested by the EN standard for fire-fighters lifts EN 81-72 [12].

Time to assist evacuees could furthermore be a significant factor, especially when elevators are not accessible for general evacuation. Also of importance is monitoring of lifts and egress and the communication to occupants as discussed in [7].

Test of on site activation time

Tests were conducted in a newly constructed 20 floor building in Reykjavik to gain more information regarding the travel time for fire-fighters ascending stairs. The fire-fighters had full breathing apparatus equipment and all other necessary equipment for initial attack, weighing between 21 and 34 kg depending on the fire-fighter's function. The stairwell in the building was 2.4 meters wide and stairs were 1.3 meters wide with intruding handrails of 0.05 m on each side. Each floor is 3.5 meters high except the bottom floor that contains shops and the height of this floor is 5.9 meters. The times of all the individual fire-fighters were measured from level 1 to level 9, 15 and 20 respectively.

Only two of the fire-fighters carrying breathing apparatus equipment (B & C) shown in Fig. 11 were measured for the time until they felt ready to perform an attack and thus the other two curves stop at their values at the 20th floor.

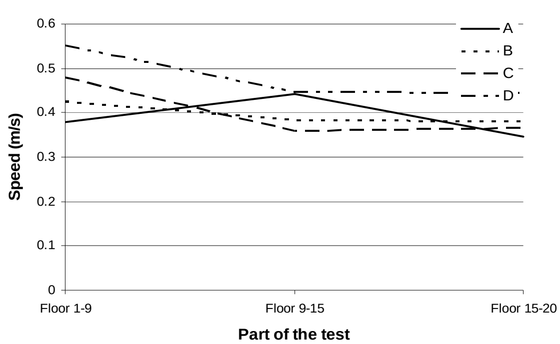

Fig. 11. Average speed between floors.

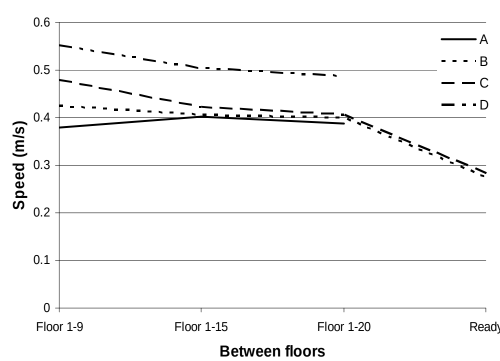

Fig.12. Overall average speed.

As seen in Figs. 11 and 12, the average speed was lower for all fire-fighters at the top floors which indicate that with higher buildings the travel times will be even longer. Using the travel times presented from different studies presented by Kuligowski & Bukowski in [8] the average speed of the fire-fighters are in the lower range of the presented study. The speed was measured as the speed over the actual distance in the staircase and not the vertical distance between the floors. This was done to be able to compare the results with previous studies, but also because the general applicability of the data is larger since it can be used at in staircases with different layouts as well. The actual distance for one floor was calculated as:

$$dist = 2*W + 2*\sqrt{L^2 + (H/2)^2}$$

W=Width of the staircase (m)

L= Horizontal length of one flight of stairs (m)

H=Height of one floor (m)

For the first 9 floors the average speed was between 0.38 m/s and 0.55 m/s, but when looking at the entire building the average speed was between 0.37 m/s and 0.46 m/s. However, when just looking at the speed for the 5 top floors the average speed had decreased even further to between 0.35 m/s and 0.45 m/s.

Once the fire-fighters have reached the fire-floor (in this case the top floor or the 19th floor) they must rest until they feel ready to activate the breathing apparatus and work on search and rescue.

This measurement relies on subjective judgment and depends on the physical attributes of the individual fire-fighter. Fire-fighter A felt ready at a pulse of 130 bpm (64% of maximum), while fire-fighter B had a pulse of 110 bpm (62% of maximum) when he felt ready. All the fire-fighters were around 95% of maximum pulse already at floor 9.

It is therefore also of interest to look at how long time it takes before the smoke divers are ready to perform their attack. In this case the fire-fighters felt ready to start their attack after 630 respectively 645 seconds. The fire-fighters had then travelled 178 meters along the stair which results in an average speed of 0.26-0.27 m/s. This value is significantly lower than the results from previous tests and our tests show that the speed probably will be even lower with higher buildings and this really highlights the need for fire-fighters lifts in high-rises.

In the test no persons were descending making the observed time non-conservative and closer to the optimal travel time instead of the most realistic one. This indicates that additional time could be added to account for the influence of people moving down the stairs and due to “distraction” from people seeking help. Further studies are thus needed not only to take the distraction factor into account but also to validate the results of this study, considering that the data material is very limited and restricted to only one layout of staircase. The results do, however, imply that the fire-fighters travel time inside the staircase might be significantly longer than previously assumed and the tests also gave the fire-fighters and officials important real life experience of how long the travel time inside the building actually might be.

PUTTING EVERYTHING TOGETHER

A spreadsheet model was used to set up and combine all the found distributions together with assigned conservative distributions of the detection time and the reliability of the installed fire safety systems. In the spreadsheet model the detection time is thus determined by the type of detection system installed; smoke detectors, heat detectors or sprinklers and their reliability. It is, however important to consider different failure modes since some failures might be connected and thus affecting both systems as for example if the automatic alarm to the fire department is disconnected, neither the activation of a sprinkler system nor a heat detector will be able to notify the fire department and the detection time will thus be significantly increased.

The total time model was set up in order to facilitate a comparative analysis of buildings built according to present regulations and buildings with alternative solutions. By running 10000 iterations of the model for the total action time a distribution of the total time was achieved. By combining this with the critical time when the fire-fighters where expected to be unable to put out the fire with their initial attack a probability of the fire-fighters putting out the fires was obtained.

Event trees and fault trees, together with the model presented here, have been used successfully in risk assessments when applying for building permits in Iceland, in order to show that the risk level is lower in a building according to the proposed design than a building built according to the current regulations [9].

APPLICATION OF THE MODEL

About the building

The model has been applied to a 19 storey building that is going to be built in downtown Reykjavik [9]. Each floor will be approximately 550 m^2 floor area and the main occupancy in the building will be offices. The building will be equipped with two over pressurized staircases with fire lobbies, sprinkler and smoke detection system as well as water-filled standpipes. The construction (concrete) is designed to withstand full natural fire scenario without collapse. There will also be a fire-fighters lift installed to reduce the action time of the fire-fighters for the upper floors. The fire-fighters lift will be made with dual-entry with a separate fire lobby to the main fire-staircase.

Sensitivity analysis

Some assumptions have to be made when performing a sensitivity analysis since there are so many parameters that have an impact on the total unmitigated fire growth time. In our analysis we have kept the distance between the fire department and the building constant to be able to use the found distributions. In this example we have assumed that the distance between the building and the fire department is 2.5 kilometers which is presented in Fig. 13. It is also necessary to decide on the number of floors and considering that the highest buildings in Iceland are 20 floors high this has been used when testing our model for high-rises.

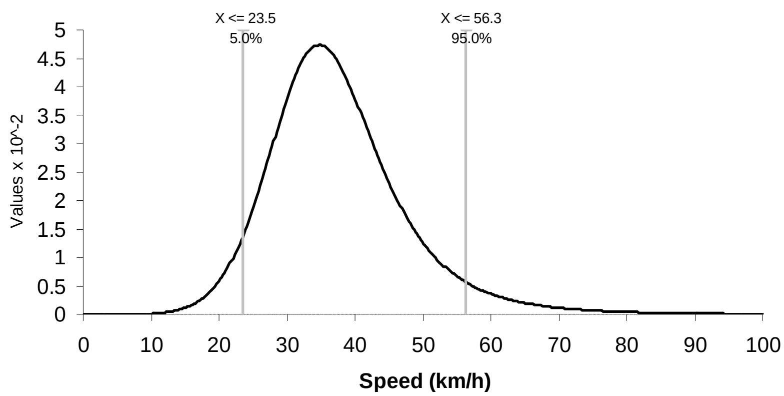

Fig. 13. Distribution of the average speed at 2.5 km distance from the fire station.

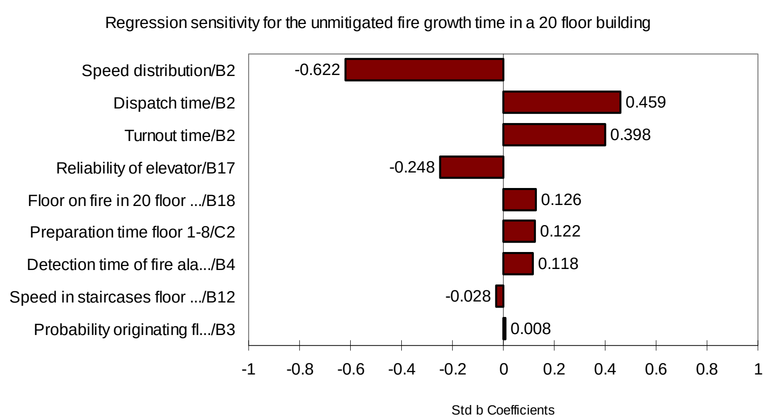

Fig. 14. Sensitivity analysis of the parameters affecting the total unmitigated fire growth time.

As can be seen in Fig. 14, the parameter that has the largest impact on the total unmitigated fire growth time is the speed followed by the dispatch time and the turnout time. After these three main parameters the reliability of elevators has the next largest impact on the unmitigated fire growth time. This can also be seen in Fig. 15 where the unmitigated fire growth time in the example building presented above is simulated with and without a fire elevator. The average unmitigated fire growth time is more than 2.5 minutes longer in a building with an installed fire-fighters elevator than in a building without one.

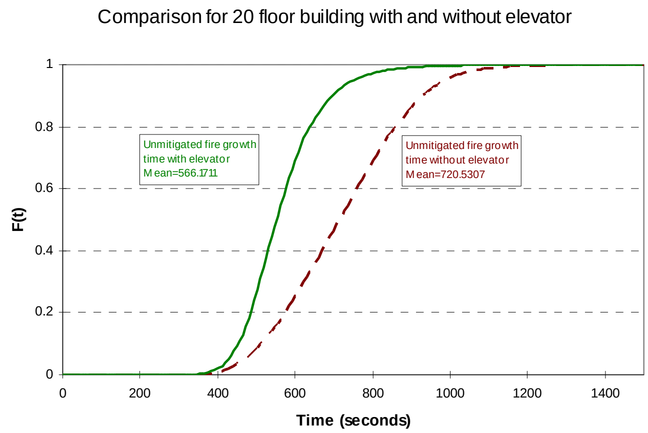

Fig. 15. Comparison of the unmitigated fire growth time in a 20 floor building with and without fire-fighters elevator.

Both the number of people subject to critical conditions and the economical consequences were modelled in event trees.

CONCLUSIONS

When assessing the risk level for high-rise buildings it is necessary to take into account the risk involved associated with the entire time from ignition to the time when the fire department begins intervention.

The paper outlines a methodology to assess the total unmitigated fire growth time and to compare this to a critical HRR when the fire-fighting intervention is expected to be unsuccessful. In order to do this a model must be set up including these various times and data must be collected.

This paper contains new data and distributions on the dispatch time, turnout time and response time and shows how this data has practical applicability when conducting risk analysis for high-rise buildings.

In addition to this, experimental studies on fire-fighters travel time in staircases have been carried out in a 20 storey building. The test simulated actual fire-fighting conditions, where the fire-fighters were carrying breathing apparatus equipment, measuring the fire-fighters physical condition and ability to carry out fire-fighting action. The result shows that the travel times are relatively long which emphasizes the need for increased fire safety measures in high-rise buildings compared to lower buildings.

The paper shows how a risk model can be built in order simulate the total response time for a fire department and what influence it has on the fire safety of the building. By using this model when evaluating the fire safety from a performance based perspective, an objective and impartial result is achieved which vouches for increased transparency and acceptance of performance based codes.

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