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Investigating Personal Safety in Case of Fire: A Probabilistic - Deterministic Analysis of a High-Rise Timber Building

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Abstract:
Due to difficulties documenting fire safety, event tree analysis is suggested as a probabilistic – deterministic analysis tool. By assessing probabilities and consequences of events, risk is identified. Quantifying risk leads to clear documentation as well as increased flexibility for fire safety engineers.

Two analyses are performed: analysing a timber and a concrete construction. By comparing the risk level between those two, the risk due to fire in the timber building is assessed, since the risk in the concrete building acts as an acceptance criterion. The analyses showed that risk was too high in the timber building, compared to the concrete building; hence, the personal safety due to fire is insufficient. However, by implementing measures, sufficient safety was documented for the timber building. Although this analysis is not complete it shows promise in regard to documentation of fire safety. Furthermore, event tree analysis is a powerful and versatile analysis tool that might be applied in many instances.

Keywords:

1. Probabilistic fire design
2. Event tree analysis
3. Quantitative risk assessment
4. Timber constructions

Abstract

After performance based building codes was introduced in Norway, documenting sufficient fire safety in buildings has proved difficult. In order to document sufficient fire safety, this thesis suggests probabilistic fire safety design, which means quantifying risk due to fire. Risk is a product of probabilities and consequences, meaning that probabilities of events and associated consequences must be identified. The probabilistic method chosen in this thesis is event tree analysis, which will be utilised to quantify personal risk due to fire.

An event tree is a logical description that describes the chronology of a fire. Events are typically related to fire protection systems such as sprinklers. Often the events are discrete, meaning that they represent systems functioning or failing. Probabilities of events are decided from statistical data, whereas consequences are decided by using well-known deterministic tools. By following different paths from the initiating event to the end of the event tree, different risks are calculated and total risk can be found.

Risk will be quantified for a timber construction, as they are becoming increasingly popular in the building industry. Products such as Cross Laminated Timber and Glue Laminated Timber allow tall timber buildings. Due to its aesthetic characteristics, it is desired that timber is visible in buildings, leading to large surface areas of unprotected timber. As timber is a combustible material and produces more smoke than allowed, a deviation from the Norwegian regulations and guidelines is caused. The deviation means that fire safety engineers must document that designs using timber are at least as safe as the solution presented by the guidelines. Documenting fire safety for timber constructions have proven to be even more challenging than documenting fire safety in buildings of incombustible materials.

Due to difficulties of documenting fire safety in timber buildings, the event tree analysis is performed at an 8-floor timber building (trial design), as well as a similar concrete building (reference building), which is an acceptance criterion. The risk levels are then compared to assess whether the safety of the trial design is sufficient or not. By comparing the results, both analyses are subject to the same uncertainties, eliminating uncertainty due to input parameters into the analysis, which is a major critique of the method.

The risk was successfully quantified in both the trial design and in the reference building. Since the risk in the trial design was approximately twice as high as the risk in the reference building, safety due to fire is too low. However, by implementing a structural measure, the risk level was reduced beneath the risk level of the reference building. Although the performed analysis is not complete, it shows promise regarding documentation of fire safety. Furthermore, several improvements have been suggested to deal with uncertain input parameters and long analysis time, which are two major critiques against probabilistic design. Moreover, the thesis showcases the opportunities of risk-based thinking, such as increased flexibility. Now the author calls upon the authorities to decide upon a quantified overall risk acceptance criterion. By doing so, fire safety engineers can create more value for all stakeholders, due to reduced computational resources.

Sammendrag

Etter funksjonsbaserte forskrifter ble innført i Norge, har dokumentasjon av tilstrekkelig brannsikkerhet vært utfordrende. I et forsøk på å forbedre situasjonen, er probabilistisk brannprosjektering foreslått. Probabilistisk brannprosjektering betyr å kvantifisere risiko, som er et produkt av sannsynlighet og konsekvens. Den valgte probabilistiske analysemetoden er hendelsestreanalyse.

Et hendelsestre beskriver hendelsesforløpet i en brann kronologisk. Nodene i hendelsestreet er hendelser som er knyttet til valgte brannbeskyttelsessystem. Hendelsene er typisk diskrete, som betyr at de beskriver funksjon eller feil. Sannsynligheter for hendelser er hentet fra anerkjent statistikk, mens konsekvenser er bestemt av velkjente deterministiske analyser. Ved å følge ulike stier gjennom hendelsestreet, kan risiko mot personsikkerheten beregnes, dermed er total risiko summen av alle kalkulerte risikoer.

Risiko kvantifiseres for et trebygg, ettersom bruk av tre blir mer og mer populært. Produkter som limtre og massivtre tillater høyere trebygg. På grunn av treets estetiske egenskaper, er det ønskelig at så mye tre er synlig som overhodet mulig. Tre er et brennbart materiale som også produserer en del røyk, derfor oppstår det et fravik fra veiledningen til reglementet. Dette medfører at branningeniører må dokumentere at sikkerheten til trebyggene er tilsvarende som sikkerheten i et bygg som følger veiledningen. Dokumentasjon av brannsikkerheten i trebygg har vist seg enda mer utfordrende enn dokumentasjon av brannsikkerhet generelt.

Pågrunn av disse utfordringene benyttes hendelsestreanalyse på et 8 etasjes trebygg og på et likt betongbygg. Risikoen til betongbygget er følgelig et risikoakseptkriterium. Risikoene er så sammenlignet for å undersøke om sikkerheten til trebygget er god nok. Ved sammenligning vil usikkerhetene ved inputen analysen bli eliminert, noe som er en stor utfordring ved bruk av hendelsestreanalyse.

Risiko ble kvantifisert for både trebygget og betongbygget. Ettersom risikoen trebygget var tilnærmet dobbelt så stor som betongbygget, var personsikkerheten for dårlig. Ved å gjennomføre et tiltak, ble derimot personsikkerheten påvist. Selv om analysen ikke er komplett, viser den lovende tendenser vedrørende dokumentasjon av brannsikkerhet. Flere forbedringer har blitt foreslått for å håndtere utfordringer som usikre input parametere og lang analysetid, to store utfordringer ved probabilistisk prosjektering. Oppgaven viser at risikobasert tenking har store fordeler som økt fleksibilitet for branningeniører. Forfatteren ønsker å se at myndighetene innfører et overordnet kvantifisert risikoakseptkriterium. Dette er fordelaktig, ettersom komparativ analyse ikke lenger er en nødvendighet, noe som sparer masse tid og ressurser. Dermed kan branningeniører konsentrere seg om å skape verdi for kundene.

Preface

This thesis concludes my 5 years doing my Master's Degree in Civil and Environmental Engineering at the Norwegian University of Science and Technology. The master thesis is written at the Department of Civil and Transport Engineering between 15th of January and 10th of June, as a specialisation within Fire Safety Engineering. The title of the thesis is: *Investigating personal safety due to fire: a probabilistic – deterministic design of a high-rise timber building.*

The topic of the thesis was suggested by Håkon Halvorsen in Norconsult AS, as an attempt to improve documentation of fire safety in buildings. It has therefore been natural to write the thesis in collaboration with Norconsult AS, in Sandvika, due to mutual interests.

I would like to thank my coming colleagues at Norconsult for bringing input to the thesis, and for making the long days at the office durable. I would also like to thank Harald Landrø for his positive encouragement. Finally, I would especially like to thank Håkon Halvorsen for assisting me in finishing this thesis. Your input has been invaluable, and it means a great deal for me that you have spent your time helping me. Thank you!

To all of you who have contributed in making the student life as amazing as it has been: Thank you for all the lessons learnt, for all the shared laughs and for all the conquered challenges.

I would like to thank my family for always being supportive and always being there for me. And last, but not least, I want to thank you Hedvik, for providing me with a clear direction throughout the last years. We made it.

"*All we have to decide is what to do with the time that is given us*" – Gandalf the Grey

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1.0 Introduction

1.1 Background

In 1997, the prescriptive buildings codes were replaced with performance based codes[1]. Due to the change, the development of buildings increased rapidly, because the flexibility of engineers increased many times. The flexibility increased because the new codes allowed solutions as long as performance were documented. Documentation of sufficient fire safety has proved challenging, since the documentation often consists of qualitative assessments of whether the design fulfils its performance or not. Qualitatively assessing if designs comply with the law is a lawyer's job, not the job of an engineer. Fire safety engineering is a young discipline, and it is highly complex due to factors such as: an uncontrollable source of energy, its interactions with buildings and the behaviour of people. That is nevertheless no excuse for not being able to document fire safety. Documentation of fire safety is important because the values of society depend on fire safe buildings. This is an excellent excuse to innovate and figure out novel ways of analysing and documenting fire safety. Probabilistic fire design is a possible answer to that question.

By utilising a probabilistic deterministic method, it is possible to quantify the risk of fire in a building. Risk is a product of the probability of an event happening and the associated consequence. To deal with probabilities an event tree is created and probabilities of events are assigned based on statistics. The consequences are evaluated by using well-known deterministic methods. This procedure is utilised to quantify the risk of fire in an 8-storey timber building, as well as the risk of a similar building that fulfils the pre-accepted solutions from the guidelines. The pre-accepted solutions specify the safety level set by the Norwegian government, meaning that the latter risk is a risk acceptance criterion. If the risk is equal to or lower than the risk acceptance criterion, the safety is sufficient; however, if the risk is higher the safety is insufficient. This leaves little room for uncertainty whether the safety is sufficient or not. Probabilistic fire design is not commonly used within the industry, as best case practices are not yet identified. The goal of this thesis is to reduce the resistance towards using probabilistic fire design.

According to the regulations, three different safety criteria must be dealt with when designing buildings with regard to fire[2]:

- Personal safety for inhabitants
- Material safety
- Environmental and societal safety

In order to do so, there are 5 things that must be considered in a performance based design[3]:

1. Load bearing capacity of structures
2. Limitation of fire and smoke spread
3. Fire spread to other areas
4. Evacuation opportunities of inhabitants
5. Ensuring safety of rescue teams

This thesis will mostly deal with 2 and 4, as well as touching on 3. These are the challenges that are identified as the most relevant regarding personal safety in case of fire. In other words, this thesis focuses solely upon personal safety in the case of fire.

One of the major innovations due to the change from prescriptive to performance-based codes is tall timber buildings. In the prescriptive code, timber buildings were limited to five floors[1]. After the change, engineers merely needed to document the performance of the building, meaning that numbers of possible solution increased. This led to new product innovations such as glue-laminated timber and cross-laminated timber, which have contributed to pushing the development even further. Although this development is positive, not all disciplines have been able to follow it, including fire safety. Many questions have remained unanswered regarding fire safety in timber buildings; hence, the documentation of fire safety in timber buildings has proved to be especially poor. By quantifying the risk due to fire in a timber building, two things are achieved: The first and foremost task of this thesis is to gain more knowledge on probabilistic design. Secondly, more insights are gained on fire design of timber structures; in other words, two birds are killed with one stone.

It is important to consider that the performance-based code was introduced in 1997. When this is written, the codes have not even been in place for 20 years. It is therefore understandable that the regulations and tools that exist to deal with this are not perfect. This coincides with fire safety engineering as a discipline, as it is very young compared to for instance structural engineering. Also it is highly complex, suggesting that it is to be expected that best-case practices have not yet been identified within the industry. With this perspective it is important to go forth with an open mind to investigate all possible solutions. The author firmly believes that this is the way to ensure a fire safe future and hopefully this work can be a part of that future.

1.2 Present Theory

This theory section is a short introduction to probabilistic design as a method, timber as a construction material as well as the regulations in Norway. It will be brief as the same topics are dealt with in chapter 2 and 3, which is method and theory successively.

1.2.1 Probabilistic design

Probabilistic design is a method, which gives a probability of failure, p_f, thus, provides the reliability of a chosen system from the equation $r = 1 - p_f$ [4]. It is a method that has been used in structural engineering for a long time. The probability of failure is the area between the probability distribution of failure and the probability distribution of the system's resistance, seen in figure 1.1. Translating this to fire safety, this is the procedure for probabilistic fire design according to Doorn and Hansson[5]:

1. Identify events that are not desirable. How does buildings catch fire?
2. Identify what accident sequences exist. If a room catches fire, the fire might spread out of the room.
3. Calculate the probability of every event. Tools that are utilised are typically empirical values or expert judgement.
4. Combine the information to a final assessment

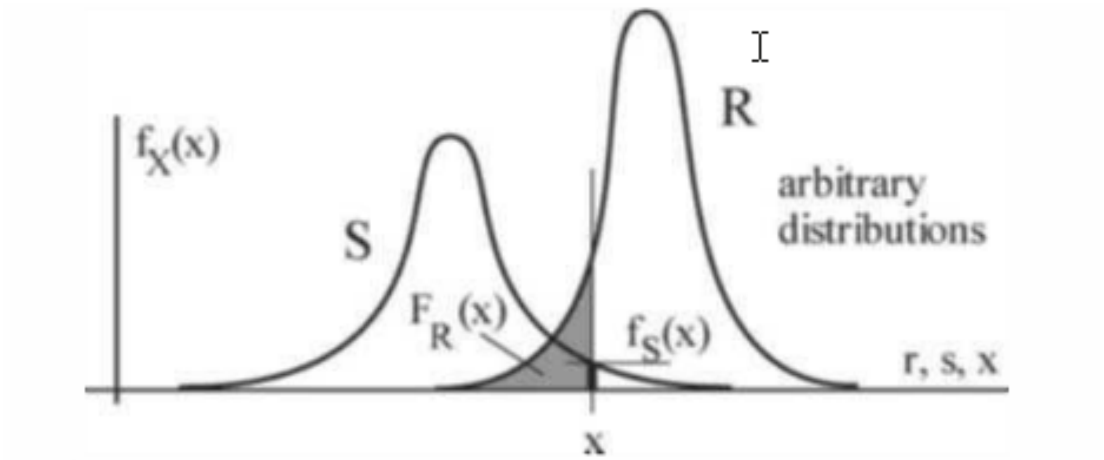

Figure 1.1 - Loads and resistance in structural engineering. S represents loads and R is resistance[4]

Probabilistic fire safety design works similarly; however, the distributions that are studied are fire resistance and fire severity. Typical parameters that are studied within fire safety are Available Safe Egress Time and Required Safe Egress Time, which is fire resistance and fire severity successively[6]. Based on these parameters, probability of events is identified; yet, the main advantage of using probabilistic design is quantifying risk. In order to quantify risk consequences of events must be found. Thus, probabilistic design coupled with deterministic methods is very suitable to calculate the risk due to fire.

Event tree analysis is a probabilistic method that provides a chronological systematic description of scenarios due to fire. According to BSI, it is most useful when there is little data available[7], as rare events can be described by more frequent sub-events. Event tree analysis starts with an initiating event, such as a fire. Then it branches out to other events, often related to the fire protection systems in place. These events describe whether the fire protection systems are functional or not, and have probabilities associated with them; thus, allowing the probability of a sequence to be calculated. A sequence is when a path is followed through all the events, leading to the consequences. Therefore, by utilising event tree analysis it is possible to calculate the probability of different scenarios and explain the consequences due to these scenarios.

Within the fire safety industry, probabilistic design is rarely used due to several reasons. Firstly, there is no common understanding of design objectives related to sufficient safety level[8, 9], meaning that no quantified acceptance criterion for sufficient safety levels exist. In turn, this means that there is no purpose of quantifying the safety level, because there is no criterion to measure it against. Secondly, probabilistic design has been criticised for not describing total risk accurately, due to large uncertainties within the probabilities; hence a sequence of uncertain probabilities does not provide an accurate picture of total risk[5]. Finally, there are challenges regarding available information and time. Probabilistic – deterministic methods are based on available statistics to determine probabilities, which is sometimes scarce. Time is also needed to perform deterministic analysis in order to evaluate associated consequences, but fire safety engineers do not always have this time available in their daily work.

In order to make probabilistic design a feasible method for fire safety engineers, it is studied in this thesis. Probabilistic design has many strengths: Firstly, quantifying risk leave no room for doubt whether the safety is sufficient or not, given that an acceptance criterion exist. Secondly, basing decisions on risk is often advantageous, as designs become more optimised. The traditional way of assessing fire safety designs is to assess the worst-case scenario, making the safety level very high. However, the worst-case scenario is not very likely to happen; in fact, scenarios with less severe consequences are more apt to affect risk. Thus, measures can be tailored towards the scenarios that actually matter to risk, which also leads to the advantage of identifying weak links in the fire safety design[5, 6]. Lastly, it is a framework on which maintenance plans can be created from.

By utilising a probabilistic deterministic method it is possible to quantify the risk due to fire. In this thesis, the risk of the timber building is compared to a building that fulfils the pre-accepted solutions. Thus, the results from the pre-accepted building is utilised as an acceptance criterion. This will eliminate many of the uncertainties regarding assumptions made in the analysis, as the same recipe is followed for both designs.

1.2.2 Timber constructions

Timber constructions have become increasingly popular the latest years. The changes in the regulations made this possible, however there are several reasons for this popularity[3]:

- Timber has a high strength to weight ratio
- Timber is aesthetical
- Timber contributes to positive indoor climate
- Usage of timber might reduce building time
- Timber is environmentally friendly.

The last reason is especially becoming more and more important as 40% of our energy use goes to building. It is also becoming advantageous to build environmentally friendly buildings, through rankings such as BREEAM.

Due to its aesthetical qualities, it is desired to expose the timber as much as possible. This creates challenges for fire safety engineers all over the world. Timber is a combustible material, so using it in walls or other structural elements, means increasing the potential severity of fires. Exposing it also becomes problematic, due to the classification in regard to reaction to fire. Timber is classified as D-s2,d0[3], meaning that timber contributes to fires and creates smoke. This has led to difficulties in documenting the safety of timber structures. Ironically, this is especially important for timber, as using it creates deviations from the pre-accepted solutions in the guidelines. To close these deviations, it must be documented that the chosen solutions are sufficiently safe.

1.2.3 Regulations and guidelines

When designing buildings in general engineers adhere to TEK 10, which contains the functional requirements to new buildings[2]. Additionally, the regulations have recommendations and if these recommendations are followed, the solutions are approved. These solutions are often referred to as pre-accepted solutions. They are found in the guidelines to TEK10, also referred to as VTEK. Fire safety engineers mostly deal with chapter 2 and 11, which is documentation and fire safety successively.

Utilising unprotected timber in buildings lead to 4 deviations from the pre accepted solutions in the guidelines. These are identified by Halvorsen[10] and presented in table 1.1.

Table 1.1 – Overview of deviations due to usage of timber structures[2].

Paragraph/requirement	Deviation
§11-1 Safety in case of fire.	Using wood is inserting additional fire load into the building. However, deciding how much that contributes in fires is not easy. Therefore quantifying fire load becomes difficult.
§11-4 Carrying ability and stability.	It is required that the main structure has the fire resistance R90 A2-s1,d0. By using unprotected timber one can achieve R90 D-s2,d0.
§11-4 Carrying ability and stability.	Secondary structures shall achieve fire resistance of R60 A2-s1,d0. When using unprotected timber it is possible to achieve R60 D-s2,d0.
§11-9 Materials and Products characteristics	Deviations occur due to combustible surfaces that produce too much smoke. This is to be avoided to prevent a potential fire to grow severe.

As previously mentioned, this thesis will deal with personal safety; thus, the last deviation is chosen for further scrutiny. This is because the main threat to personal safety is during the early fire development. If the surrounding structures contribute to early fire development, this will have impact on the personal safety of inhabitants. The chosen failure mode will be discussed further in chapter 3.

1.3 Goals

The overall goal of this thesis is to achieve a sufficient fire safety level in Norway. In order to achieve that, documentation of fire safety is central. Probabilistic fire design is a way to quantify risk due to fire; hence, it provides fire safety engineers with clear documentation. However, much is still uncertain in regard to probabilistic design. To provide fire safety engineers with a tool to analyse and document fire safety, this thesis must address these bullet points:

- Quantify the safety level in a timber building by utilising probabilistic deterministic design
- Analysis of probabilistic design
    - What are the strengths of this method?
    - What are the challenges of using this method?

In addition to this, timber constructions will be slightly dealt with by showing what this analysis reveals about fire safety in timber structures.

- Timber constructions
    - What are special considerations that must be made when designing timber constructions?

1.4 Limitations

To limit the scope of the thesis within reasonable boundaries, a few limitations have been chosen. Firstly, this thesis will address buildings within fire class 3 and 4. Fire class 3 is where the challenges of documenting the safety level due to fire first appear. Additionally, fire class 3 deals with buildings taller than five floors. To increase the safety level and allow further innovation, the regulations related to tall buildings must be addressed. Fire class 4 is included in this thesis as high-rise timber buildings could possibly be placed in fire class 4, due to the high fire load.

In order to build timber constructions taller than five floors, heavy timber products must be utilised. The relevant products are glue-laminated timber, cross-laminated timber and solid wood; hence, this thesis will focus on heavy timber products. Using such products is especially advantageous, due to pre fabrication of elements. Thus, giving a shorter building time compared to for instance concrete, while maintaining structural stability and decreasing environmental footprints. It is therefore assumed that these products will become more and more popular. Therefore, the design methods and regulations must be sophisticated enough to handle the development.

When designing buildings against fire safety, engineers look to ensure safety for people, material values and environmental and societal conditions. In this thesis only personal safety will be addressed. It is the author's firm belief that personal safety comes first. Besides the value of one human life is estimated to 30 million NOK to society[11], showing that it is in society's interest to reduce fatalities due to fire. The criterion chosen to decide when people are at risk is visibility. When the visibility at 2 meters height is 10 meters or less, the failure mode has been reached. Other failure modes could be chosen, such as: radiation, smoke layer temperature or toxic gases. Smoke is chosen because it is central to how people behave and it is easy to quantify.

As the main focus of this thesis is on the probabilistic-deterministic method, the accuracy of the deterministic methods will be diminished. Deterministic methods are time consuming and this thesis has time constraints. Thus, the simulations performed will not be as accurate as they would have in research projects. The purpose of this thesis is to study how well this method works, not a simulation exercise. Hence, the calculated risk of the building is not definite, but it gives an indication of the risk level in the building. As the same assumptions are used for the comparative case, it is still possible to compare the reference and the comparative case. This devalues the conclusive results compared to an absolute acceptance criterion. Furthermore, this means that the results regarding timber constructions are not as trustworthy as they otherwise could have been.

1.5 Guidance to reader

This thesis is organised in the following manner:

- Chapter 1 deals with motivation of the thesis, goals and objectives
- Chapter 2 deals with the methods chosen for this research.
- Chapter 3 is the theory chapter. It establishes the foundation of the thesis and it deals with choices made for later chapters.
- Chapter 4 is the analysis of a timber building created for this purpose.
- Chapter 5 is the analysis of a pre-accepted building similar to the building in chapter 4. Furthermore, the chapter contains a sensitivity analysis, where risk is studied by changing different parameters. This part discusses the results as well as presenting them.
- Chapter 6 is an extension of the analysis, containing the implementation and analysis of a measure to mitigate risk.
- Chapter 7 contains the discussion of the results and probabilistic design
- Chapter 8 is the conclusion of this thesis

As this thesis goes in depth on a topic that is mostly relevant for fire safety professionals, expected readers are from the fire safety community. Researchers, engineers or legislators that work with fire safety could all have interest of reading this work. The reader is therefore expected to have some knowledge of fire safety; consequently, the language is suited accordingly.

From this point, the analysed timber building will be referred to as the trial design. By doing this consequently, confusion is avoided, although it might lead to lack of variation. Similarly, the analysed concrete building is referred to as the reference building. Both expressions coincide with the English expressions used in several standards.

The following abbreviations are frequently used:

- ASET – Available Safe Egress Time
- CLT – Cross Laminated Timber
- FDS – Fire Dynamics Simulator
- FSE – Fire Safety Engineer
- HRR – Heat Release Rate
- RSET – Required Safe Egress Time

If an s is added to the acronyms, they are in plural form.

2.0 Method

This chapter describes the methods used to create the results from this study. Furthermore, the steps taken to obtain the results are presented, which ensures the validity of the results and that the study can be repeated.

2.1 Literature study

The theoretical approach in this thesis command the need for background information and theory; thus, a literature study was performed. The literature study was utilised to extract the following information:

1. Probabilistic design and the use of event tree analysis.
2. Theoretic studies about the behaviour of timber constructions in fires.
3. Norwegian rules and regulations
4. Classification regimes within fire safety

The quantitative method analysed in this thesis is little used within fire safety engineering yet. To establish the foundation for the method and identify best-case practice, published literature is studied. All articles used in the state of the art section are peer reviewed except for a doctoral thesis and a standard from British Standards Institute. To ensure the relevance of the articles they must not be older than 2004. Since the standard from BSI was released in 2003, the work after this point seems to be more relevant for the requirements of today.

In order to evaluate the consequences to the associated risk, the behaviour of timber structures in fires must be known. The literature study focused on full-scale tests to gain accurate insights to how timber behaves. As there are few full-scale tests on timber structure, sources that are not peer reviewed are included in the literature study. One is a report from a full-scale test performed by SP Fire in Norway. Although it is not peer reviewed, both supervisors and the fire community in Norway deems it as a high quality source. The other report is a master thesis from Canada. Although the thesis itself is not peer reviewed, it is later used in a published study, deeming the quality of the source as solid. The other sources come from well-known authors such as Hakkarainen and Frangi. These studies are peer reviewed, ensuring high quality studies.

As the thesis focuses on deviation from the guidelines in Norwegian regulations due to use of timber, the Norwegian regulations are studied further. Both chapter 2 and 11 in the Norwegian technical regulations are studied. The chapters deal with documentation of performance and fire safety successively, in orders to describe the deviations as accurately as possible. The purpose of the requirements is also identified for applicability in the quantitative analysis.

Classification due to reaction to fire is highly relevant in this thesis, as the identified failure mode depends on it. Therefore a section about the classification regimes is included in the theory. This section draws on the different standards that exists, and is an overview of how the classification regime works.

2.2 Qualitative analysis

In order to quantify the risk, a qualitative analysis must be performed first. To ensure quality regarding the qualitative analysis, the steps in NS 3901 will be followed. The qualitative analysis will not be finished due to time constraints in this project, and the focus is on the quantitative analysis. Only the analysis is performed in this instance; hence, only chapter 6 is followed. The steps in NS 3901 are[12]:

1. Description of the object. This means including activities in the building and central parameters such as fire load.
2. Choice of analysis. Probabilistic – deterministic method is already chosen.
3. Risk acceptance criteria.
4. Hazard identification. Identify potential hazards, based on the use of the building and information already known. Look at relevant fire hazards. Specify which scenarios the hazards belong to. Present it in a systematic fashion.
5. Analyse causes and probabilities. Potential chain of events. Focus is still on the qualitative part, probabilities are decided later.
6. What are fire scenarios? There are 4 scenarios that always should be considered. In this thesis only one scenario will be analysed, due to time constraints.
7. Analysis of consequences. The consequences are what are on the end of the chain of events. For this analysis, number of fatalities is the relevant measure. In this section, the event tree will be presented along with the associated probabilities. The deterministic analysis is also performed to evaluate consequences.
8. Uncertainty analysis
9. Sensitivity analysis
10. Description of risk. Summarises the analysis, hence considering the risks and consequences altogether. The descriptions are supposed to be quantitative for the analysis in this thesis. Total risk is compared to the acceptance criteria. This is the after report of the analysis, but within this thesis it is the process that is important, not the actual results.

In order to identify hazards, discussion with supervisors and FSEs are utilised. This is to ensure the most complete picture possible. In turn, this will lead to the most complete quantitative analysis possible.

2.3 Quantitative analysis

It has already been established that event tree analysis is the probabilistic method utilised in this thesis. The initiating event in the event tree is a fatal fire; hence, the other events are the fire protection systems, also called barriers. These barriers have probabilities for success and for failure. In order to calculate the probabilities of scenarios occurring, these probabilities are used. Hence, the total probability of a sequence is the product of all probabilities in that sequence. Sequences means when a path is followed from the initiating event to the end of the events. Figure 2.1 shows a simplified example of an event tree. There are two potential outcomes, which have different probabilities and consequences.

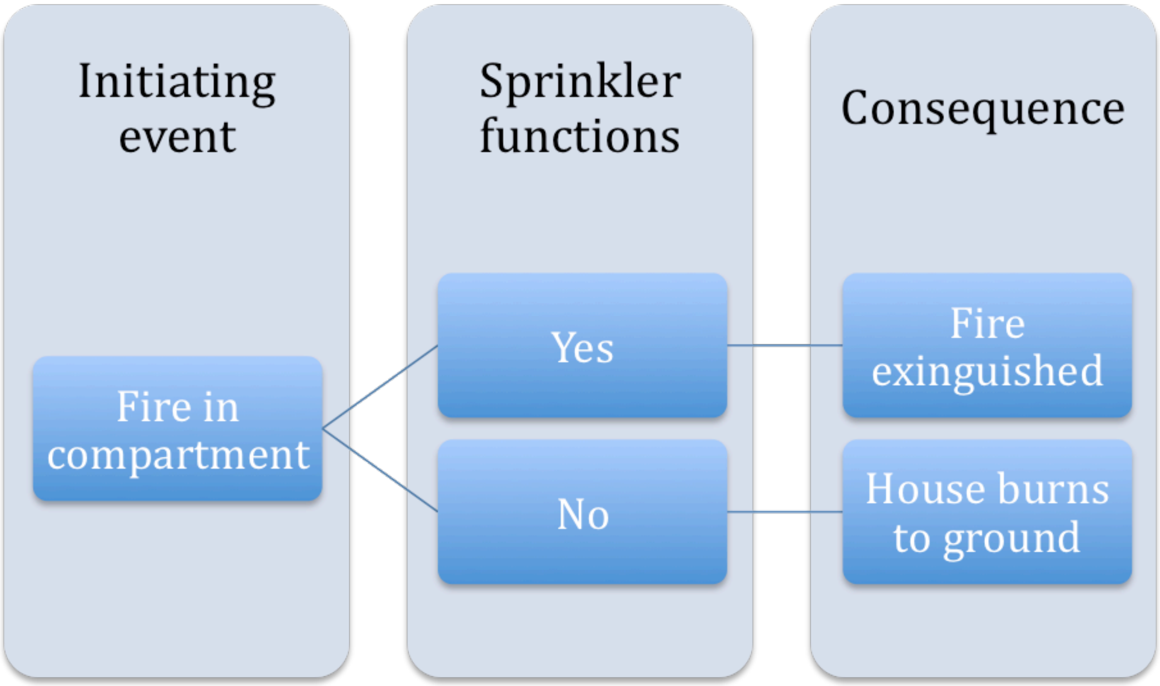

Figure 2.1 – Example of event tree

To bypass the issue regarding total risk, the same method is utilised on a building that has a sufficient safety level according to Norwegian authorities. This eliminates the uncertainties in the assumptions made for the analysis, as the same uncertainties are present for both cases. By comparing those risks it is possible to decide whether the safety level is sufficient or not.

2.4 Deterministic analysis

Risk is a measure that includes both probability of the event happening and the consequence of the event happening. To evaluate the consequences of the different events, deterministic analysis will be performed. According to NS 3901, a deterministic analysis is a method that uses scientific mathematical models to produce the same output as long as the same input data is utilised[12]. Examples of deterministic methods are smoke simulation, evacuation simulation and calculations of fire resistance. The methods utilised in this thesis are presented below.

Firstly FDS is utilised to predict the smoke spread in both the trial design and the reference building, whereas Pyrosim is used to visualise the results. The point is to evaluate when the escape route is compromised, so that escape through this route is impossible. FDS is based on Computational Fluid Dynamics, meaning that the smoke spread is based on actual laws of physics, which makes it suitable for this purpose. The assumptions made for each scenario are described in the analysis chapters.

Secondly, Pathfinder is used to evaluate the evacuation from the building and to determine how many people that are endangered by the fire. It is possible to study evacuation by using hand calculations, however, the advantage of using Pathfinder is that it considers the creations of queue, providing a more accurate picture of the evacuation.

Lastly Barnett's Cumulative Radiation Energy method is used to calculate the fire resistance of doors. The method has shown promise when calculating the fire resistance of especially doors and walls[13]. It is based on the knowledge that radiation is the main method of transferring energy when temperatures are high. Hence it uses Stefan Boltzmann's law to determine the radiation energy from different fire developments. Equation 2.1 describes Boltzmann's law.

$$Q_r = \varepsilon \sigma T^4 \quad (2.1)$$

$Where$

$Q_r - Radiative\,Flux\,[W/m^2]$

$\varepsilon - Emissivity$

$\sigma - Boltzmann's\,Constant\,[W/m^2K^4]$

$T - Temperature\,[K]$

Equation 2.1 – Boltzmann's Law

The emissivity is decided to be 1, which is a conservative assumption because it is assumed that the fire is a black body. Furthermore, the cumulative radiation energy (CRE) can be found by using equation 2.2

$$CRE = \int_0^t Q_r dt \quad (2.2)$$

Equation 2.2 – Cumulative Radiation Energy

This method is used to calculate the fire resistance of elements exposed to other fire developments than the standard curve.

2.5 Summary

The methods used in this thesis are presented above. In this section, the process used to obtain the results is described.

1. The first step in the process is to perform the qualitative analysis in accordance with NS 3901, which is important to ensure a high quality analysis. The qualitative analysis will not be finished due to time constraints.
2. Based on the qualitative analysis, an event tree is created. In this case the barriers are: smoke detectors, sprinklers and door. The event tree shows different paths depending on the barriers functionality. To analyse the consequences due to fire, the hydrocarbon curve is chosen as the design fire. This is due to the observations made in Fossli's project thesis[14]. Furthermore, the reliability of the barriers is kept constant, although the probability of failure of the sprinklers depends on the size of the fire for instance. This is to avoid highly complex solutions that would arise if the probabilities depend on each other.
3. The different nodes in the event tree are analysed, using deterministic methods. Firstly, the detection of smoke has an impact on evacuation time. Early detection time will influence the total required evacuation time, which will be analysed by using Pathfinder. Secondly, the fire development in the compartment will be investigated, utilising Pyrosim FDS. There are many factors that will affect the fire development, such as breaking of the window, whether the door is open and functionality of the sprinklers. Due to time constraint in the thesis, not all of these factors will be considered. To achieve a fire development similar to the studied literature, the HRRs are adjusted. It is also an assumption that if the sprinklers are functional, the fire will no longer pose a threat to personal safety, since the sprinklers will either extinguish or delay the fire. As the first 10-15 minutes of the fire are the most critical considering personal safety, this seems to be a legitimate assumption. Additionally, it will give extra time for the occupants to evacuate. Finally, the last barrier explains whether the door to the stairwell is open or not. If the door is closed, the fire resistance of the door must be calculated; hence, the time to the fire spreads into the stairwell is known. As mentioned in the previous section, this will be done, utilising a method called Cumulative Radiation Energy.

Ultimately this provides knowledge on the consequences and probabilities for those events to occur. This is then combined into a final assessment, where the total risk is described, but as this is not an assessment of the design, it will not be very thorough. Then the process will be repeated on a pre-accepted building; consequently, the safety levels for the two buildings can be compared. The reference building will be analysed by utilising the standard fire curve as a design fire, as the standard curve represents the worst-case scenario for compartments fires. This is a similar assumption as making the hydrocarbon curve as the design curve for the timber compartment

3.0 Theory

This chapter contains the foundation on which this thesis is built on. The theory encompasses topics such as:

- State of the art on probabilistic design
- The fire development in timber structures
- Classification of materials
- Review of deviations from the Norwegian guidelines
- Overall acceptance criterion

These topics are introduced and discussed in depth. This is to ensure that the information revealed from this chapter is applicable in the analysis. Decisions are also made in this chapter such as:

1. Which failure mode from section 3 is chosen for analysis?
2. What is chosen the overall acceptance criterion for fire safety in Norway?
3. Design fire of the student compartment.

3.1 State of the art

Since event tree analysis is the chosen method to analyse the case probabilistically, this section will deal with recent experiences with event tree analyses. Furthermore it will contain general observations around quantitative analysis methods.

The foundation of probabilistic design can be found in PD 7974-7[7]. As it is a standard, it is regulating how probabilistic design is performed in Great Britain. The basis of probabilistic analysis is identifying risk, which is a product of probability and consequences. Moreover, different applications of probabilistic risk assessment are suggested such as[7]:

- Identifying fire scenarios
- Deciding on input parameters into deterministic analyses
- Local analysis of buildings
- Global analysis of buildings.

There are few limitations to probabilistic risk assessment. Lacking statistic information is especially mentioned as a challenge for simplistic PRA methods. Otherwise it is possible to utilise mathematical techniques in order to retrieve the necessary information.[7]. PRAs are also considered as time consuming and might not be appropriate for all purposes.

According to Bsi, event trees are most applicable when there is little information[7]. Event trees explain rare events, by dividing it into several events where information is available. The first node in the event tree describes an initiating event. Depending on the outcome of this event occurs or not, it branches out to other events. By following a path from the beginning to the end, a sequence is defined. At the end of the sequence is the ultimate consequence of this sequence. The consequence has an associated probability, as every event is described by a probability. By knowing the probabilities of operating sprinklers and the outcome of that event, it is possible to define risk.

In a doctor thesis from Finland, Kati Tillander worked on characterising fires by utilising statistics[15]. As statistics become more readily available, the accuracy of quantitative methods increases. Hence the work of Tillander is a foundation for quantitative analysis in Finland. Based on the retrieved statistics, an event tree analysis was performed[15]. In this case the event tree was utilised to obtain costs due to fire. Hence the consequence of each sequence was related to material losses and thus costs of fires. The chosen failure is flashover, which is quantified using Monte Carlo simulations[15]. These results were verified by utilisation of FDS 3. Probabilities of each event were calculated by using conditional probabilities or a Markov process[15].

Personal safety was not quantified, as the detection time was challenging to decide. Detection time depends on many factors such as the development fire and the state of the occupants. Moreover, there were also insufficient statistical data. Tillander emphasises that the result is sensitive to input parameters[15]. This uncertainty was handled by using Monte Carlo simulations to account for the difference in input parameters. Due to uncertainty, the achieved value is deemed as not very accurate[15].

Similar techniques have been tried, where the focus have been quite different. A time dependent event tree was used to analyse the effect of fire protection systems on spread of fire and smoke[16]. In this study, several input parameters were treated like stochastic variables. These parameters include:

- Fire development
- Pre movement time
- Reliabilities of fire protection systems

In opposition to the studies of Tillander, the probabilities in the event tree are considered to be independent[16]. Thus conditional probability was not considered. Furthermore, it is argued that probabilities change over time. This is handled by using a Markov chain, combined with the time dependent event tree[16]. The Markov chain leads to a 9x9 matrix, which gives the probabilities of every scenario described in the event tree.

In order to decide on consequences, evacuation time and fire development are treated as stochastic variables[16]. Thus the number of people at risk is decided for every scenario depicted by the event tree, leading to total expected risk to life safety. In this case risk was overestimated, thus the authors argued that more research was needed to address uncertainties. In a similar study the authors utilised the event tree to assess risk to personal safety[17]. However in this case, a lower and upper bound of risk was identified; hence, the actual risk was identified by utilising Supersoft Decision Theory[17]. This was used to distinguish between using sprinklers or smoke detection and deluge system. Interestingly the consequences for both cases were identical; however, due to lower probability of failure, the risk was lower for the case with sprinklers[17]. These authors used essentially the same technique to assess the fire protection system. However uncertainties were handled by utilisation of Supersoft Decision Theory instead of Markov Chain.

Another way to handle the uncertainties regarding probability of barriers is by imposing time dependent probabilities. It is argued that probabilities change during the fire development, for instance the probability of fire detector sounding increases as the fire grows[18]. To achieve this, the authors impose different criteria for the event to occur. Fire detection depend on obscuration in the ceiling for instance. As different fire developments are studied, cumulative probability distributions are gathered from the information[18]. Furthermore these distributions are utilised to decide the probabilities of the scenarios in the event tree. The authors explicitly mentions issues with using static probabilities in the event tree, which explains their approach.

The same authors propose other ways to achieving the same goals. In the former study, the cumulative probability distributions were coupled with Markov Chain in order to deal with uncertainty. However this approach drops the Markov Chain and instead focuses on Available safe egress time and Required safe egress time as two interdependent stochastic variables[19]. Similar to the previous study, probability of events is time dependent. In this study, both ASET and RSET are assigned the same fire development[19]. This method is utilised to assess a previously occurred fire. As it was performed in the study, it underestimated the severity of the real fire.

In another study, event tree analysis was utilised to investigate the effect of the most common fire protection barriers[20]. Stochastic values were chosen for pre movement time and fire scenarios. As this was an on going project, results were used from a previously released paper[21]. These were somewhat modified in this study. Interestingly the author points out that making changes on the evacuation side is advantageous. This is because fire simulations can be recycled, thus a lot of time and resources are saved[20]. Although stochastic values were chosen for pre movement time and fire scenarios, point probabilities were utilised for reliabilities[20]. Of the presented research, this is the first were this approach is chosen. However this is also one of the weaknesses of the research according to the author[20]. The input values are generally criticised for not being accurate enough, which is an ongoing theme through this research.

The presented studies are all research projects, however the method has also been utilised for more practical purposes. In Sweden, event tree analysis and other methods were used to investigate the safety in sprinklered buildings[22]. Nystedt combined the event tree analysis with deterministic methods to a large extent. As a matter of fact, several of the inputs in the event tree was determined deterministically[22]. Despite the input being deterministic, the event tree analysis is still considered as a probabilistic method. Moreover it has advantages over pure deterministic methods in the sense that it considers likelihood of event occurring[22]. Thus risk is the parameters on which decisions are made, not just consequences.

In order to treat uncertainties, event tree analysis offers the opportunity of performing sensitivity analysis. Hence it is easy to vary parameters that might affect the risk to some extent. Nystedt distinguishes between events that are related to fire development and events that are related to safe evacuation[22]. It is therefore easier to change parameters related to safe evacuation, as less computation resources are needed. Moreover Nystedt suggests that worst credible scenarios are represented within the scenarios[22]. In this manner uncertainty is handled by acting on the safe side.

3.2 Fire development in timber structures

This section presents full-scale tests on timber modules. Results such as temperature development, heat release rates, charring rates and time to flashover are presented.

When discussing fire development, it is natural to look at temperature or heat release rate within the investigated compartment. This has recently been done in Norway, in relation to the construction of a student village in massive tree. The aim of the study was to investigate[23]:

- Fire development including duration, time to flashover and temperature development
- Charring rate in both protected and unprotected walls
- Fire spread out of the fire cell.

The compartment tested was 2,3 meters wide, 5,75 meters long and 2,8 meters tall[23]. Fire spread was investigated through the corridor and the window on the other side of the compartment. The door was left open to ensure sufficient ventilation during the test, and the size of the door was 0,9 x 2,0 m. Thus resulting in an opening factor of 0,036 $m^{1/2}$. This was however changed when the window broke after approximately 6 minutes. The dimensions of the window were 1,2 m x 1,6 m (width x height), hence changing the opening factor to 0,061 $m^{1/2}$. To investigate the charring rate in cladded walls, some of the walls in this test were cladded in gypsum board. Walls that connected apartments where also cladded in fire proof gypsum board[23]. Some of the walls were not cladded at all. In total, the fire load was estimated to 8708 MJ, which means 658 MJ/m^2, per floor area.

Results from this test show that the compartment temperature is high. Following flashover after 4 minutes and 10 seconds it resembles the hydrocarbon curve, which can be seen from Figure 3.1. The blue line shows the measured temperature in the room. There were some problems with the measuring instruments during the test. It was assumed that they fell down or malfunctioned. Results after 30 minutes are not included for that reason[23]. However observations stated that the intensity of the fire did not diminish. The test had to be manually extinguished after 95 minutes as the roof collapsed[23].

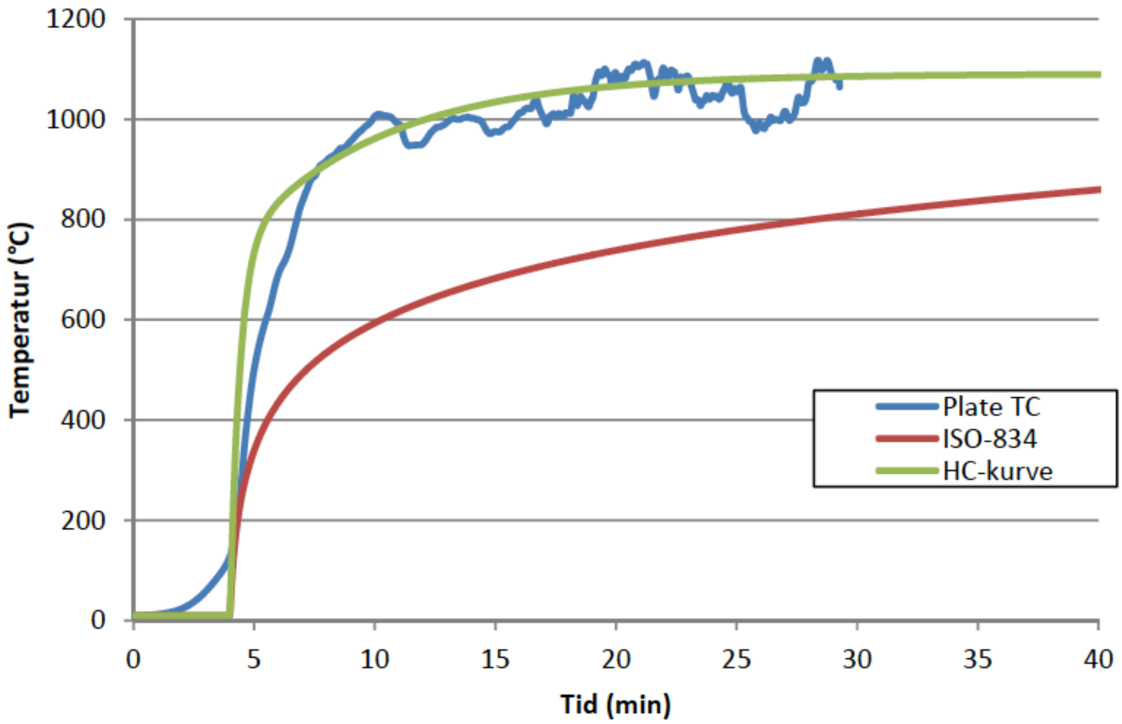

Figure 3.1 – Fire Development in the compartment[23].

The smoke spread out to the corridor already after 1 minute and 24 seconds. Whereas the fire spread to the corridor in about 8 minutes[23]. During the test, the fire in the corridor had to be controlled manually to avoid collapse. The average charring rate through the wall was calculated to 1,1 mm/min and in the roof the rate was approximately 1,0 mm/min[23]. Delamination of the CLT from the wall was observed. This is one of the reasons to the high charring rate.

Throughout the years, similar tests have been performed. Hakkarainen performed similar experiments as the previously mentioned. However the compartment size and ventilation factor differs. The size of the room was 3,5 x 4,5 x 2,5 m, and the opening was a window with the dimensions 2,3m x 1,2m (width x height) [24]. Resulting in an opening factor of $0{,}042m^{1/2}$. For the test relevant to this thesis, the walls were unprotected and consisted of heavy laminated timber. Total fire load density was 720 MJ/m^2 per floor area, not including the embedded wood.

Despite having a similar test setup, the results from the experiments differ. Flashover occurred after 4 minutes and 50 seconds. Then the temperature stayed at around 700 °C for almost 30 minutes before it started to increase, as seen in Figure 3.2. In the discussion section, the author theorised that this might be due to creation and warming up of pyrolysis gases from the unexposed wooden walls. This leads to poor ventilation conditions, thus preventing higher temperatures[24]. Eventually the mobile fire load burned up, which decreased the creation of pyrolysis gases. This allowed more oxygen to enter, thus the temperature in the compartment increased[24].

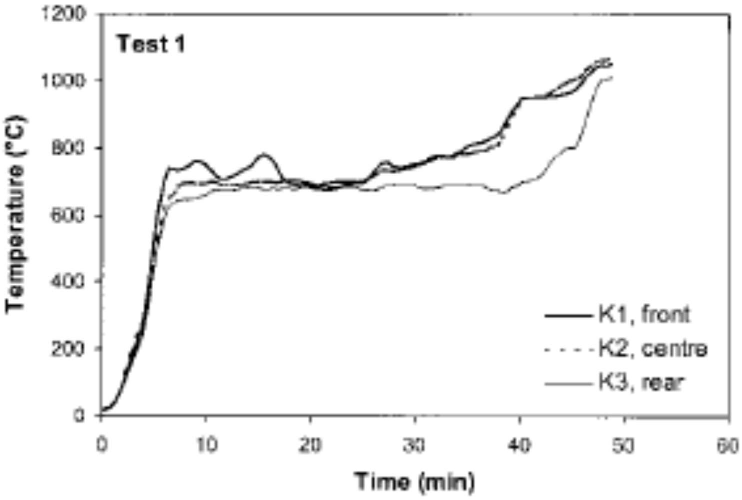

Figure 3.2 – Temperature-time curve for exposed wooden compartment[24].

A consequence of poor ventilation conditions in the compartment is that burning took place outside. Figure 3.3 shows the heat flux above the window for all the tests performed. Eventually test 1 has the highest heat flux out of the window. After 30 minutes the flux is approximately 100 kW/m^2 and it keeps on rising. Finally, the observed charring rate was 0,8 mm/min.

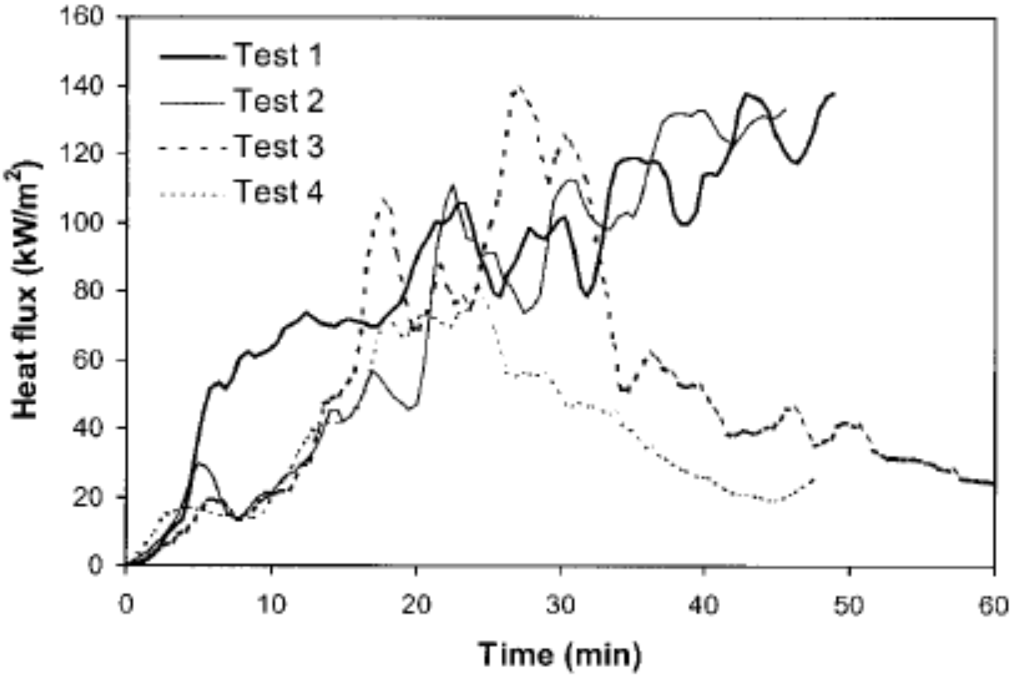

Figure 3.3 – Heat Release Rate measured above the window[24].

Moreover tests that confirm these results to some extent have been performed[25].This study was originally performed to assess the contribution of the massive tree to fire in McGregor's master thesis[26]. Later the results were also used to look at temperature development, heat release rate and charring rate[25]. The dimensions of the room were 3,5 x 4,5 x 2,5 m high. The test was made similar to the one Hakkarainen performed for comparing purposes. 6 tests were performed where test 3 is the most relevant in this context. The walls were unprotected Cross – Laminated Timber and the ignition source was modelled as fire in furniture[26]. Similar to the previous test, a door was left open to ensure sufficient ventilation. The opening factor was calculated to 0,042 $m^{1/2}$, as the door area was 1.069 m x 2 m (width x height).

The fire development is similar to the test performed in Norway. According to observations, smoke exited the door after 2 minutes and 10 seconds (McGregor, 2013). Furthermore, flashover occurred after 5 minutes and 19 seconds. As seen in Figure 3.4, the yellow dotted line depicts temperature for test 3. After 20 minutes the temperature is almost constant just below 1200°C. It lasts until the test was aborted to maintain the structural integrity of the structure, which is after approximately 60 minutes[26]. It can also be seen that the temperature is much higher than the standard curve for quite some time. The charring rate of 0,85 mm/min in the walls in this test might be due to the high temperatures. The charring rate in the roof was estimated to be 1 mm/min. This is partly due to delamination of the CLT[26].

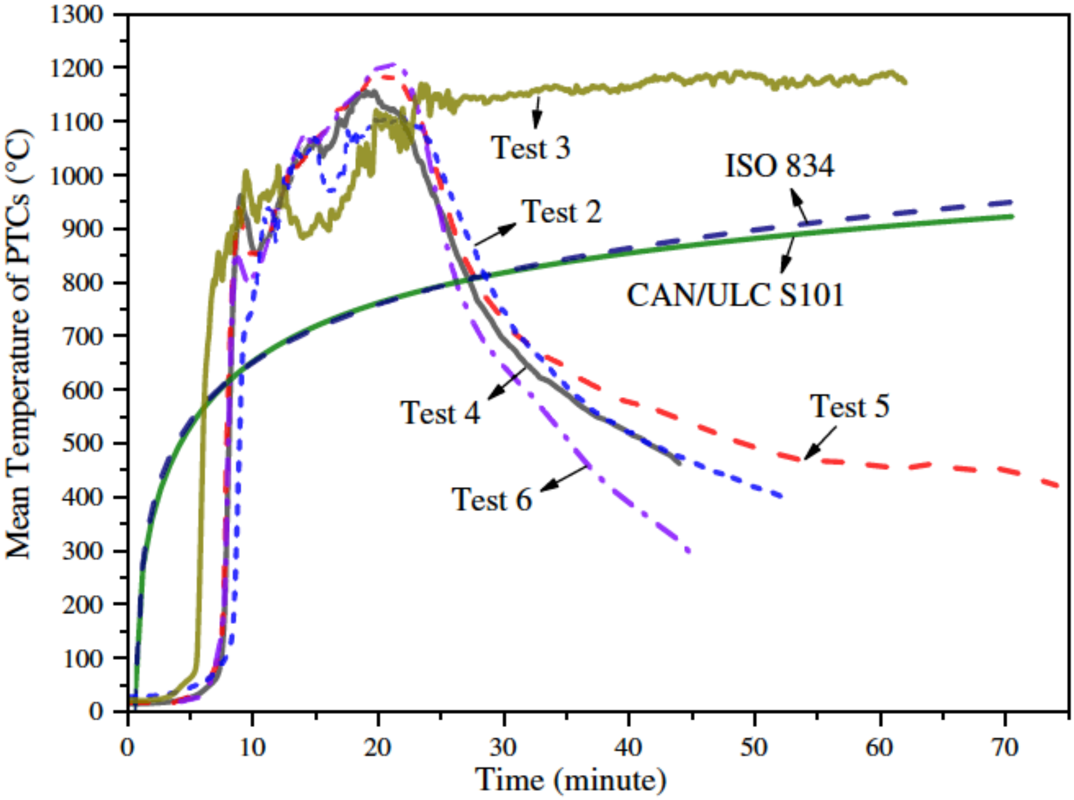

Figure 3.4 – Temperature-time curve for test 3[25].

For this test the authors measured total heat release rate as well. This includes heat released out the door [25]. As seen in Figure 3.5, the heat release rate for test 3 is quite high compared to the other tests. This is similar to the tendency seen by Hakkarainen, although the development is inverted in this test compared to Hakkarainen. The authors also theorise that this is due to the high release of pyrolyse gases from the CLT walls. Poor burning conditions inside the compartment leads to burning on the outside. Figure 3.5 also shows a second peak in heat release rate. At this time delamination of the massive tree was observed[26].

McGregor also used the heat release rate to look at the contribution from the massive tree to the fire. According to his calculations the contribution is around 5 MW during the first peak in Figure 3.5. In the second peak the contribution is 6 MW[26], in other words almost the entire heat release rate. On this basis, it was decided that the fire load from the wood was 612 MJ/m^2 per floor area.

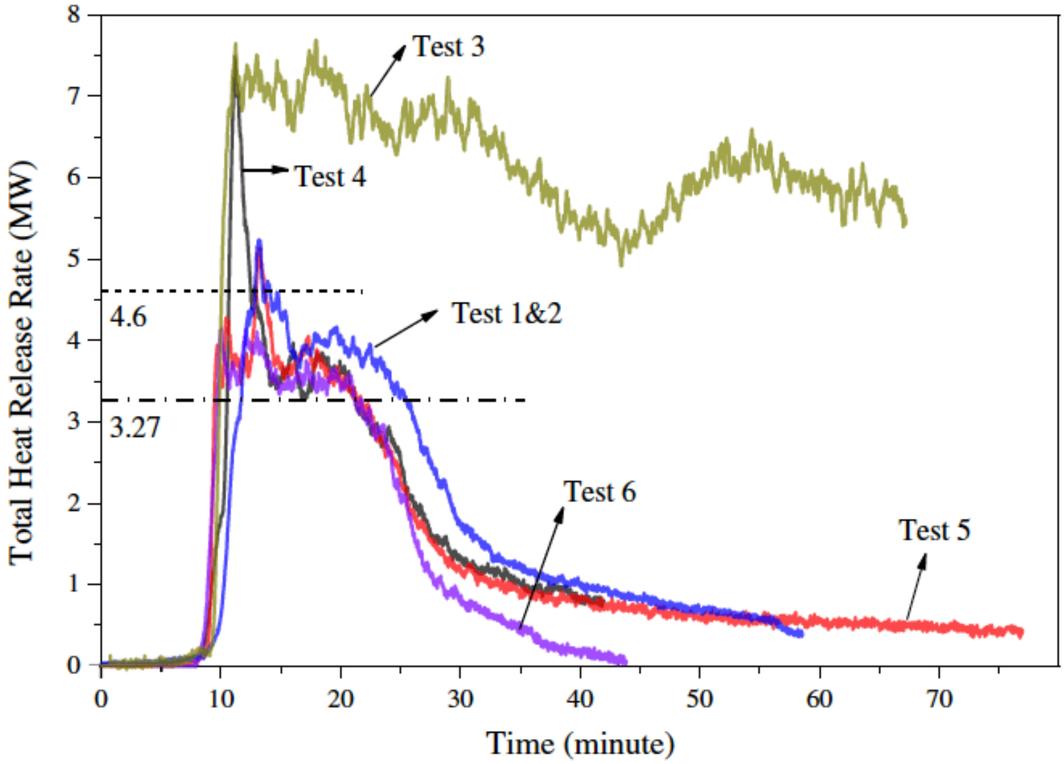

Figure 3.5 – Total heat release rate[25].

To summarise the conditions in which these tests were performed, table 3.1 was made.

Table 3.1 – Summary of conditions in full-scale tests.

Test	**Specific Fire Load [MJ/m²] Structure excluded**	**Opening factor [m¹/²]**	**Geometries [length m x width m x height m]**	**Enclosure**
Hox	122	0,036 – 0,061	5,75 x 2,3 x 2,8	Partly protected by gypsum board
Hakkarainen	160	0,042	4,5 x 3,5 x 2,5	Unprotected massive wood
McGregor	117	0,042	4,5 x 3,5 x 2,5	Unprotected massive wood

Looking at the temperature development, two out of three tests resemble the HC curve to a large extent. Interestingly the temperature is higher for McGregor compared to Hox, despite Hox having larger opening factor. It is expected that opening factor influence the temperature a lot, due to the production of pyrolysis gases. Another observation is that intensity of the fire did not decrease for any of the tests. Eventually the tests were aborted due to structural failure of the module. Furthermore, when using unprotected wood, fire spread becomes an issue due to production of pyrolysis gases. A lot of the burning takes place on the outside, such as out windows or doors. Finally, in the two most recent tests, delamination of the CLT was observed.

Based on these observations and the conclusion made in Fossli's project thesis, the Hydrocarbon curve will be used as a design curve for small wooden compartments in this thesis. Normally one would have used the parametric fire curve; yet, it is impossible to disregard the results from these studies. The fires studied are more severe compared to the parametric fire curve. Also, choosing the Hydrocarbon curve as a design curve is deemed as conservative compared to the parametric fire curves.

3.3 Fire classification

The next section contains information on the Norwegian rules and guidelines. A central part of that is the classification of materials. Thus a section about classification of materials follows, to provide an overview of the regimes and the different terms. First central terms for this chapter are presented. Furthermore reaction to fire and fire resistance are discussed.

Terms presented in NS-EN 13501[27]:

- ΔT – Change in temperature [°C]
- Δm – change in mass [%]
- t_f – time of sustained burning [s]
- PCS – [MJ/kg]
- FIGRA – Fire Growth Rate index [W/s]
- LFS – Lateral Fire Spread [-] visual observation
- THR – Total Heat Release [MJ]
- F_s – Fire spread [-] visual observation
- SMOGRA – Smoke Growth Rate index [m^2/s^2]
- TSP – Total Smoke Production [m^2]

3.3.1 Reaction to fire

To ensure a harmonized way to understand how products are classified, NS-EN 13501 was introduced. The standard gives a brief overview of what the classifications mean, as well as reference to the related test standard. It deals with construction products, floorings and linear pipe products[27]. Construction products will mainly be discussed in this section, but floorings will also be mentioned. When a product is tested, three characteristics are given. This is an example of how a product can be classified:

A2-s1, d0

How to interpret the results will be handled in this section. As the products are tested in accordance with several standards, the list of standards will be provided in the end of this section, along with a short explanation.

- A2: The first part looks at ignitability, heat release and flame spread. In order to do so; Fire Growth Rate (FIGRA), Total Heat Release (THR) and Flame spread F_s is measured. It assigns a letter to the material, in accordance with the performance related to combustibility. The following table gives a quantitative description of the classification as well as the relevant tests.

Table 3.2 - Quantitative classification of fire performance[27].

Class	Test	Quantitative criteria
A1	EN ISO 1182 And	$\Delta T \leq 30 \leq$°C; and $\Delta m \leq 50\%$; and $T_f = 0$ s
	EN ISO 1716	PCS ≤ 2,0 MJ/kg
A2	EN ISO 1182 Or	$\Delta T \leq 50 \leq$°C; and $\Delta m \leq 50\%$; and $T_f = 20$ s
	EN ISO 1716 And	PCS ≤ 4,0 MJ/kg
	EN 13823	FIGRA ≤ 120 W/s LFS < edge of specimen and $THR_{600s} \leq 7,5$ MJ
B	EN 13823 And	FIGRA ≤ 120 W/s LFS < edge of specimen and $THR_{600s} \leq 7,5$ MJ
	ISO 11925 Exposure time: 30 s	$F_s \leq 150$ mm within 20 s
C	EN 13823 And	FIGRA ≤ 250 W/s LFS < edge of specimen and $THR_{600s} \leq 15$ MJ
	ISO 11925 Exposure time: 30 s	$F_s \leq 150$ mm within 20 s
D	EN 13823 And	FIGRA ≤ 750 W/s
	ISO 11925 Exposure time: 30 s	$F_s \leq 150$ mm within 60 s
E	EN ISO 11925 Exposure time 15 s	$F_s \leq 150$ mm within 20 s
F	No performance	

The values in table 3.2 lack context. Hence a qualitative description of the different classes are added in table 3.3

Table 3.3 - Qualitative description of fire performance.

Class	Combustibility (contribution to fire)	Heat of combustion (total heat release)
A1	Non combustible	No fire growth
A2	No significant contribution to fire growth	No flashover
B	Very limited contribution to flashover	No flashover
C	Limited contribution to flashover	Flashover after 10 minutes
D	Contribution to flashover	Flashover between 2 to 10 minutes
E	Significant contribution to flashover	Flashover before 2 minutes
F	No performance or not achieving an E	No performance determined

Floorings have a similar classification to the ones in table 3.3, however "FL" is denoted as subtext. An example is: $A1_{FL}$.

- S1: This is a parameter related to smoke. Smoke reduces visibility and might contain toxic gases. For classification purposes, the relevant parameters are SMOGRA (Smoke Growth Rate) and Total Smoke Production (TSP). Hence composition of gases is not included. The quantitative values related to smoke test is explained in table 3.4.

Table 3.4 – Classification related to smoke production[27].

Class	Test	Criteria
s1	EN 13823	SMOGRA $\leq 30\ m^2/s^2$ and $TSP_{600s} \leq 50\ m^2$
s2	EN 13823	SMOGRA $\leq 180\ m^2/s^2$ and $TSP_{600s} \leq 200\ m^2$
s3	No performance, or not achieving s2.	

It is challenging to qualitatively describe smoke production. However, as a reference point if a product achieves s1 it should not produce smoke in case of fire.

- The last letter in the chain is d. It explains the production of burning droplets. Table 3.5 shows the class and the corresponding explanation:

Table 3.5 - Classes related to production of burning droplets[27].

Class	Test	Explanation
d0	EN 13823	No production of burning droplets within 600 s.
d1	EN 13823	No production of burning droplets persisting more than 10 s, within 600 s.
d2	EN 13823 Or	No performance or not achieving s2.
	EN ISO 11925-2	If the product ignites the paper.

As several standards has been cited, a list of sources with a short description is included:

- *NS-EN 13501 Fire classification of construction products and building elements.* This is the standard that connects the classification framework. For each class, it refers to a test performed in accordance with another standard. As well as it contains the criteria for each class[27].
- *NS-EN ISO 11925-2:2010 Reaction to fire tests. Ignitability of products subjected to direct impingement of flame. Part 2: Single-flame sourced test*. This standard is relevant to most of the classes. It explains the process on how to test ignitability of a product exposed directly to a small flame. The duration of the test is either 15 or 30 seconds; depending on which class the material is tested for[28].
- *NS-EN 13823 Reaction to fire tests for building products. Building products excluding floorings exposed to the thermal attack by a single burning item.* As seen in table 3.2, 3.4 and 3.5 this standard is used to determine classification within production of burning droplets, production of smoke and combustibility. It explains the single burning item test, which is performed on many occasions due to wide applicability and possibilities for small samples[29].
- *NS-EN ISO 1716 Reaction to fire tests for products. Determination of the gross heat of combustion (calorific value).* This standard is only used if a product achieves either A1 or A2 classification. It gives information on the heat combustion of a product. For A1 and A2 classified materials, information is not easily gathered due to low combustibility. Hence heat of combustion is measured using a bomb calorimeter[30].
- *NS-EN ISO 1182 Reaction to fire tests for products. Non-combustibility test.* As the previous standard, this standard is only valid for class A1 and A2. It is a test developed for materials that produce little flame and heat[31].

3.3.2 Fire resistance

Fire resistance is the ability an element has to withstand fire exposure. It is tested in accordance to ISO 834 Fire resistance tests – Elements of building constructions[32]. There are four characteristics integrated into the fire resistance term. These will be presented and explained below:

- R – Structural resistance. This measure gives the duration in which an element will continue to carry its load. The element is exposed to a standard fire exposure, and then the time to collapse or the time to a certain deflection is measured[32].
- E – Integrity. Measures the duration the element prevents the fire from spreading. This means that the element has to prevent both fire and smoke from coming through. A way of testing this, is to see if a cotton pad is ignited within the time of interest[32].
- I – Insulation. The insulation criterion is related to temperature rise on the unexposed side of the element. When the temperature has increased with 140 K, the element has failed[32].
- M – Mechanical resistance. Explains the elements ability to withstand mechanical impact. This characteristic is highly challenging to test.

Typically an element is assigned with a combination of these letters and numbers. An example is: REI 90. This means that the element must withstand 90 minutes of standard fire exposure, while keeping the mentioned characteristics intact.

3.4 Review of the Norwegian regulations and guidelines

In Halvorsen's master thesis[10], four deviations due to use of timber in buildings were identified. These deviations are presented in this section. The deviations are analysed to showcase the function of the overall requirement. Hence different failure modes are identified. A failure mode is a quantified measure for when inhabitants are exposed to fatal conditions. These failure modes are utilised later to quantify the safety level in the analysis buildings. Fire class 3 is assumed for this section as well, as this encapsulates tall buildings. The Norwegian regulations and guidelines are rigorously cited in this chapter and often referred to as TEK or TEK 10.

3.4.1 Deviation 1: Safety in case of fire – Fire energy

Fire energy is the energy released when an object is burned. It is the product of the calorific value [MJ/kg] of a material and the amount of the material [kg][33]. Hence fire energy is given in MJ. It is divided into two categories:

- Movable fire energy. This is the energy resulting from movable objects within a room. An example of this is clothes.
- Immovable fire energy. This includes the energy due to objects that are not movable within a room. An example of that is a timber wall.

Specific fire energy is a term often used in guidelines and standards and it means fire energy on a given area [MJ/m^2]. It is distinguished between floor area and total area of the compartment. The regulations operate with fire energy per total area. When specific fire energy is mentioned, this is the definition in place unless otherwise stated. This is also known as the fire load of a compartment.

Fire energy is the basic, in which a big part of the fire safety strategy is based on. It directly influences choice of fire cells and compartmentation [2]. These are central factors when deciding design for fire safety. However the influence of fire energy can be extended beyond that. Fire energy can be used to identify fire scenarios through for instance the parametric fire curve[34] . This information is also used to calculate the charring rate, which is a central parameter when deciding fire resistance. Additionally fire energy is used when classifying buildings into fire classes. As fire class 3 is assumed for this work, this is not discussed further. It can be seen that fire energy is an important parameter in fire safety design.

Decision of fire energy is a deviation due to the difficulties of deciding the contributions from timber to the fire. The process to decide the immobile fire load due to timber structures will be discussed further. Based on section 3.2, it was seen that the contribution from unprotected CLT was immense. McGregor calculated the maximum contribution from timber to 6 MW, and translated this into 612 MJ/m^2 [26]. The severity of the fire was also shown as much more severe than the parametric fire curve[14].

The purpose of this functional requirement is to establish the foundations on which the fire safety design is built on. TEK states that:
"*The premises for the fire safety design must be decided and described. These are amongst others:*

- *Fire energy and special risk (activities or storage of combustible material)* " [2]

Furthermore the fire energy in a building impact several decisions made in the fire safety strategy. TEK10 specifies this.
"*In the fire safety strategy, the following must be decided:*

- *Fire energy that amongst other is used to decide maximum area without compartmentation, to dimension automatic extinguishing tools and might affect requirements regarding the carrying system of the building in case of fire.*"

Identifying failure modes for this requirement is difficult, as it is not directly linked to any performance requirement in the regulation. It is however very important for the fire safety design. The author questions why fire energy as a single parameter influences the fire safety design to such a degree. Fire energy alone does not predict the severity of the fire, albeit it is a measure of potential energy. As fire energy is not directly related to any performance requirement, it is challenging to quantify the safety level of its performance. Thus it will not be dealt with in the quantitative analysis.

3.4.2 Deviation 2: Fire Resistance of carrying main structure

For fire class 3, the main carrying structure shall not collapse (§11-4 (4)). The pre accepted alternative to this is to have a fire resistance of R90, A2-s1, d0[2]. However a timber structure will only fulfil R90, D-s2,d0 as stated in 3.4.1. Consequently this means that an unprotected timber structure contributes to the fire in an extent too large and it produces too much smoke.

This requirement has several reasons to exist. The different classification factors will be presented successively with a description to why it exists:

- R90 – The building shall maintain its structural stability during the course of the entire fire. This has several reasons. §11-1 (1) states that:
  "Buildings shall be designed so that satisfying safety for people, material values and the environment is maintained throughout a fire." [2]
  R90 is directly related to this paragraph, as it states that the building will not collapse during the course of fire. It is assumed that an early collapse of a building during course of fire, will lead to casualties. Additionally it allows inhabitants of the building to escape, which is paragraph 11-2 in TEK. Furthermore, keeping the structural integrity of the building is of high importance for fire fighters to extinguish fires or rescue people. Otherwise fire fighters cannot enter the building to perform their job without being at an unnecessary high risk.
  Lastly this requirement is related to protection of material and environmental values (§11-1(1)). If the building collapses, material values inside may get lost. However, it may also cause damage to neighbouring buildings or infrastructure thus resulting in increased material loss.
- A2 – The main carrying system shall have no significant contribution to the fire. Similar to the previous requirement, this is to ensure safe evacuation and safety for people. If the contribution to the fire is large, the fire might become more severe. Thus leading to increased heat and smoke production, which increases the danger for people inside the building.
  Additionally, this requirement is related to §11-1(3). It states:
  "Buildings shall be designed, located and executed so that the probability of fire spreading to other buildings is low"
  Fire in the main carrying system might increase the risk of fire spreading to other buildings. Hence, explaining why this requirement exists.
- s1 – Burning of the main carrying system shall not produce any smoke. In burning compartments, smoke production often increases the severity of fire due to re radiation and high temperatures. Increasing severity means higher risk for inhabitants, which is related to §11-1(1). The relevance of smoke production extends to safe evacuation for inhabitants. Production of smoke diminishes visibility, hence reducing the inhabitants' ability to evacuate. Smoke might also contain poisonous gases. In fact, a vast majority of the casualties due to fire is because of smoke.
- d0 – Combustion of the main carrying system shall not lead to production of burning droplets. Burning droplets might increase the severity of fire, leading to decreased safety levels for people.

This requirement has several potential failure modes. Firstly collapse of the building is a potential failure mode. Collapse of the building is not supposed to occur during the entire fire development. If a building were to collapse before the inhabitants had evacuated, it would mean several casualties. Thus it poses a threat to personal safety. However a building in fire class 3 is supposed to withstand collapse during the entire fire. Therefore it is deemed as highly unlikely that the building is going to collapse when people are present. Maintaining the structural integrity of the building is therefore assumed to protect material values.

Another potential failure mode is flashover or the time to flashover. As the main carrying system of timber will contribute more to fire than the requirement allows, the probability of flashover is higher. Also the time to flashover might decrease. However the area of the main carrying system is disappearing compared to all the surfaces in a building. Hence this is not regarded as the most relevant failure mode for this requirement.

The last failure mode of this requirement is smoke production. Utilising unprotected timber structures lead to excessive smoke production. The potential failure mode could be limited visibility due to high smoke concentration. Similar to the previous failure mode, the main carrying system has small impact compared to the total surfaces in a building. Given that these surfaces are exposed timber. It is therefore not regarded as the most relevant failure mode for this requirement.

As this requirement is directly related to structural stability, it is natural that structural collapse is the most important failure mode. This is also evident from the previous discussion. Earlier it was stated that structural stability is most relevant for protecting material values, especially as the main evacuation strategy in Norway is evacuating everyone simultaneously. As this thesis focuses on personal safety, this requirement is not deemed relevant for the scope of this thesis and it will not be quantified further.

3.4.3 Deviation 3: Fire resistance of secondary structural system

The requirement of the secondary structural system is according to TEK:

"Secondary constructions and constructions that only carry one floor or roofs, shall maintain satisfactory structural integrity in the time needed to evacuate people or animals from the building."[2]

In §11-4 table 1, the pre accepted fire resistance for secondary constructions is given as R60, A2, s1, d0[2]. It is similar to the previous deviation except for structural integrity, which is R60 in this case. This means that the structure shall withstand a standard fire for 60 minutes. Whereas the main purpose of the main carrying system is to prevent global collapse, the purpose of the secondary structural system is to prevent local collapse.

Similar to the main carrying structure, the failure modes are:

- Local collapse
- Flashover
- Smoke production

Both flashover and smoke production is dominated by the surfaces and claddings in a building. Besides exposed surfaces due to secondary structures are incorporated in the next deviation. Hence the most relevant failure mode is local collapse. This requirement is aimed to protect lives of people and animals. As the requirement is R60, the secondary structure should at least maintain its structural integrity for 60 minutes. In 60 minutes, it is safe to assume that people have evacuated the building. Therefore it is assumed that the requirement is aimed to protect fire fighters and rescue teams. In other words, this requirement is aimed on personal safety. However the safety of the inhabitants in the building must be prioritised first. Fire fighters might choose not to go into a building if it is deemed unsafe. This deviation will therefore not be quantified further.

3.4.4 Deviation 4: Surfaces' and cladding's characteristics in case of fire

These are the two functional requirements in §11-9. Materials and product's abilities in case of fire:

1. Buildings are to be designed and executed so that the probability of a fire occurring, developing and spreading is low.
2. Materials and products shall not lead to unacceptable contributions to the fire. Important parameters are ease of ignition, speed of heat release rate, production of smoke, production of burning droplets and time to flashover

The failure modes for this requirement are related to contribution to fire, smoke production and fire spread. Similarly to 3.4.2, timbers contribution to fire is problematic. As seen in section 3.2, timber is ignitable and has a high heat of combustion. The difference from 3.4.2 is that the area of the surfaces in a building is a lot larger than of the main carrying structure. Hence flashover is a failure mode that is highly relevant for this requirement. Increased areas of the surfaces also increase the risk of actually contributing to the fire. Hence the risk of flashover is highly relevant to quantify.

When considering smoke production, it is important to consider two different factors. Smoke production and the composition of the smoke, i.e. toxicity of the smoke. Smoke production threatens personal safety as it reduces visibility, making escape difficult. If the smoke is toxic, the danger is increased but this is nearly impossible to quantify, as it depends highly on what other fuels are burned.

Section 3.2 showed the potential severity of fires in compartments of exposed heavy timber. A recurring observation from these tests was the intense burning outside the compartments. The authors theorise that this is due to high production of pyrolysis gases that results in poor burning conditions within the compartment. Hence resulting in intense burning on the outside of the compartment[24, 25]. This makes vertical fire spread a potential failure mode for deviation 4. From the research made by Hox, the window broker after 5 minutes and 45 seconds[23]. Observations told a tale of intense burning from the window. With combustible materials on the exterior surface the risk of vertical fire spread is even larger. This poses a threat to personal safety as the fire might quickly spread to other parts of the building. Thus compromising the life safety of an extensive amount of the inhabitants. A potential failure mode for fire spread could be breakage of the window above the burning compartment, or flashover in the compartment above.

All failure modes are highly relevant to personal safety. However there are some slight differences between the three. Ignitability and contribution to fire mainly contributes to the probability of a fire growing big. It affects the consequences regarding personal safety less, as casualties rarely occur due to high temperatures and heat release rates. Smoke does not affect the probability of fire, as it is a result of the fire. However it does affect consequences of a fire, especially regarding personal safety. It is a well-known fact in the fire safety community that most casualties occur due to smoke. Vertical fire spread also affects the consequences of fire with focus on life safety. However this is dealt with in little detail in TEK. There is also little statistics that can support a quantification of vertical fire spread as a failure mode. Hence the failure mode chosen is smoke production. The tenability limit is 10 meters of visibility at 2 meters height[35];

consequently, when the visibility is less than 10 meters in the escape corridor, the remaining inhabitants are in danger.

3.5 Acceptance criterion

In the introduction, lack of acceptance criterion was stated as one of the issues regarding probabilistic design. Acceptance criteria exist so that it is possible to give context to the quantified safety levels. Hence it is possible to measure and evaluate the safety levels to the consequences of failure. This chapter focuses on establishing an overall acceptance criterion so that the achieved safety levels can be put into context.

This thesis focuses on personal safety. Thus it is natural to limit amount of casualties due to fire. Figure 3.6 shows the development of casualties due to fire in buildings since 2009.

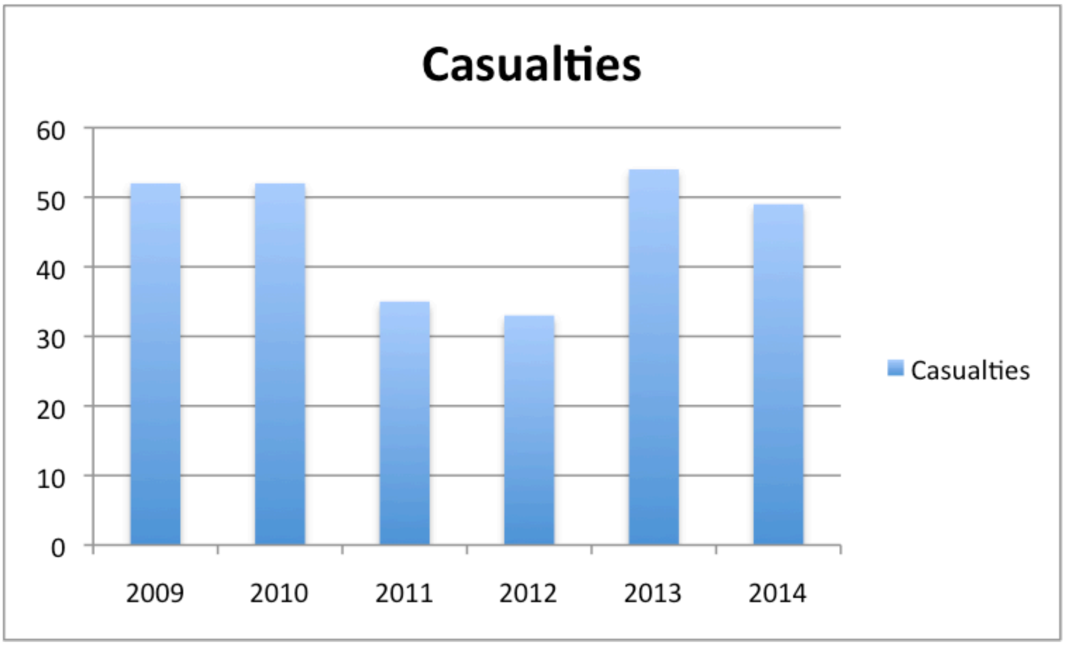

Figure 3.6 - Casualties from building fires since 2009, source: Direktoratet for samfunnssikkerhet og beredskap. Number of casualties from fires in buildings. Fetched: 28.04.2016

These numbers represent fatalities in buildings in Norway due to fire. As seen in figure 3.6 no evident trend exists. The average casualties per year are 45.8, given this way of measuring it. Although there is no evident trend, these numbers must be compared with the number of fires in buildings. Figure 3.7 shows amounts of fires in buildings since 2010.

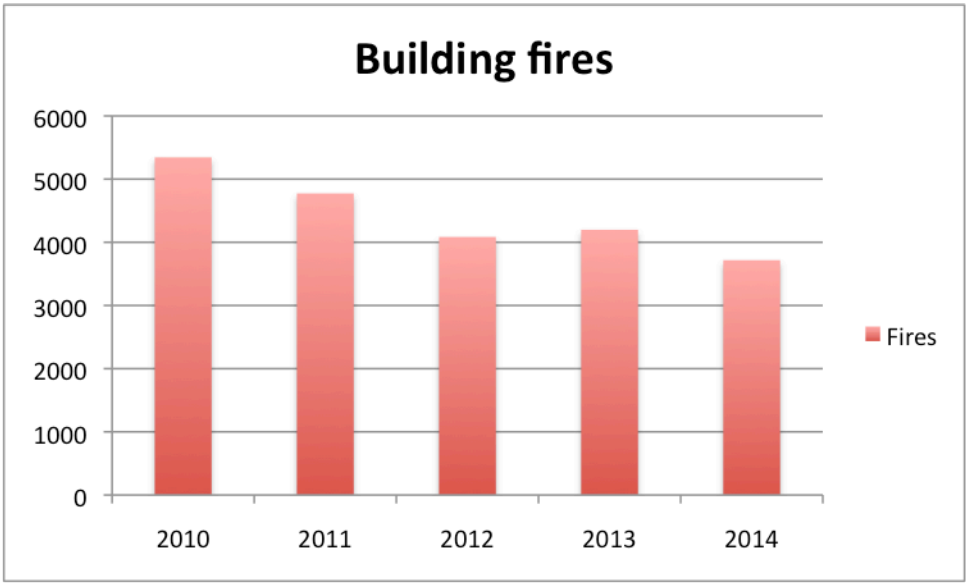

Figure 3.7 - Building fires since 2010, source: Direktoratet for samfunnsikkerhet og beredskap. Number of building fires in Norway. Fetched: 28.04.2016

This statistic includes chimney fires as a building fire. It also includes all kinds of buildings including cabins. Figure 3.7 shows an evident trend, which is that the amount of building fires is decreasing. This information can be used for several things. Firstly it is possible to establish probability of casualties per building fires. Secondly the falling trend can be used to argue an acceptable number of casualties per year. Table 3.6 shows casualties per fire. 2015 is not included due to the uncertainty regarding casualties.

Table 3.6 – Casualties per building fire.

Year	2010	2011	2012	2013	2014
Building fires	5344	4773	4084	4198	3716
Casualties	52	35	33	54	49
Casualties/fire	0.00973	0.00733	0.00808	0.0129	0.0131

Whereas the amount of building fires is falling, the amount of casualties per fire is increasing. However, this factor is highly influence by the number of casualties, which is a lot lower than building fires. Therefore, it does not make sense to utilise casualties per fire as an acceptance criterion. Casualties due to fire in buildings per year are decided as a fitting criterion to evaluate the personal safety in buildings.

Casualties per year due to building fires are the acceptance criterion chosen for the scope of this thesis. To decide the acceptable number of casualties, the presented statistics are studied. Figure 3.6 shows number of casualties due to all kinds of fire in Norway. It seems to be random, and table 3.6 shows that it does not correlate with building fires. In deciding an acceptance criterion, it is important to be ambitious, but realistic. This is to ensure a safer society within reasonable costs. Thus the values from 2010 to 2014 are evaluated. This is to avoid the "extreme" values from 2009 and 2009, which increases the average value. And the uncertain value from 2015 is excluded as well. The average casualty per year is then 45.8.

It is important to take note that old buildings are included in this statistic. The fact that new buildings have more strict requirements to safety must be considered. According to a report made by DSB, approximately 11% of fires are set ablaze, 25% due to open fire, 21% due to electrical fault, 19% due to misuse electrical, 18% unknown and the rest is due to other various reasons[36]. It is amongst other natural to assume that the fires due electrical fault will be reduced with time, due to heightened safety requirements, suggesting that the number of casualties should be reduced further.

Utilising 30 casualties per year means reducing the average value of casualties per year by 15.8. This means saving the Norwegian society for NOK 474 million, assuming that each life is worth 30 million NOK[11] . This is a drastic reduction from today's level, however it is realistic due to the reasons stated previously.

4.0 Quantitative Analysis of Trial Design

The qualitative analysis is done in accordance to NS-EN 3901 as described in the Method chapter. It is important to take note that the analysis will not be finished qualitatively, as the focus of the thesis is on the quantitative analysis. Still, a major part of the qualitative analysis must be performed in order to perform the quantitative analysis. In summary, the steps from chapter 6 in NS 3901 are followed until the consequence analysis, where the quantitative analysis begins.

This chapter contains considerable amounts of input from externals such as supervisors and other FSEs. Drawing on their experience, it is possible to ensure a high quality qualitative analysis. As this is the foundation of the quantitative analysis, it is important.

Description of object

For this analysis, a fictional case has been created. The fictional building contains 8 floors and serves as a student accommodation; hence the purpose of the building is habitation. As 12 students live on 7 floors, 84 people inhabit this building, placing the building in risk class 4 in accordance with table in §11-2 in TEK10[2]. This also suits the pre-accepted solution in VTEK. As the building is in risk class 4 and more than 5 floors high, it falls within fire class 3.

The description of the floor plan for the upper floors of the building is supported by figure 4.1. As the 1st floor is not analysed it is only described shortly. 1st floor contains entrance and reception. There are common areas such as a tv room, a pool table and a study room in the first floor. Both a stair and an elevator are utilised for transport. The 7 floors above are identical and built up as shown in figure 4.1. When entering a floor from either elevator or stair, one enters the common room. The common room consist of kitchen facilities for 12 people, area for a couch and a television and a hallway all around the floor leading to the living areas. Additionally, there are windows that let in light to the common areas, which is shown in figure 4.1. The walls and the roof in this floor consist of unprotected cross-laminated timber, whereas the floor is covered by linoleum.

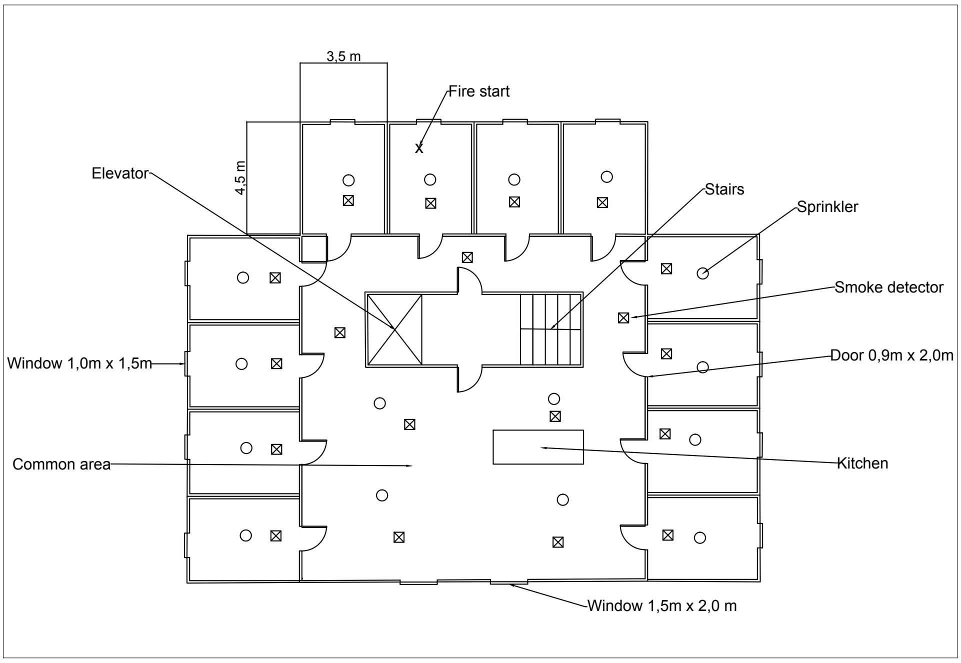

Figure 4.1 - Floor plan representing floors 2-8. Drawn in Autocad

There are 12 living units on the floor, each of the size 3,5m x 4,5m whereas the height is 2,5 m making total floor area 15,75 m^2. The fire load per floor area is chosen as 529MJ/m^2. To identify the specific fire load, equation 4.1 is utilised:

$$q_{t,d} = q_{f,d} \cdot \frac{A_f}{A_t} \quad (4.1)$$

Equation 4.1 – Specific fire load

This results in a specific fire load of 122 MJ/m^2, thus, allowing comparison with the theory section and especially the work of McGregor. There are two openings in the living units, which are the window and the door. The walls and the roof in the compartment consist of exposed cross-laminated timber, but the contribution is not calculated within the fire load. Similar to the common area, the floor is covered with linoleum. Figure 4.1

also shows the placement of smoke detectors. There are also sprinklers within the compartment, as shown in figure 4.1.

In addition to sprinklers, the fire safety strategy is based on making the whole floor a fire cell, meaning that the doors and walls between the compartments and the common area are not classified. In case of fire, two possible escape routes exist: Inhabitants might escape through the stairs or the windows in the common rooms. The windows in the common rooms are designed so that escape is possible, leading to an external stair intended for evacuation only. Furthermore, the fire brigade is assumed to be in possession of equipment to support this. As the entire floor is considered as one fire cell, figure 4.1 shows that the stair fulfils Tr 1, which is in accordance with the pre-accepted solution[2]. Thus the requirements for the staircase are:

- Self closing door with E30 classification
- Surrounding walls must fulfil EI 60 A2 – s1, d0

The staircase in this building fulfils all these requirements except for reaction to fire.

To evaluate probabilities, statistics have been identified. According to Nordstat, there have been 35 154 building fires between 1996 and 2014. 6 746 of these have been in block of flats, which is equivalent to the case building. Furthermore, fatalities have occurred in 278 fires, leading to 323 fatalities. There are 18 years between 1996 and 2014, which means that in average there are 15.4 fatal fires each year. The ratio between fatalities and fatal fires is 1.16 for block of flats. By dividing the total number of fires in block of flats with the fatal fires, the probability of a fatal fire is calculated. This value is approximately 0,0412.

According to a cause report from DSB [36], this is the distribution of the main causes for housing fires.

Table 4.1 – Causes for fires in housing[36]

Cause	Percentage occurrence [%]
Fires set ablaze	10,70
Open fire	24,54
Electric fault	21,40
Misuse of electric equipment	19,42
Unknown	17,80

To gain some more information, the numbers from table 4.1 is broken down further. Under the open fire category the main reasons for fires are smoking, candles and other, making up approximately 15 of the 24,54 percent. Other is main component of electrical fault, making out 14 out of 21,40 %. And ultimately, 11,36/19,42 % of misuse of electric equipment is due to dry boiling or overheating. This will be discussed further at a later point.

Choice of analysis method

It has already been stated that the purpose of this thesis is to evaluate probabilistic – deterministic fire design. Hence an Event Tree Analysis (ETA) has been chosen as the quantitative method. To support this analysis, different deterministic methods are chosen such as fire and evacuation simulation.

Risk acceptance criterion

The risk acceptance criterion for this analysis will be the quantified risk from the analysis of the reference building.

Hazard identification

The hazards in buildings utilised for habitation are well represented by the statistics in the description of analysis object. In this section the hazards will be presented and discussed further. There are two possible scenarios envisioned for this case, which are fire starting in a student compartment or in the common room. The different hazards will be placed into either those two scenarios.

1. There will always be a risk of *arson*. It is challenging to design with this in mind, because if someone wants to sabotage it is always possible however it must be accounted for. It is difficult to say which scenario this hazard belongs to, as someone might set the building ablaze on the outside, in the common area or in a student compartment. Hence this hazard belongs to all possible scenarios.
2. According to the statistics, *open fire* is a major hazard for housing buildings. It accounts for approximately 25% of the fires. However, in this case it is less relevant. The student accommodation has no fireplace nor is it allowed to smoke inside either. Thus, some of the major contributors to this category are eliminated. Fires due to open fire might take place inside the compartments or in the common area; therefore this hazard is assigned to both interior fire scenarios.
3. Fires due to *electrical fault* make out approximately 20% of all building fires. There are electrical components both within the student's compartment and in the common area. It is therefore possible that fires in both areas start due to this hazard. An interesting observation in this regard, is that the statistics from 2008 contains all housings in Norway. This encompasses old buildings, which does not fulfil the requirements of today. The building in this case is recently built, which means that it has strict requirements regarding the safety of electrical systems. Thus it is possible to assume that the probability of fire due to electrical fault could be lower in this instance. Majority of reasons to electrical faults are unknown, making it difficult to place it in a specific scenario. Hence, it belongs to both scenarios.
4. *Misuse of electrical components* is a quite common reason for fire in buildings. One of the major mistakes within this category is dry boiling or overheating. This is mostly related to activity limited to the kitchen; hence it is assumed that this category is most relevant for a fire starting in the common area.
5. The last hazard is *unknown.* As little is known of this category, it belongs to both scenarios.

List of relevant initiating fires:

- Fire starting in either student compartment or common area due to arson.
- Fire starting in either student compartment or common area due to careless handling of open flame such as candles.
- Fire starting in kitchen due to dry boiling of rice or forgotten pizza in the oven.
- Fire starting in the student compartment due to failure of electrical systems such as charger, computer or TV.

- Fire starting in the common area due to failure of electrical systems such as refrigerator, washing machine, stove or TV.

According to the statistics, a small amount of fires also start due to explosions, lightning strike and spontaneous combustion. However these are not included, as they are not deemed as relevant for the possible fire scenarios.

Analysis of causes and probability
Firstly the probabilities given earlier will be discussed, as the same conditions do not apply for the reference building as for the buildings presented in the statistics. Thus, the presented categories will be discussed to decide how the probabilities are to be changed. Then probabilities will be assigned to each scenario, so that a probability for each scenario can be derived.

1. The probability for *arson* will be kept constant. There is no evidence to support the change of this probability, thus it remains at 11%.
2. As stated previously, main parts of the *open fire* category consist of smoking, open candles and other. In this building, smoking is not allowed and there is no fireplace either, which eliminates the risk of fire in the pipes. Hence this probability can be removed entirely. This means a reduction from 24,54 to approximately 15%.
3. Fault in the *electrical system* consist of 21,40% of the fires in housing buildings. The statistics from 2008 contains information from all the buildings in Norway. Including old buildings, which have not been upgraded in many years. Thus, it is safe to say that the probability of fire due to fault in the electrical system must be reduced somewhat as the trial design is from 2016. That means that the requirements to safety regarding the electrical systems are strict. It is challenging to estimate the factor with which this category can be reduced. However, by reducing the entire category by 25%, the probability is not reduced excessively. Hence the probability for fire due to fault in electrical systems is decided to be 15%.
4. Previously, it was discussed that dry boiling and overheating were the main reasons for fire due to *misuse of electrical equipment.* They make out 11,36 out of 19,42%. However, in new buildings in Norway “stove guards” are installed. These instalments are designed to prevent such accidents from happening; hence the probability of fire due to overheating or dry boiling can be halved. This means that the total probability for fire due to misuse is approximately 13%, making dry boiling or overheating representing 4,94% of the total.
5. The *unknown* category will be kept unchanged. It makes out approximately 18% of the fires reported.

As not all probabilities have been included and some have been reduced, a new distribution needs to be calculated. Round numbers have been chosen due to simplicity leading to an updated probability of fire of 72. Table 4.2 sums up the new distribution as well as how each category contributes the initiating fires. New probabilities are calculated assuming that 72 make out 100%. By dividing the new probabilities with 72, the new probabilities are identified.

Table 4.2 - Redistributed probabilities for fire

Category	Total probability	Compartment fire	Fire in common room
Fires set ablaze	15,3%	7,65%	7,65%
Open fire	20,8%	10,4%	10,4%
Electrical fault	20,8%	10,4%	10,4%
Misuse of electric systems	18,1%	5,6 %	6,9 + 5,6 = 12,5%
Unknown	25%	12,5%	12,5%
Total	100%	46,55%	53,45%

Table 4.2 shows the new representation of probabilities after the reduction, as well as how the different categories of hazards contribute to initiating fires. Mostly, the probabilities are distributed evenly to each scenario due to lack of information. However, a larger amount is distributed from misuse of electric to fire in common room, as of the main contributors to this category is dry boiling and overheating. They are assigned to the kitchen only, thus initiating a fire in the common room.

Fire scenarios

In NS 3901 it is required to analyse 4 different fire scenarios. Those are:

1. Worst case scenario
2. Fire that is initiated in a room that is not usually occupied, and that might threaten a large amount of people.
3. A slowly developing fire, which will not trigger the alarm or sprinklers.
4. Robustness scenario. This is a statistically probable fire, which is analysed to uncover weaknesses in the design.

For this analysis 1 and 4 is assumed to be the same, thus only one scenario will be analysed, due to the time constraints in finishing this thesis. They are also considered as the most relevant scenarios to analyse, because the robustness of the design is essentially what is tested in this thesis. The scenario is chosen as a quickly growing fire, initiated in one of the student's compartments. Although the probability of a fire starting is higher for the fire starting in the kitchen, the other is chosen as this scenario is studied in the theory. As more is known about the scenario, it is easier to simulate. By utilising the results from the theory, parameters such as HRR can be decided, eliminating as much uncertainty as possible.

Statistically there is no obvious reason for a fire starting in the compartments. Thus, it is decided that this fire scenario is initiated due to an electrical fault in the computer of a student. Imagine this. As the student's computer is rendering a movie, the student goes out in the common room in the second floor to kill some time. The student lives in the compartment across the stairway, marked with x in figure 4.1. A malfunction in the electrical system causes a tiny ignition in some paper at the floor. The fire spreads to the bed, where clothes and linen quickly catches fire. Then the fire alarm sounds, but it has happened before so the students are slow to react. In the meanwhile, the fire is growing and starts licking up the timber walls. The sprinklers are activated, but they fail to extinguish the growing fire. After 5 minutes flashover have occurred, which means that the flames are spreading out the door that the student left open. Luckily the students in second floor could smell the smoke so they evacuated quickly. As one of the students are moving out of the flat, she kept the door to the staircase open with wedges. The fire has now spread out to the corridor and the smoke is quickly spreading all over the floor. Some of it escapes into the stairwell and is driven upwards due to the buoyancy from the heated air. In 10 minutes the escape route is compromised, meaning that the students in the higher floors cannot evacuate via the familiar staircase. This is the worst-case scenario, given the presented floor plan. However, it is possible as shown in the theory chapter and it is definitely life threatening.

This description shows the possible development of the fire, the location of the fire and the barriers installed to prevent it from growing. The design fire chosen for this scenario is the Hydrocarbon curve shown in Figure 4.8 suggesting that the probability of the fire being large must be included in this calculation. In this case, the second floor and the entire escape path are compromised, possessing a threat to personal safety. When the visibility in the escape path is less than 10 meters, experience has shown that inhabitants turn around[37], compromising the escape path. The remaining inhabitants are then considered at risk for their lives; hence, the risk to personal safety will be calculated.

Consequence analysis

The previously depicted fire scenario gives the event tree in figure 4.2.

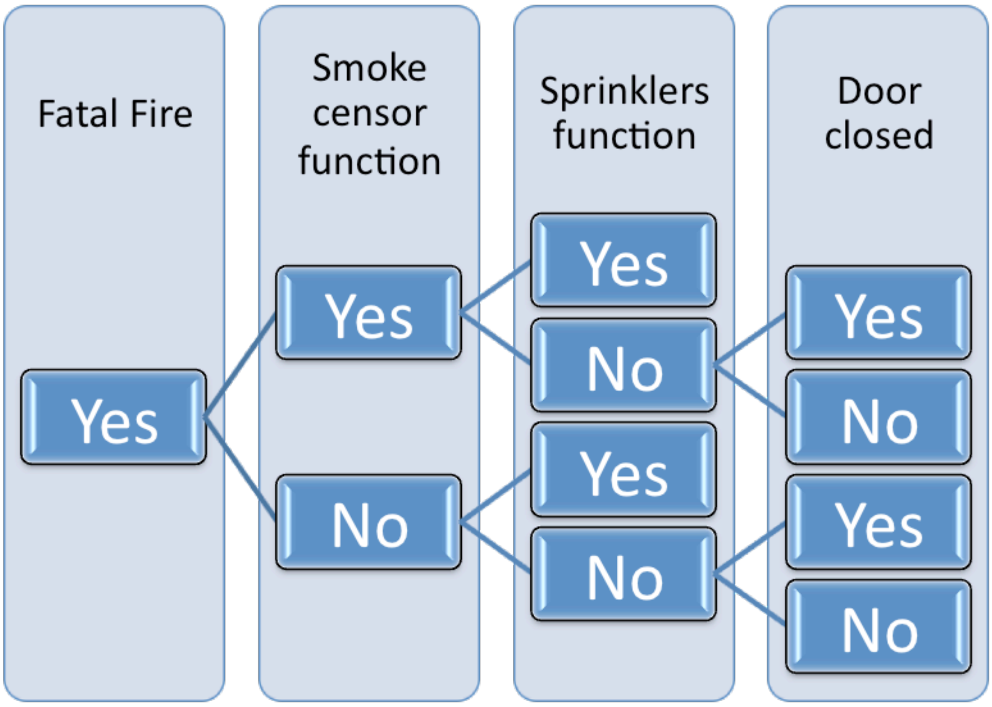

Figure 4.2 – Event tree depicting the fire scenario. Made in Excel.

These sequences all have different consequences and associated risks. The consequences of the different sequences will be described in this section, evaluated by tools such as Pyrosim and Pathfinder. Table 4.3 contains the probabilities associated with figure 4.2. The probability of fatal fires is derived from the statistical data from Nordstat, which is presented in the description of object. It is however reduced by a factor of 0,72, as some of the probabilities were reduced; thus the probability of a fatal fire equals 0,029. Furthermore, the reliability of fire detectors are estimated to 0,987[38]. Sprinklers reliability consists of two components, ability to detect fire and ability to extinguish it. According to NFPA, this lead to a reliability of 0,87[39]. Lastly the probability of a self-closing door being closed is estimated to 0.90[7].

Table 4.3 - Table showing probabilities that corresponds with Figure 4.2.

Event	**Fatal Fire**		**Smoke censor function**		**Sprinklers function**		**Door closed**	
Probabilities	Yes	No	Yes	No	Yes	No	Yes	No
	0,029	0,96	0,99	0,01	0,87	0,13	0,90	0,10

Simulation Results

In this section, the results from the different simulations are presented, making this a part of the consequence analysis. The different scenarios will be presented shortly in the sense that assumptions made for each case are presented. Firstly, the general assumptions regarding all cases for both FDS and Pathfinder are presented in the next two paragraphs.

FDS:

FDS is utilised to predict the smoke development in the building. Two meshes are created: one for the two lower floors and one for the floors above. The lower mesh is finer than the upper mesh, with each cell size being 0,2m x 0,2m x 0,2m. As a result, the accuracy of the calculations is not considered as very precise. To achieve as accurate results as possible, some parameters in Pyrosim are manipulated to fit the results from the theory section. The easiest way of doing this is by manipulating the HRR from the fires in Pyrosim; consequently, the HRR is fitted to the results achieved by McGregor[26]. The fire is modelled as a vent, where the HRR is increasing with a t^2 development. Flashover is assumed to occur after 300 seconds after ignition of fire. This value is chosen for simplicity and because it corresponds to the results from section 3.2. Simultaneously, the door to the common area is removed. As the entire floor is a fire cell, the door and wall are assumed to have little resistance, meaning that fire spread from the common area to the rooms or vice versa is accepted. After 300 seconds another fire is started outside the room of fire origin, as seen in figure 4.3, where the red area is where the fires are placed. The fire is started in the 2nd floor. Figure 4.3 shows the floor plan that corresponds to figure 4.1. The stairwell is the room in the middle, where the stairs are modelled as a hole. In order to decide when the failure mode is reached, a slice measuring visibility is inserted at 2 meters height.

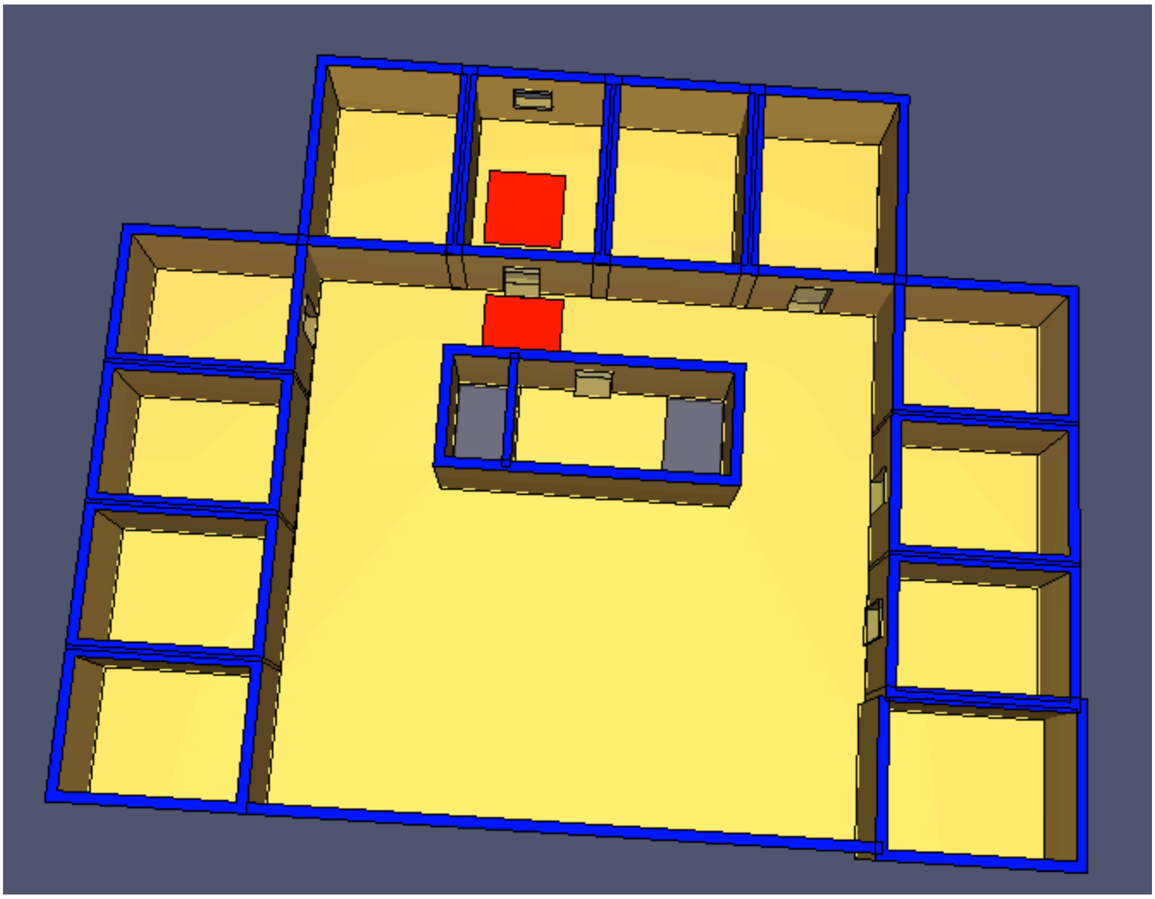

Figure 4.3 – The 1st floor in the Pyrosim model

Several simplifications are made in order to make the workload manageable. Firstly, the surfaces of the walls are selected as inert. This is a conservative assumption, as the smoke cools down faster, which decreases the height of the smoke layer. Hence, the smoke spreads faster to corridors and rooms. Secondly, only one of two doors to the stairwell is open. As this is the robustness scenario, this is deemed as the worst case. Additionally, adding barriers will increase the number of scenarios exponentially, increasing analysis. As this is an analysis of the probabilistic-deterministic method itself, this is not desirable. Lastly, an open window is inserted inside the burning compartment, which can be seen in figure 4.3. This is done because a room is not airtight, however Pyrosim models it as airtight, causing issues due to high-pressure gradients. It is also a conservative choice, as oxygen is added to the fire. If any of these assumptions are changed it will be described in the description of scenarios.

Pathfinder:

As with Pyrosim, the model created in Pathfinder also have some limitations and assumptions to it. Firstly, the ordinary walking speed is set to 0.9 m/s, due to recommendations from Sintef Byggforsk[40]. This is valid for normally healthy people in good conditions. However, the walking speed down the stairs is set to 0.25 m/s, despite the recommendation from Sintef Byggforsk being 0.5 m/s. As seen in figure 4.4, the stairs are modelled quite poorly with the length of the stair almost equalling the height. To account for this, the recommended walking speed is halved; thus, reducing the angle of the stairs drastically. Secondly, the detection time is set to 1 minute and 10 seconds, which is based on the results from section 3.2. Furthermore the reaction time is set to two minutes. This value is rooted in the assumption that the inhabitants are awake and reacts to the alarm. Especially this assumption will be discussed at a later stage. Lastly, it is assumed that 84 inhabitants are present at the time of fire. They are modelled as the blue columns seen in figure 4.4. Figure 4.4 focuses on the 1st floor in the model. The inhabitants are in their rooms, waiting to start evacuation whereas the orange stripes at the floor are doors.

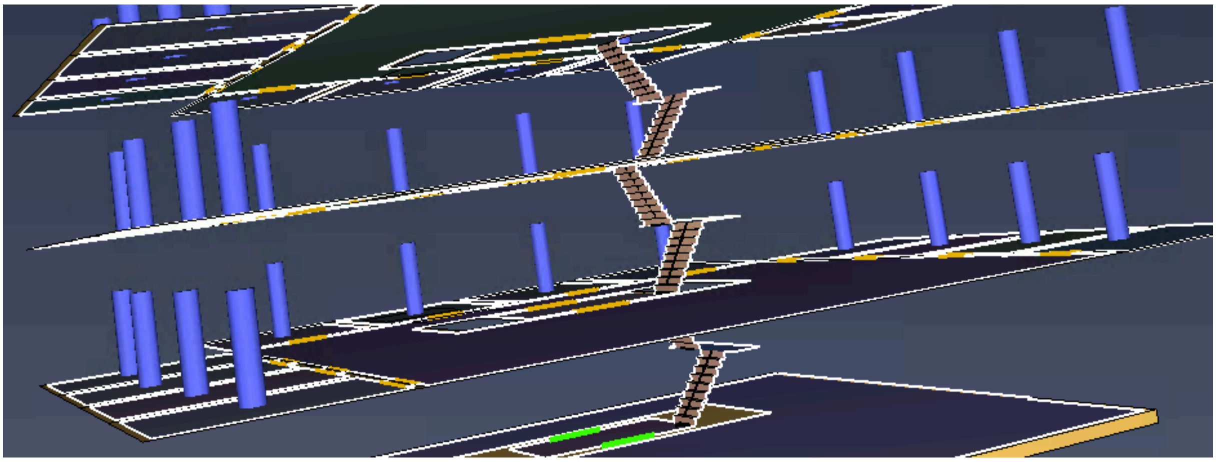

Figure 4.4 – The 1st floor in Pathfinder.

1. Scenario 1

The first sequence analysed shows what happens when the smoke censors work, sprinklers malfunction and the door to the escape path is open. After the fire spreads out, smoke is distributed over the entire floor. In this scenario, the door to the stairwell is open, as well as the smoke censors goes off immediately after the fire is initiated. This means that inhabitants start evacuating after 3 minutes and 10 seconds.

Figure 4.5 shows the development of the HRR in the room, which merely shows that the development of the fire is somewhat equal to the once seen in the theory. This is especially important in this scenario, due to the short duration of the fire.

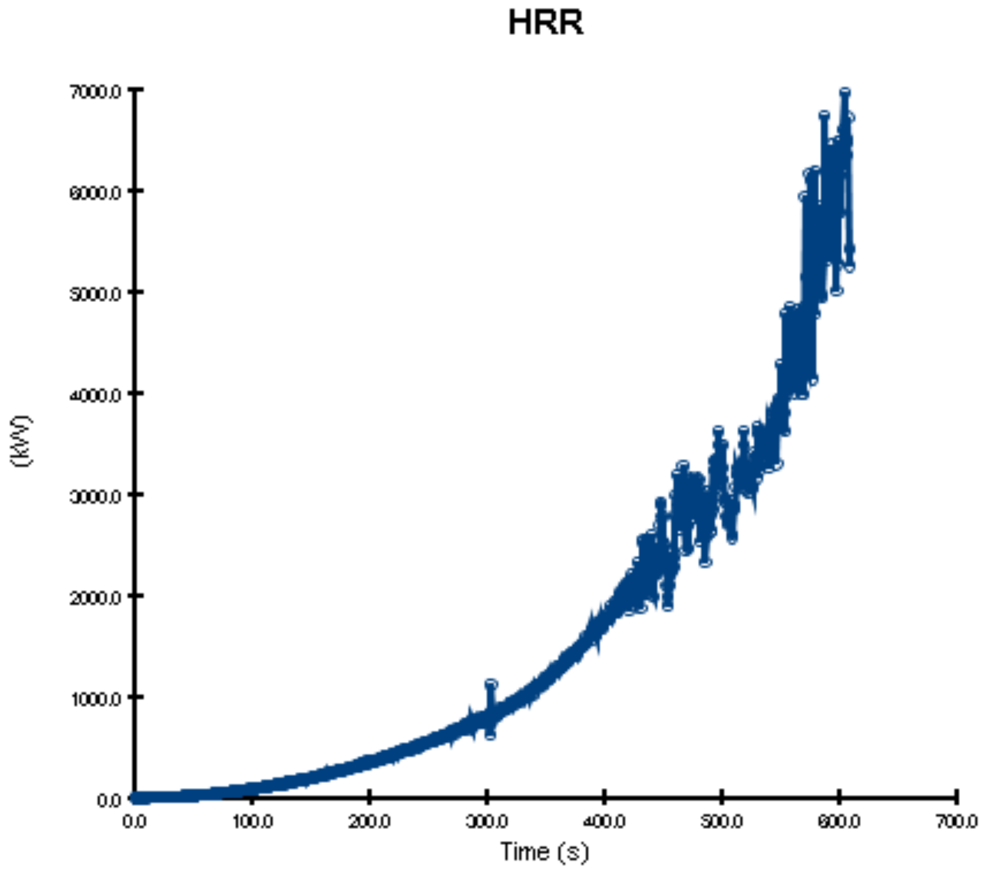

Figure 4.5 – Heat Release Rate in the room of the fire origin

While figure 4.5 confirms that the severity of the fires is equal, figure 4.6 shows the smoke spread in the floor. The different colours show the visibility in the different parts of the floor. At the right hand side, there is a column that shows which colour corresponds to what visibility. It is marked at 10 meters, as this represents the chosen failure mode. The time at which this occurs can barely been seen in the left lower corner, showing that this picture is snapped after 480,5 seconds. Figure 4.6 shows that the evacuation path is compromised due to low visibility, meaning that remaining occupants are in a fatal situation.

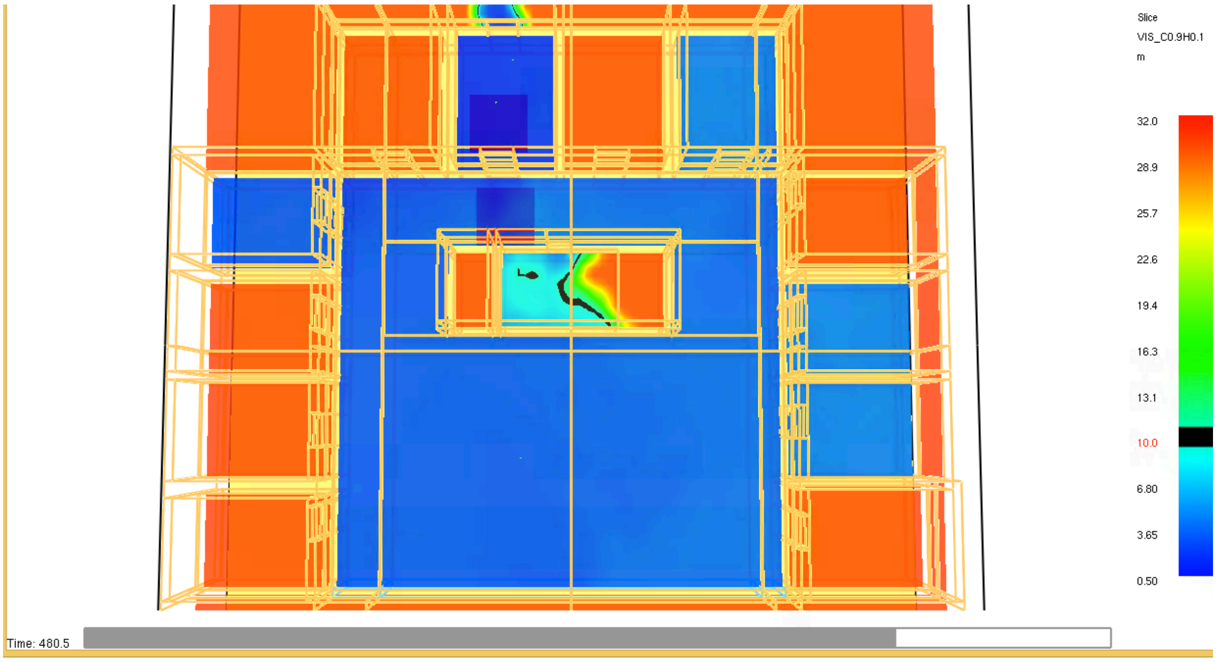

Figure 4.6 – Distribution of smoke in the floor plan. Snapped from Pyrosim.

Corresponding with figure 4.6 is figure 4.7. Figure 4.7 shows the progress of the inhabitants evacuating the building, simultaneously as the corridor is deemed untenable. Figure 4.7 shows that 62 out of 84 has exited at this time, and at least four inhabitants seem to have passed the compromised corridor. The picture is snapped 480,3 seconds after ignition, which corresponds to figure 4.6

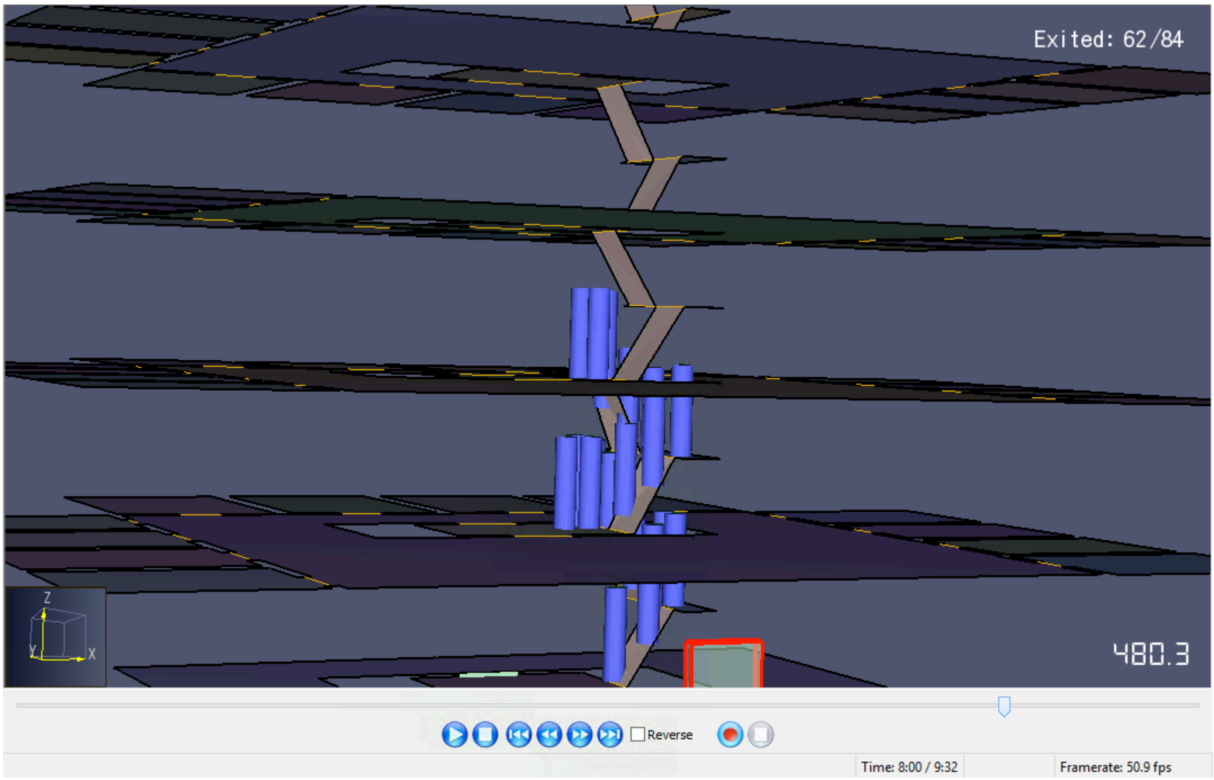

Figure 4.7 – Evacuating inhabitants. Snapped from Pathfinder.

At this point, there seem to be 18 people that are in danger for their lives in accordance with the definition chosen for this analysis.

2. Scenario 2

The next scenario is the sequence where smoke censors work, sprinklers malfunction and the door to the evacuation route is closed. It is modelled similarly to scenario 1, however the door to the stairwell is closed when the fire spreads to the common area. After the fire has spread out in the corridor in the common area, the fire resistance of the door to the evacuation area is calculated to 13 minutes. This calculation is based on Barnett's cumulative radiation energy method, explained in the chapter 2. The analysed design fires are the Hydrocarbon curve and the standard fire curve, which are shown in figure 4.8. The hydrocarbon curve is the red line, whereas the standard curve is the blue. Temperature is shown at the vertical axis, whereas the horizontal axis depicts time in minutes. By using Stefan Boltzmann's law, it is shown that the cumulative radiation energy from a 30 minutes standard fire equals the cumulative radiation energy from a 13 minutes hydrocarbon fire. The calculation is performed in Microsoft Excel and can be found in Appendix A.

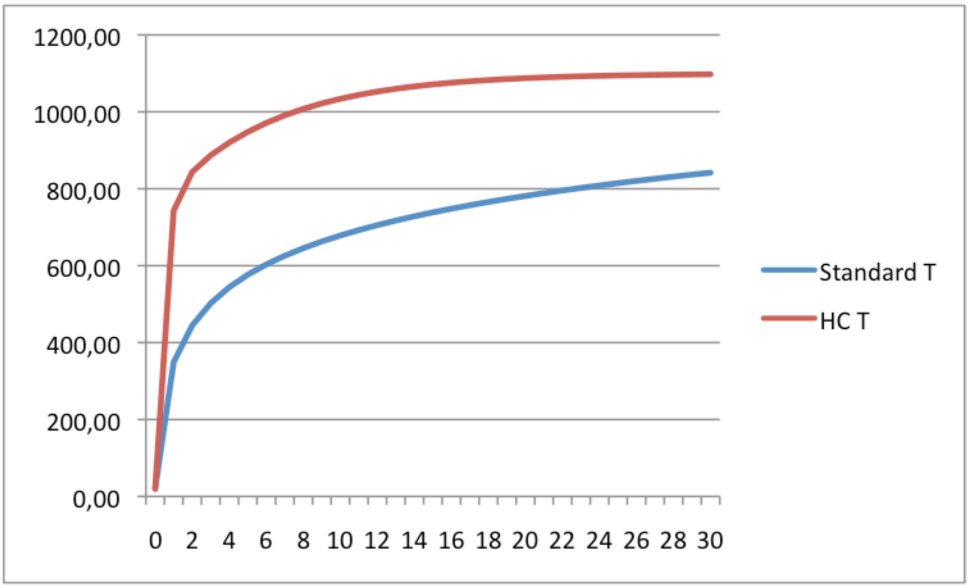

Figure 4.8 – Hydrocarbon curve and the standard curve. Made in Excel

This scenario is modelled somewhat different than the others. When utilising high heat release rates, Pyrosim often encountered numerical instability. Thus, the surfaces were changed to adiabatic and temperature became the main indicator if the simulation was similar to the full-scale tests. Additionally, the heat release rate was lowered substantially. As the fires rage outside the corridor for 13 minutes, this allows the smoke layer to lower sufficiently. Hence, the lower heat release rate does not make a difference, which is seen in figure 4.10, where the escape corridor is compromised 9 seconds after the failure of the door. Figure 4.9 shows the temperature development in the compartment.

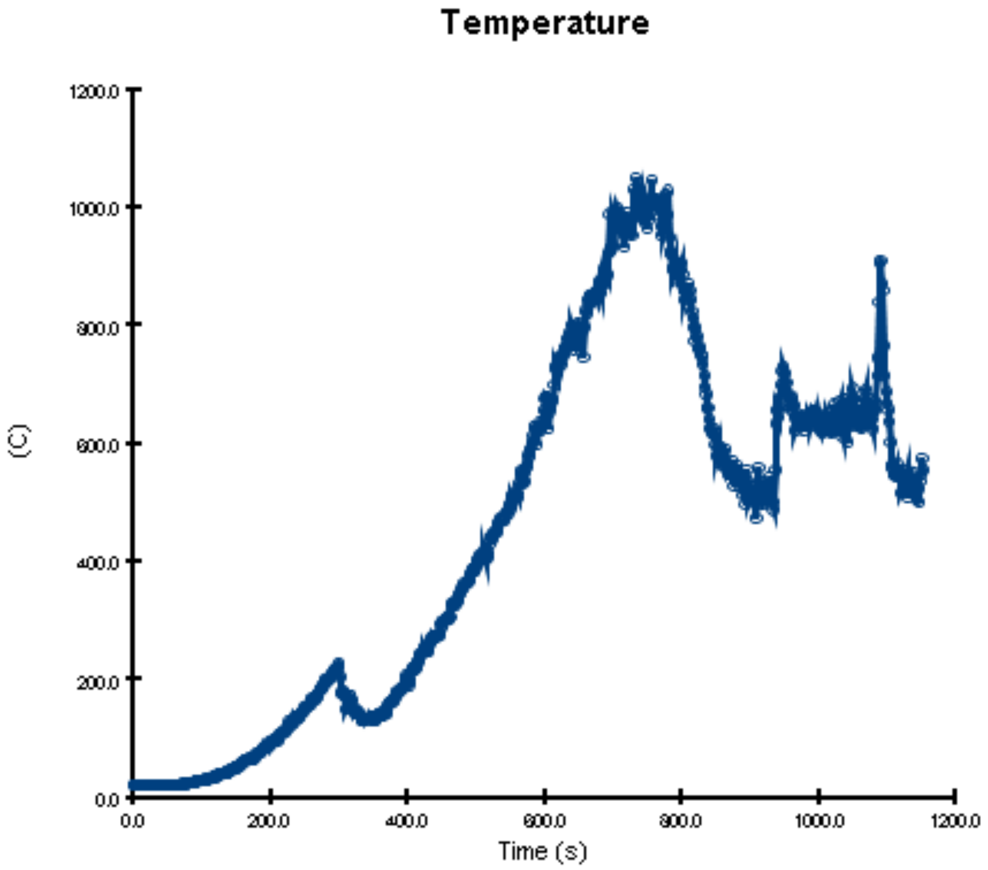

Figure 4.9 – Temperature development in the compartment of the fire start. Extracted from Pyrosim.

The temperature development shows somewhat similar behaviour to cases studied in section 3.1. Although it is not identical, it is deemed sufficient as the smoke layer had time to lower. As the exact temperature development was used for calculation of the fire resistance of the door, the door was removed accordingly. Therefore, as the temperature development is of less importance this will suffice. Figure 4.10 shows the visibility within the stairway after 1089 seconds.

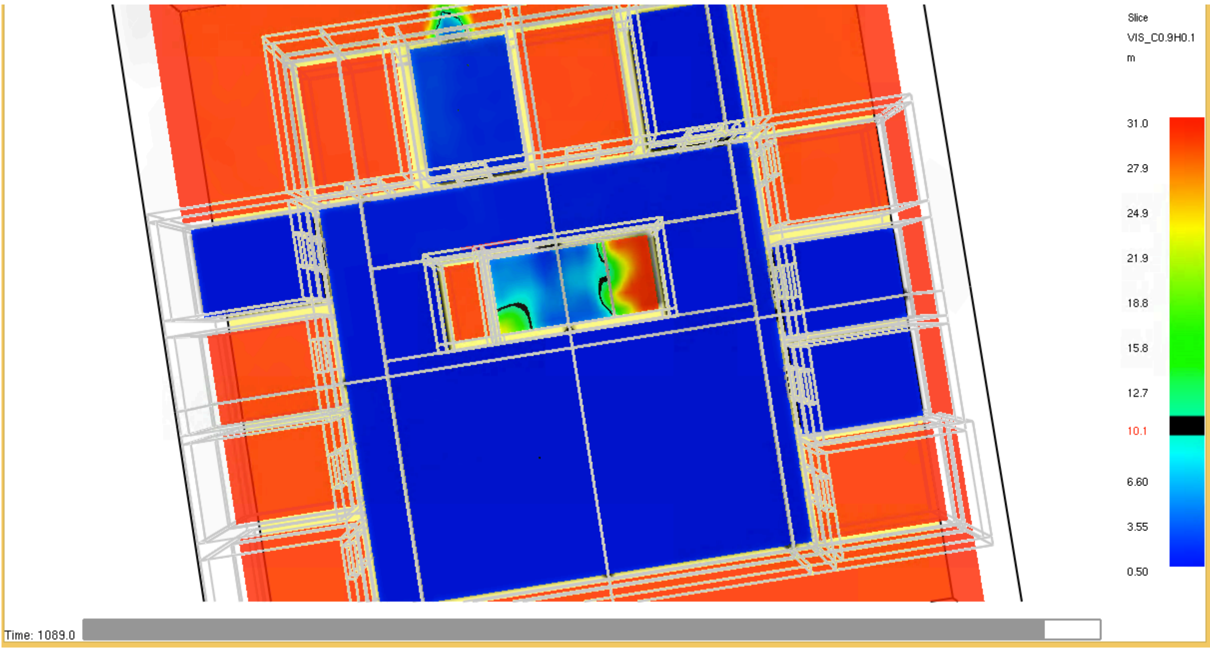

Figure 4.10 – Visibility in stairway for scenario 2.

For this scenario, all inhabitants had evacuated at the time the door failed. This is shown in figure 4.11, where the evacuation had ran its course. As seen in the picture, it took 9 minutes and 32 seconds to evacuate this building completely with the given assumptions.

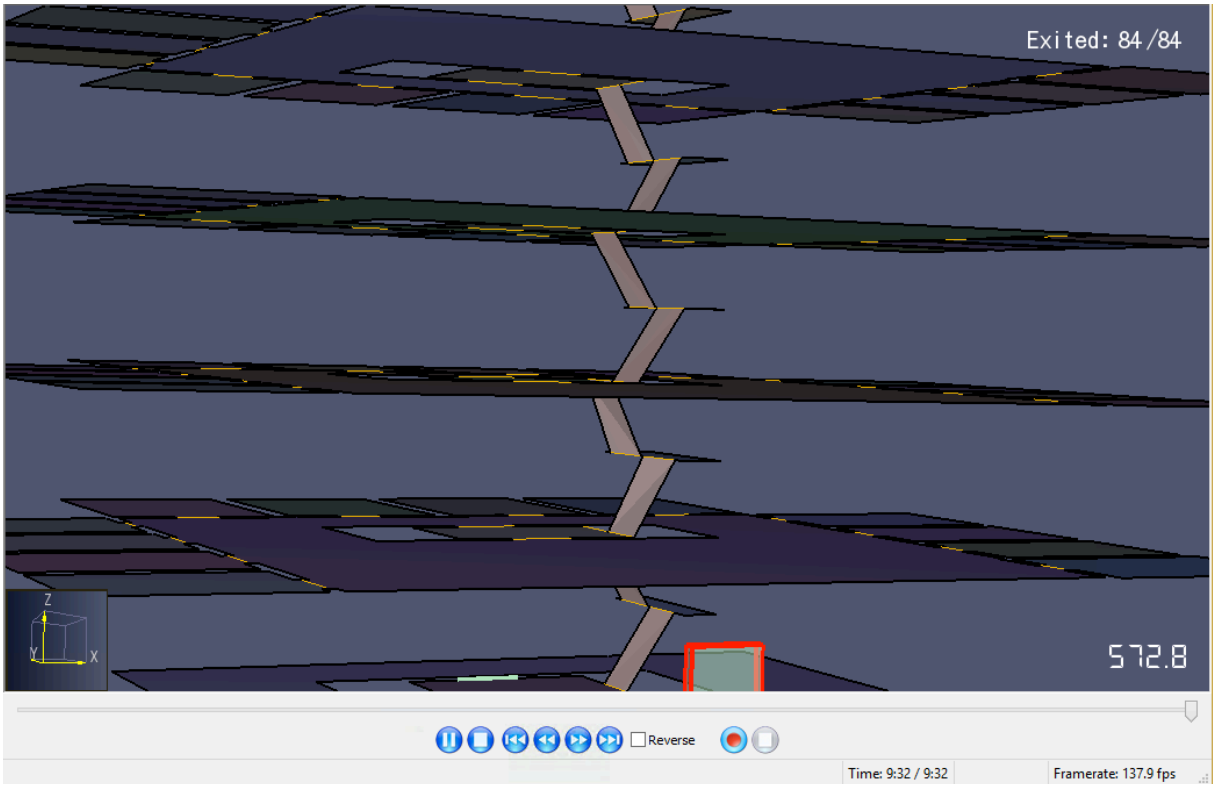

Figure 4.11 – Escape path for scenario 2.

In this scenario no inhabitants were in danger during the course of the fire.

3. Scenario 3

Scenario 3 accounts for the sequence where smoke censors does not function, sprinklers do not function and the door is open. This is simulated in the exact same way as scenario 1 in Pyrosim. Figure 4.12 is therefore identical to figure 4.6, but the overall results are quite different, as the alarm system does not go off before 5 minutes after initiation. This means that people do not start evacuating until 8 minutes and 10 seconds after ignition.

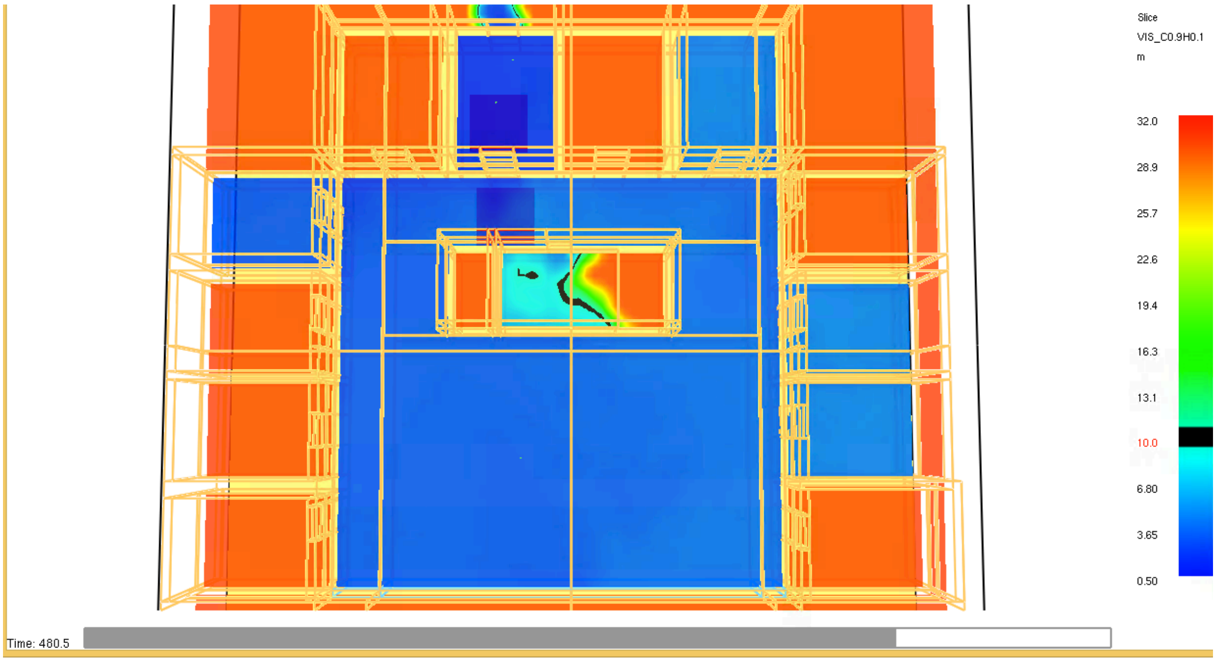

Figure 4.12 – Visibility in the staircase.

At this time inhabitants have not started to evacuate, according to Pathfinder. This is seen in figure 4.13, where all inhabitants stand still in their rooms. Based on this data, scenario 3 poses a threat to all 84 inhabitants in the building.

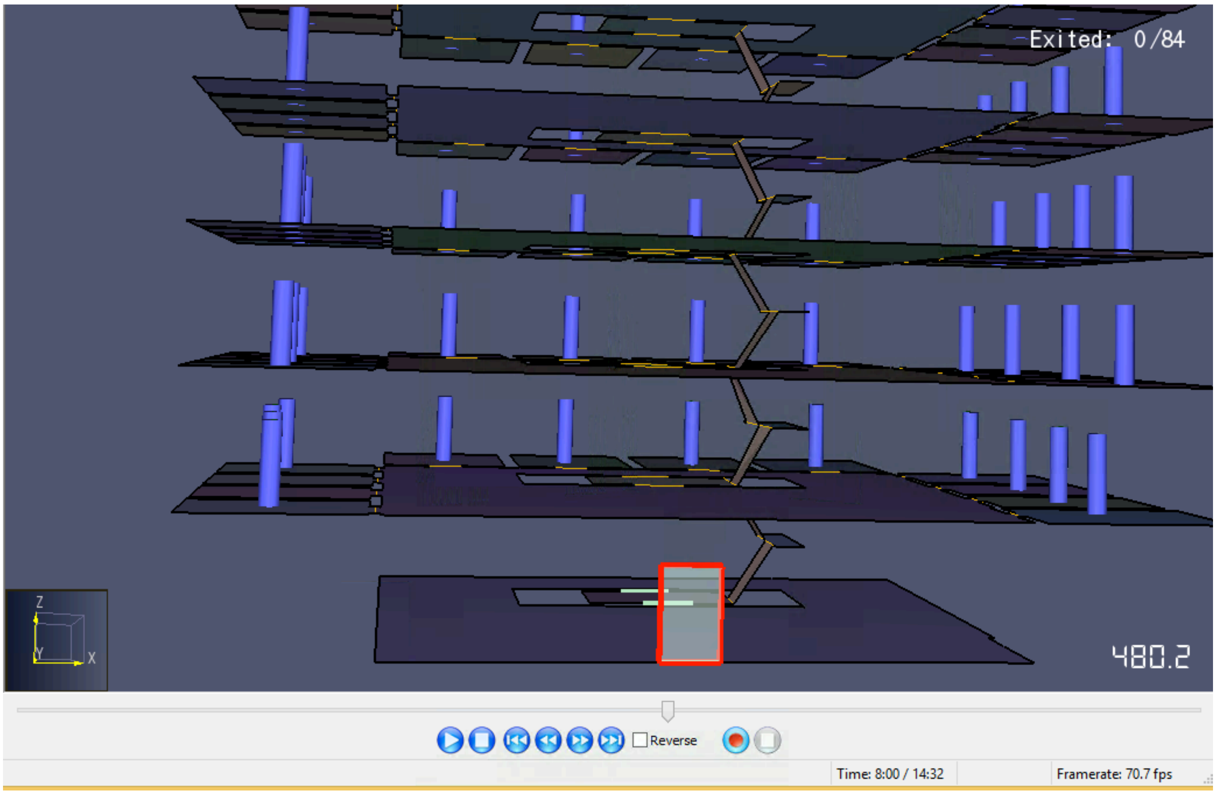

Figure 4.13 – Inhabitants at the time when the escape path is compromised.

4. Scenario 4

The last scenario describes the sequence where smoke censors do not function, sprinklers malfunction and the door is closed. This is also simulated the same way as scenario 2 in Pyrosim, meaning that the same results are yielded. As seen in figure 4.14 the escape corridor is compromised after 1089 seconds. In Pathfinder, inhabitants do not start evacuating before 8 minutes and 10 seconds, similar to scenario 3.

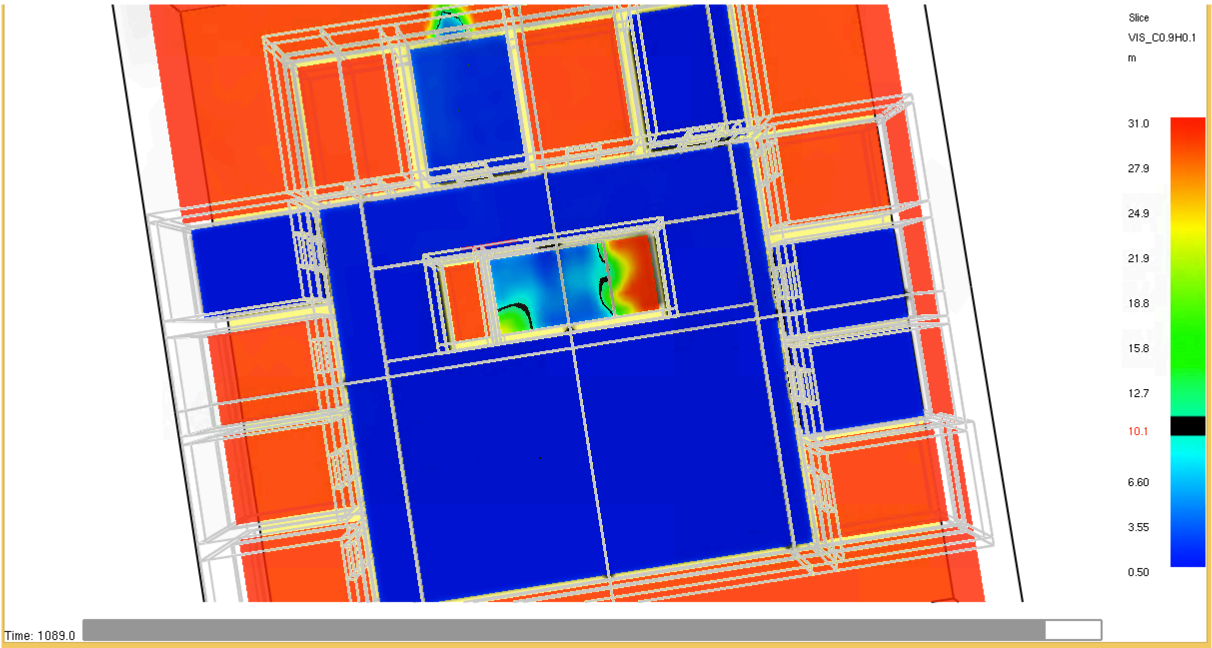

Figure 4.14 – Compromised stairway after 1089 seconds.

In scenario 4, all of the inhabitants have evacuated at the time where the escape path is compromised. This is illustrated in figure 4.15, where no inhabitants are left after 872.8 seconds. Hence no inhabitants are considered to be in danger for this scenario.

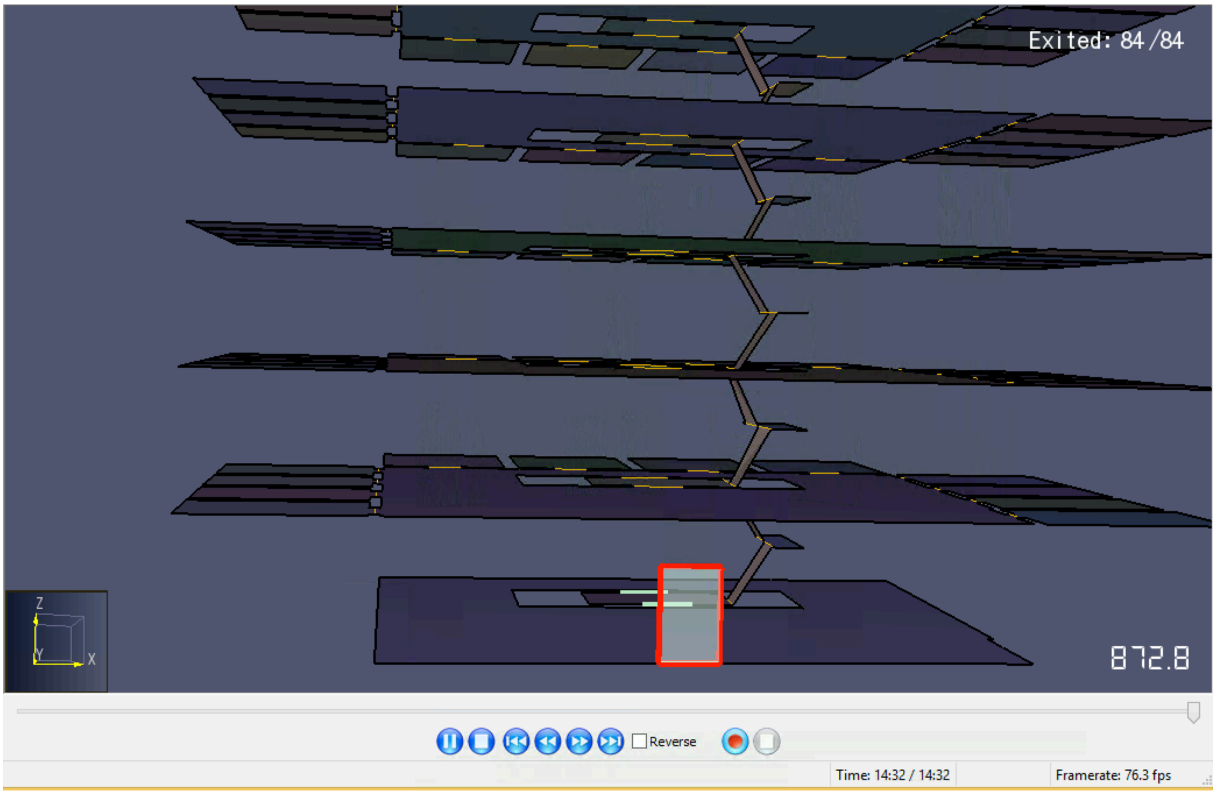

Figure 4.15 – All inhabitants successfully evacuated within the given time window.

Analysis of uncertainty

With this being a comparative analysis, several uncertainties are dealt with in the sense that the same uncertainties apply for the other case as well. However, uncertainties are also treated in a sensitivity analysis in chapter 5.

Sensitivity analysis

A sensitivity analysis will be performed in chapter 5, after the risk of the reference building is calculated.

Description of risk

The results are presented in table 4.4. Probabilities are calculated based on the fact that the events in the event tree are considered independent. Hence, the probability of all events occurring in a sequence is the product of the probabilities in the sequence[41]. Equation 4.2 shows the correlation between the probabilities of independent events.

$$P(A \cap B) = P(A)P(B) \quad (4.2)$$

Equation 4.2 – Joint probability of events

$P(A \cap B)$ is the joint probability of event A and B. P(A) is the probability of event A happening, whereas P(B) is the probability of event B happening.

Risk is then calculated as the product of probability of failure and lives endangered. The risk will not be discussed further as it will be dealt with in the discussion chapter.

Table 4.4 - Summary

Scenario	Time to failure [s]	Probability of failure	Lives endangered	Risk
1	480,5	$0{,}029*0{,}99*0{,}13*0{,}10 = 3{,}73*10^{-4}$	18	$6{,}71*10^{-3}$
2	1089,0	$0{,}029*0{,}99*0{,}13*0{,}90 = 3{,}36*10^{-3}$	0	0
3	480,5	$0{,}029*0{,}01*0{,}13*0{,}10 = 3{,}77*10^{-6}$	84	$3{,}17*10^{-4}$
4	1089,0	$0{,}029*0{,}01*0{,}13*0{,}90 = 3{,}39*10^{-5}$	0	0
Total Risk			$7{,}03*10^{-3}$	

5.0 Quantitative Analysis of Reference Building

To evaluate the results from the original analysis, a comparative analysis must be performed. The comparative analysis will follow the same structure as the original analysis. Many of the aspects in the original analysis will be reused. However the cases are different, because the comparative case analyses a building that follows the pre-accepted solutions. Hence, it is possible to compare the safety level of the trial design towards the safety level of a pre-accepted building. Additionally, the chosen design fire in the fire compartment will follow the standard fire curve to increase the simplicity of the calculations at a later stage. In the end of this chapter, the sensitivity of the results is discussed. This section is quite extensive, as it intends to show the possibilities derived from this method. The results from the sensitivity analysis will be discussed somewhat in this chapter.

Description of object

The comparative case is completely similar to the case described in the qualitative analysis. This means that the building has 8 floors, with 84 inhabitants. Also meaning that the building falls within fire class 3. However, this building follows the pre-accepted solution, regarding surface materials' reaction to fire. The surface and construction material for this building is concrete. Figure 5.1 shows the floor plan, which is exactly the same as the previous case.

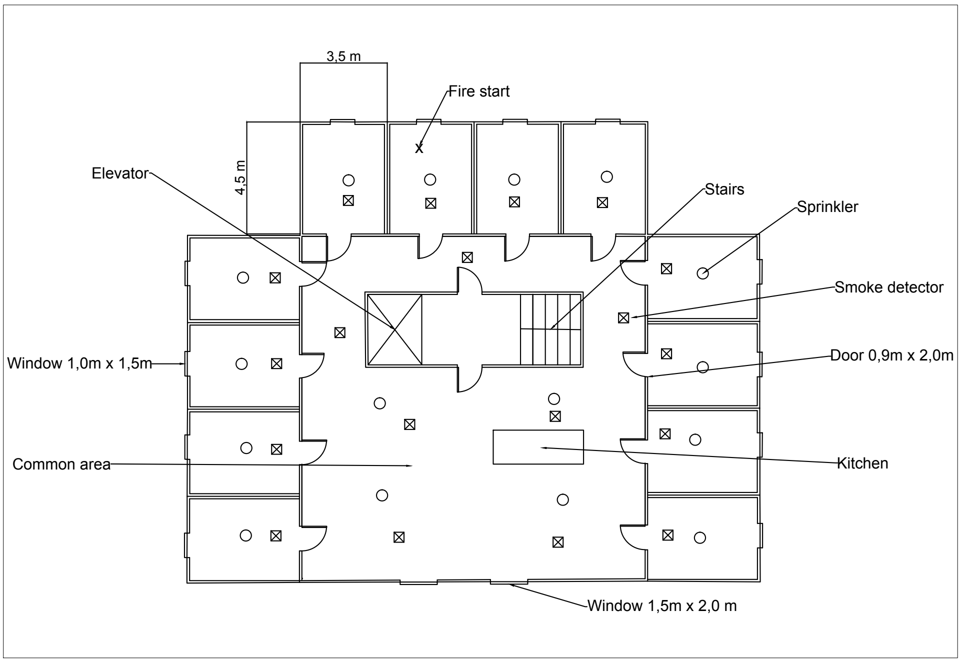

Figure 5.1 – Ordinary floor plan. Drawn in Autocad

There are 12 living units on the floor, each of the size 3,5m x 4,5m whereas the height is 2,5 m, making the total floor area 15,75 m^2. The fire load per floor area is chosen as 529MJ/m^2 resulting in a specific fire load of 122 MJ/m^2, identical to the trial design. There are two openings in the living units, which are the window and the door. The walls and the roof in the compartment consist of concrete. Similar to the common area, the floor is covered with linoleum.

In case of fire, inhabitants have two possible escape routes: stairs or the windows in the common room. The windows in the common rooms are designed so that escape is possible. On the outside is an external stair intended for evacuation only. Furthermore, the fire brigade is assumed to be in possession of equipment to make this possible. Smoke sensors are also placed as shown in figure 5.1. Sprinklers are placed in every compartment and close to the kitchen, shown in figure 5.1. As the building contains 8 floors there are also requirements to the stairway. Tr 1 is chosen for the reference building as it is placed in risk class 4 with 8 floors. Thus, the requirements of the stairwell are:

- Self closing door with E30 classification
- Surrounding walls must fulfil EI 60 A2 – s1, d0

The stairwell in this building fulfils all the pre-accepted requirements.

To evaluate probabilities, statistics have been identified. According to Nordstat, there have been 35 154 building fires between 1996 and 2014. 6 746 of these have been in block of flats, which is equivalent to the case building. Furthermore, fatalities have occurred in 278 fires, leading to 323 fatalities. There are 18 years between 1996 and 2014, which means that in average there are 15.4 fatal fires each year. The ratio between fatalities and fatal fires is 1.16 for block of flats. By dividing the total number of fires in block of flats with the fatal fires, the probability of a fatal fire is calculated. This value is approximately 0.0412.

According to a cause report from DSB in 2008[36], this is the distribution of the main causes for housing fires.

Table 5.1 - Causes for fires in housing [36]

Cause	**Percentage occurrence [%]**
Arson	10,70
Open fire	24,54
Electric fault	21,40
Misuse of electric equipment	19,42
Unknown	17,80

To gain some more information, the numbers from table 5.1 is broken down further. Under the open fire category, the main reasons are smoking, candles and other, making up approximately 15 of the 24,54 percent. Other is main component of electrical fault, making out 14 out of 21,40 %. And ultimately, 11,36/19,42 % of misuse of electric equipment is due to dry boiling or overheating. This will be discussed further at a later point.

Choice of analysis method

The Event Tree Analysis will also be utilised for the comparative case. By using the same methods for both cases, uncertainties are eliminated.

Risk acceptance criterion

Quantified risk from this analysis is the risk acceptance criterion.

Hazard identification

The hazards in buildings utilised for habitation are well represented by the statistics in the description of the analysis object. In this section the hazards will be presented and discussed further. There are two possible scenarios envisioned for this case. Either the fire is starting in the compartment of the students or in the common room. The different hazards will be placed into either those two scenarios.

1. There will always be a risk of *arson*. It is challenging design with this in mind, because if someone wants to sabotage it is always possible.

However it must be accounted for. It is difficult to say whether scenario this hazard belongs to, as someone might set the building ablaze on the outside, in the common area or in a student compartment. Hence, this hazard belongs to all possible scenarios.

2. According to the statistics, *open fire* is a major hazard for housing buildings. It accounts for approximately 25% of the fires; however in this case it is less relevant. The student accommodation has no fireplace and smoking is not allowed. Thus, some of the major contributors to this category are eliminated. Fires due to open fire might take place inside the compartments or in the common area; therefore this hazard is assigned to both interior fire scenarios.
3. Fires due to *electrical fault* make out approximately 20% of all building fires. There are electrical components both within the student's compartment and in the common area. It is therefore possible that fires in both areas start due to this hazard. An interesting observation in this regard, is that the statistics from 2008 contains all housings in Norway. This encompasses old buildings, which does not fulfil the requirements of today. The building in this case is recently built, which means that it has strict requirements regarding the safety of electrical systems. Thus, it is possible to assume that the probability of fire due to electrical fault could be lower in this instance. Majority of reasons to this number is unknown, meaning that the category is divided onto both scenarios.
4. *Misuse of electrical components* is a quite common reason for fire in buildings. One of the major mistakes within this category is dry boiling or overheating. This is mostly related to activity limited to the kitchen. Therefore it is assumed that this category is most relevant for a fire starting in the common area.
5. The last hazard is *unknown.* As little is known of this category, it belongs to both scenarios.

List of relevant initiating fires:

- Fire starting in either student compartment or common area due to pyromania.
- Fire starting in either student compartment or common area due to careless handling of open flame such as candles.
- Fire starting in kitchen due to dry boiling of rice or forgotten pizza in the oven.
- Fire starting in the student compartment due to failure of electrical systems such as charger, computer or TV.
- Fire starting in the common area due to failure of electrical systems such as refrigerator, washing machine, stove or TV.

According to the statistics, a small amount of fires also start due to explosions, lightning strike and spontaneous combustion. These are not included, as they are not deemed as relevant for the possible fire scenarios.

Analysis of causes and probability

Firstly the probabilities given earlier will be discussed. This is because the same conditions do not apply for the reference building as for the buildings presented in the statistics. Thus the presented categories will be discussed to decide how the probabilities are to be changed. Probabilities will then be assigned to each scenario, so that a probability for a fire can be derived.

1. The probability of *arson* will be kept constant. There is no evidence to support the change of this probability, thus it remains at 11%.
2. As stated previously, main parts of the *open fire* category consist of smoking, open candles and other. In this building, smoking is not allowed. There is no fireplace either, which eliminates the risk of fire in the pipes. Hence this probability can be removed entirely. This means a reduction from 24,54 to approximately 15%.
3. Fault in the *electrical system* makes out 21,40% of the fires in housing buildings. The statistics from 2008 contains information from all the buildings in Norway including old buildings, which have not been upgraded in many years. Thus, it is safe to say that the probability of fire due to fault in the electrical system must be reduced somewhat since the reference building is from 2015. That means that the requirements to safety regarding the electrical systems are strict. It is therefore assumed that the probability of fire due to this is lower for the reference building than for the general mass of buildings. It is challenging to estimate the factor with which this category can be reduced. However, by reducing the entire category with 25%, the probability is not reduced excessively. Hence the probability for fire due to fault in electrical systems is decided to be 15%.
4. Previously, it was discussed that dry boiling and overheating were the main reasons for fire due to *misuse of electrical equipment.* They make out 11,36 out of 19,42%. However in new buildings in Norway, “stove guards” are installed. These instalments prevent such accidents from happening; hence the probability of fire due to overheating or dry boiling can be halved. This means that the total probability for fire due to misuse is approximately 13%.
5. The *unknown* category will be kept unchanged. It makes out approximately 18% of the fires reported.

As not all probabilities have been included and some have been reduced, a new distribution needs to be calculated. Round numbers have been chosen due to simplicity. The new total probability for fire is 72. Table 5.2 sums up the new distribution as well as how each category contributes the initiating fires. New probabilities are calculated assuming that 72 make out 100%. By dividing the new probabilities with 72, the new probabilities are identified. This value is further utilised to reduce the probability of a fatal fire in the reference building. However, it is natural that the probability of a fire starting in the trial design is higher than for the reference building. This is because timber surfaces increase the risk of a fire starting, as discussed in section 3.4. Thus the reduction factor for the reference building is decided as 0,50. Which means a reduction of approximately 30% compared to the trial design. This is an uncertain value, which cannot really be obtained until more is known about how new buildings behave in fires. It is however natural that it is lower than for the trial design; consequently, a reduction factor of 0,50 is therefore chosen to assess the buildings. This will be discussed in the discussion chapter.

Table 5.2 – Redistributed probabilities for fire

Category	Total probability	Compartment fire	Fire in common room
Fires set ablaze	15,3%	7,65%	7,65%
Open fire	20,8%	10,4%	10,4%
Electrical fault	20,8%	10,4%	10,4%
Misuse of electric systems	18,1%	5,6 %	6,9 + 5,6 = 12,5%
Unknown	25%	12,5%	12,5%
Total	100%	46,55%	53,45%

Table 5.2 shows the new representation of probabilities after the reduction as well as how the different categories of hazards contribute to initiating fires. Mostly, the probabilities are distributed evenly to each scenario, due to lack of information. However, a larger amount is distributed from misuse of electric to fire in the common room, because one of the main contributors to this category is dry boiling and overheating. These are assigned to the kitchen only, thus initiating a fire in the common room.

This section is identical to the trial design, although some of these probabilities could be reduced. In the theory section it was discussed that the analysed deviation both increases the probability and the consequence of fire. As the comparative case does not deviate from the regulations, both consequences and the probability of fire must be reduced. Utilising a design fire that is less severe than that of the reference case reduces the consequences. By reducing the probability of a fatal fire occurring, the probability of fire is reduced in the event tree.

Fire scenarios

In NS 3901 it is required to analyse 4 different fire scenarios[12]. Those are:

1. Worst case scenario
2. Fire that is initiated in a room that is not usually occupied, and that might threaten a large amount of people.
3. A slowly developing fire, which will not trigger the alarm or sprinklers.
4. Robustness scenario. This is a statistically probable fire, which is analysed to uncover weaknesses in the design.

Similar to the original case, it is the robustness scenario that is studied. However, this fire is less intense than the original fire, due to different surface materials. It is assumed that the compartment fire follows the standard fire curve. Although this might not be realistic, it is done to assure simplicity in the following calculations. The standard curve is assumed to be a worst-case scenario for compartment fires[42], thus this assumption is conservative. On this basis, the consequence analysis for the comparative case is made.

Consequence analysis

The event tree for the comparative case is identical to the previously studied case. If sprinklers work, the fire is assumed to no longer affect personal safety, even if the smoke detector does not work. This gives the event tree shown in Figure 5.2, whereas the associated probabilities are shown in table 5.3.

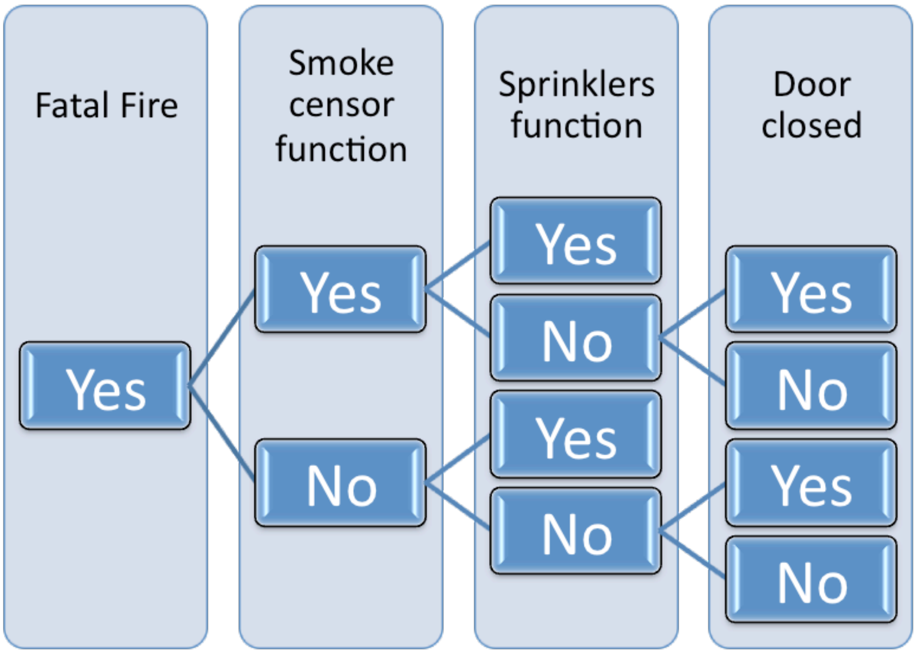

Figure 5.2 - Event tree for the comparative case. Made in Excel

The probability of fatal fires is derived from the statistical data from Nordstat, which is presented in the description of object. As it is further reduced by a factor of 0,50 it is equal to 0,02. Furthermore, the reliability of fire detectors are estimated to 0,987[38]. Sprinklers reliability consists of two components: ability to detect fire and ability to extinguish it. According to NFPA, this lead to a reliability of 0,87[39]. Finally, the probability of a self-closing door being closed is estimated to 0.90[7].

Table 5.3 - Table showing probabilities that corresponds with figure 5.2.

Event	**Fatal Fire**		**Smoke censor function**		**Sprinklers function**		**Door closed**	
Probabilities	Yes	No	Yes	No	Yes	No	Yes	No
	0,02	0,98	0,99	0,01	0,87	0,13	0,90	0,10

Scenario 1

In the first scenario the smoke censors function, sprinklers do not and the door to the stairwell is open. Firstly, this is modelled in FDS as a fire is started in the compartment marked with x on figure 5.1. After 5 minutes, it is assumed that the fire spreads out to the corridor. Since the entire floor is a fire cell, minimal resistance can be expected from walls and within the fire cell. Thus, another fire is initiated outside of the student's apartment where the door to the evacuation path is open. Evacuation starts after 3 minutes and 10 seconds, based on the same assumptions made in chapter 4. As this compartment fire is less severe than the compartment fire in chapter 4, the heat release rates are lowered. As seen in figure 5.3, the heat release is lower compared to figure 4.6. Additional evidence of this is seen in Figure 5.4, as the stairwell is compromised at a later stage, compared to the same scenario in the trial design.

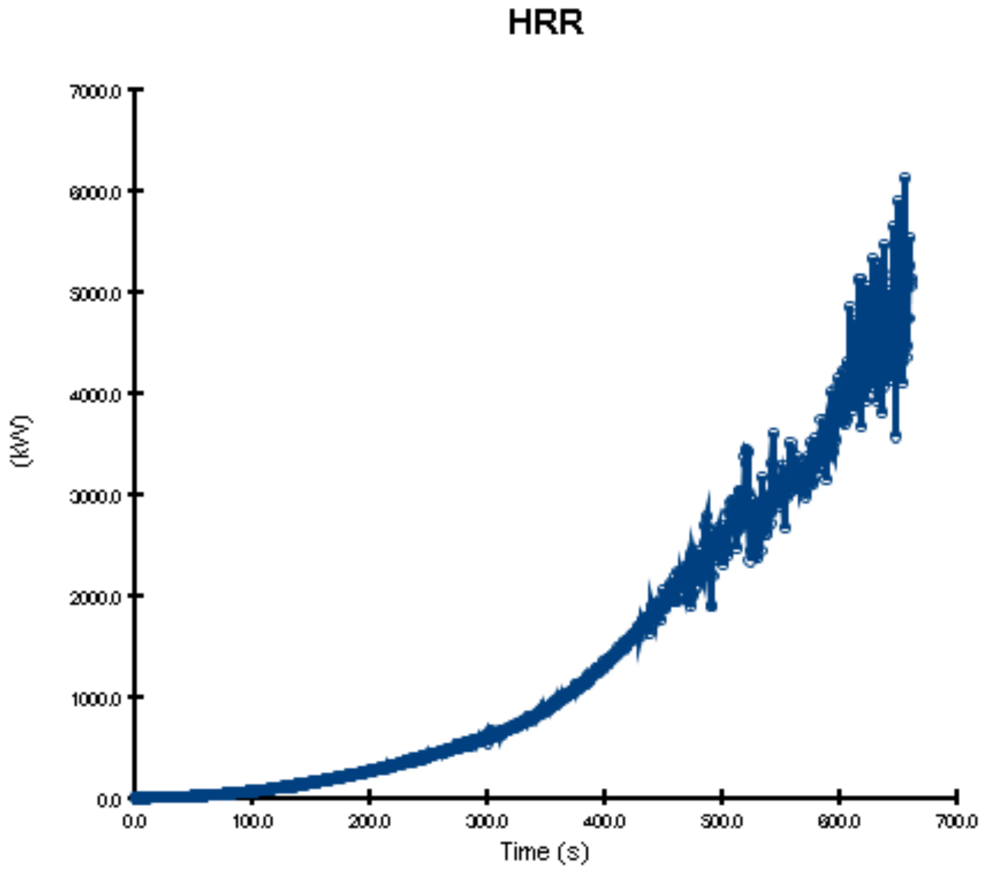

Figure 5.3 – Heat release in the compartment of the pre-accepted case

Figure 5.4 show the visibility in the stairwell, after 497 seconds, which is the moment when the escape route is considered as compromised.

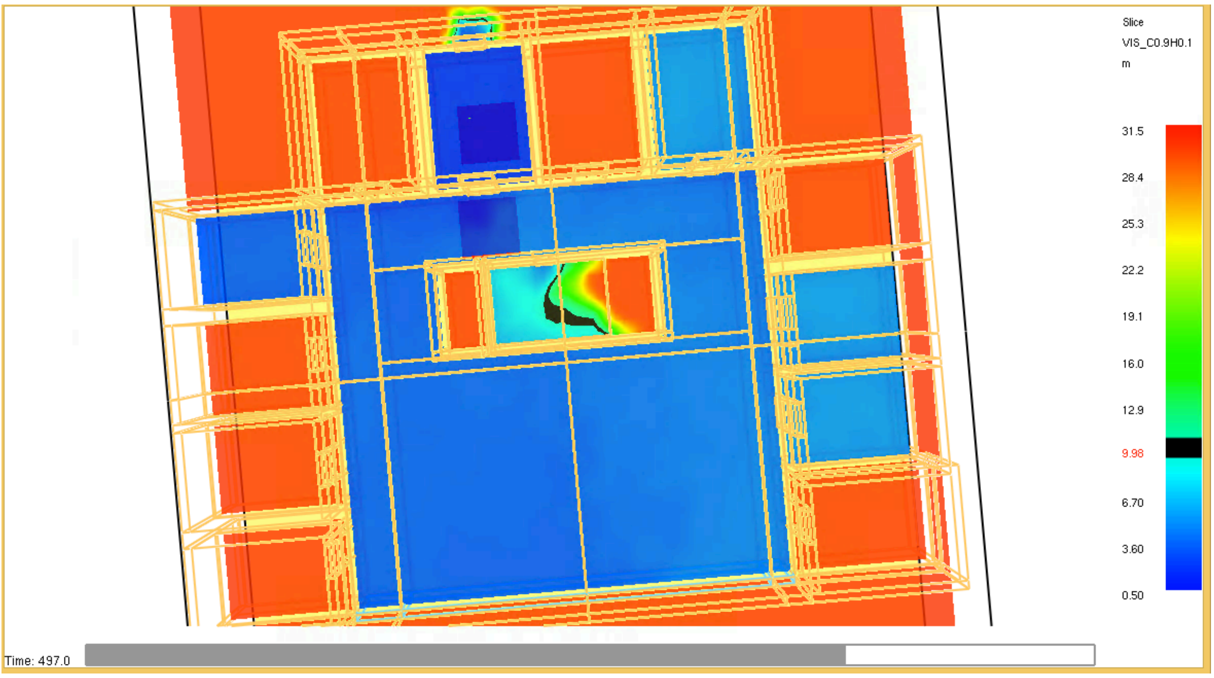

Figure 5.4 – Visibility in the 1st floor of the comparative building

After 497 seconds post ignition, there are still 18 inhabitants left in the building. However, it seems like 5 have passed the compromised hallways, leaving 13 inhabitants in danger due to this fire. This is shown in figure 5.5.

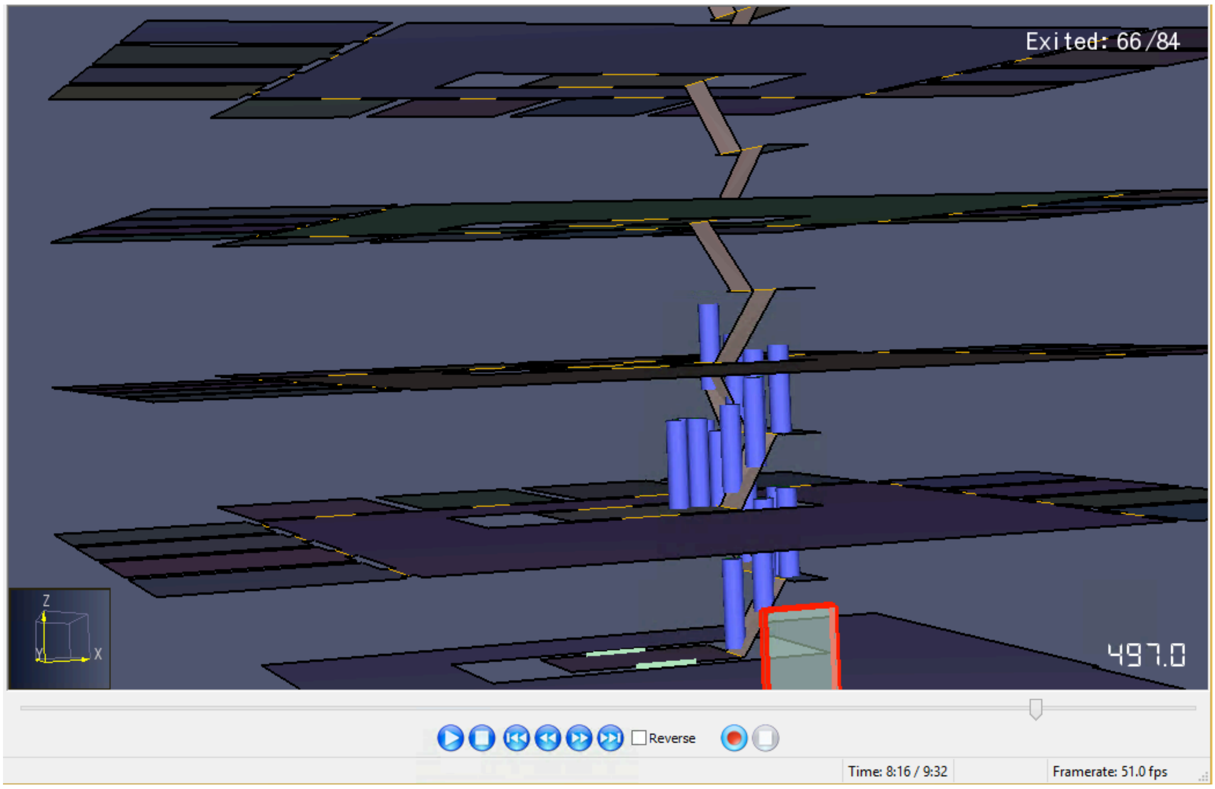

Figure 5.5 – Inhabitants evacuating in Pathfinder

13 lives are endangered from this scenario.

Scenario 2

In the second scenario smoke censor function, sprinklers do not and the door to the stairwell is closed. Earlier it has been discussed that the design fire for this case is the standard fire curve; hence, the door to the evacuation path lasts 30 minutes. As the fire does not spread to the corridor until 5 minutes, this gives a total evacuation time of 35 minutes. Subtract the 3 minutes and 10 seconds before evacuation start; 31 minutes and 50 seconds remain. Based on the previous simulation, people have already evacuated before this time. Hence, the risk due to this scenario is zero because no people are in danger at the time when evacuation is compromised.

Scenario 3

The third scenario shows then smoke censors are not functioning, sprinklers are not functioning and the door to the stairwell is open. This is modelled similarly as scenario 1 in FDS; however, it is different in Pathfinder. As the smoke censors inside of the compartment are not functional, the fire is not detected until 5 minutes after the fire starts. This is when the fire spreads into the common area. In Pathfinder this means that evacuation does not start until 490 seconds after ignition. Figure 5.6 shows the compromised stairwell.

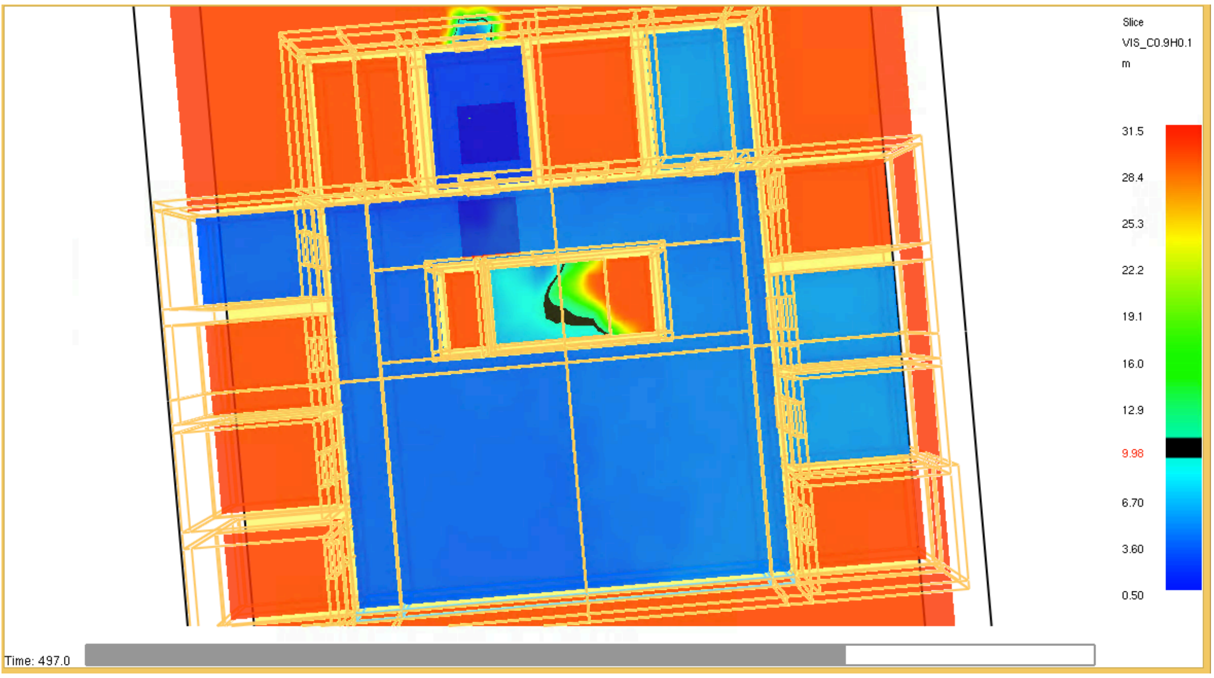

Figure 5.6 – Stairway is compromised after 497 seconds.

At this time all 84 inhabitants are still remaining in the building, which is shown in figure 5.7.

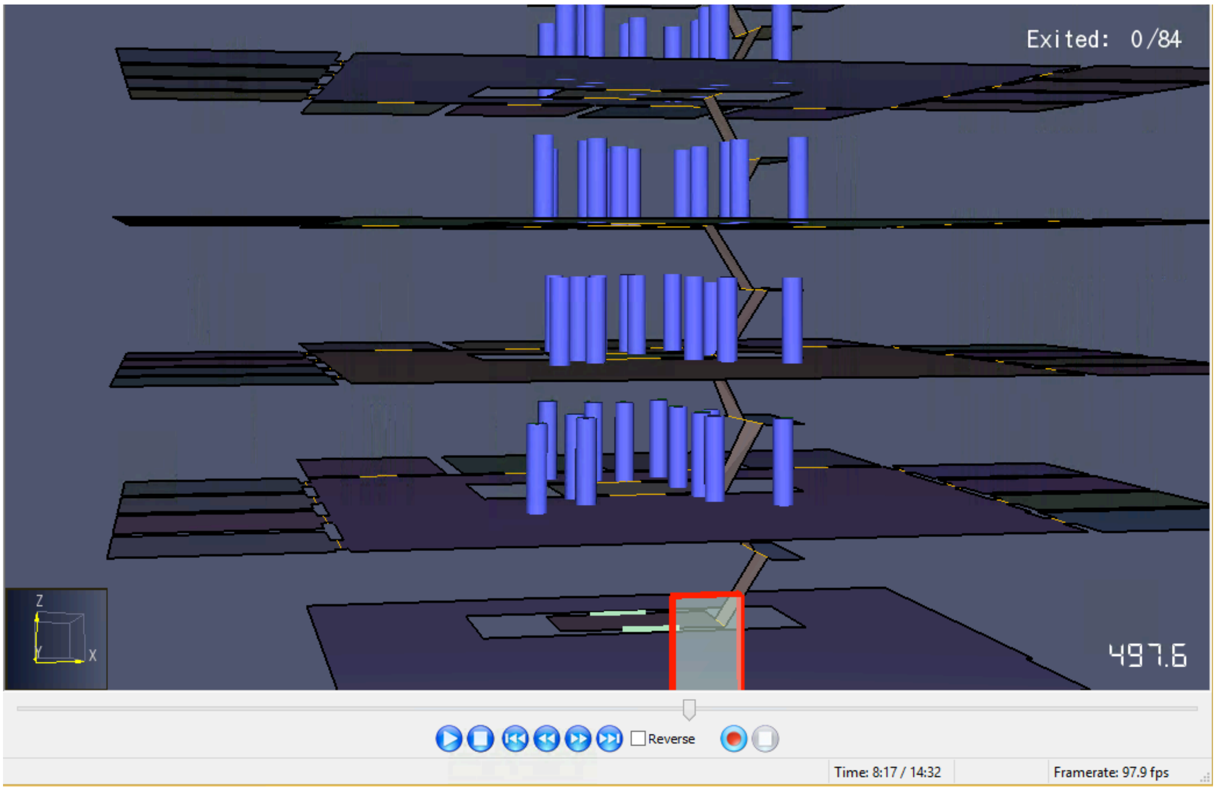

Figure 5.7 – Inhabitants 497.6 seconds after ignition

In this scenario, the fire endangers all 84 inhabitants.

Scenario 4

The last scenario describes when smoke censors are not functioning, sprinklers are not functioning and the door to the stairwell is closed. Similar to 3, the fire is not detected until 5 minutes after ignition of the fire. However the door still has 30 minutes fire resistance against a standard fire; thus providing evacuation time of 26 minutes and 50 seconds after subtracting response time. Previous results have shown that inhabitants are evacuated by this time, resulting in zero consequences.

Analysis of uncertainty

This analysis is essentially performed to deal with uncertainty. However, there are still uncertainties that will be dealt with in the discussion chapter.

Description of risk

The results are presented in table 5.4. Probabilities are calculated based on the fact that the events in the event tree are considered independent. Thus, the probability of all events occurring in a sequence, is the product of the probabilities in the sequence[41], similar to chapter 4.

Risk is then calculated as the product of probability of failure and lives endangered.

Table 5.4 – Summary of results for quantitative analysis of reference building.

Scenario	Time to failure [s]	Probability of failure	Lives endangered	Risk
1	497,0	$0,02*0,99*0,13*0,10$ $= 2,57*10^{-4}$	13	$3,34*10^{-3}$
2	2100,0	$0,02*0,99*0,13*0,90$ $= 2,31*10^{-3}$	0	0
3	497,0	$0,02*0,01*0,13*0,10$ $= 2,60*10^{-6}$	84	$2,18*10^{-4}$
4	2100,0	$0,02*0,01*0,13*0,90$ $= 2,34*10^{-5}$	0	0
Total Risk			$3,56*10^{-3}$	

Table 4.4 is repeated below to enable comparison of risks.

Table 4.4 – Recapped for comparison purposes

Scenario	Time to failure [s]	Probability of failure	Lives endangered	Risk
1	480,5	$0,029*0,99*0,13*0,10$ $= 3,73*10^{-4}$	18	$6,71*10^{-3}$
2	1089,0	$0,029*0,99*0,13*0,90$ $= 3,36*10^{-3}$	0	0
3	480,5	$0,029*0,01*0,13*0,10$ $= 3,77*10^{-6}$	84	$3,17*10^{-4}$
4	1089,0	$0,029*0,01*0,13*0,90$ $= 3,39*10^{-5}$	0	0
Total Risk			$7,03*10^{-3}$	

The analyses show that the risk to personal safety for the trial design is approximately twice as high as the risk to personal safety in the reference building. This means that the risk level is of the trial design is unacceptable and the safety level is too low. There are two factors affecting the risk, leading to this result. Firstly, the probability of fire is higher for the trial design than the reference building. This is accounted for by imposing reduction factors to reduce the overall risk, since these buildings have more stringent requirements than many of the buildings in the statistics. The reduction factors for the trial design and the reference building successively are 0,72 and 0,50. Secondly, the potential consequences are higher for the trial design compared to the reference building. .

Sensitivity analysis

The results achieved from these analyses are highly dependable on the many assumptions made for these cases. It is not possible to draw global conclusions from this analysis, as the results are only valid for the provided case buildings. Examples of assumptions and how they affect risk are many. The first example of assumption is the chosen walking speed, which is based on recommendations given from Sintef Byggforsk. However, there are some possibilities that are not accounted for, one of them being evacuation of handicapped people. A person in a wheelchair will need to be aided down the stairs, which will reduce walking speed of everyone behind, because there is no possibility to pass down the stairs. Furthermore, walking speed is known to decrease when smoke enters the evacuation path. This is not accounted for in this analysis, as the walking speed is assumed to be constant.

Number of people within the building is a large uncertainty. Increased number of people, means increased risk due to possibly increased consequences. In the performed analysis, all inhabitants were assumed present, as well as there were no visitors. This might change and then it is interesting to know how risk will change accordingly. Lastly, pre movement time is a critical parameter when determining risk, as it affects total evacuation time. If people are sleeping, the time before they start evacuating is increasing compared to an awaken state. The same goes for intoxicated people. As pre movement time is changed, risk is changed accordingly. The calculated risk for these buildings is based on all of these assumptions; thus, the absolute value of the risk is uncertain. This explains why it is so difficult to measure a quantified safety level towards an overall acceptance criterion. However, by comparing the calculated risk level with the risk level of a pre-accepted building, it is possible to gauge the safety level in the analysed building. It is then highly important that the same assumptions are made for the trial design and the reference object. To investigate how these parameters affect risk, a sensitivity analysis is performed on some of these parameters.

In the analysis there were made some assumptions, one of them being a constant pre movement time of 3 minutes and 10 seconds. This is a necessary simplification, but it is flawed in many ways. Firstly, the pre movement time will depend on the inhabitants and the fire development. Some will choose to ignore the alarm, whereas some will start evacuation immediately. Furthermore, it is natural to assume that the inhabitants in the 1st floor will spot the fire in this scenario. Hence, initiating evacuation and sounding the alarm, which will speed up the evacuation process. On the other hand, a fire may be initiated while inhabitants are sleeping or maybe some are intoxicated. Hence, the pre movement time might be either slower or quicker than the chosen value. To investigate how pre movement time affects the risk, a sensitivity analysis is performed. In order to do so, only Pathfinder is utilised. The initial delay is set to range between 0 seconds and twice the already chosen value, in other words 6 minutes and 20 seconds. Thus a correlation of pre movement time and risk is obtained for both the trial design and the comparative building.

This leads to tables 5.5 and 5.6, which explains how total risk is affected by the change of pre movement time. These results are also presented in figure 5.8.

Table 5.5 – Total risk for the trial design when pre movement times are changed.

Scenario	**Time to failure [s]**	**Probability of failure**	**Lives endangered**		**Risk**	
			t_{res} = 0 [s]	t_{res} = 380 [s]	t_{res} = 0 [s]	t_{res} = 380 [s]
1	480,5	0,029*0,99*0,13*0,10 = $3{,}73*10^{-4}$	0	61	0	$2{,}30*10^{-2}$
2	1089,0	0,029*0,99*0,13*0,90 = $3{,}36*10^{-3}$	0	0	0	0
3	480,5	0,029*0,01*0,13*0,10 = $3{,}77*10^{-6}$	42	84	$1{,}58*10^{-4}$	$3{,}17*10^{-4}$
4	1089,0	0,029*0,01*0,13*0,90 = $3{,}39*10^{-5}$	0	0	0	0
Total Risk					$1{,}58*10^{-4}$	$2{,}30*10^{-2}$

Table 5.6 shows risk in the reference building.

Table 5.6 – Total risk for the reference case when pre movement times are changed.

Scenario	**Time to failure [s]**	**Probability of failure**	**Lives endangered**		**Risk**	
			t_{res} = 0 [s]	t_{res} = 380 [s]	t_{res} = 0 [s]	t_{res} = 380 [s]
1	497	0,02*0,99*0,13*0,10 = $2{,}57*10^{-4}$	0	57	0	$1{,}50*10^{-2}$
2	2100	0,02*0,99*0,13*0,90 = $2{,}31*10^{-3}$	0	0	0	0
3	497	0,02*0,01*0,13*0,10 = $2{,}60*10^{-6}$	37	84	$9{,}62*10^{-5}$	$2{,}18*10^{-4}$
4	2100	0,02*0,01*0,13*0,90 = $2{,}34*10^{-5}$	0	0	0	0
Total Risk					$9{,}62*10^{-5}$	$1{,}50*10^{-2}$

This leads to Figure 5.8 that shows how the risk is changing with changing pre movement times. It is quite evident that the timber building is more sensitive to changes in pre movement time, than the reference building, as the slope is steeper for the timber building.

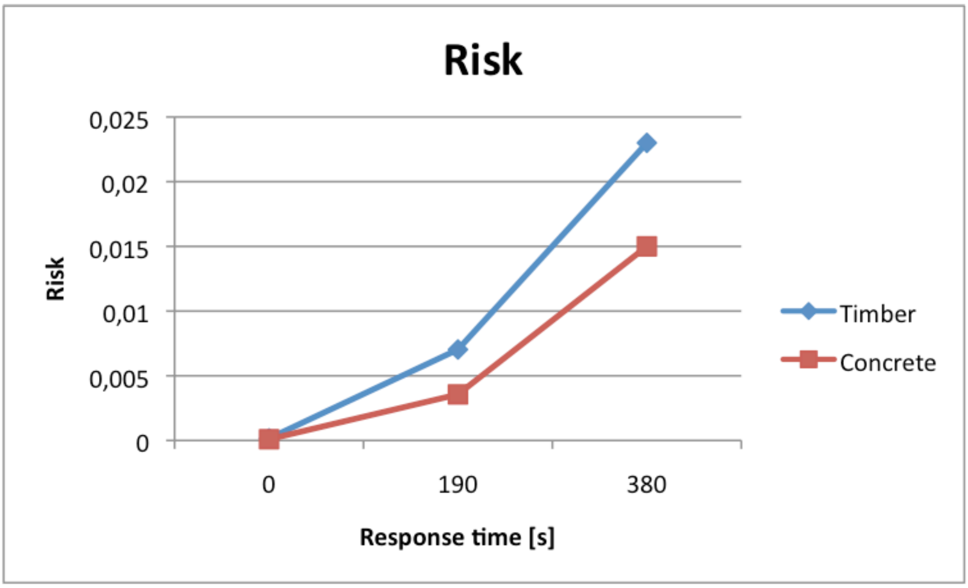

Figure 5.8 – Change in risk for changing response times

It is not possible to draw many conclusions based on figure 5.8. Timber is obviously more sensitive to changes in pre movement time than the reference building. However, it would be interesting to assess whether this is a trend for timber or not. If usage of exposed timber leads to more sensitive buildings, meaning that the buildings are less flexible. In turn, this might lead to economic losses and less safety. To investigate whether this is a trend or not, the effect of change in number of people in the buildings is also investigated. First, two persons are added to each floor, making the total number of inhabitants 98. In the second investigation, two persons are subtracted from each floor, making the total number of inhabitants 70. Table 5.7 shows the results for the timber building.

Table 5.7 – Changing risk for trial design with number of occupants.

Scenario	**Time to failure [s]**	**Probability of failure**	**Lives endangered**		**Risk**	
			# of inhabitants			
			70	98	70	98
1	480,5	0,029*0,99*0,13*0,10 = $3,73*10^{-4}$	1	30	$3,73*10^{-4}$	$1,12*10^{-2}$
2	1089,0	0,029*0,99*0,13*0,90 = $3,36*10^{-3}$	0	0	0	0
3	480,5	0,029*0,01*0,13*0,10 = $3,77*10^{-6}$	70	98	$2,64*10^{-4}$	$3,69*10^{-4}$
4	1089,0	0,029*0,01*0,13*0,90 = $3,39*10^{-5}$	0	0	0	0
Total Risk					$6,37*10^{-4}$	$1,16*10^{-2}$

The next table shows the pre-accepted building.

Table 5.8 – risk in the reference building with changing number of occupants

Scenario	Time to failure [s]	Probability of failure	Lives endangered		Risk	
			# of inhabitants			
			70	98	70	98
1	497	0,02*0,99*0,13*0,10 = $2,57*10^{-4}$	0	25	0	$6,43*10^{-3}$
2	2100	0,02*0,99*0,13*0,90 = $2,31*10^{-3}$	0	0	0	0
3	497	0,02*0,01*0,13*0,10 = $2,60*10^{-6}$	70	98	$1,82*10^{-4}$	$2,55*10^{-4}$
4	2100	0,02*0,01*0,13*0,90 = $2,34*10^{-5}$	0	0	0	0
Total Risk					$1,82*10^{-4}$	$6,69*10^{-3}$

This leads to figure 5.9 that show how risk changes with number of occupants.

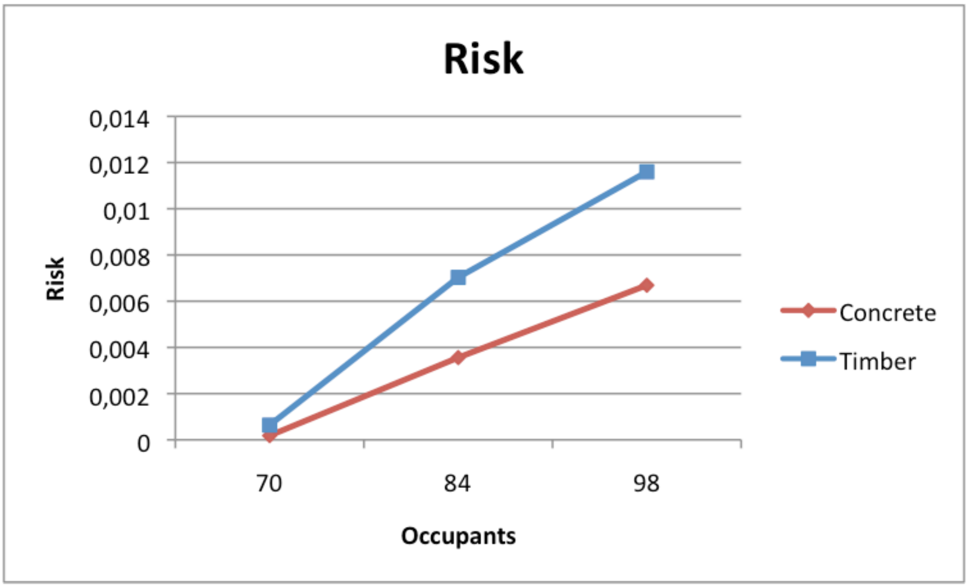

Figure 5.9 – Sensitivity of risk with changing occupants.

Figure 5.9 shows that risk increasing faster for the trial design compared to the reference building. It is evident that utilising exposed timber surfaces in this building leads to a more sensitive design. This means that slight changes in parameters mean larger changes for risk for the trial design, compared to the reference building. Thus, the trial design is less suited for changes during its lifetime, which might lead to unforeseen economic losses in the future. It would be interesting to perform a life cycle analysis on the two buildings, to investigate how the decreased flexibility affects economy. However, this is outside the scope of this thesis.

Additionally, it could be interesting to investigate what happens to risk if changes are made to the event tree. As an example, during the lifetime of a building several upgrades need to be made. For some of these the water needs to be shut down, thus compromising the sprinklers. This is not accounted for in the probabilities presented in the analysis. Therefore, the sprinklers are removed from the event tree, giving the event tree in figure 5.10.

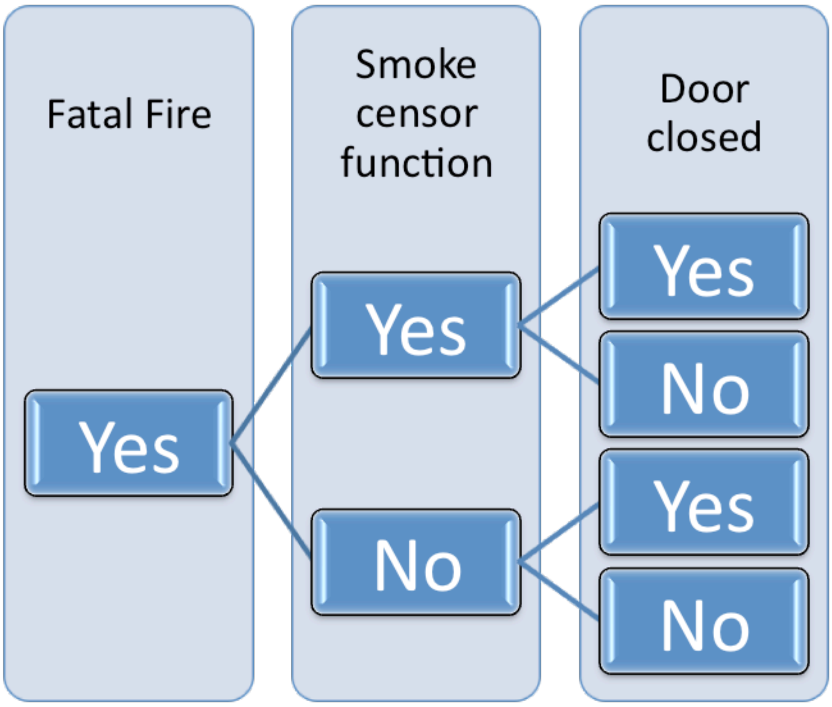

Figure 5.10 – Event tree with no sprinklers

The scenarios in this event tree are already known, as the consequences are already evaluated. However, since the sprinklers are removed, the different sequences are weighted differently than previously. This will give the risk of both the trial design and the reference building, as shown in table 5.9 and 5.10 successively. The pre movement time is chosen to be 190 seconds for this analysis, identical to the original analysis.

Table 5.9 – Risk when sprinklers are removed for the trial design.

Scenario	**Time to failure [s]**	**Probability of failure**	**Lives endangered**	**Risk**
1	480.5	$0,029*0,99*0,10 = 2,87*10^{-3}$	18	$5,20*10^{-2}$
2	1089	$0,029*0,99*0,90 = 0,026$	0	0
3	480.5	$0,029*0,01*0,10 = 2,90*10^{-5}$	84	$2,43*10^{-3}$
4	1089	$0,029*0,01*0,90 = 2,61*10^{-4}$	0	0
Total Risk			$5,40*10^{-2}$	

Table 5.10 shows the risk for the reference building.

Table 5.10 – Risk when sprinklers are removed for the reference building.

Scenario	Time to failure [s]	Probability of failure	Lives endangered	Risk
1	497	0,02*0,99*0,10 = 1,98*10^{-3}	13	2,57*10^{-2}
2	2100	0,02*0,99*0,90 = 0,0178	0	0
3	497	0,02*0,01*0,10 = 2,0*10^{-5}	84	1,68*10^{-3}
4	2100	0,02*0,01*0,90 = 1,80*10^{-4}	0	0
Total Risk			2,74*10^{-2}	

According to §11-12 1a, sprinklers are required for all buildings in risk class 4 with a need of an elevator[2]. This becomes quite evident when these results are presented. From table 5.4 the accepted risk level is 3,56*10^{-3}, while the risk level in both table 5.9 and 5.10 go way beyond this and is therefore unacceptable. This illustrates why this paragraph exist and that it makes a large impact on the risk level in a building. An additional consequence of this observation is that the sprinklers must be operational at all times. Firstly, this means that it is highly important to maintain and check the sprinklers. Furthermore, this has consequences for larger rehabilitations where sprinklers might be turned off. To allow inhabitation of the building, measures must be made to reduce the risk. The risk should be reduced to the level from the pre-accepted building, meaning 3,56*10^{-3}.

Obviously the risk of the trial design is too high in this instance. For this building to be accepted measures must be taken to mitigate the risk; thus it would be highly interesting to study how risk changes with changes in numbers of floor. Therefore, the upper floor (8th) has been removed from Pathfinder. As earlier, it is of interest to investigate how many lives that are endangered. The pre movement time is still kept at 190 seconds. Table 5.11 shows the risk for the trial design with 7 floors, meaning that there are only 72 inhabitants in this building.

Table 5.11 – Risk in trial design with 7 floors.

Scenario	Time to failure [s]	Probability of failure	Lives endangered	Risk
1	480,5	0,029*0,99*0,13*0,10 = 3,73*10^{-4}	3	1,12*10^{-3}
2	1089,0	0,029*0,99*0,13*0,90 = 3,36*10^{-3}	0	0
3	480,5	0,029*0,01*0,13*0,10 = 3,77*10^{-6}	72	2,71*10^{-4}
4	1089,0	0,029*0,01*0,13*0,90 = 3,39*10^{-5}	0	0
Total Risk			1,39*10^{-3}	

By reducing total numbers of floors from 8 to 7, the risk is acceptable compared to the pre-accepted 8-floor building. Table 5.12 shows how risk changes for the reference building if one floor is removed.

Table 5.12 – Risk in the reference building with 7 floors.

Scenario	Time to failure [s]	Probability of failure	Lives endangered	Risk
1	497	0,02*0,99*0,13*0,10 = $\underline{2{,}57 \cdot 10^{-4}}$	0	0
2	2100	0,02*0,99*0,13*0,90 = $\underline{2{,}31 \cdot 10^{-3}}$	0	0
3	497	0,02*0,01*0,13*0,10 = $\underline{2{,}60 \cdot 10^{-6}}$	72	$1{,}87 \cdot 10^{-4}$
4	2100	0,02*0,01*0,13*0,90 = $\underline{2{,}34 \cdot 10^{-5}}$	0	0
Total Risk			$1{,}87 \cdot 10^{-4}$	

This is interesting, because the relative difference in risk is increasing. In the original case, the risk for the trial design was approximately twice as high as the reference building. When the floors are reduced to 7, the risk in the trial design is approximately 10 times as high, despite the consequences almost being similar. If the number of floors were reduced to 6, the consequences due to fire would be identical; thus the only difference would be the difference in probability of a fire occurring.

6.0 Evaluation of Risk

This chapter concludes the analysis in this thesis. The risks will be summarised and elaborated to understand why there are differences between the trial design and the reference building. This understanding is then used to identify a measure to mitigate risk, allowing a new risk to be calculated. The chapter follows the structure of chapter 8 in NS 3901 mostly[12].

6.1 Comparison of risk and risk acceptance criterion

The results from the analyses were presented in chapter 5, however they are presented again in table 6.1 with a few other key numbers.

Table 6.1 – Summary of results and other key numbers

	Trial Design	Reference Building	Difference	Ratio
Risk	$7{,}03 \cdot 10^{-3}$	$3{,}56 \cdot 10^{-3}$	$3{,}47 \cdot 10^{-3}$	1,97

According to these numbers, the safety is insufficient in the trial design. Earlier, it was explained that this is due to higher likelihood of fire occurring and consequences. When exposed timber is utilised, the additional likelihood of fire is something that FSEs must live with. Applying combustible surfaces leads to a higher likelihood of a fire being initiated, compared to incombustible surfaces. It is an axiom. Consequences on the other hand, can be affected by measures. Then why are the consequences different from the trial design to the reference building?

The common factors for the two sequences that lead to fatal consequences are:

- Non-functional sprinklers
- Open door to the stairwell

For the trial safety design, the stairwell was compromised earlier than for the reference building. This is due to higher smoke production for the timber surfaces compared to the concrete surfaces. Thus, the smoke layer lowered quicker and infiltrated the stairwell. In terms of consequences, sequence 3 was identical for both cases; however, due to low probability the sequence makes little impact on risk. Hence, sequence 1 is focused upon. Failure occurred as untenable limits were reached regarding visibility, meaning that the visibility was less than 10 meters in the escape path at 2 meters height.

6.2 Measures

In order to reduce the risk level of the trial design, many measures are considered, but only one will be analysed. The chosen measure is another barrier within the stairwell, as shown in figure 6.1. Surrounding walls are classified as EI 60 D, s2-d0, similar to the walls surrounding the stairwell. The door is E30 classified, making the stairwell a Tr 2 stair[2].

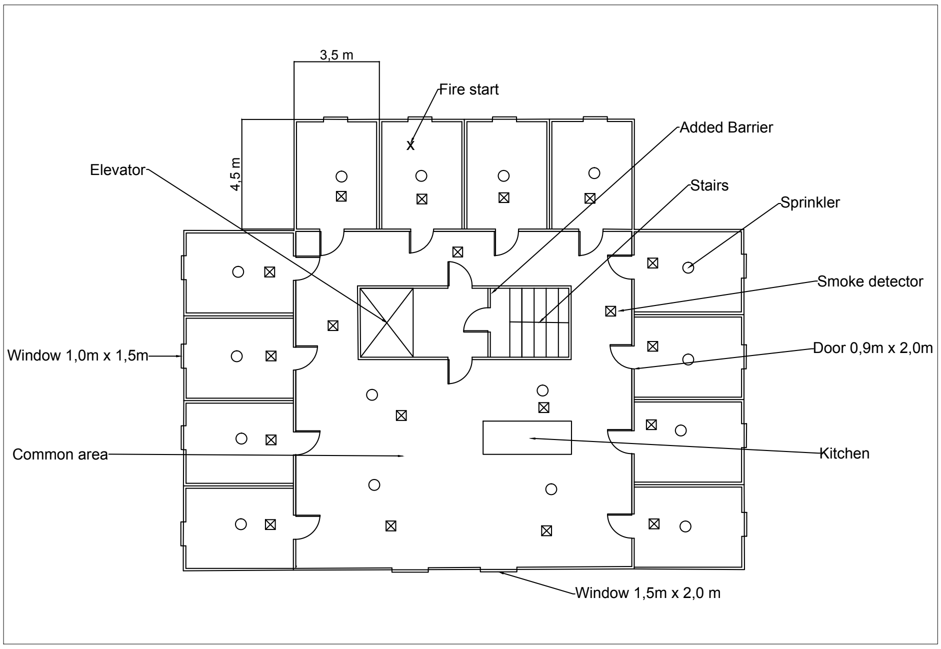

Figure 6.1 – Floor plan after adding measure.

Many of the calculations that are performed earlier are applicable to this case also. If the first door into the stairwell is closed, it will be 13 minutes until it breaks down due to fire. The fire has now entered the fire cell before entering the stairwell, thus the failure mode is not yet reached. If the second door to the stairwell is closed, there will be another 13 minutes until the door breaks down, making the total time of fire 31 minutes. However, if the door is open the fire will quickly spread into the stairwell. In the worst-case scenario where both doors are open, the fire will spread into the stairwell in about 5 minutes. It is however uncertain when the failure mode will be reached, since the stairwell is open vertically, the smoke has a much larger area to cover than in the trial design. Hence, it is assumed that it will take much more time for the smoke to stabilise at 2 meters. To be conservative, the same time is chosen for this case as in chapter 4, meaning that failure will occur after 480 seconds.

Due to changes with doors, there is uncertainty whether the evacuation will remain the same or not. Therefore a simulation is performed in Pathfinder where the mentioned door is inserted. Furthermore, a wall is placed approximately 90 cm out from the door, to model an open door in which the evacuating inhabitants have to pass. The result is basically identical to the results from the previous analyses, meaning that 18 lives are endangered at the chosen time. This is shown in figure 6.2.

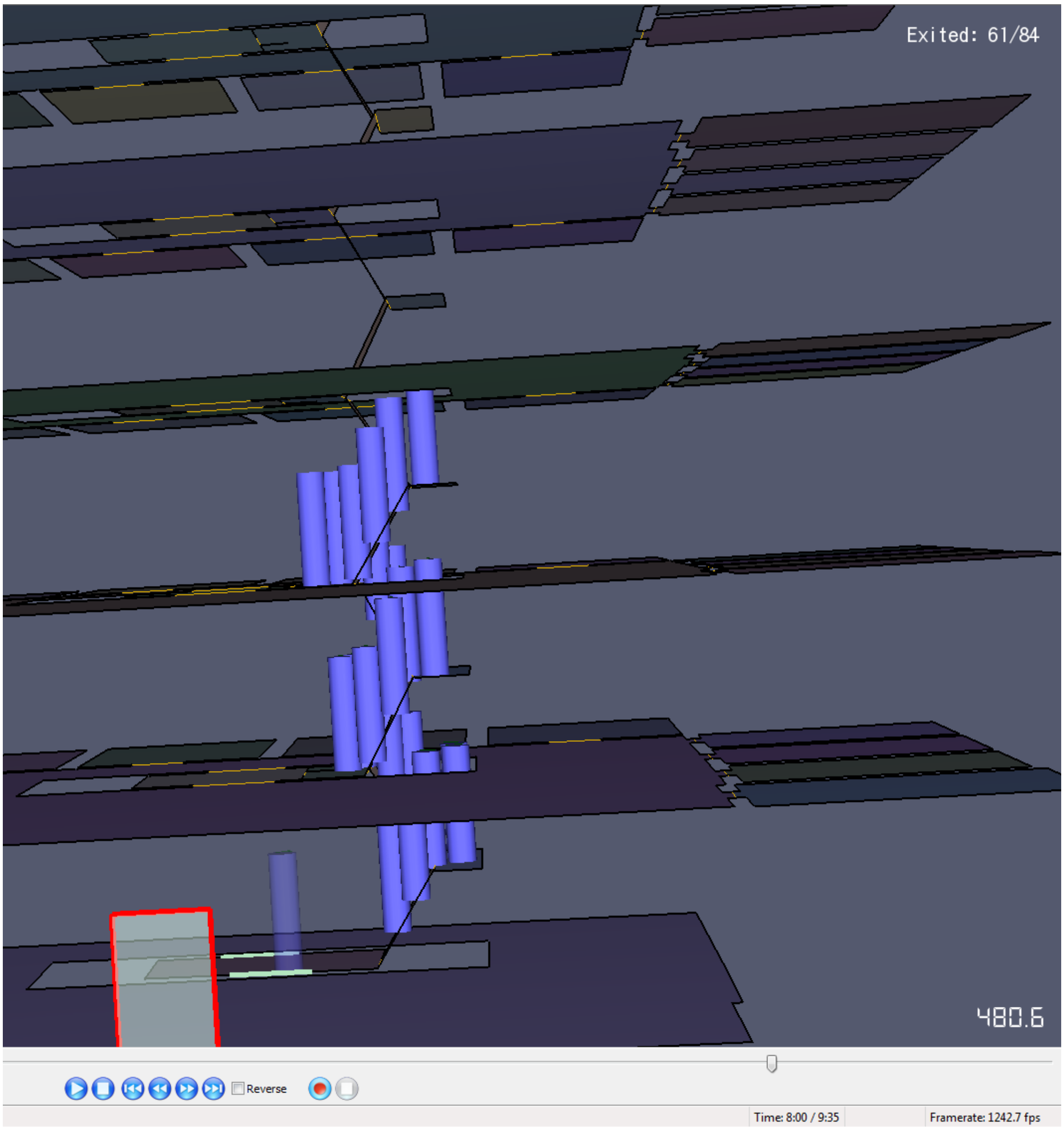

Figure 6.2 – Evacuation after the measure is implemented.

Risk is calculated for the scenario where smoke detection is successful, as the scenario where smoke detection fail has little impact on risk. The only change from the case in chapter 4 is that an additional barrier is added to the calculation. This barrier is a self-closing door as it is the weakest point in the new wall; thus the reliability is already known, which gives the risk in table 6.2

Table 6.2 – Risk for trial design after measure is implemented

	Probability of failure	Endangered lives	Risk
New case	0,029*0,99*0,13*0,10 0,10= 3,73*10^{-5}	18	6,71*10^{-4}

The calculated risk is beneath the risk of the pre-accepted building, indicating that the measure successfully reduces the risk to acceptable levels. Due to the uncertainty in the qualitative analysis, it would be advantageous to further quantify the results. Therefore FDS is utilised to control the results.

6.3 Deterministic control

Due to the uncertainty of the qualitative assessment, FDS is used to verify the results. The setup is similar to the setup in chapter 4; however, the wall and the door are added within the stairwell, leading to the results are shown in figure 6.3.

According to the FDS simulation, failure occurs at an earlier stage than without the measure. As the area where the smoke comes from is decreased, the smoke is distributed more densely. Hence, the failure mode is reached faster than earlier, approximately after 464 seconds. This is shown in figure 6.3 that is clipped from Pyrosim. As the black line covers the entire escape path, the failure mode is reached.

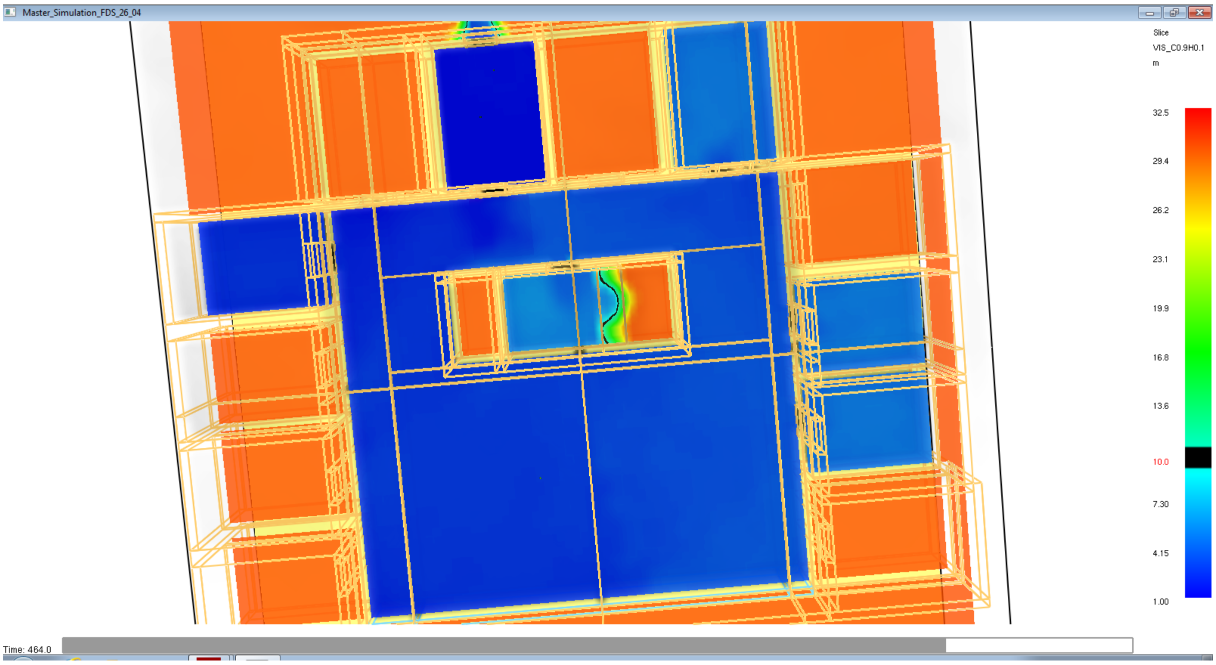

Figure 6.3 – Failure mode reached after 464 seconds after imposing measure.

As this is 16 seconds before the previous estimation the first estimate of inhabitants at risk was wrong. Figure 6.4 shows the evacuation at that time.

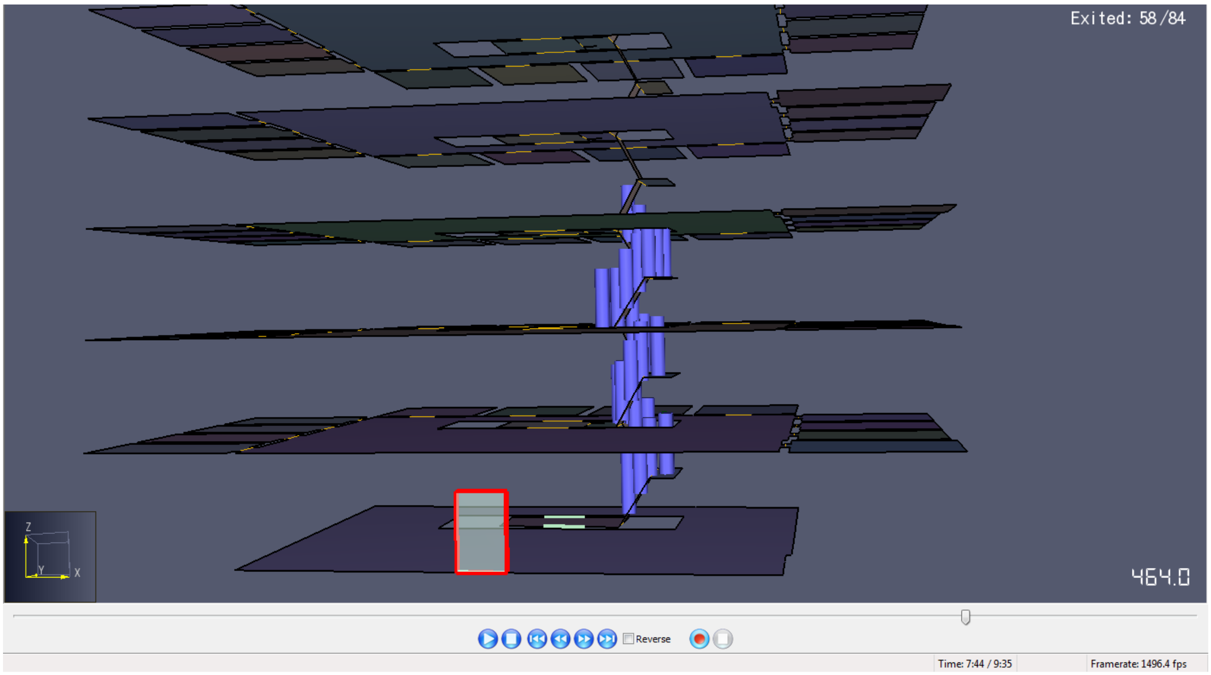

Figure 6.4 – Evacuation at time of failure mode.

From figure 6.4 it is seen that 58 people have exited at this time. There seem to be 6 people that have passed the compromised area, in other words there are 20 people left that are in risk of fatality. The consequences are more severe after the measure is implemented. Table 6.3 shows how this impacts risk.

Table 6.3 – Risk after measure is implemented

	Probability of failure	**Endangered lives**	**Risk**
New case	0,029*0,99*0,13*0,10 0,10= $3{,}73*10^{-5}$	20	$7{,}46*10^{-4}$

Risk has increased compared to the qualitative analysis from the last section. This is because the potential consequences increased, meaning that the qualitative analysis was inaccurate. However, the newly calculated risk is still beneath the risk levels of the reference building.

6.4 Summary

The measure was evaluated both qualitatively and quantitatively where both analyses showed that risk was sufficiently low. However, the quantitative analysis showed that the consequences increased by implementing this measure. Despite this, the risk decreased below $3{,}56*10^{-3}$ meaning that the design is sufficiently safe.

7.0 Discussion

The discussion chapter goes into depth on the findings from the analysis. However, more than discussing the actual results, the discussion chapter will focus on the probabilistic deterministic method. It deals with was done, what has not been done, what went well as well as challenges that had to be handled along the way. Finally, the discussion presents some thought on fire safety in buildings of timber. These thoughts have arisen throughout the analysis.

7.1 Summary of analysis

When an FSE analyses a building, there are some things that always needs to be covered. Regardless whether the analysis is analytical or prescriptive, some topics always need to be addressed. In this section the topics that this analysis addresses are discussed as well as the topics that are not addressed. Of the left out topics, fire spreading to other areas of the building is further delved into, as vertical fire spread is considered relevant for personal safety.

Originally, this was an analysis of the fourth deviation due to use of unprotected timber in buildings; yet, it turned out to be a lot more. There are 5 points that need to be covered in a performance-based design[3]:

1. Evacuation of occupants
2. Limitation of spread and generation of fire
3. Fire spread to neighbouring areas
4. Load bearing capacity
5. Safety of rescue teams

The two first bullet points are dealt with, whereas the third will be discussed later. In addition to lacking the two last bullet points, this analysis has further shortcomings. The deficiencies of this analysis will be discussed to illustrate what is needed for a complete analysis of buildings.

In the analysis, the analysed scenario was a compartment fire initiated in one of the student's compartment. Although the probability of a fire starting in the common room was higher, it was chosen to analyse the compartment fire because more is known about the scenario through full-scale tests. However, to gain a complete picture of the risk in a timber building, the common room scenario must also be analysed. As a matter of fact, a third fire scenario has been identified as relevant to complete the analysis, which is a fire starting in the escape path.

A fire starting in the escape path is relatively easy and can therefore be analysed qualitatively. Looking back at table 5.1, the main causes of this scenario would be arson fires or fires due to unknown reasons. A fire in the reference building would be dependent on movable fire load, meaning that the fire would eventually burn out. For the trial design, the fire could grow quite severe due to the immovable fire load embedded in the timber walls. However, this fire scenario only compromises the original escape path, suggesting that the floors and the secondary escape path are still intact. Inhabitants therefore have the possibility to wait for further information or to escape through the windows. As the failure mode would have been reached, people would have been in danger per definition. The failure mode would have been reached for both scenarios, suggesting that the risk would be almost identical.

Matters would be more complicated if a fire was initiated in the common room. In this scenario, both the original and the redundant escape path might be compromised. The original escape path would be compromised in the same manner as calculated in the analyses in chapter 4 and 5. On the other hand, the redundant escape path is compromised if the windows are broken. Thus, the received heat flux from the window would not allow anyone to pass in the exterior escape. Quantifying this is highly difficult as little is known about fires in such enclosures. If the fire reaches a size where it is impossible to extinguish, the remaining inhabitants would be in great danger. Furthermore, such a risk could be avoided by utilising incombustible surfaces. This would reduce the fire load drastically and limit the fire to the movable fire load, making inhabitants safer.

A structural analysis must be performed in addition to the analysis performed in this thesis. According to SN INSTA/TS 950, this should be done in accordance with the requirements from EN 1990 and 1991-1-2[43]. The structural analysis must be carried out using different fire scenarios than the previous analysis. SN-INSTA 950 suggests grouping fire scenarios in accordance to their relevance[35]. After identifying the relevant fire scenarios for structural safety, the steps in NS-EN 1991-1-2 can be followed.

Moreover, the safety of the rescue teams must be considered. This is considered as a combination between personal safety and structural safety. In chapter 3.4 collapse of secondary structural components was identified as highly relevant for rescue teams. Hence, the safety of rescue teams is a combination between personal safety and structural safety. It is also important to consider when the fire is so large that extinguishing will be impossible.

Fire spread to neighbouring areas is a topic of high importance when dealing with timber structures. In all of the full-scale tests presented in section 3.2, large heat release rates out of openings were observed. It was theorised that this was due to high production of pyrolysis gases. This led to poor burning conditions on the inside of the compartment; leading to combustion taking place on the outside. Thus horizontal, vertical and lateral fire spread must be considered, particularly when dealing with unprotected timber structures.

As this thesis focuses on personal safety, vertical fire spread was identified as a failure mode in chapter 3. Since each floor is a fire cell, this means that the fire is spreading between fire cells, which is not allowed according to §11-8(2) in the technical regulation[2]. In 2005 Frangi and Fontana investigated vertical fire spread from a compartment with combustible surfaces[44]. The setup was a light frame timber wall, thus it was not included in the theory for this thesis. However, the deviation occurs due to the surfaces not having an acceptable classification, which is the same deviation investigated in this thesis. In this test two modules were investigated, where one was on the top of the other. The lower module was ignited with both door and window closed. Similar to the tests in section 3.2, severe burning was seen on the outside when the window broke. However, this was quantified further in the study, as the upper window broke after 7 minutes after ignition[44]. This illustrates the potential consequences of fire with combustible surfaces. According to Sintef Byggforsk, the consequences of vertical fire spread may be higher than horizontal fire spread[45], due to increased difficulties of extinguishing and escape. It is therefore of high interest to dig deeper into this.

According to §11-8 in the guidelines, there are 4 pre-accepted measures to avoid fire spread between floors[2]:

1. Cooling zone between windows. The height of the cooling zone must equal the height of the lower windows
2. Every other floor has a façade with a classification of E30.
3. Drawn in areas of façade with at least 1,2 m or a 1,2 m screen out from the façade. Needs at least the fire resistance of the floor divider
4. The building has automatic extinguishing.

The reference building is fine according to the pre-accepted solution. As the consequences due to vertical fire spread seem to be more severe for timber buildings, it is of interest to analyse. Thus, literature supporting the regulations and recommendations were studied. Sintef Byggforsk recommends studying NS-EN 1991-1-2 to assess the risk of fire spread[45]. The results from this method will thus be compared with the pre-accepted building. Since the compartments earlier analysed were identical to those from McGregor's research, those are the same compartments analysed in this. However, the window will be changed somewhat in size, as the opening in McGregor's test was a door, not a window. The size is therefore not appropriate to study, as it is 2 meters high. It is replaced with a window that is 2,3 x 1,2 (w x h), which makes out the same opening factor[24].

The calculation of vertical fire spread was performed in Appendix A. It did not show any difference in risk for vertical fire spread between the trial design and the reference building. This is because the method was unable to distinguish between the timber compartment and the concrete compartment in any way. Hence, making the fire spread method in the Eurocode little suitable to determine risk of fire spread for timber buildings. Furthermore, the results are assumed to be highly conservative for the concrete compartment. Results from using this method are therefore inconclusive. Vertical fire spread will remain an unanswered question in this thesis, but it is expected that the risk increase due to vertical fire spread from timber compartments.

7.2 Strengths

The analyses performed in this thesis showcases many of the strengths of probabilistic design. Fire safety engineering is dependent on many different parameters that affect the safety level of the design. In the sensitivity analysis, it was shown how different parameters could be changed quickly. Moreover, presentation of information becomes easy when risk is quantified. This makes it possible to investigate the assumptions made in the analysis, and to showcase the effects of changing them. It is therefore a suitable tool to handle uncertain input parameters, which is corroborated by Nystedt[22] As information is presented easily, it becomes easier to explain why the design is good or the safety is insufficient. This might assist in breaking down barriers between FSEs and other professionals. In this case, major changes were performed on the evacuation side, as Pathfinder is easy to change and give quick results. It would not be as easy to make changes in Pyrosim, as FDS simulations require more computational resources. Albrecht agrees with this, arguing that recycling of FDS results are advantageous[20]

Quantified risk means that it is easy to make risk informed decisions and to illustrate this, the risk without sprinklers is investigated. The risk for the trial design without sprinklers was quantified as $5,4*10^{-2}$. From the original risk level of $7,03*10^{-3}$, this is an increase of 7.7 times the original risk. Furthermore, the pre-accepted level was $3,56*10^{-3}$, showing an increase more than 15 times, telling two stories. Firstly, if sprinklers are compromised, measures need to be made in order to ensure sufficient safety. Ensuring fire safety during special situations such as rehabilitations is the owner's duty[46]. The goal of such a measure is to reduce risk to the pre-accepted level. A possible measure is to reduce the amount of inhabitants in the building. Table 5.7 shows the risk in the trial design when 70 inhabitants are present. If this information is combined with table 5.9, risk with 70 inhabitants and no sprinklers can be calculated. This is shown in table 7.1.

Table 7.1 – Risk in the trial design with 70 inhabitants and no sprinklers

Scenario	Probability	Lives endangered	Risk
1	0,029*0,99*0,10	1	$2,88*10^{-3}$
3	0,029*0,01*0,10	70	$2,03*10^{-3}$
Total Risk			$4,91*10^{-3}$

The risk in table 7.1 is slightly higher than the risk in the reference building. Reducing the number of inhabitants somewhat further will reduce the risk sufficiently, allowing major upgrades, for instance during summer vacation. It is important to take note that this is sufficient in terms of personal safety, but it might not be the case in terms of material safety. Secondly, the impact sprinklers have on risk is huge. Hence, it is of high importance to maintain sprinklers so that the building stays sufficiently safe.

Another example of this can be found by studying the event tree from the original analysis, or table 4.4. Whenever the door is closed, the fire has no consequences to personal safety. All of the other analyses show the same. If the door to the escape path is functional, no risk to life safety is observed. This illustrates the importance of keeping this door closed, which means that the building owner might tailor strategies based on this observation. Moreover, the impact of the door can be compared with the impact of the sprinklers on risk. As they have the same consequence, reliabilities must be studied. Self-closing door has a reliability of 90% whereas sprinklers are reliable 87% of the time. Consequently, self-closing door will actually have a higher impact on risk for this building, compared to sprinklers. A similar observation was made in a research article by Chu and Sun[17]. Quantitatively this explains why having a self-closing door is a requirement in the pre-accepted solution and it illustrates that it is a good measure to reduce risk.

Furthermore, event tree analysis allows engineers to evaluate measures against each other. By replacing barriers in the event tree, it is possible to calculate how risk is affected. This was how Chu and Sun compared the different fire protection systems mentioned in the last paragraph[17]. Hence, it is possible to evaluate the risk reduction against the additional cost of the measure. This is an advantage of quantifying risk, as the business is growing highly competitive. To add value for customers, it is important to reduce risk while keeping the price as low as possible. If this method allows FSEs to decide which design is beneficial in terms of risk and cost, it could lead to a competitive advantage. Be aware that by adding barriers in the design, the amount of outcomes increases exponentially. This increases the analysis time, which at some point might not be favourable. Furthermore, utilising FDS to predict fire development is time consuming. If the barrier is intended to change the fire development, it might cost time to analyse.

7.3 Challenges

The challenges with using probabilistic design are many, so in order to make it a feasible design method, the challenges must be addressed. This section will deal with challenges experienced while working with the thesis, as well as challenges that might be relevant but are not yet experienced. The section is structured so that questions are asked first, then the author's answer follows.

What were the challenges experienced while performing this analysis?

1. This analysis has been time consuming and there are several reasons for this. Firstly, as no structure exists for doing this analysis the steps were made through a creative process, which is time consuming. Not knowing where to begin was also a central factor in making this analysis time consuming. Much time was spent on thinking how to create probability distributions for the relevant properties, similar to what is done in the literature. This is a common mistake when performing quantitative analyses, as focus is placed on the quantitative analysis, but missing the big picture. Hence, following the steps from NS 3901 is a very good start when performing such an analysis. Performing a qualitative analysis first is of imminent importance before performing a probabilistic assessment, a view that is corroborated by BSI[7]. A qualitative analysis enables the analyser to gain the necessary data to perform the quantitative analysis. It is the basic in which the probabilistic analysis is based on; furthermore, a big picture understanding is acquired through finishing the analysis qualitatively. This was illustrated in this thesis, where the fire scenarios were not described qualitatively. Hence, the compartment fire was quantified without further thought, although it was later realised that this fire might not be the fire that affects risk the most. The common room fire is more likely to occur and it is potentially more severe, thus it affects risk more than the compartment fire. Although this is so, it was still the correct choice to analyse the compartment fire. As more is known about the compartment fire, less uncertainty is introduced to the analysis. Hence it becomes easier to trust the results acquired from for instance FDS.

   The following figure suggests a flowchart for probabilistic design by using event tree analysis:

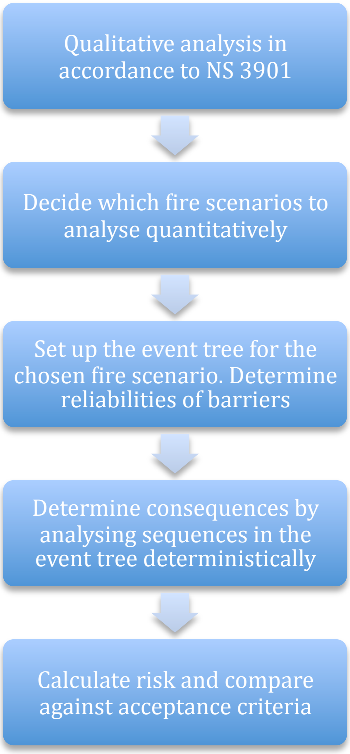

Figure .7.1 – Flowchart for probabilistic design by event tree analysis

If the risk is similar to, or lower than the chosen acceptance criteria, the design is okay, meaning that the FSE can go ahead and document the solution. If the risk is higher than the acceptance criteria, changes need to be made in form of measures. To affect risk, measures must either reduce consequences, or increase reliability of measures. This process will be discussed as a question on its own.

Take note that the flowchart only encompasses personal safety. It is natural to start with personal safety in a fire safety design, because it is most prevalent in the initial phases of the fire. In doing this: generation and spread of fire, evacuation and spread of fire to neighbouring areas are handled. If the risk is sufficiently low, the designer can go on to verify the safety of the structural system. There is no point of analysing the structural system, if the personal safety of the design is insufficient. Structural safety is evaluated based on different scenarios and different acceptance criteria. Furthermore, the safety of rescue teams and material safety is a combination of structural and personal safety. As these are not dealt with in this thesis, it will not be discussed further.

2. The deterministic analysis was highly time consuming, especially FDS. This is due to the author's limited experience with using such programs. It was therefore a long learning process, which takes time. However, utilising Pyrosim as an FDS requires a lot of computational resources, and in this analysis there where potentially 16 scenarios to analyse. The solution in this instance was to qualitatively assess the scenarios and discard the irrelevant scenarios. That left 6 scenarios left to analyse, which is still a large amount of work. Luckily the differences in these scenarios were not connected to the fire development, but rather to the evacuation process. Consequently, changes could be made in Pathfinder, which is easier and quicker than to make changes in Pyrosim. The

FDS results were then reused, meaning that only 3 scenarios were actually analysed using FDS. Looking for ways to reuse results is a possibility to decrease analysis time. Experience and knowledge is needed in order to ensure that the analysis is complete and sufficient. Another possibility to reduce analysis time is to choose other ways of analysing the building deterministically, perhaps an easier method is possible to utilise. It is however recommended that computer programs are utilised to assess evacuation, as these programs are easy to handle and quite fast, as well as they provide more accurate results than hand calculations or Excel sheets.

3. When performing a probabilistic analysis, statistics play a central role. To determine the probability of fires, fire scenarios or the reliability of barriers statistics are needed. In this thesis, statistics are gathered from several different sources. Reliability data is acquired from studies in Finland, NFPA and BSi, whereas data on fires in Norway is collected from DSB and Nordstat. This is both time consuming and misleading as the different statistics come from different assumptions. Use of probabilistic design suffers from this, as the myriad of information and statistics become a barrier to even get started. It is therefore necessary to establish a framework from where information can be extracted with ease.

   Statistics regarding fires in Norway can be collected from DSB and Nordstat. Examples of relevant reports and the information they contain are:
   - DBS – Statistics of fire causes[36]: Contains statistics on where and how fires are started. Can be used when several fire scenarios are measured against each other, similar to what was done in chapter 4.
   - DSB – Characteristics of fatal fires and fatalities in fires[47]: Contains statistics on fatal fires. For instance this document provides information on the time of fatal fires. According to this document, most fatal fires occur at night. This information could be used to decide pre movement time to inhabitants in the building. Furthermore, this information can be used to weigh different scenarios, for instance if 60% of fires occur during night and 40% during the day, those are two scenarios that provide different risk.
   - Nordstat.net: This website contains overall statistics on fires in the northern countries. It is possible to identify number of building fires, fatal fires and fatalities in different types of buildings.

   By utilising these sources it is possible to derive frequencies of fires in different building, prioritise fire scenarios and make assumptions such as pre movement time based on time of initiated fire.

   Reliability data is found in several different sources however; the reliability data vary a lot. This might be due to different data sets, timing or different assumptions made in testing. For the users of the data this poses challenges, as it is difficult to decide what data to use at what time. British Standard Institute has standardised this information so that it is readily available[7]. However, this standard is usually not available for Norwegian users. It is therefore recommended that the Norwegian government create a similar standard, to enable FSEs to utilise probabilistic design. The reliabilities from BSi are given in intervals, so in order to decide on reliabilities, numbers are identified from other sources. These sources are then cross-referenced with BSi, to ensure that the data is somewhat similar, before it is included in the thesis. This procedure is possible to use, until a similar standard is released, or it is possible to utilise the British standards if available.

If the safety is insufficient and measures have to be made, must the process then be repeated?
This is to some extent shown in chapter 6, however the process will be further explained in this section. Firstly, many solutions were considered, but few addressed the actual problem except for the selected solution. Take note that the 3rd sequence was not included in the calculation, nor was it simulated. This was an active choice to reduce analysis time. The risk of sequence 3 is approximately 20 times lower than the risk of sequence 1; consequently, it was assumed that it has little impact on risk. As the measure affects sequence 3 similarly to sequence 1, the risk must be reduced similarly. Moreover, the learning from the original analysis was applied in chapter 6, as the analysis was performed qualitatively before it was quantified. As a matter of fact, all measures thought of was qualitatively analysed before a choice was made, which ensures that the measure actually reduces risk.

Following the qualitative evaluation is the quantitative evaluation. The quantitative evaluation was performed as the measure changed the design quite a lot. It was therefore uncertainty regarding the outputs from the qualitative analysis, an example of this being time to failure. As the time to failure changed after implementing the measure, this proved to be a good choice, but another analysis might not always be necessary. According to NS 3901, the measure is to be evaluated qualitatively on an overall level, unless the suggested measure changes the design significantly[12]. A qualitative evaluation is advantageous, as analysing scenarios deterministically is time consuming. However, deterministic tools provide much clearer answers to whatever questions might remain. Furthermore, this assures clear documentation on whether the safety level is sufficient or not. The example provided in chapter 6 illustrates the importance of performing the quantitative analysis.

This discussion leads to the following checklist, which describes how to incorporate measures into probabilistic design:

1. Investigate the sequences that lead to potential fatalities. Why do they lead to fatalities? What do they have in common? And what is the contribution to risk? Based on this information it is possible to tailor the measures towards the common problems of the scenarios leading to fatalities, ensuring that measures actually address the problems. If a sequence contributes little to risk, perhaps it does not need to be addressed at all. This was done in chapter 6, where sequence 3 was assumed to affect risk so little that it was neglected in the further calculations. By doing this, time is spent on what matters the most and it also challenges the FSE’s skills and experiences in assessing what measures that might reduce risk the most.
2. When the actual problems are known, possible measures must be identified, which is a process that might benefit from opinions from several FSEs. When a measure is identified, it is important to assess it qualitatively. The qualitative assessment does not need to be documented; however, it is of imminent

importance that the measure addresses the actual problem. Furthermore, understanding is acquired on how the design is affected by the possible changes that are suggested.

3. After identifying a suitable measure, it must be documented. By qualitatively describing how the measure affects risk, it becomes clear what the designer has actually thought by implementing the measure. In chapter 6.2 it was evident that the qualitative descriptions was not enough, hence a deterministic analysis had to be performed.
4. If needed, perform the deterministic analysis. In this thesis there was some uncertainty in regard to how the measure affected the fire development, thus it was chosen to analyse it deterministically. As risk increased compared to the risk from the qualitative assessment, the deterministic analysis proved to be a good decision. Analysing measures might not be necessary for all cases, and that is up to the FSE to decide. However, if there are some uncertainties it is recommended that the analysis be finished deterministically, as the documentation becomes very clear in regard to whether the measure succeeded in reducing risk or not.
5. Document the results

By following this checklist, it is possible to come up with effective measures and documenting the effect from it. The checklist was derived from performing the process once and could therefore be improved upon. Other things that should be evaluated are the cost of the measures and also whether the design is possible to build or not.

Earlier it was stated that lack of acceptance criteria is a drawback for probabilistic design. How is it possible to overcome this challenge?
There are essentially two ways of doing this: Measure risk towards an absolute acceptance criterion or perform a comparative analysis. This section distinguishes between global and local analyses where global means analysing the entire building, whereas local means analysing a part of the building. In this section absolute acceptance criterion and global comparative criterion are mostly discussed, while local criterion will be mentioned briefly.

1. Overall acceptance criterion is the accepted safety level set by the authorities in a country. The safety level of a building should therefore be equal to or lower than this number, which also means that the pre-accepted solutions should follow this safety level. There are different types of safety in regard to fire. As this thesis focuses on personal safety, the acceptance criterion is the risk of one individual being exposed to fatal conditions in a fire. The chosen risk corresponds to the risk that was calculated in the analysis.

   Deciding on an overall acceptance criterion for life safety is difficult. Statistics encompasses old buildings as well as new ones, and it is difficult to distinguish between the buildings with the safety level of today and old. Several attempts on deciding an acceptance criterion have been observed. In a book on Quantitative fire risk assessment, the suggested level was $1*10^{-4}$[48]. This means allowing that every 10 000th person is exposed to fatal conditions due to fire in a year. It is important to note that this level was intended for Great Britain. In a draft standard released by SP Tech, the suggested safety level for Nordic countries is $1*10^{-6}$; namely, the safety level is 100 times as high as the previous suggestion[49]. For Norway this means allowing 5 persons to be exposed to fatal conditions due to fire during a year. Compared with the acceptance criterion in section 3.4, this is a reduction by 6 times. Section 3.4 was subject to the ambiguity of the statistics. The chosen safety level is highly ambitious, but such a reduction will save the society for unnecessary high costs due to fire. It is therefore adopted throughout the rest of the discussion.

The pre-accepted safety level calculated in chapter 5 is $3{,}56 \cdot 10^{-3}$, which is 3560 times as high as the suggested safety level; however, these numbers are not directly comparable. In the calculations performed in chapter 4 and 5 the risk of fatal fires was assumed to be $4{,}12 \cdot 10^{-2}$. In fact, this is not the overall risk of a fatal fire, but it is the risk of a fatal fire, given that a fire has occurred. To calculate the overall risk of fatal fires, Bayes Theorem is utilised as given in equation 7.1[41]:

$$P(R_{FF} | R_{fi}) = \frac{P(R_{fi} | R_{FF}) \cdot P(R_{FF})}{P(R_{fi})} \quad (7.1)$$

Equation 7.1

Where:
$P(R_{FF})$ – is the overall risk of a fatal fire in a block of flats per year
$P(R_{fi})$ – is the overall risk of a fire in a block of flats per year
$P(R_{fi} | R_{FF})$ - Is the risk of fire given that a fatal fire is occurring. This value is 1.
$P(R_{FF} | R_{fi})$ - Is the risk of a fatal fire given that a fire is occurring. This value is already calculated to $4{,}12 \cdot 10^{-2}$.

The overall risk of fire can be calculated by considering the statistics presented in chapter 4 and 5. There have been 6746 fires between 1996 and 2014 in block of flats. This means that 375 fires occur in an average year. According to SSB, there were 558 969 block of flats in Norway in 2014. This means that the probability of a fire occurring in a block of flats is: $6{,}71 \cdot 10^{-4}$. Thus the overall risk of a fatal fire is calculated accordingly: $P(R_{FF}) = 6{,}71 \cdot 10^{-4} \cdot 0{,}0412 = 2{,}75 \cdot 10^{-5}$. It is now possible to update the calculated risks from chapter 4 and 5, shown in table 7.2.

Table 7.2 – Calculated risk utilising overall risk of fatal fire.

Building	**Sequence**	**Risk Calculation**	**Updated risk**
Trial Design	1	$2{,}75 \cdot 10^{-5} \cdot 0{,}72 \cdot 0{,}99 \cdot 0{,}13 \cdot 0{,}10 \cdot 18$	$4{,}59 \cdot 10^{-6}$
	3	$2{,}75 \cdot 10^{-5} \cdot 0{,}72 \cdot 0{,}01 \cdot 0{,}13 \cdot 0{,}10 \cdot 84$	$2{,}16 \cdot 10^{-7}$
Total risk			$4{,}81 \cdot 10^{-6}$
Reference	1	$2{,}75 \cdot 10^{-5} \cdot 0{,}50 \cdot 0{,}99 \cdot 0{,}13 \cdot 0{,}10 \cdot 13$	$2{,}30 \cdot 10^{-6}$
	3	$2{,}75 \cdot 10^{-5} \cdot 0{,}50 \cdot 0{,}01 \cdot 0{,}13 \cdot 0{,}10 \cdot 84$	$1{,}50 \cdot 10^{-7}$
Total risk			$2{,}45 \cdot 10^{-6}$

The risks from table 7.2 can be compared to the overall acceptance criterion.

Firstly the risk of the trial design is approximately 5 times as high as the acceptance criterion. Objectively this shows that the personal safety in the analysed building is not good enough; consequently, measures must be taken to reduce risk. Perhaps more interesting is that the safety level of the reference building is more than twice as high as the acceptance criterion. The pre-accepted safety level is supposed to be the accepted safety level set by the government. In this instance, the calculated risk level of a pre-accepted building is too high compared to the safety level a group of experts have agreed on. Hence, it seems like there is a discrepancy in risk acceptance criterion between the authorities and the expert group. It is possible that the expert group wants to reduce the risk level further. On the other hand, it is possible that the pre-accepted solutions are not actually fit to ensure the desired safety level. Take note that the calculated values in table 7.2 are subject to several uncertain assumptions. These values should therefore be treated as indicators, more than conclusive results.

A similar calculation should be performed to the risk after the measure was implemented. The risk was sufficiently low compared to the pre-accepted solution; however, it was seen that the risk of the pre-accepted solution was not sufficiently low compared to the absolute risk criterion. While table 7.3 shows the newly calculated risk after implementing the measure, these values originate from table 6.3.

Table 7.3 – Risk after discussed measure is imposed.

	Probability of failure	**Lives endangered**	**Risk**
Sequence 1	$2{,}75 \cdot 10^{-5} \cdot 0{,}72 \cdot 0{,}99 \cdot 0{,}13 \cdot 0{,}10 \cdot 0{,}10 = 2{,}55 \cdot 10^{-8}$	20	$5{,}10 \cdot 10^{-7}$
Sequence 3	$2{,}75 \cdot 10^{-5} \cdot 0{,}72 \cdot 0{,}01 \cdot 0{,}13 \cdot 0{,}10 \cdot 0{,}10 = 2{,}57 \cdot 10^{-10}$	84	$2{,}16 \cdot 10^{-8}$
Total risk			$5{,}32 \cdot 10^{-7}$

It seems as though the risk is sufficiently low compared to the absolute criterion as well. Furthermore, it is evident that the risk of sequence 3 could be neglected as first assumed. Since the failure was identical to sequence 1, the same calculation could be used for sequence 3 as well.

What does these numbers mean exactly? They describe the risk of a person being exposed to fatal conditions in a year. Since the acceptance criterion meant allowing 5 people exposed to fatal conditions due to fire each year, the risk in the trial design is 5 times as large, meaning that it represents a risk level where exposition of 25 persons to fatal conditions is allowed. Remember that this value is based on many uncertain assumptions. Due to the stringent requirement from the draft standard, it is assumed that the reduction factor should have been lower than used in this thesis. Furthermore, due to the inaccuracy in the deterministic models, these results must be considered carefully. They should be treated like indicators more than conclusive results.

Having an overall acceptance criterion is advantageous because FSEs only have to perform one analysis. In this thesis, two analyses were performed in order to determine if the safety was sufficient. Probabilistic design has already been critiqued for being time consuming; thus, only having to perform one analysis means reducing the design time. This allows FSEs to create more value for their customers, compared to the value created by performing comparative analyses. The method as performed in this thesis has weaknesses. Absolute risk level depends on all the assumptions that are made throughout the analysis. Hence a sequence of uncertain assumptions makes the end result even more uncertain. Dealing with this will be addressed further at a later stage.

2. Since there is no commonly accepted overall acceptance criterion, comparative analyses are often performed, using SN INSTA 950 and NS 3901 as typical guidelines. In a comparative analysis, the trial design is compared to a reference building that follows the pre-accepted solutions[12, 35]. This means that the buildings shall have same type of use, same kind of inhabitants and they are similar in as many ways as possible.

   In the sensitivity analysis, it became evident that the risk in the trial design was too high, compared to the risk in the reference building. However, the risk in a 7-floor building similar to the trial design in any way except number of inhabitants and floors was sufficiently low. These buildings are the same in terms of use, inhabitants and also design; consequently, they are in the same risk class and fire class. Why are they not comparable then?

   The following suggestion is a reduction in the safety level from today; yet, the safety level is not reduced below an acceptable level. It is argued that buildings in risk class 4, between 5 and 8 floors are the same. If a building in risk class 4 has less than 5 floors it is in fire class 2 and if a building in risk class 4 has more than 8 floors, the pre-accepted solutions require several measures to be taken. The additional measures are to ensure a sufficient safety level, despite that the fire brigade is unable to intervene for higher buildings. It is therefore argued that buildings in risk class 4 between 5 and 8 floors are the same, meaning that the risk in the 8-floor pre-accepted building is the highest accepted risk for these types of buildings. The implication of this is that buildings in the same fire class and between 5 and 8 floors are compared to a similar building of 8 floors. As this is the highest allowed risk (HAR) for these buildings, the risk level is not unacceptable. In this thesis, similar buildings are in the same risk category.

   Imposing risk categories means that if a 6-floor timber building is analysed by use of comparative analysis, it is compared to a similar 8-floor pre-accepted building. It is of high importance that the two upper floors in the pre-accepted buildings are similar to the floors of the trial design. They must be similar in terms of activity, design, number of inhabitants and size; otherwise, the risk level cannot be compared. As mentioned previously, this is a reduction of the safety level of today. It is not unacceptable however, because this risk level is already accepted. Therefore it is a matter of allowing FSEs to make good choices within reasonable risk limits. As such, imposing risk categories might increase the flexibility of many buildings and potentially allows more use of timber as well.

   As this thesis only deals with fire class 3 and 4, this suggestion is aimed at high-rise buildings. To avoid misuse of this suggestion, a clear structure is needed, meaning that buildings between 5 and 8 floors are placed into one risk category. TEK 10 was studied, in order to identify natural HAR limits, similar to 8th floor;

however, the first change is when a building reaches 16 floors where the fire class changes to fire class 4. For buildings taller than this, full analysis must be performed, suggesting that there is a gap between 9th floor and the 16th floor where the pre-accepted solutions offers no measures to mitigate the increasing risk. If chapter 4 and 5 is studied, it is seen that the risk increases approximately 7 times for the trial design when one floor is added, because the number of inhabitants increases at the same time as the length of evacuation increases. In other words, the potential consequences of a fire increase. There must therefore be a clear distinction in risk levels after which FSEs might aim towards.

Due to the increasing risk levels, it is suggested that another level of safety is inserted. The limits of the next risk level must be further quantified in order to ensure the validity of the measure, but the tentative suggestion is as following:

- Category 1: Buildings between 5-8 floors within same risk class
- Category 2: Buildings between 9-12 floors within same risk class
- Category 3: Buildings between 13-16 floors within same risk class
- Taller buildings are placed into fire class 4, thus a full analysis must be performed.

Probabilistic design is a must, in order to make risk categories feasible. Risk is the parameter on which decisions are made; therefore, it is important to utilise a method that quantifies risk. Quantifying risk means that deterministic analysis alone is not sufficient; however, coupled with a probabilistic method a powerful tool for decision-making is at hand. The possibilities of imposing risk-based thinking are so many.

In order to introduce this way of thinking a research project must be conducted. The aim of this research is documenting the safety level of high-rise buildings, built after TEK 10. By doing so, quantitative data from the existing buildings are derived. It is possible to use this data to decide the risk limits for the different risk categories. An important factor to consider is that all kinds of safety must be considered. This means that personal, material, structural and environmental safety must be considered in this study. It is further envisioned that the highest allowed risk for all risk categories merge together to one commonly accepted acceptance criterion.

3. Local acceptance criteria means using local pre-accepted solutions as highest acceptable risk. In order to make this happen, the pre-accepted solutions must be possible to analyse. Some solutions are analysed in this thesis, for instance use of sprinklers; however, not all requirements are possible to analyse, making this way of documenting safety challenging. An example of this is: §11-10 Technical Installations (1). Pre-accepted solutions – water and drainpipes, central vacuum cleaner facilities and similar. Requirement 2 and 3 are highly specific, thus difficult to quantify. How is a FSE supposed to document that the risk of fire spread is similar too or lower for other solutions than these? Consequently, the purpose of the pre-accepted solutions must be explained to enable analysis of these solutions. As this is not dealt with much in this thesis it will not be discussed further.

7.4 Limitations

Although some limitations have been mentioned throughout the thesis, this section deals with them explicitly. It is important to address the limitations of this method, as they make impact on this research as well, so the limitations will be explicitly handled in the following section.

In the state of the art review, many of the researchers addressed input values as limitations of this method, which is also an issue in this thesis. Due to uncertainty of the input values, the results also become uncertain. Examples of such input values are:

- Pre movement time
- Fire severity
- Reliabilities of fire protection systems
- Number of inhabitants

Typically, research treats these values as stochastic values, providing the researchers with the entire risk spectre. Furthermore, the draft standard from INSTA recommends treating such values by imposing probabilistic distributions[49]. Although the accuracy of the risk calculations increases, it also increases analysis time. The time consumption is already addressed as a limitation of this method. But creating probability distributions for several input parameters makes it even more time consuming.

There are several alternatives to creating probability distributions of the input parameters. In this thesis, pre movement time and number of inhabitants were investigated through a sensitivity analysis. As the input parameters were adjusted, the change in overall risk level was studied. Nystedt supports this technique in his report on how to verity the safety of sprinklered buildings[22]. According to Nystedt, this is one the advantages of utilising event tree analysis. By investigating how risk changes with different input parameters, it is possible to decide whether the design is sufficiently safe or not. If the change in parameters causes a switchover of the findings, also called a switchover analysis, the trial design is not sufficiently safe[22]. The steps for performing a switchover analysis are as following[22]:

1. All possible variables that are expected to affect risk are identified. These variables are similar to the list explaining input values.
2. Thus, the identified variables are varied to study whether the building is still safe or not.
3. Finally, the FSE must consider if it is likely that a switchover will occur. If the safety margin is sufficient, the design is okay; however, if the safety margin is insufficient changes must be made to the design.

In doing so, it is possible for a FSE to investigate if the design truly is safe.

It is also possible to study input parameters similar to the researchers. Instead of treating input parameters as stochastic variables, it is possible to use point values from probability distributions. By using tools to create probability distributions, point probabilities can easily be retrieved. An example of such a tool is B-RISK. B-RISK allows probabilistic presentation of fire simulations results[50]. By using B-RISK it is possible to run for instance 1000 simulations quickly. It is then possible to retrieve probabilistic distributions on all the input parameters described in the list of inputs. Figure 7.2 shows an example run by using B-RISK. It shows 30 temperature-time curves from a similar room to the analysed compartment from this thesis.

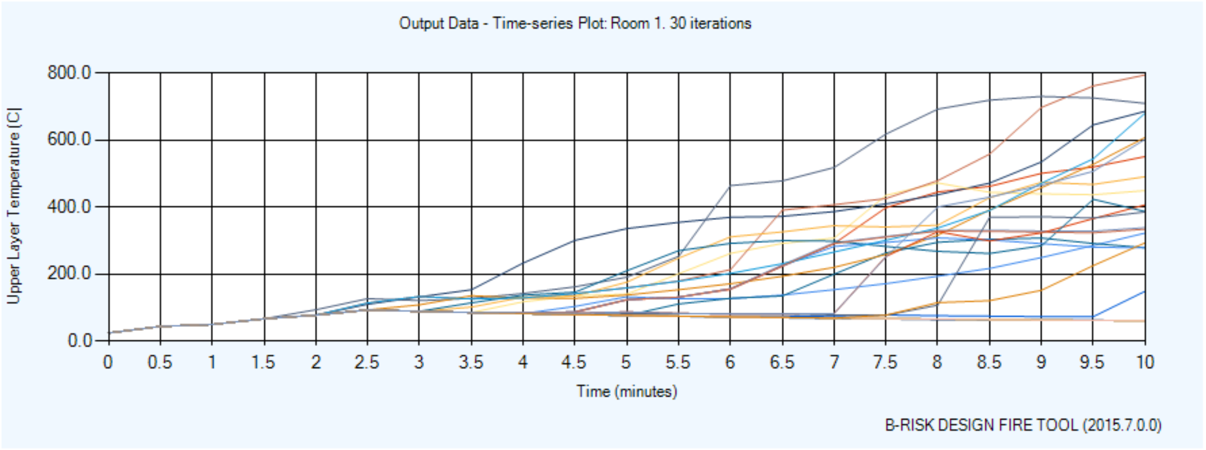

Figure 7.2 – Example runs of simulation in B-RISK

By utilising such tools, it is possible to derive stochastic distributions for different parameters easily. It is then possible to pick a point value from that distribution, for instance it is possible to identify a design fire that is within the 95 percentile. Thus, the chosen scenario will occur 95 out of 100 times. Another possibility is to study the effect of fire protection systems. The certainty of chosen values cannot be arbitrary. It is therefore of imminent importance that these values are set by a country's government. As the government is responsible to decide the safety level of a country, they must decide the certainty in which is operated upon. By utilising one of these suggestions, it is possible to compare the risk level of a building to an overall acceptance criterion. As this saves the FSE for one analysis, it is advantageous compared to comparative analyses.

One input that causes a lot of uncertainty in this thesis is the deterministic analysis, especially the FDS simulation. In the introduction it was stated that the accuracy of the deterministic analysis would be diminished in order to diminish the computational resources. Therefore, the results derived from the deterministic analysis are not trustworthy, meaning that the values for absolute risk are inconclusive. It is therefore not possible to utilise these values to make concluding remarks on the safety level of neither the reference building nor the trial design. Comparing risks is still valid, as both designs are exposed to the same uncertainties; however, it is not possible to compare absolute risks to an overall acceptance criterion due to this uncertainty.

7.5 Use of timber structures

By performing this analysis, some interesting results have been revealed about fire safety in timber structures have been revealed, such as:

- The results of the discussion
- Sensitivity
- Fire spread

The findings regarding these topics will be discussed in this section.

7.5.1 Results

The results are quite clear regarding the safety level of the trial design, which has twice as high risk compared to the reference building. Usage of unprotected surfaces of timber leads to higher risk due to the probability of fire being higher and the consequences of fire being more severe. It was however proven that it is possible to achieve sufficient safety levels in such a building, by imposing an additional door in the stairwell. This is advantageous because it shows that it is possible to utilise unprotected timber surfaces and still achieve sufficient fire safety for people. Often, the preferred measure is to clad the surfaces with gypsum board. The effect of gypsum board cladding was tested in a project run by ETH Zurich in Switzerland and CNR-IVALSA in Italy[51]. In this test it was proved that gypsum board could be utilised to successfully protect timber surfaces in case of fire. Furthermore, Halvorsen argued that sprinklers and protection of gypsum board was necessary to ensure structural fire safety in timber buildings[10]. However, one of the arguments of using timber is that it is aesthetical, but utilising gypsum board as protection opposes this argument. Another argument for using timber is because it is environmentally friendly. The question remains how environmentally friendly it is to utilise two layers of gypsum board to protect the timber surfaces, similar to the study performed by Frangi et al[51]. Hence, being able to quantify sufficient safety levels in an unprotected timber building is one step toward to more environmentally friendly and aesthetic buildings.

There are however some limitations to these conclusions. Firstly, this analysis is not complete in regard to personal safety, meaning that all relevant fire scenarios are not yet analysed. It is expected that the common room scenario will increase the risk of the trial design. Secondly, the analysis at whole is not complete, meaning that a structural analysis still must be performed, as well as safety of rescue teams must be considered. At this moment, the author has no opinion on how this will affect the risk level. Lastly, the safety level is calculated based on one failure mode, i.e. the visibility criterion. It is possible that other failure modes are more prevalent such as radiation, smoke temperature and toxicity[43].

As an answer to the first and the second limitation, a completion of the analysis must be performed. Until this analysis is complete, there is no knowing how the risk will be affected. As for the last limitation, most of these failure modes can be dealt with using already present information. The FDS calculations contain information on smoke temperature and radiation as well; hence, this is easily incorporated into the analysis. In regard to toxicity, this is more challenging, as already argued in 3.4. Perhaps future research might address and correct this issue.

7.5.2 Sensitivity

The sensitivity analysis in chapter 5 provided some clues on the sensitivity of the trial design. As both number of inhabitants and evacuation time increase, the risk of the trial design increases faster than the risk of the reference building. This might indicate that the risk of unprotected timber buildings is more sensitive to changes than for instance concrete buildings. No literature has been found that confirms or declines these findings, thus it is not possible to conclude on anything based on these findings. Nonetheless, this is an interesting observation that might have implications for fire safety in timber structures.

On a small scale, this means that unprotected timber have less flexibility to change because changes in the design of the buildings mean large changes in risk. A building is built to last at least 100 years. During the lifetime of a building, many changes may be made to the design. As the risk is more sensitive to these changes, they might have to be carefully planned. Maybe the planned changes are not even possible to go through with.

This might have a major economical impact, as changes are often necessary to maintain the value of the building.

For arguments sake it is said that risk sensitivity is higher for buildings with unprotected timber surfaces than for other buildings. This means that risk increases faster for every floor that is added to such a building compared to a building with incombustible surfaces. The implication of this is that measures must more often be made to mitigate the risk. At some point, this will no longer be cost effective or beneficial despite the advantages of using timber. It is predicted that this will cause the limitation of floors in timber buildings in the future.

7.5.3 Vertical fire spread

Vertical fire spread has been identified as an unanswered question throughout this discussion. An analysis on vertical fire spread was attempted, and albeit the analysis gave an answer, it failed to address the issue timber represents, which is high heat release rates out openings. Fire spread becomes more and more relevant as buildings become taller and are placed closer to each other. Therefore fire spread should generally be studied further. Especially the pre-accepted solutions to ensuring sufficient safety towards vertical fire spread should be investigated more closely.

Another relevant question is whether vertical fire spread is relevant for personal safety or not. In the study by Frangi and Fontana, the fire spread to the upper compartment in 7 minutes[44]. 7 minutes mean 420 seconds, which is a point where evacuation was well initiated, according to chapter 4 and 5. Moreover, it is assumed that this time will be later in new buildings. Today's windows often have three layers, whereas the windows in the mentioned test only had two. Therefore it is possible that this will occur at a later time. If this incident were to occur during night-time, vertical fire spread could potentially pose a threat to personal safety. Whatever effects vertical fire spread has on personal safety, there can be no doubt that fire spread adds onto total risk. Whether it is personal safety, structural safety or material safety. Hence, when dealing with buildings where large areas consist of unprotected timber vertical and horizontal fire spread must be addressed in the analysis.

7.6 Summary

The analysis of the analysis has shown that probabilistic design by event tree analysis is a powerful analysis tool regarding fire safety. There are many parameters that might be varied, to investigate how the risk level changes. Furthermore, it allows FSEs and building owners to make risk informed decisions. Appropriate use of this tool might open a greater variety of solutions, which is advantageous for all stakeholders. Although the method has flexed its muscles throughout this thesis, it is still immature and needs refining. Therefore, the discussion chapter has suggested a framework for probabilistic design, which includes how to handle measures. In order to perform probabilistic design efficiently, statistics must be readily available, thus a presentation is offered on where to find the relevant statistics.

Quantification of risk allows further opportunities. By implementing risk acceptance criteria, documentation of fire safety becomes easy. Hence, an alternative way of performing comparative analyses is offered in the discussion. The suggestion means lowering the general fire safety level of buildings; yet, not to unacceptably low levels. Additionally, quantification of risk creates more predictability for fire safety professionals as well as all other stakeholders in the building process.

The event tree analysis might also be extended. As personal safety was dealt with in this thesis, the risk of endangered lives was quantified, but it is fully possible to analyse for instance property damage instead. Calculating the risk of fire scenarios and consequences in form of material losses has been done in other instances[15]. Additionally, this analysis was global, meaning that the entire building was considered. Many of the deviations encountered as a FSE are local. An example of this is if having more than 30 meters from fire cell to nearest exit, which is a deviation from §11-14(1) 3c from VTEK [2], and is an issue that is often discussed. Such issues might also be analysed by utilising this method, which is also suggested by BSI in the state of the art section[7]. In the present moment, it is yet a time demanding tool, which is why it might be suitable to use it on analyses with large volumes at first. By using those experiences, it is possible to extend the tool so that its scope of application increases.

8.0 Conclusion

This thesis set out to achieve a sufficient fire safety level in Norway by suggesting an alternative way of documenting fire safety. Probabilistic design by event tree analysis was analysed as an analysis method. By quantifying risk, probabilistic design provides clear documentation whether a design is sufficient or not. Clear documentation of safety was achieved in this thesis, where the risk to personal safety was quantified for a timber and a concrete building. Yet, questions have been raised whether the method is suitable for FSEs or not. To address this issue, the following questions have been asked:

- What are the strengths of probabilistic design by event tree analysis?
- What are the challenges of utilising probabilistic design?

A by-product of the analysis is additional information regarding fire safety of timber structures. The conclusion will present the main findings followed from these questions. The implications of these findings are presented and the conclusion will be ended with suggestions for further work.

8.1 Concluding remarks

Probabilistic design has several strengths as an analysis tool. Documentation of the safety level in buildings becomes easy when the risk level of the trial design is quantified and compared towards a quantified acceptance criterion. Both overall acceptance criteria and comparative acceptance criteria exist. Since the method is still regarded as immature, uncertainties are prevalent when risk is compared to an overall acceptance criterion. But with the improvements suggested in this thesis, comparison to an overall acceptance criterion might be possible. Moreover, a new recipe for comparative analyses has been suggested in chapter 7.3, where quantification of risk is required. As the recipe increases flexibility for FSEs, it is advantageous compared to comparative analysis as it is done today. Furthermore, probabilistic design by event tree analysis is a versatile and complete analysis method. Input parameters can be changed to investigate how risk is affected and it is also possible to expand the analysis, so that it encompasses structural and material risk as well.

The two main challenges of probabilistic fire design are uncertainties of input parameters and time consumption. Engineers can mitigate uncertainties by performing sensitivity and switchover analysis, or by utilising tools to vary input quickly. Sensitivity analysis challenges the skill and experience of an FSE, as the parameters that affect risk the most must be identified. Using computer programs to vary input also challenges FSEs to expand on their toolbox. Both options are viable options in order to deal with uncertainties. The time consuming nature of probabilistic design is inevitable and although many suggestions are made in order to reduce analysis time it is still the main challenge of using probabilistic design. A reduction of analysis time is expected, as FSEs grow accustomed to using the method. Since probabilistic design by event tree analysis covers 3 out of 5 requirements of performance based design, probabilistic design is highly suited for large analyses. Hence, it is recommended that large analyses are performed by use of probabilistic design, so that experiences can be used to further develop the analysis tool.

Fire safety in timber constructions remains an unanswered question. Although it is possible to document the safety of timber buildings by use of probabilistic design, there are far too many uncertainties left to be conclusive. If a building has large areas of unprotected timber, both probability and the consequence due to fire are higher; indicating, that costs of achieving sufficient fire safety are higher than the costs of securing a concrete building.

This master thesis has shown that probabilistic design by event tree analysis is a versatile and powerful analysis tool. By quantifying risk, unlimited solutions exist to any problem, thus the skills and experience of FSEs are challenged. Moreover, it is advantageous, as safer and cheaper designs can be achieved at the same time as safety can be documented. As of today, there is no commonly accepted risk criterion to measure quantified risk towards. This is a drawback for users of probabilistic design, as comparative analysis becomes a must. As probabilistic design is a time consuming method this is an obstacle to making it competitive. FSEs now have a method to quantify risk, meaning that the ball is now in the hands of the Norwegian government.

8.2 Future Research

Throughout the thesis, several questions of interest have arisen. However, it is natural for Norway to move towards more risk-based approaches. Therefore the suggested research projects from this thesis are:

- Utilising probabilistic methods for local analysis. Closing deviations from the regulations.
- Utilising other probabilistic methods such as Bayesian Belief Nets and Fault Trees.
- Studying the sensitivity of timber buildings. A cost-benefit analysis.
- Using probabilistic models on structural safety.
- Creating analysis tools for fire spread.

A large research project that is of the authors liking is already mentioned in the discussion. By perfecting event tree analysis, it could be used to quantify risk due to fire in buildings built after TEK 10. In doing so, it would be possible to gauge what the actual safety level is in new buildings. Furthermore, it is possible to utilise these results to perform comparative analysis as presented in the discussion, using Highest Allowed Risk. In the long run, this is supposed to merge into one common acceptance criterion. It is important to emphasise that this project encompasses structural and material safety as well as personal safety. By doing so, the fire safety community is allowed to move towards a safer and more predictable daily life.

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Appendix A - Calculations

Calculation of vertical fire spread

The method in NS-EN 1991-1-2 identifies both flame height and the temperature at that point[34]. Thus it is possible to calculate heat transfer to the window, by radiative and convective heat transfer. In this instance, the flame height and temperature will be calculated. The method can be found in annex B.4 and is as following[34]:
First the rate of combustion is calculated by utilising equation A.1.

$$Q = \min\left(\frac{(A_f \cdot q_{f,d})}{\tau_F}; 3{,}15\left(1 - e^{\frac{-0{,}036}{O}}\right) A_v \left(\frac{h_{eq}}{D/W}\right)^{\frac{1}{2}}\right) \quad (A.1)$$

Equation A.1 – Rate of combustion

Where
A_f – Floor area of the compartment [m^2]
$q_{f,d}$ – Fire load per floor area [MJ/m^2]
τ_F - Time of an external fire (1200 s)
O – Opening factor [$m^{1/2}$]
A_v – Area of openings [m^2]
h_{eq} – height of the opening [m]
D – Depth of compartment [m]
W- Width of compartment [m]

Thus the flame height - L_l - is calculated by utilising equation A.2. This is the flame height from the top of the window.

$$L_l = 1{,}9\left(\frac{Q}{w_t}\right)^{\frac{2}{3}} - h_{eq} \quad (A.2)$$

Equation A.2 – Flame height

Where
w_t – is the width of the window [m]

The total flame height, including the window is calculated by equation A.3.

$$L_f = L_l + \frac{h_{eq}}{2} \quad (A.3)$$

Equation A.3 – Total flame height

, as $h_{eq} < 1{,}25w_t$

Now the temperature at the lower window must be calculated. This value is later used to calculate the temperature in Kelvin at the top of the flame. Equation A.4 is utilised.

$$T_w = 520/(1 - 0{,}4725(L_f \cdot w_t / Q)) + T_0 \quad (A.4)$$

$$With \quad L_f \cdot w_t / Q < 1$$

Equation A.4 – Temperature outside of window

T_0 – is the original temperature. 293 K.

Then the temperature can be found at the top of the fire, by setting L_x equal to L_f, and utilise equation A.5.

$$T_z = (T_w - T_0)(1 - 0{,}4725(L_x \cdot w_t / Q)) + T_0 \quad (A.5)$$

$$With \quad L_x \cdot w_t / Q < 1$$

Equation A.5 – Temperature along the axis

Table A.1 shows the value of the different parameters. The fire load for both cases comes from the study of McGregor. In the trial design, the fire load due to the CLT surfaces are added. Whereas in the reference building, only the movable fire load is included.

Table A.1 – Input parameters for cases

	Trial Design	**Reference Building**
A_f [m^2]	3,5 x 4,5 = 15,75	3,5 x 4,5 = 15,75
$q_{f,d}$ [MJ/m^2]	529 + 612 = 1141	529
O [m$^{1/2}$]	0,042	0,042
A_v [m^2]	2,3 x 1,2 = 2,76	2,3 x 1,2 = 2,76
h_{eq} [m]	1,2	1,2
D [m]	4,5	4,5
W [m]	3,5	3,5
w_t [m]	2,3	2,3

Thus the next table shows the calculated values for each case.

Table A.2 – Calculated values

	Trial Design	**Reference Building**
Q [MW]	5,41	5,41
L_l [m]	2,16	2,16
L_f [m]	2,76	2,76
T_w [K]	1455	1455
T_z [K]	812,6	812,6

Firstly, the temperature calculations are misleading. In both cases, there was a condition $L_x \cdot w_t / Q < 1$, which was not fulfilled in either. However the calculations were performed because a result was wanted. The result in itself is probably conservative, as both fires reaches to 1/3 of the upper window. This is based on each floor being 3 meters, as illustrated in figure A.1.

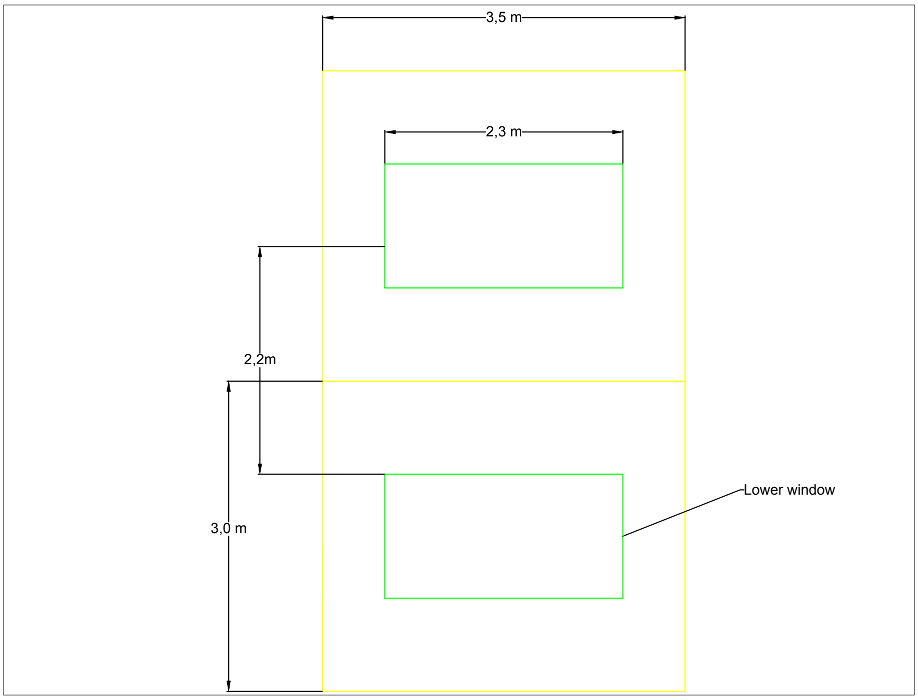

Figure A.1 – Flame height from lower window

Calculation of fire resistance of door

Attachment 1: Calculation of fire resistance of the door leading to the stairwell
Filename: CRM Calculation.xlsx
Description: Raw data supporting the calculation of Cumulative Radiation Energy. Leads to a 13 minutes fire resistance of the door.