Consequences of using Quantitative Risk Assessment as a verification tool

Joey Öström | Division of Fire Safety Engineering | Faculty of Engineering (LTH) | LUND UNIVERSITY

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Author: Joey Öström

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Abstract

What are the consequences of using Quantitative risk assessment (QRA) as a verification tool? Performance-based building codes differ from prescriptive-based codes in that they define specific objectives to be met, enabling the building designer to choose which solution to use so long it meets the objectives. This master's thesis explores the consequences of using QRA as a verification tool in comparison to existing verification methods currently in use in Australia. The thesis consists of a literature study examining currently existing quantitative risk-based methods, and a case study to test and illustrate the application of the proposed Part A8 of The Building Code of Australia (BCA) 2022, which contains quantitative risk criteria, followed by evaluation and analysis of the results. The study was limited to an already existing residential building with suggested fire safety measures. An event tree based QRA approach was used to quantify the individual and societal risk for the building. The results show that the already existing building meets most of the risk-based criteria of the proposed legislation. Improving the reliability of certain fire protection systems is shown to reduce the risk level for the building. The use of QRA to verify fire safety is expected to lead to a more holistic fire safety design and may lead to a more robust fire safety design. However, there are several challenges related to the use of QRA to verify fire safety in buildings.

Brandteknik
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

www.brand.lth.se
Telefon: 046 - 222 73 60

Division of Fire Safety Engineering
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

www.brand.lth.se
Telephone: +46 46 222 73 60

Summary

Countries have requirements regarding the design of buildings. Many building codes can either be classified as prescriptive-based or performance-based. Prescriptive based building codes prescribe a set of mandatory requirements that a building needs to meet. Performance-based building codes differ from prescriptive-based codes in that they define a specific objective to be met, allowing the designers of the building to choose which solution to use so long it meets the objectives.

Quantitative and qualitative methods are examples of two different methods that can be used to verify fire safety in performance-based building codes. Quantitative methods can be divided into deterministic and probabilistic methods. Using the probabilistic method, a quantified risk can be determined based on the frequency and consequences of a hazard.

The Australian Building Codes Board (ABCB) has proposed to incorporate in the Building Code of Australia (BCA) 2022 version a method whereby compliance with a set of fire engineering Performance Requirements is determined through a probabilistic framework. As part of this, quantitative risk criteria are proposed to be introduced into the legislation in Part A8 of BCA 2022.

The general objective of this thesis is to identify and evaluate the consequences of using Quantitative Risk Assessment (QRA) as a verification tool in comparison to existing verification methods currently in use in Australia.

This thesis consists of three parts. The first part takes the form of a literature study with the aim of examining currently existing quantitative risk-based methods and approaches. The second part of the thesis consists of a case study testing and illustrating the application of the proposed Part A8 of BCA 2022. The third and final part of this thesis consists of compiling, evaluating, and analysing the information gathered from the literature study and case study.

The literature study will be conducted with the aim of examining currently existing quantitative risk-based methods and approaches, gathering background information as well as data for the case study. At the literature study phase, information regarding how the proposed legislation has been developed and is being applied will be gathered.

An event tree based QRA approach was selected to be used for the case study, and frequencies and consequences for each scenario was estimated. The case study is limited to an already existing residential building, with suggested fire safety measures to support the Performance Solutions for the building. Combustible cladding was not included in the assessment, and the risk to the life of occupants evacuating the building from falling debris and the release of flaming droplets was not evaluated. In addition, fire brigade intervention was not included in the analysis. The conducted quantitative risk analysis was limited to the methods chosen based on the findings of the literature study.

Based on the conducted case study, the criteria in the proposed Part A8 are considered to be met for the building, except for societal risk and one criterion related to the spread of fire between buildings. The sensitivity analysis shows that improving the reliability of certain fire protection systems lowers the individual risk and societal risk for the building. However, the calculated societal risk was still determined to exceed the upper tolerable limit for the case building.

Using QRA for evaluating fire safety in buildings is expected to lead to a more holistic fire safety design for a building compared to just evaluation specific selected performance

requirements for the identified departures from deemed-to-satisfy provisions. In addition, a more robust fire safety design may result as a consequence of using QRA for evaluating fire safety due to the evaluation of potentially a large number of scenarios and by considering the probability of success for different fire protection systems. However, evaluating fire safety by the use of QRA comes with several challenges, including limited availability of data, selection of scenarios, and uncertainties related to available data.

The legislation was developed through a process containing several stages, including a review of documents, the derivation of variables to be considered, development of an issues matrix, consolidation of all fire safety-related Performance Requirements into two requirements, and providing a text for inclusion in a public comment draft. The first part of the legislation, Part A8.1 specify the application of Part A8.2 and A8.3. The two other parts of the legislation, Part A8.2 and A8.3 applies to the interpretation of a number of specified Performance Requirements that relate to departures from the Deemed-to-Satisfy provisions. The legislation is considered to be hard to interpret in some cases since explanatory information is not provided.

Based on the literature study, the SFPE Guideline seems to be the most appropriate guideline for a fire risk assessment. Further, it is recommended to adopt an event tree based QRA approach, which is useful when examining a large number of scenarios and provides a rational method for quantitative risk analysis.

Sammanfattning (Summary in Swedish)

Länder har regler gällande hur byggnader utformas. Många byggregler kan antingen klassificeras som preskriptiva eller funktionsbaserade. Preskriptiva byggregler föreskriver obligatoriska krav som en byggnad måste uppfylla. Funktionsbaserade byggregler skiljer sig från preskriptiva genom att de definierar ett specifikt mål som ska uppfyllas, vilket gör det möjligt för de som designar byggnaden att välja vilken lösning som ska användas så länge den uppfyller målen.

Kvantitativa och kvalitativa metoder är exempel på två olika metoder som kan användas för att verifiera brandsäkerhet i funktionsbaserade byggregler. Kvantitativa metoder kan delas in i deterministiska och probabilistiska metoder. Med en probabilistisk metod kan en kvantifierad risk bestämmas utifrån uppskattad frekvens och konsekvens av en fara.

Australian Building Codes Board (ABCB) har föreslagit att införa en metod där funktionsbaserade krav verifieras genom ett probabilistiskt ramverk. Som en del av detta föreslås kvantitativa riskbaserade kriterier införas i del A8 av lagstiftningen Building Code of Australia (BCA) 2022.

Det allmänna syftet med det här examensarbetet är att identifiera och utvärdera konsekvenserna av att använda kvantitativ riskbedömning (QRA) som ett verifieringsverktyg i jämförelse med befintliga verifieringsmetoder som för närvarande används i Australien.

Denna uppsats består av tre delar. Den första delen består av en litteraturstudie med syfte att undersöka befintliga kvantitativa riskbaserade metoder och tillvägagångssätt. Den andra delen av uppsatsen består av en fallstudie som testar och illustrerar tillämpningen av den föreslagna del A8 av BCA 2022. Den tredje och sista delen av uppsatsen består av att sammanställa, utvärdera och analysera informationen som samlats in från litteraturstudien och fallstudien.

Litteraturstudien genomfördes i syfte att undersöka nuvarande kvantitativa riskbaserade metoder och tillvägagångssätt, samla in bakgrundsinformation samt data för fallstudien. Samtidigt samlades information om hur den föreslagna lagstiftningen har utvecklats och tillämpats in.

En händelseträdbaserad QRA-metod valdes för fallstudien, och frekvens samt konsekvens uppskattades för varje scenario. Fallstudien är begränsad till ett redan befintligt flerbostadshus, med föreslagna brandsäkerhetsåtgärder för att stödja den analytiska dimensioneringen som är gjord för byggnaden. Brännbart ytskikt ingick inte i bedömningen, och risken de boende som evakuerar byggnaden utsätts för från fallande spillror och frigörandet av brinnande droppar utvärderades inte. Dessutom inkluderades inte räddningstjänstens insatser i den utförda analysen. Den genomförda kvantitativa riskanalysen var begränsad till de metoder som valts utifrån resultatet av litteraturstudien.

Kriterierna i den föreslagna del A8 av lagstiftningen anses mestadels uppfyllas för byggnaden baserat på den utförda fallstudien, bortsett från kriteriet för samhällsrisk och ett av kriterierna kopplade till brandspridning mellan byggnader. Den utförda känslighetsanalysen visar att en förbättring av tillförlitligheten hos vissa brandskyddssystem sänker den uppskattade individ- och samhällsrisken för byggnaden. Den beräknade samhällsrisken bedöms dock fortfarande överstiga den övre acceptabla risknivån för byggnaden som användes i fallstudien.

Att använda QRA för att utvärdera brandsäkerhet i byggnader förväntas leda till en mer holistisk design jämfört med att enbart utvärdera utvalda funktionsbaserade krav för de identifierade avvikelserna från de preskriptiva kraven. Dessutom skulle en mer robust design kunna resultera som en konsekvens av att använda QRA för att utvärdera brandsäkerhet, eftersom ett potentiellt stort antal scenarier utvärderas tillsammans med att hänsyn tas till tillförlitligheten för olika brandskyddssystem. Att utvärdera brandsäkerhet med hjälp av QRA medför dock flera utmaningar, såsom begränsad tillgänglighet till data, urval av scenarier och osäkerheter relaterade till tillgängliga data.

Lagstiftningen har utvecklats genom en process innehållande flera steg, inklusive en granskning av rapporter, framtagande av variabler för beaktning, utveckling av en frågematris, konsolidering av alla brandsäkerhetsrelaterade funktionsbaserade krav till två krav, och tillhandahållande av en text för inkludering i ett offentligt kommentarutkast. Den första delen av lagstiftningen, del A8.1 specificerar tillämpningen av del A8.2 och A8.3. De två sista delarna, del A8.2 och A8.3 specificerar hur ett antal specificerade funktionsbaserade krav kopplat till avvikelser från de preskriptiva kraven ska tolkas. Lagstiftningen anses i vissa fall vara svårtolkad eftersom förklarande information saknas.

Baserat på litteraturstudien verkar SFPE-riktlinjen vara den mest lämpliga riktlinjen för en brandteknisk riskanalys. Vidare rekommenderas det att använda en händelseträdbaserad QRA-metod, vilket är en användbar metod när man undersöker ett stort antal scenarier och utgör en rationell metod för kvantitativ riskanalys.

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Joey Öström, Lund 2022

Terminology and definitions

Definitions

Available Safe Egress Time

Time available for an occupant to egress. Calculated from the time of fire ignition to untenable conditions is reached.

Building Occupant Warning System

A system that provides the occupants of a building with a warning in case of fire.

Deemed-to-Satisfy

Prescriptive compliance with the Building Code of Australia.

Event Tree

A diagram displaying and structuring possible event sequences starting from an initial event, followed by intermediate events, and ending with different scenarios.

Fire safety measure

Safety measure to be implemented in a building to support a suggested Performance Solution.

FN curve

An FN curve shows the cumulative frequency of a consequence and can be used to present societal risk.

Initial event

The initial start event in an event tree, usually fire ignition or initial fire.

Individual risk

The frequency of exposure to a hazard for an individual during a specific period, usually one year.

Intermediate event

An event occurring between the initial fire and an end point in an event tree.

Performance Solution

A building solution that achieves compliance with the relevant performance requirements of the BCA by other means than prescriptive compliance.

Scenario

The end point of an event tree.

Societal risk

Risk experienced by a whole group of people being exposed to a specified hazard, e.g., a fire.

Sole Occupancy Unit

Apartment

Required Safe Egress Time

Required time for an occupant to egress.

Risk analysis

The use of available information to identify hazards and estimate the risk to, e.g., individuals and society.

Quantitative risk analysis

A risk analysis presenting numerical estimates for probabilities and/or consequences.

Risk triplet

Kaplan & Garrick (1981) define risk by three questions, forming the risk triplet: What can happen? How likely is it to happen? If it does happen, what are the consequences?

Quantitative risk assessment

The process of quantitative risk analysis and risk evaluation.

Abbreviations

ABCB	The Australian Building Codes Board
AFEG	Australian Fire Engineering Guidelines
ALARP	As Low As Reasonably Practicable
ASET	Available Safe Egress Time
BCA	Building Code of Australia
BOWS	Building Occupant Warning System
CFAST	Consolidated Fire Growth and Smoke Transport Model
DtS	Deemed-to-Satisfy
FED	Fractional Effective Dose
FER	Fire Engineering Report
NCC	National Construction Code
RSET	Required Safe Egress Time
RTI	Response Time Index
SOU	Sole Occupancy Unit
QRA	Quantitative Risk Assessment

Symbols

α	Fire growth coefficient [kW/s^2]
A_f	Horizontal burning area of a fuel [m^2]

c_i	Consequence for scenario i
ΔH_c	Complete heat of combustion [MJ/kg]
$\dot{m}''$	Mass burning rate per unit area [kg/s·m^2]
n	Number of scenarios
p_i	Probability for scenario i
$\dot{q}''$	Radiative heat flux [kW/m^2]
$\dot{Q}$	Heat release rate [kW]
R_0	Distance to a target from the centre of the flame [m]
t_a	Alarm time [s]
t_{det}	Detection time [s]
t_{RSET}	Required Safe Egress Time [s]
t_{pre}	Pre-movement time [s]
t_{trav}	Travel time [s]
χ	Combustion efficiency
χ_r	Fraction of total energy radiated

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1 Introduction

This master's thesis constitutes the finalization of a Master of Science in Risk Management and Safety Engineering and a Bachelor of Science in Fire Protection Engineering at The Faculty of Engineering (LTH) at Lund University, Sweden. The introduction to this master's thesis intends to present the background to the problem, the general and specific objectives of this thesis, the problem definition including questions to be answered, specify the scope of the study, and present the method used.

The Australian Building Codes Board (ABCB) has proposed to incorporate in the Building Code of Australia (BCA) 2022 version a method whereby compliance with a set of fire engineering Performance Requirements is determined through a probabilistic framework. As part of this, quantitative risk criteria (individual and societal risk) are proposed to be introduced into the legislation in Part A8 of BCA 2022.

The general objective of this thesis is to identify and evaluate the consequences of using QRA as a verification tool in comparison to existing verification methods currently in use in Australia. This thesis has been written with the help of RED Fire Engineers Pty Ltd, which is an Australian fire engineering consultancy company. RED Fire Engineers has provided an external supervisor for this thesis together with access to a private library, computer modelling programs, and support throughout the duration of this thesis. In addition, RED Fire Engineers has provided permission to use an already designed building for the conducted assessment. It should be noted that the details of the job have been edited out, and no reference is therefore given to the existing Fire Engineering Report.

1.1 Background

Many building codes can either be classified as prescriptive-based or performance-based. Prescriptive based building codes prescribe a set of mandatory requirements that a building needs to meet. Performance-based building codes differ from prescriptive-based codes in that they define specific objectives to be met, allowing the designers of the building to choose which solution to use as long as it meets the objectives. Different methods can be used to show that the building meets these objectives depending on the building code. (Hadjisophocleous & Bénichou, 2000)

In Australia, provisions for construction and technical design are primarily governed by the National Construction Code (NCC), which is produced and maintained by The Australian Building Codes Board (ABCB) on behalf of the Australian Government and each State and Territory Government. The NCC is a performance-based building code and consists of three volumes, Building Code of Australia (BCA) Volume 1, Building Code of Australia (BCA) Volume 2, and the Plumbing Code of Australia (PCA). (ABCB, 2019).

The Performance Requirements of the NCC can either be satisfied by a Deemed-to-Satisfy (DtS) solution, a Performance Solution, or a combination of both. (ABCB, 2019) Figure 1 shows the compliance option structure of the NCC.

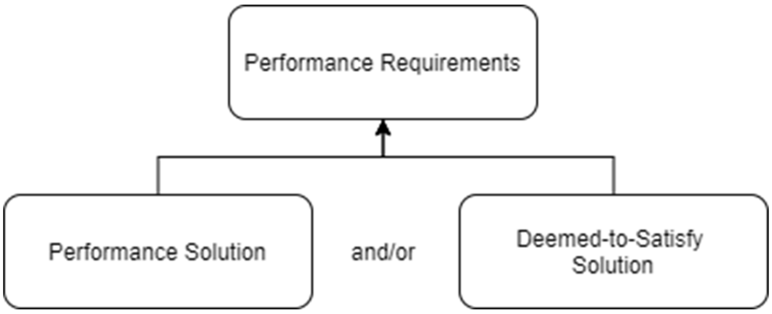


Figure 1: Compliance option structure of the NCC (adapted from (ABCB, 2019))

Two different methods to verify fire safety that can be used in performance-based building codes are quantitative and qualitative. When using a qualitative method, a comparative or absolute approach can be used. A comparative method aims to determine if the proposed performance solution is considered to be equivalent or better than the DtS provisions, i.e., equivalent or better than prescriptive compliance with the BCA. An absolute method aims to match the result of the conducted analysis against the specified performance requirements. When using an absolute method, no comparison is made with the DtS provisions. (ABCB, 2021)

Quantitative methods can be divided into deterministic or probabilistic methods. When using a deterministic or probabilistic method, a comparative or absolute approach can be used. Just like for qualitative analysis, a comparative method used in a quantitative analysis aims to determine if the proposed performance solution is considered to be equivalent or better than the DtS provisions, i.e., equivalent or better than prescriptive compliance with the BCA. An absolute method aims to match the result of the conducted analysis against the specified performance requirements in the building code for quantitative analysis as well. No comparison is made with the DtS provisions when using an absolute method in a quantitative analysis. (ABCB, 2021)

In the deterministic method, the hazard will be expressed in terms of consequences. Using the probabilistic method, a quantified risk can be determined based on the frequency and consequences of a hazard (Frantzich, 1998).

The Australian Building Codes Board (ABCB) has proposed to incorporate in the Building Code of Australia (BCA) 2022 version a method whereby compliance with a set of fire engineering Performance Requirements is determined through a probabilistic framework. As part of this, quantitative risk criteria (individual and societal risk) are proposed to be introduced into the legislation in Part A8 of BCA 2022.

This master's thesis will be looking at the consequences of using Quantitative Risk Assessment (QRA) as a verification tool in comparison to existing verification methods currently in use in Australia.

1.2 Aim

The general objective of this thesis is to identify and evaluate the consequences of using QRA as a verification tool in comparison to existing verification methods currently in use in Australia. The specific objectives of this thesis are to:

- Conduct a case study to test and illustrate the application of the proposed Part A8 of BCA 2022.

- Identify and evaluate different QRA methods that can be used since the current proposed legislation does not specify which method to use.
- Highlight how the legislation has been developed and how it is being applied, as well as potential difficulties encountered during the application of the proposed legislation.

1.3 Problem definition

There are several potential problems related to the use of risk-based criteria in the proposed legislation. Some examples based on previous case studies conducted for the ABCB (2020) and comments from the informative discussion regarding Consultation on National Construction Code (NCC) 2022 public comment draft (stage 1) hosted by the Society of Fire Safety (SFS) (2021) regarding the proposed changes are:

- Fire engineers in Australia might not have the appropriate knowledge of risk assessment.
- Available data for determining the probabilities of fire starts is limited in Australia.
- There is no clarity as to how the ABCB determined the allowable risk thresholds.
- The potential for increased costs in fire engineering services derived from the application of Part A8.
- Uncertainty in the scope of application of Part A8 – does the entire building need to be evaluated for a simple departure in the basement?
- There is currently no guidance on minimum levels of analysis. There is also no guidance on the maximum practical extent of using a probabilistic method.

The questions this thesis intends to answer is:

- What are the consequences of using QRA as a verification tool? What are the advantages and disadvantages of using QRA as a verification tool? What difficulties arise? What happens to robustness?
- How has the proposed legislation been developed, and how is it being applied? What potential difficulties are encountered during the application of the proposed legislation?
- How would one select which QRA method to use?

1.4 Scope

This thesis will explore the consequences of using QRA as a verification tool in comparison to existing verification methods currently in use in Australia. The case study will be limited to an already existing 4-storey residential building, with suggested fire safety measures to support the Performance Solutions for the building. According to the Fire Engineering Report (FER) prepared for the existing building by RED Fire Engineers, the proposed Performance Solutions meets the Performance Requirements for the building. Combustible cladding will not be included in the assessment, and the risk to the life of occupants evacuating the building from falling debris and flaming droplets will not be evaluated. In addition, fire brigade intervention will not be included in the analysis. A more detailed description of the building is presented in Section 4.2. The conducted risk analysis will be limited to the method or methods chosen based on the findings of the literature study.

1.5 Method

This thesis consists of three parts, as shown in Figure 2. The first part takes the form of a literature study with the aim of examining currently existing quantitative risk-based methods and is presented in Section 2. Based on the findings in the literature study, a method will be selected for use in the case study. At the literature study phase, information regarding how the proposed legislation has been developed and how it is being applied will be gathered. This is presented in Section 3.1.2.

The second part of the thesis consists of a case study testing and illustrating the application of the proposed Part A8 of BCA 2022. During this part of the thesis, the benefits and challenges relating to the proposed probabilistic framework are to be identified. The case study is presented in Section 4.

The third and final part of this thesis consists of compiling the information gathered from the literature study and case study. The complied information will then be evaluated and analysed.

Figure 2: Flow chart showing the three parts of the thesis

2 Literature study

The literature study was conducted with the aim of examining currently existing quantitative risk-based methods and approaches, gathering background information as well as data for the case study. The literature search was mainly conducted via LUBsearch, which functions as a digital search engine of all libraries connected to Lund University. In addition to using LUBsearch, literature in the form of publications and student literature was gathered from the website of the Division of Fire Safety Engineering at Lund University. Further literature was found by applying the "snowball technique", i.e., scanning the reference list of relevant literature for this thesis to find additional relevant literature. Some of the literature found via the snowball technique could not be found via LUBSearch. This literature was instead found by searching for the literature on Google Scholar.

The keywords for the literature study were chosen to capture a broad range of literature for potential use in the thesis. Relevant literature was selected by reading the topics and abstracts of the literature found through LUBSearch. The relevant literature was then read in more detail, and additional relevant literature was found using the snowball technique described above.

A broad literature study was conducted, and the following keywords were used: 'QRA,' 'quantitative risk assessment', 'quantitative risk analysis', 'risk assessment', 'risk analysis', 'risk criteria', 'performance-based', 'verification tool', 'design fires', 'residential fires', and 'probabilistic'. In addition, a search was conducted to find relevant literature from the following authors: 'Armin Wolski', 'Brian Ashe', 'Brian Meacham', 'Henrik Bjelland', 'Marvin Rausand', 'Ove Njå', 'Kevin Frank', 'David Charters', 'Vladimir Moser', and 'Greg Baker'.

The literature used for this thesis consists of books, papers in peer-review academic journals, official guidelines, handbooks, manuals, and Ph.D. and student theses. In addition, literature from RED Fire Engineers private library and The Australian Building Codes Board (ABCB) has also been used for this thesis.

The result of the literature study can be seen in the information gathered from relevant sources, which have been referred to in the subsections below and throughout this report. In addition, another result of the literature study was the selection of methods for the case study conducted in this thesis.

The following subsections will present different methods for verification of fire safety and the risk management process and its contents. Under the risk assessment subsection (Refer Section 2.2), the definition of the word 'risk', quantitative risk assessment, quantitative risk analysis, hazard identification, risk evaluation, risk criteria, risk assessment methods, quantitative methods, risk measures, and reliabilities and probabilities will be presented.

2.1 Methods for verification

As mentioned in the background section, building codes are often classified as prescriptive-based or performance-based. A prescriptive-based building code specifies a number of requirements that need to be complied with, while a performance-based building code state desired objective that needs to be met. Instead of complying with the requirements specified in a prescriptive-based code, the desired objective can be met by several different types of solutions in a performance-based code (Hadjisophocleous & Bénichou, 2000). The performance requirements of the NCC can either be satisfied by a deemed-to satisfy solution, a performance solution, or a combination of both (ABCB, 2019).

A performance solution can be based on a qualitative or quantitative methodology. When using a qualitative approach, a comparative or absolute approach can be used. By using a quantitative methodology, the performance requirements can be demonstrated to be met utilizing, e.g., hand calculations and computer simulations of fire development, smoke spread, and people movement. A quantitative analysis can be deterministic or probabilistic. When using a deterministic or probabilistic method, a comparative or absolute approach can be used. A comparative approach is an approach where the aim is to determine if the proposed performance solution is considered to be equivalent or better than the DtS provisions, i.e., equivalent or better than prescriptive compliance with the BCA. An absolute approach aims to match the result of the conducted analysis against the specified performance requirements. When using an absolute approach, no comparison is made with the DtS provisions. (ABCB, 2021)

In the deterministic method, the hazard will be expressed in terms of consequences. Using the probabilistic method, a quantified risk can be determined based on the frequency and consequences of a hazard (Frantzich, 1998).

2.1.1 Risk management

The risk management process contains several elements (ISO, 2018):

- Communication and consultation
- Scope, context, and criteria
- Risk assessment
- Risk treatment
- Monitoring and review
- Recording and reporting

Risk assessment is described in ISO 31000:2018 as the overall process of risk identification, risk analysis, and risk evaluation. Risk assessment is, in turn, part of the risk management process. A figure showing the risk management process is shown in Figure 3 below.

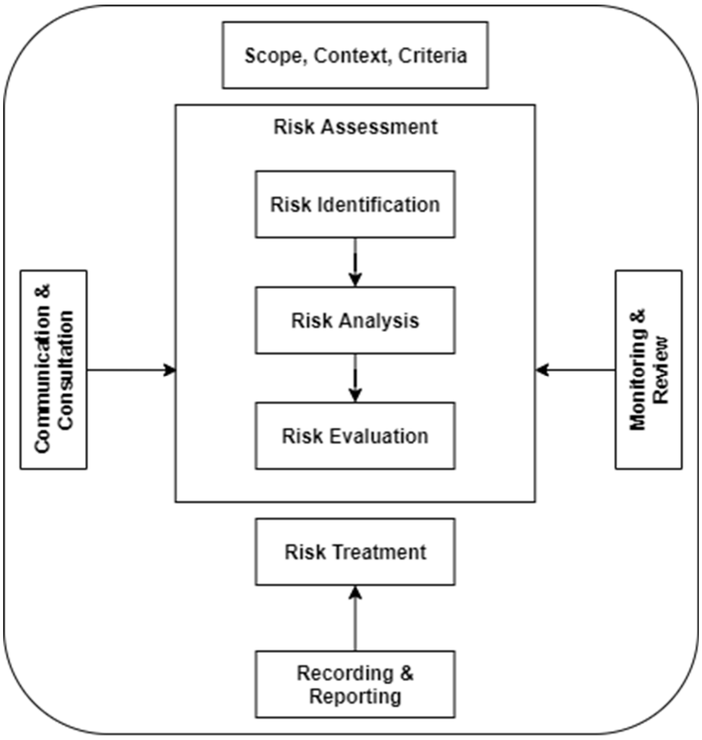


Figure 3: Risk management process (adapted from (ISO, 2018))

2.1.2 Risk analysis

According to Rausand (2011), a risk analysis is carried out in three steps:

1. Hazard identification
2. Frequency Analysis
3. Consequence analysis

The objective during the Hazard identification, which is the first step, is to identify potential hazards and hazardous events related to the system. This step also includes the identification of assets that might be harmed. (Rausand, 2011)

During the second step, frequency analysis, the causes of each hazard or hazardous event are identified. In addition, the frequency of the identified causes is estimated during this step (Rausand, 2011).

In the third and final step, consequence analysis, the objective is to identify all potential sequences of events and consequences resulting from the events together with their probability of occurrence through analysis. (Rausand, 2011)

Several factors should be considered in a risk analysis according to the ISO 31000:2018 guidelines. Those are the likelihood of events and consequences, the nature and magnitude of consequences, complexity and connectivity, time-related factors and volatility, the effectiveness of existing controls, sensitivity, and confidence levels (ISO, 2018). The results from the risk analysis provide input to the risk evaluation phase of a risk assessment (ISO, 2018).

2.2 Risk assessment

Risk assessment can be described as the process of risk identification, risk analysis, and risk evaluation (ISO, 2019). According to Rausand (2011), a risk assessment is a joint process of carrying out a risk analysis and risk evaluation. The author includes risk or hazard identification in the risk analysis process. Further, five steps to carrying out a risk assessment are outlined. The five steps are: 'identify the hazard', 'decide who might be harmed and how', 'evaluate the risks and decide on precautions, 'record your findings and implement them', and 'review your assessment and update if necessary'. Risk assessments can either be qualitative or quantitative (Rausand, 2011).

Risk assessment can be used in performance-based design to estimate the safety of a building. When used in performance-based fire safety design, the inputs for various performance measures such as reliability of detectors, sprinkler detection, and risk are all associated with degrees of uncertainty. The intention of a risk assessment is to describe risk via the identification of hazards, to analyse the causes and consequences of the identified hazards, and to evaluate risk-reducing measures. (Borg & Njå, 2013)

Borg & Njå (2013) state that a disadvantage of risk assessment is that it does not have the predictability and precision required to test a theory for use in scientific methods. This is because quantitative risk analysis tries to model events with a low probability of occurring, which differs from other fields of applied science, according to the authors. Consequently, validity cannot be addressed in the same way in risk assessments as it would in other areas.

This chapter will look at the definition of the word 'risk', quantitative risk assessment, quantitative risk analysis, hazard identification, design fires, calculation methods and computer programs, risk evaluation, risk criteria, risk assessment methods, quantitative methods, risk measures, and reliabilities and probabilities.

2.2.1 Defining risk

The word 'risk' has a different meaning to different people. This section will present a quantitative definition of risk, as well a definition of risk as a social construct. In many cases, 'risk' is defined as 'probability times consequence' (Kaplan & Garrick, 1981). According to Kaplan & Garrick (1981), this definition is misleading. Instead, Kaplan & Garrick (1981) suggests defining risk as 'risk and consequence'. When analysing risk, we try to picture how a certain course of action or inaction affects the future (Kaplan & Garrick, 1981). According to Kaplan & Garrick (1981), a risk analysis consists of answering the following three questions, forming the risk triplet:

- What can happen?
- How likely is it to happen?
- If it does happen, what are the consequences?

The risk triplet can also be presented as:

$$R = \{< s_i, p_i, x_i >\}$$

where s_i is the scenario identification, p_i is the probability of the identified scenario, and x_i is the consequence of the identified scenario for the specific scenario i.

Risk can also be seen as a social construct. Slovic (2016) states that the public often has a broader perception of risk incorporating, e.g., fear, equity, and risk to future generations into their perception of risk. The author states that because of this different view of risk, it should not come as a surprise that the usage of risk statistics has, in many cases, not affected people's perspective. These additional risk metrics cannot be incorporated into a Quantitative Risk Assessment, according to the author. An example of this can, according to the author, be seen in the question of whether the risk from cancer, which is a feared disease, is worse than the risk from car accidents, which is not as feared.

For this thesis, the definition of risk as a risk triplet will be used as described above, and additional definitions will not be expanded upon.

2.2.2 Quantitative risk assessment

Quantitative Risk Assessment (QRA) is used to assess the frequency of an event and the consequences (e.g., fatalities) of that event (Smith, 2017). The two parts of a quantitative risk assessment, quantitative risk analysis and risk evaluation are described in Sections 2.2.3 and 2.2.5.

2.2.3 Quantitative risk analysis

A risk analysis, as presented in Section 2.1.2, can be of quantitative nature. Estimates for probabilities and/or consequences are provided by a quantitative risk analysis (Rausand, 2011). Based on the quantitative risk analysis, the individual and the societal risk can be calculated (Frantzich, 1998). When conducting a quantitative risk analysis, each hazard or hazardous event identified during the hazard identification phase will be followed by a sequence of events. An event tree can be used to structure the sequence of events starting with the initial event based on the hazardous event identified, followed by intermediate events, and ending with scenarios with consequences attached to them. (Rausand, 2011)

2.2.4 Hazard identification

The hazard identification process attempts to answer the first question in the risk triplet presented previously. Several different methods exist which can be used to identify potential fire hazards in a building. Examples of such methods are Hazard and Operability Analysis (HAZOP), checklists, and Preliminary Hazard Analysis (PHA).

HAZOP was originally developed for use in a process plant (ISO, 2019). By using the method, dangerous situations and departures can be identified for the process plant (ISO, 2019). The checklist method for hazard identification is based on analysing whether hazards or hazardous events on a list can happen for the subject system (Rausand, 2011). PHA can be used at an early stage in the design process of a system to identify, e.g., hazards and threats to assets that need protection (ISO, 2019). The identified hazards or threats can then be addressed as the design process continues (ISO, 2019).

2.2.4.1 Fire hazards

The Australian Fire Engineering Guidelines (AFEG) suggest that a systemic review should be undertaken to identify potential fire hazards. To identify potential hazards, the review should be based on the information collected when the principal building characteristics are determined for a subject building. There are several factors to consider when trying to identify and determine hazards according to the guidelines; those are general layout, activities, ignition sources, and fuel sources. Following the identification of hazards, different safety measures installed to prevent the hazards need to be identified. The installed safety measures can be connected to the different sub-systems listen in the AFEG (ABCB, 2021):

- SS-A – Fire initiation, development, and control
- SS-B – Smoke development, spread, and control

- SS-C – Fire spread, impact, and control
- SS-D – Fire detection, warning, and suppression
- SS-E – Occupant evacuation and control
- SS-F – Fire services intervention

2.2.5 Risk evaluation

Conducting risk evaluation includes comparing results acquired from the risk analysis with the established risk-based criteria (ISO, 2018). By comparing the results with the established criteria, a determination can be made whether any specific action should be taken (ISO, 2018).

It is important to specify what to measure and how to evaluate what is being measured when performing a risk assessment. Rausand states that the information gained from risk analysis and the validity of our conclusions are dependent on how we measure risk. (Rausand, 2011)

Since achieving zero risk is impossible, a 'tolerable' or 'acceptable' level must be specified. Risk evaluation for quantitative analysis frequently includes risk criteria. Risk-reducing measures should be part of the assessment if the estimated risk is deemed to be unacceptable or if ALARP zones are used. (Borg, Bjelland, & Njå, 2014)

2.2.6 Risk criteria

According to Smith (2017), an acceptable level of risk means that people or society accept and find the probability of a consequence (e.g., fatality) reasonable given the circumstances and that not much additional effort will be spent in reducing the risk further.

The definition of the term acceptable risk has, according to Rausand (2011), been disagreed about for a few decades. Acceptable risk problems can be described as decision problems which means that they are problems that require a selection among several different options (Fischhoff, Lichtenstein, Slovic, Derby, & Keeney, 1981). Because of this, the acceptable risk being chosen might not be the option with the lowest level of risk (Rausand, 2011).

Tolerable risk is described as the risk level people or society are prepared to live with. However, unlike acceptable risk, a continuous review is performed, and additional measures might be taken to reduce the risk further. When it comes to reducing a tolerable risk further, the cost is often considered. Any further reduction in risk needs to be compared to the cost required to achieve it. (Smith, 2017)

Several principles can be used when managing risk. Two of those principles are As Low As Reasonably Practicable (ALARP) and So Far As Is Reasonably Practicable (SFAIRP). For the first of the two mentioned principles, ALARP, measures will be taken to reduce the risk ratings for scenarios found to have a tolerable risk. Further risk-reducing measures will be assessed until it is demonstrated that the benefits of further risk-reducing measures are outweighed by the costs associated with those measures. ALARP can be presented by an ALARP triangle or a diagram, as shown in Figure 4 and Figure 5. The ALARP triangle and diagram are divided into three different regions based on risk level. These different regions are an unacceptable region, a tolerable or ALARP region, and a broadly acceptable region. An ALARP diagram can be used to compare an upper and lower limit risk criterion to an estimated risk level. (Rausand, 2011)

The second mentioned principle, SFAIRP, is a principle with a similar concept to ALARP. The Society of Fire Safety (SFS) (2019) recommends the SFAIRP approach to be used for façade fire safety designs in their Practice Guide. The guide describes that the SFAIRP approach differs from ALARP in that it is more precaution focussed. This principle will not be further expanded upon in this thesis.

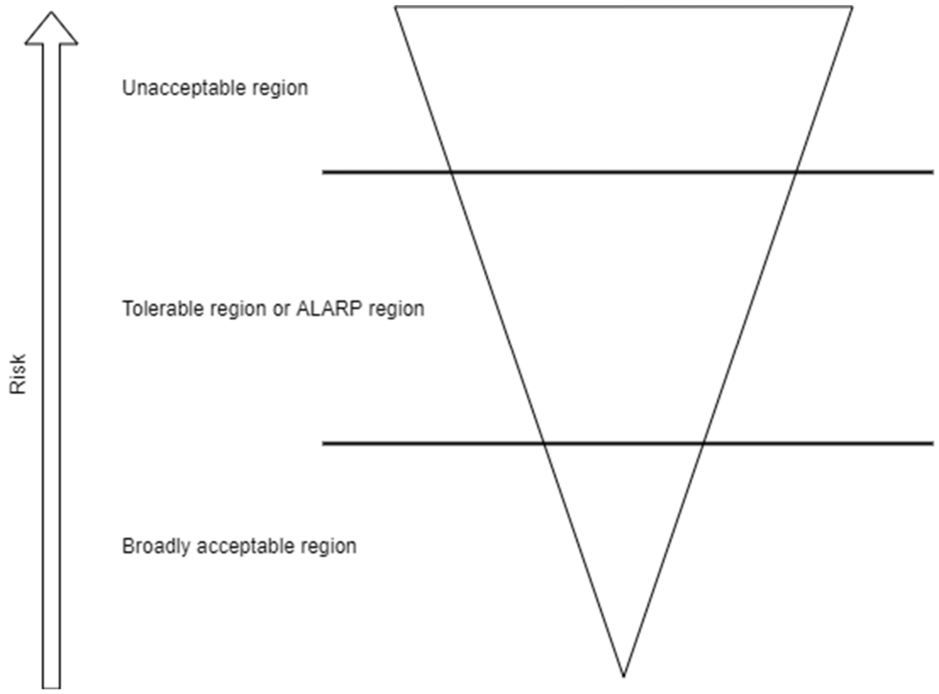


Figure 4: Example ALARP triangle, (adapted from (Department of Planning, 2011))

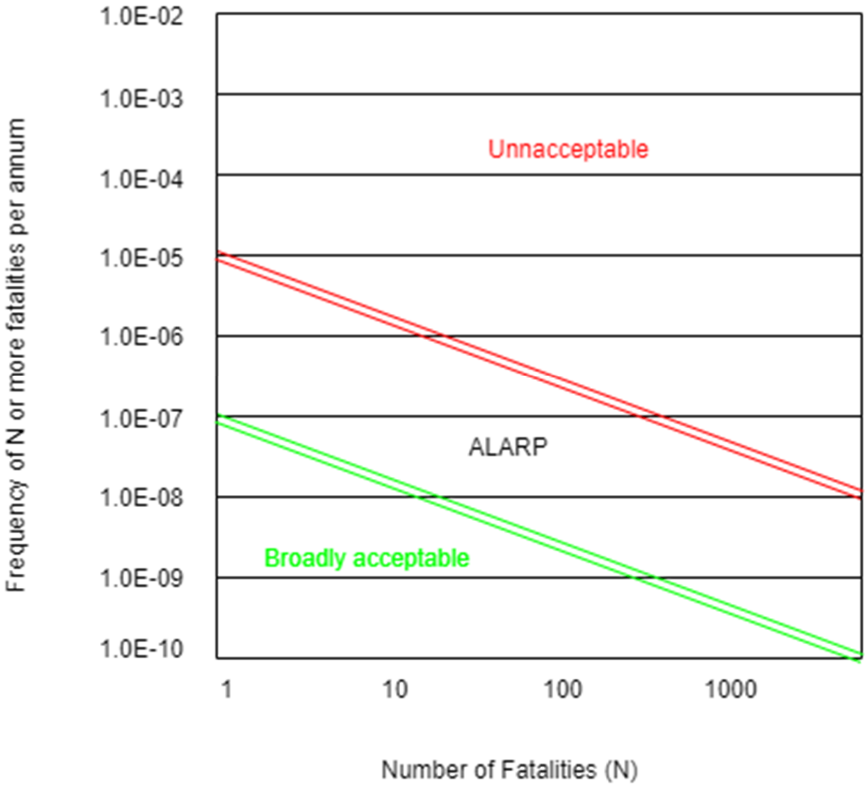


Figure 5: Example ALARP diagram (adapted from (Department of Planning, 2011))

2.2.7 Risk assessment methods

Several approaches can be used when performing a risk assessment. According to Rausand (2011), several factors should be considered when selecting which method to use for a study:

- The objective of the study
- The type and complexity of the object being studied
- The resources available
- Access to input data, etc.

Rausand (2011) presents an evaluation of different analysis methods for various stages of a risk assessment. Some of the risk assessment methods that are considered to be suitable during the design stage are:

- HAZOP
- Fault tree analysis
- Bayesian networks
- Event tree analysis

2.2.8 Quantitative methods

As previously mentioned, a risk assessment consists of joint risk analysis and risk evaluation. There are several different official documents guiding methods for use in quantitative risk assessments. When conducting quantitative risk analysis as a part of a QRA, several probabilistic methods can be used. This section aims to identify relevant quantitative risk assessment methods and probabilistic methods that can be used during a quantitative risk analysis based on previous research and official guidelines and manuals.

2.2.8.1 Methods for Quantitative risk assessment

Cadena Gomez (2021) evaluated different fire risk assessment methodologies. The evaluation is based on the review of documents available to guide professionals in performing quantitative or probabilistic risk assessments. The conducted evaluation aimed to determine how appropriate each guideline or manual is for quantifying fire risk. For the evaluation, the following guidelines and manuals were reviewed:

- NFPA 551 – Guide for the Evaluation of Fire Risk Assessments
- SFPE Engineering Guide to Application of Risk Assessment in Fire Protection Design
- PD 7974-7:2019 – Application of fire safety engineering principles to the design of buildings – Part 7: Probabilistic risk assessment
- ISO 16732-1:2012 Fire safety engineering – Fire risk assessment Part 1: General
- SN-INSTA/TR 951:2019 – Fire Safety Engineering Guide for Probabilistic Analysis for Verifying Fire Safety Design in Buildings

The author identified the following important elements related to the implementation of probabilistic risk assessments:

- The principles of the design process
- The process to identify the hazard and create scenarios based on the identified hazards

- How uncertainty is described and quantified to stakeholders

To evaluate the different guidelines, several criteria were created based on different aspects. The aspects chosen to determine the applicability of each guideline were design philosophy, risk ownership, uncertainty, risk as a function of time, and assumptions. The specific criteria were developed for each aspect. The created criteria are described below. (Cadena Gomez, 2021)

Design philosophy – This aspect looks at the role of risk assessment, hazard identification, and gradual approach to risk assessment. More specifically, the criteria look at the following:

- Does the document contain a distinct statement regarding the role of the methodology in supporting a particular design philosophy?
- Is the role of hazard identification defined and structured in the guidance document?
- Does the document guide towards a gradual transition towards quantitative assessments, including the use of deterministic analysis and qualitative screening of scenarios? (Cadena Gomez, 2021)

Risk ownership – This aspect considers stakeholder identification and risk owner. The criteria look at the following:

- Does the document guide a structure's process to identify different stakeholders, their roles, and responsibilities regarding fire safety?
- Is guidance provided in the guideline to recognize the key responsibilities of the risk owner regarding ensuring that an adequate fire safety performance is achieved? (Cadena Gomez, 2021)

Uncertainty – This aspect considers epistemic uncertainty, data limitations, precision requirement, and non-probabilistic alternatives. The criteria look at the following:

- Does the guideline provide suggestions on managing epistemic uncertainty?
- Does the guideline provide suggestions on how to identify and manage uncertainty in a model?
- Does the guideline provide suggestions on the limitations of scenario discovery?
- Is guidance provided on how to analyze alternatives in case of either low-quality data or the absence of data needed to support reliability and probability calculations?
- Is guidance provided on how the precision of the assessment result can be explicitly quantified? Is guidance provided to verify that estimates do not become incorrect in case of invalid assumptions?
- Does the guideline provide a suggestion of alternatives to non-probabilistic uncertainty analysis in cases where the application of probabilistic risk analysis is not granted? (Cadena Gomez, 2021)

Risk as a function of time – This aspect considers time dependency assumption and data gathering. The criteria look at the following:

- Does the guidance provide in the guideline explicitly accept that risk needs to be managed effectively throughout the building's entire life cycle?

- Does the guideline provide suggestions on how to obtain or determine reliability data for the system being studied? (Cadena Gomez, 2021)

Assumptions – This aspect considers key assumptions, documentation, and peer review. The criteria look at the following:

- Is suggestion on how to manage key assumptions of the methodology and the key assumptions presented in the guidance document?
- Does the guideline suggest how key results and assumptions on the conducted risk assessment should be documented to enable auditing and peer-review?
- Does the guideline provide a suggestion for a peer review process that is structured and examines the key assumptions central to the risk assessment to complement the result of the assessment? (Cadena Gomez, 2021)

For the evaluation, Cadena Gomez (2021) judged each criterion as:

- DC – not being met
- PC – partially met
- MC – met

Due to the evaluation process being qualitative, different experts in the field conducted a peer review of the evaluation. (Cadena Gomez, 2021)

Cadena Gomez (2021) describes the different contents, scopes, complexity, and intended audience for the different documents or guidelines. A short description of the different guidelines and which criteria they meet based on the review is presented below.

NFPA 551

The author states that the NFPA 551 guideline diverges from the other reviewed guidelines in that it does not aim to provide a framework to conduct fire risk assessments. Based on the author's review, the guideline only partially meets the risk ownership criteria and some of the criteria for uncertainty and assumptions. In addition, the guideline manages to meet some of the criteria for design philosophy, uncertainty, risk as a function of time, and assumptions. Some criteria related to design philosophy, uncertainty, and risk as a function of time are unmet.

SFPE Engineering Guide

According to the author, the SFPE Engineering Guide intends to guide the selection and use of different fire risk assessment methodologies. Further, the author states that the definition of risk differs from other literature related to fire risk assessments. In the SFPE Engineering Guide, the risk is defined as a function of unwanted adverse consequences, appropriate scenarios, and their associated frequencies. Based on the guideline review, it manages to meet two of three criteria for design philosophy, one of two for risk ownership, three of six for uncertainty, one of two for risk as a function of time, and two of three for assumptions. It should be noted that the SFPE Engineering Guide only failed to meet two criteria in total.

PD 7974-7:2019

The author states that PD7974-7 provides one of the most detailed guides on conducting a probabilistic risk assessment. However, the guideline failed to meet every risk ownership criterion and only met certain criteria for uncertainty.

ISO 16732-1:2012

The ISO 16732-1 guideline is the only guideline not managing to meet any criteria related to the different aspects evaluated. Some criteria are partially met for design philosophy, uncertainty, and assumption, but every other criterion is not met. (Cadena Gomez, 2021)

SN-INSTA/TR 951:2019

According to the author, the SN-INSTA/TR 951 guideline differs from the other guidelines in that it provides suggestions for acceptance criteria to be used in the risk evaluation process. The author also states that the scope and purpose of the guideline differ from the other documents since it addresses fire safety when a departure from prescriptive provisions is part of the building design. Based on the review, the guideline failed to meet every criterion for design philosophy and risk ownership. The guideline also did not meet or partially meet the criteria related to uncertainty, either met or did not meet the criteria for risk as a function or time, and met or partially met the criteria related to assumptions.

Evaluation summary

Based on the result of the evaluation, it was determined that none of the reviewed guidelines met all 16 evaluated criteria. The SFPE Guide met the largest number of evaluated criteria, with nine met, five partially met, and two unmet. However, the other evaluated guidelines failed to meet between four to eight different criteria. More specifically, the SPFE Guide is ranked as number one for the evaluated aspects of design philosophy, risk ownership, and risk as a function of time. Cadena Gomez considered BS 9497-7:2019 to be the best performing guideline for the uncertainty aspect, and SN-INSTA/TR 951:2019 the best concerning the assumption aspect. (Cadena Gomez, 2021)

2.2.8.2 Methods for Quantitative risk analysis

This section will present different methods which can be used in quantitative risk analysis based on reviewed literature and a selection from guidelines.

2.2.8.2.1 Quantitative risk analysis

Several methods which can be used for the evaluation of probabilities are presented in the different guidelines. Some methods presented include the event tree method, fault tree method, Monte Carlo analysis, bow-tie, Bayesian network model, and the safety index (β) method. More detailed descriptions of these methods are presented further below.

Frantzich (1998) suggests that the optimal choice of assessment method for a quantitative risk analysis can be determined by answering the following questions:

- Is the calculation tool a computer program, or is it an analytical expression?
- To what extent is variable uncertainty explicitly considered?
- Is the analysis concerned with a single scenario or the entire event tree?

By answering these questions, a method can be selected by following the step-by-step diagram in Figure 6.

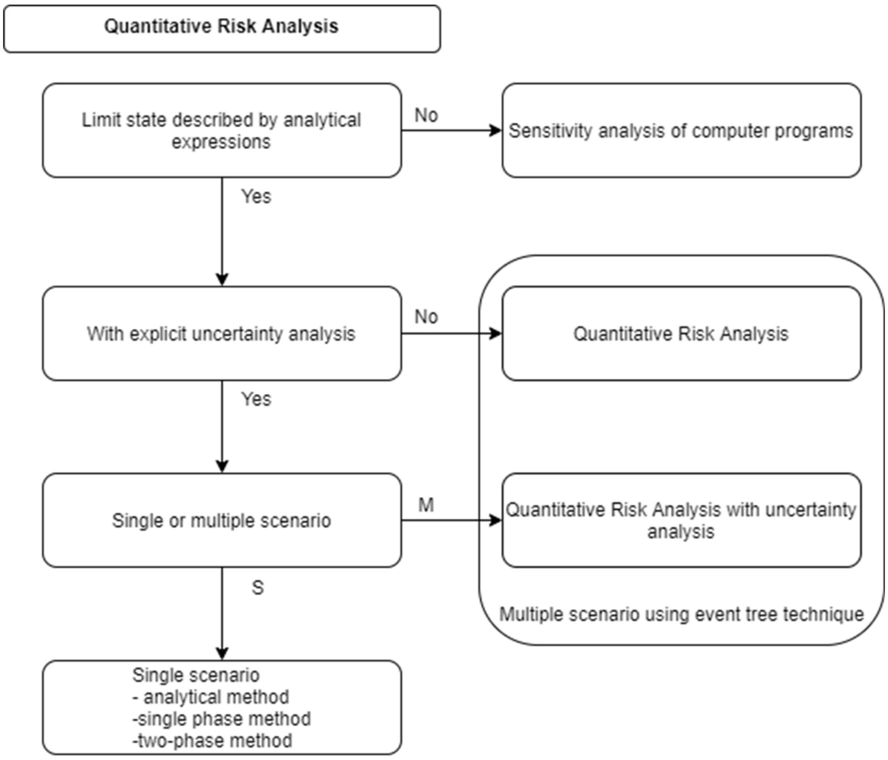


Figure 6: Step-by-step diagram for quantitative risk analysis (adapted from (Frantzich, 1998))

The analysis of a single scenario is not considered adequate for this thesis due to the expected provision of multiple fire protection systems in a building. Therefore, only the quantitative risk analysis and quantitative risk analysis with uncertainty analysis methods in Figure 6 will be described below.

Frantzich (1998) describes quantitative risk analysis as a probabilistic method based on a large number of scenario estimates. Depending on the objective of the quantitative analysis method, the probabilities and consequences can either be examined as a system or individually. The quantitative risk analysis method uses information related to the questions defined in the risk triplet. An event tree structure can be used if the risk triplet is used as the definition of risk.

The quantitative risk analysis method can be used to calculate both the societal risk and the individual risk for a system. The values assigned to the variables in the quantitative risk analysis are often conservative estimates of credible worst cases. It should be noted that uncertainty analysis is not included in the quantitative risk analysis. Adding uncertainty analysis to the quantitative risk analysis turns it into a quantitative risk analysis with uncertainty analysis. (Frantzich, 1998)

2.2.8.2.2 Quantitative risk analysis with uncertainty analysis

Quantitative risk analysis with uncertainty analysis explicitly considers uncertainty, as mentioned above. In this type of quantitative risk analysis, uncertainty is considered in the variables. When uncertainty is explicitly considered, the individual risk can be expressed in terms of a distribution instead of a single value. (Frantzich, 1998)

2.2.8.2.3 Event tree

An event tree starts with an initial event and structures the possible event sequences as intermediate events following the initial event (e.g., alarm failure, sprinkler failure, etc.).

Each division of an event tree leads to additional intermediate events. By using an event tree, a logical graphical description of plausible scenarios can be created. In an event tree, each intermediate event is defined by its consequence and probability. Therefore, the event tree is useful when examining a large number of intermediate events and provides a rational method for quantitative risk analysis. (Frantzich, 1998) An example event tree is shown in Figure 7.

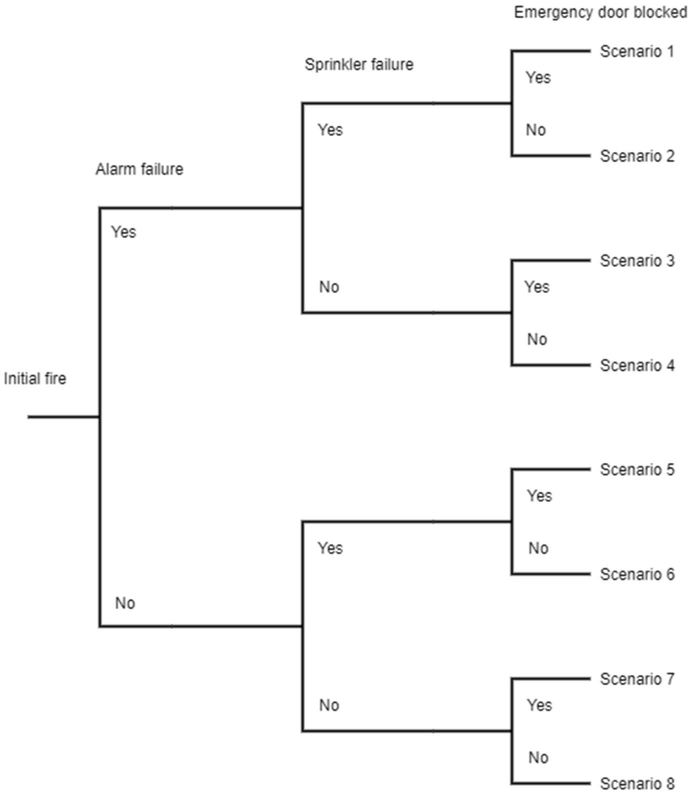


Figure 7: Example Event tree (adapted from (Frantzich, 1998))

2.2.8.2.4 Fault tree

A fault tree starts with the choice of a system failure event that is of interest. This first event in the fault tree is called the top event. Following the choice of the top event, other events which may contribute to the top event to happen are identified. The identified events following the top event should be considered in relation to their effect on the selected top event. The identified events are then connected logically to the top event via ‘AND’ or ‘OR’ gates. (Zio, 2007) An example fault tree is shown in Figure 8.

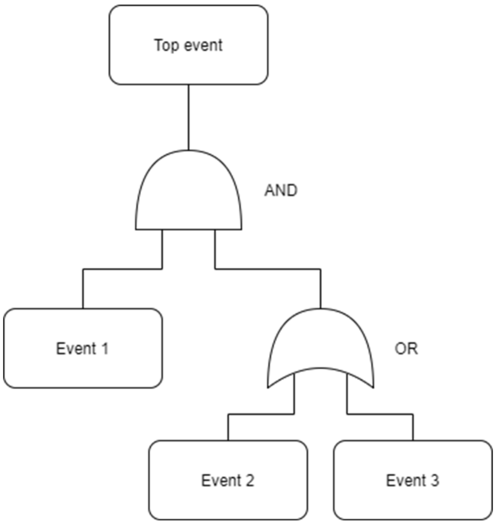


Figure 8: Example fault tree (adapted from (INSTA, 2019))

2.2.8.2.5 Bow-tie

It is possible to combine an event tree diagram and a fault tree diagram into a single diagram called a bow-tie diagram (INSTA, 2019). A bow-tie diagram can be used to show the relationship between causes or hazards leading to a potential event, escalation factors, escalation controls, prevention controls, mitigation and recovery controls, and consequences of the potential event (Vinnem, 2007). The bow-tie diagram can be useful for communicating risks or giving an overview but have limitations concerning quantifying risk (INSTA, 2019). An example bow-tie diagram is shown in Figure 9.

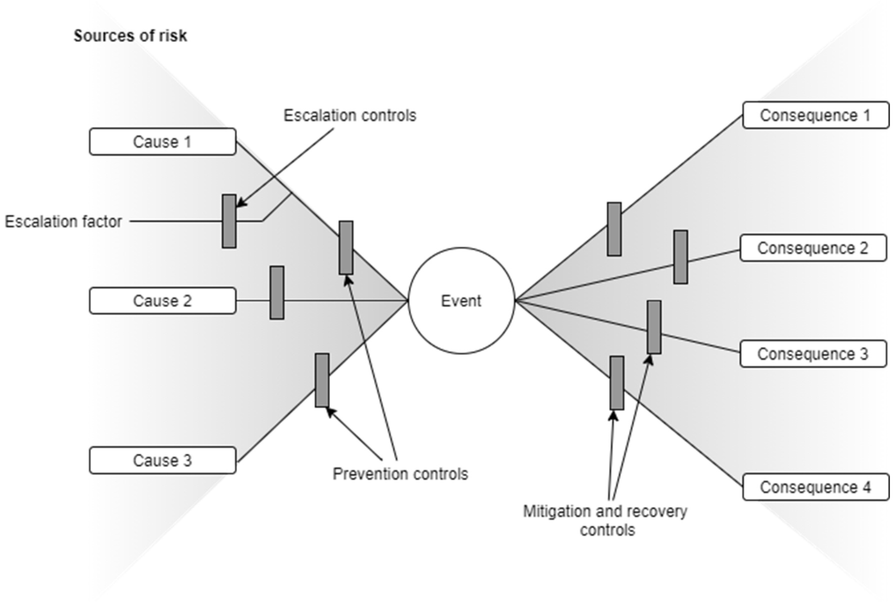


Figure 9: Example bow-tie diagram (adapted from (INSTA, 2019))

2.2.8.2.6 Bayesian network model

A Bayesian network is a model that combines Bayesian probability theory and graph theory. The model is a graphical model that can be used as a tool to manage uncertainty. Bayesian networks consist of a set of probabilities and a graphical structure. (INSTA, 2019)

2.2.8.2.7 Safety index (β) method

The Safety or Reliability (β) index method can be used to calculate the probability of failure of, e.g., a component or subsystem in fire safety engineering. By using this method, the safety margin β can be expressed. (Magnusson, Frantzich, & Harada, 1995)

2.2.8.2.8 Monte Carlo simulations

Monte Carlo simulations can be used in risk analysis to illustrate how uncertainty propagates in analytical mathematical models. When using Monte Carlo simulations, the user must select a probability distribution for each variable based on their knowledge about the specific uncertainty. Repeated sampling of each variable's probability distribution is performed by the Monte Carlo simulation. The mean and sample variance can then be determined. (Rausand, 2011)

2.2.9 Risk measures

Risk to humans can be classified and divided into two different groups: individual risk (IR) and societal risk (SR) (Rausand, 2011). The two different groups are described in the subsections below.

2.2.9.1 Individual risk

Individual risk can be described as the risk that an individual is exposed to during a specific period, usually one year (Rausand, 2011). This can also be expressed as individual risk per annum (Rausand, 2011), as shown in Equation 1:

$$\mathrm{IRPA_a} = \frac{\text{number of fatalities per year due to hazard a}}{\text{number of people at risk}} \qquad \textbf{Equation 1}$$

When calculating the individual risk per annum, historical data can be used (Rausand, 2011).

Frantzich (1998) presents another method to calculate the individual risk as the probability of being affected by an unwanted consequence per year. In this case, individual risk is calculated as shown in Equation 2:

$$\mathrm{IR} = \sum \mathrm{p_i} \text{ for all } \mathbf{i} \text{ in which } \mathrm{c_i} > 0 \qquad \textbf{Equation 2}$$

Where p_i is the probability of scenario i occurring. The individual risk is, in this case, calculated for every scenario where at least one person is affected by an unwanted consequence per year. As long as at least one person is affected by an unwanted consequence, no consideration is taken to the number of people affected with this method.

It should be noted that this method assumes that a fire inside of a building is confined within an enclosure. Therefore, occupants inside of the enclosure of fire origin will be exposed to the highest individual risk. This means that different occupants within the same enclosure will have the same individual risk. (Frantzich, 1998)

2.2.9.2 Societal risk

The societal risk or group risk can be described as the risk experienced by a whole group of people being exposed to a specified hazard, e.g., a fire (Rausand, 2011). Societal risk is often presented by using the Frequence Number (FN) curve (Meacham, van Straalen, & Ashe, 2021). The FN curve shows the cumulative frequency of a consequence (Frantzich, 1998).

Frantzich (1998) presents a method to create an FN curve based on the risk triplet presented earlier. In the method, the triplets are ordered based on increasing consequences.

An example of an FN curve is shown in Figure 10 below.

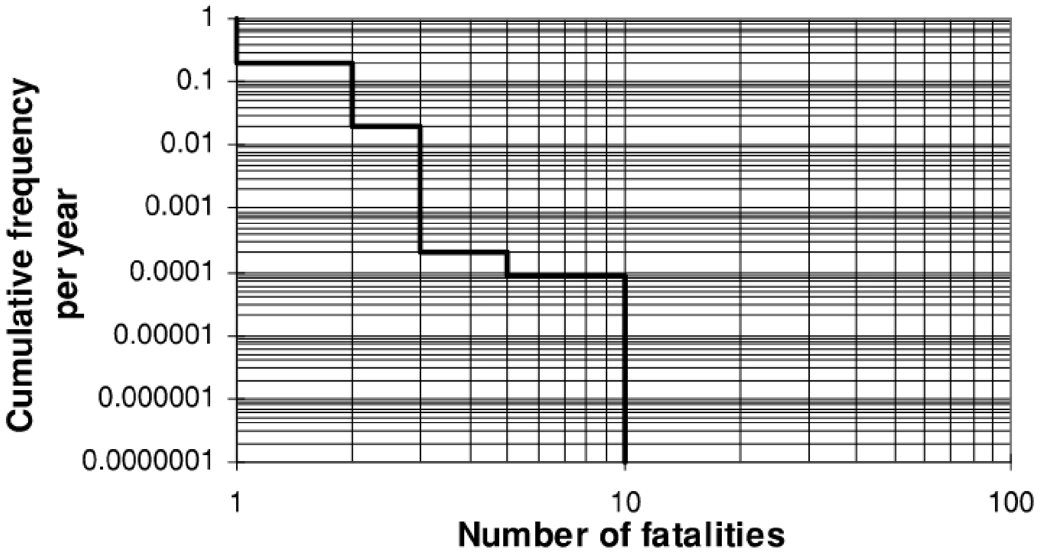


Figure 10: Example FN curve (Frantzich, 1998)

2.2.10 Reliabilities and probabilities

The following subsections present statistics on the reliability of different fire protection systems and probabilities for manual fire detection and manual fire extinguishment. Conservative probabilities will be selected to try to manage uncertainties for use in the case study. By using conservative variables for probabilities, the probabilities for the different scenarios might be overestimated.

2.2.10.1 Fire protection systems

Bukowski et al. (2002) present reliability estimates of different active fire and passive fire protection systems based on a literature review of several different studies. The different studies reviewed was the Warrington Delphi UK Study (Warrington Fire Research, 1996), the Fire Engineering Guidelines Expert Study (Fire Code Reform Centre, 1996), statistics from the Tokyo Fire Department (Tokyo Fire Department, 1997), and the results from a study on fire protection systems in Japan (Watanabe, 1979). The reliability of different systems is shown in Table 1.

Table 1: Reliability of fire protection systems

Fire protection system	Warrington Delphi UK study (%)	Fire Engineering Guidelines Australia Expert Study (%)	Japanese Studies (Incident data)	
	Flaming	Flaming	Tokyo Fire Department	Watanabe
Heat detector	89	90	94	89
Home smoke alarm	79	75	n/a	n/a
System smoke detector	90	80	94	89
Beam smoke detectors	88	80	94	89
Aspirated smoke detector	n/a	95	n/a	n/a
Sprinklers operate	95	95	97	n/a
Sprinklers control but do not extinguish the fire	64	n/a	n/a	n/a
Sprinklers extinguish the fire	48	n/a	96	n/a
Masonry construction	81 29% probability an opening will be fixed open	95 if no opening 90 if opening with auto closer	n/a	n/a
Gypsum partitions	69 29% probability an opening will be fixed open	95 if no opening 90 if opening with auto closer	n/a	n/a

The Fire Safety Verification Handbook Data Sheets (FSVM) present probability data for sprinkler reliability, walls, and service penetrations in commercial buildings, as shown in Table 2 to Table 4 (ABCB, 2020). It should be noted that some of this data overlaps with the data presented in Table 1.

Table 2: Sprinkler reliability data

NCC Building Class	Effectiveness (Typical)	Effectiveness (Low)	Effectiveness (High)
Residential 2	92%	87%	97%

Table 3: Reliability of walls

Type of wall	Warrington Delphi UK Study (%)	Fire Engineering Guidelines 1st edition (%)	BS DD240 (%)
Masonry	81	95	N/A
Gypsum	69	95	N/A
Concrete	N/A	95	95

Table 4: Percentage of unprotected service penetrations in commercial buildings

System	% Unprotected
Small penetrations	20
Large penetrations	50
Collar system	20

Zhang et al. (2014) present reliability data for detection and alarm systems as shown in Table 5 and Table 6.

Table 5: Reliability data for different detectors

System	Reliability
Local alarm	0.75
Smoke detectors	0.9
Heat detectors	0.9

Table 6: Reliability of central and voice alarm in buildings

System	Reliability
Central alarm	0.9
Voice alarm	0.9

Based on the reliability data presented above in Table 5 and Table 6, the probability of alarm failure can be estimated using a fault tree. For the alarm to fail in the corridor scenarios, both smoke detection and the Building Occupant Warning System (BOWS) must fail, the probability of alarm failure can therefore be estimated as follows:

$$\mathrm{P(alarm\ failure)} = 0.9 \cdot 0.9 = 0.81$$

BSI (2019) also presents the probability of fire doors in a residential apartment with self-closers being closed, as shown in Table 7.

Table 7: Probability of doors with self-closers being closed

System	Lower Bound (%)	Upper Bound (%)
Probability of fire doors (sleeping accommodation) with self-closing devices being closed	85	95

2.2.10.2 Manual detection and firefighting

Hasofer et al. (2007) present statistics on human response to fire in apartments. A person's response to a fire and the probability of cue recognition varies depending on whether the person is, e.g., awake or asleep and the location of the person in relation to the fire. For occupants in the fire apartment of origin, the probabilities of cue recognition are presented in Table 8.

Table 8: Probabilities of cue recognition for occupants in fire apartment of origin

Cue	State	Probability of recognition (%)
Light smoke	Awake	100
	Sleeping	10

Ghosh (2009) presents statistics on manual extinguishment based on a survey done in some European countries and the UK in 2000. According to the survey, a portable fire extinguisher extinguished a fire in 80% of the cases. In addition, statistics are presented on the use of fire extinguishers based on statistics from Sweden. According to the author, fire extinguishers are used in 17% of recorded incidents based on a report published in 2006.

Ghosh also presents statistics regarding the use of fire hoses and fire extinguishing equipment in dwellings in Norway based on a study from the year 2000. The study was commissioned to evaluate regulations issued in Norway in 1990. The issued regulations required the provision of smoke detection in residences and that: "*All residences shall be equipped with fire extinguishing equipment that can be used in all rooms*". Based on the study, fire hoses and fire extinguishing equipment prevented fire spread in 15% of all fires per year. (Ghosh, 2009)

Kobes et al. (2010) note that very little information is available in the literature relating to fire extinguishing by building occupants. However, the authors suggest that around three-quarters of fires in Australia and Great Britain are extinguished by occupants or self-extinguish.

2.2.10.3 Fire spreading via a window to another floor

Korhonen & Hietanemi (2005) presents statistics on the probability of a fire spreading via a window to another floor for a building with a non-combustible façade. Based on their study, the suggested probability of a fire spreading to another floor can be estimated to be 0.002. The study is further expanded upon in Section 4.4.8.

3 Methodology

As previously mentioned, the ABCB has proposed to incorporate in the BCA 2022 version a method whereby compliance with a set of fire engineering Performance Requirements is determined using a probabilistic framework. As part of this, quantitative risk criteria are being introduced into the legislation in Part A8 of BCA 2022. The following subsections will present the proposed legislation and highlight how it has been developed, how it is being applied, its application to the case study, and the usage of performance solution as a benchmark. To determine if the criteria in the proposed legislation are met by the case study building and be able to use performance solution as a benchmark as presented in 3.3, information gathered during the literature study presented in Section 2 will be used. Applying the legislation to the case study as presented in 3.2 requires a quantitative risk assessment to be conducted.

3.1 The BCA Approach

The proposed part A8 of BCA2022 contains quantified metrics that are required to be used when interpreting the specified fire safety performance requirement in Part A8.1 which in turn are either not quantified or not quantified to the necessary degree. The metrics specify criteria for fire safety and the spread of fire, which are covered in Part A8.2 and A8.3. The proposed Part A8 consists of three subparts, Part 8.1, 8.2, and 8.3. The following paragraphs describe the content of the proposed legislation. (ABCB, 2019)

3.1.1 Part A.8 of BCA 2022

A8.1 specify the application of Part A8.2 and A8.3:

a) *A8.2 of this Part applies to the interpretation of Performance Requirements CP1, CP2, CP3, CP4, CP5, CP6, CP7, CP8, CP9, DP4, DP5, DP6, DP7, EP1.1, EP1.2, EP1.3, EP1.4, EP1.6, EP2.1, EP2.2, EP3.2, EP4.1, EP4.2, EP4.3, GP4.1, GP4.2, GP4.3, and GP4.4."*

b) *A8.3 of this Part applies to the interpretation of Performance Requirements CP1, CP2, CP3, CP8, CP9, EP1.4.*

c) *This Part does not apply where—*

   i. *a Performance Solution is achieved by a demonstrating that the solution is at least equivalent to the Deemed-to-Satisfy Provisions in accordance with A2.2(1)(b)); or*

   ii. *the Assessment Method used to assess a Performance Solution is shown to comply with the relevant Performance Requirements in accordance with A2.2(2)(d)).*

Part A8.2 states the following:

As a result of a fire occurring within a building, the risk of exposure of occupants to untenable conditions must not exceed the values provided in Table A8.2a and Table A8.2b, with consideration of—

a) *hazards, building characteristics and occupant characteristics including—*

   i. *function or use of the building; and*

   ii. *fire load; and*

   iii. *potential fire intensity; and*

   iv. *height of the building; and*

    - v. *number of storeys; and*
    - vi. *location in alpine areas; and*
    - vii. *proximity to other property; and*
    - viii. *size of any fire compartment / floor area; and*
    - ix. *other elements providing structural support; and*
    - x. *number, mobility and other occupant characteristics; and*
    - xi. *travel distance; and*
    - xii. *exit above and below ground; and*
- b) *prevention / intervention measures hazards as applicable including—*
    - i. *control of linings, materials and assemblies to maintain tenable conditions for evacuation; and*
    - ii. *(ii) occupants intervention using firefighting equipment (fire hose reels and fire*
    - iii. *extinguishers); and*
    - iv. *(iii) automatic fire suppression; and*
    - v. *(iv) fire brigade intervention, including- -*
        - A. *fire brigade access; and*
        - B. *fire hydrants; and*
        - C. *fire control centres; and*
        - D. *automatic notification of Fire Brigade; and*
        - E. *emergency lifts; and*
- c) *means of managing the consequences, including—*
    - i. *maintaining building structural stability; and*
    - ii. *avoiding spread of fire to exits; and*
    - iii. *protection from spread of fire and smoke to allow for orderly evacuation as appropriate or as part of defend in place strategies or provisions of temporary refuges for occupants requiring assistance to evacuate; and*
    - iv. *behavior of concrete external walls in fire; and*
    - v. *provide barrier protection from high hazard service equipment; and*
    - vi. *provide protection to emergency equipment; and*
    - vii. *fire protection of openings and penetrations; and*
    - viii. *provision of exits; and*
    - ix. *construction of exits; and*
    - x. *provision of fire isolated exits; and*

xi. provisions for paths of travel to, through and from exits; and

xii. evacuation lifts; and

xiii. automatic warning for sleeping occupants; and

xiv. safe evacuation routes; options for consideration include one or more of the following if necessary:

  A. smoke detection

  B. smoke management systems

  C. automatic suppression

xv. visibility in an emergency – emergency lighting; and

xvi. identification of exits – exit signage; and

xvii. emergency warning and intercom systems.

Table 9 and Table 10 below show the allowable individual and societal risks of exposure to untenable conditions.

Table 9: Individual risk criteria

Number of people exposed to untenable conditions	Individual risk per annum (lower tolerable limit)	Individual risk per annum (upper tolerable limit)
≥1	5.0×10^{-6}	5.0×10^{-4}

Table 10: Societal risk criteria

Number of people exposed to untenable conditions	Societal risk per annum (lower tolerable limit)	Societal risk per annum (upper tolerable limit)
≥5	8.9 x 10^-7	8.9 x 10^-5
≥10	3.2 x 10^-7	3.2 x 10^-5
≥20	1.1 x 10^-7	1.1 x 10^-5
≥50	2.8 x 10^-8	2.8 x 10^-6
≥100	1.0 x 10^-8	1.0 x 10^-6
≥200	3.5 x 10^-9	3.5 x 10^-7
≥500	8.9 x 10^-10	8.9 x 10^-8
≥1000	3.2 x 10^-10	3.2 x 10^-8

A diagram showing the upper and lower tolerable limits of the societal risk criteria in the proposed Part A8 is shown in Figure 11.

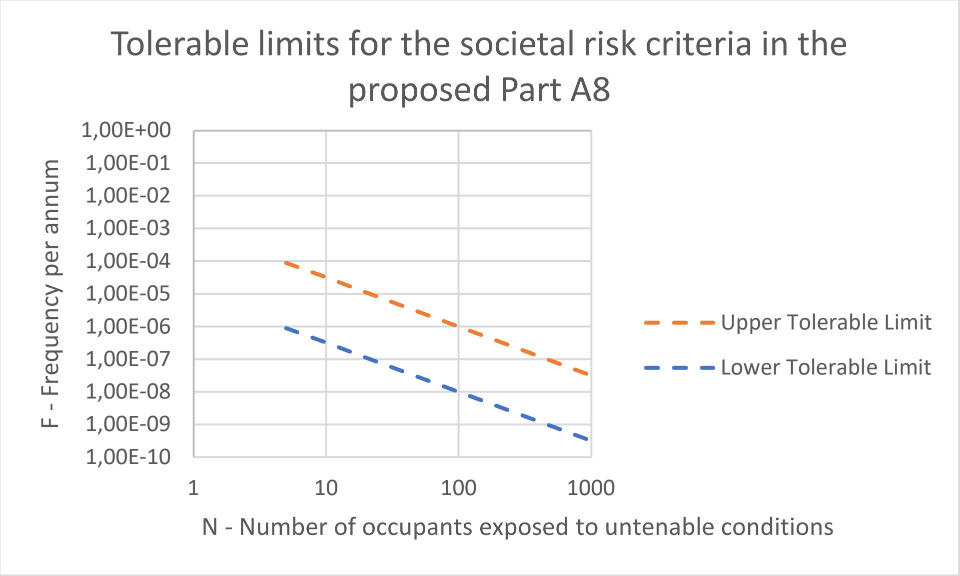


Figure 11: Diagram showing the societal risk criteria in the proposed Part A8

The following explanatory information is also provided for Part A8.2 related to the tolerable limits for individual and societal risk:

- *If the lower tolerable limits (individual and societal) are not exceeded by the proposed Performance Solution the individual and societal risk criteria can be considered to be satisfied.*
- *If the upper tolerable limits (individual or societal) are exceeded by the proposed Performance Solution the individual or societal risk criteria have not been satisfied and modifications to the proposed solution will be required.*
- *If the individual and / or societal risks presented by the proposed Performance Solution lie between the lower and upper allowable risks the proposed Performance Solution can be considered to have been satisfied if the following additional criteria is satisfied if it can be demonstrated that:- the individual and / or societal risk presented by the Performance Solution is less than or equal to that presented by a similar Deemed-to-Satisfy compliant reference building that is considered to represent a tolerable risk.*

Part A8.3 specifies that the following criteria apply concerning the spread of fire:

The probability of a reportable fire in a building causing heat fluxes greater than the values listed in Table 11 must not exceed 0.001 at the stated distance from the boundary on an adjacent allotment or the distances between buildings on the same allotment.

The probability of a building not being able to withstand the heat flux listed in Table 8.3a for 30 minutes must not exceed 0.01. (Refer Table 11)

The probability that the external façade of the building cannot ***withstand*** *the following exposure from reportable fires must not exceed 0.001:*

- *Flames venting through and opening from an enclosure fire within the building; and*
- *Burning items adjacent to the structure such as a vehicle, waste bin, collection of combustible rubbish depending on the use and access to adjacent areas; and*

- *A fire occurring on a balcony*

A building must avoid the spread of fire within the building such that when a reportable fire occurs, the probability of the fire spread does not exceed:

- *to spread outside of an SOU for Class 2 building; and*
- *to spread between storeys*
- *the values in Table 8.3b* (Refer Table 12)

Table 11: Maximum heat flux

Maximum heat flux (kW/m2)	Distance from the boundary (m)	Distance between buildings on the same allotment (m)
80	0	0
40	1	2
20	3	6
10	6	12

Table 12: Fire spread limits

Building classification	Floor area	Volume	Maximum probability of spread beyond specified floor area and volume
5, 9b	3000 m^2	18000 m^3	0.01
6, 7, 8, 9a, 9c	2000 m^2	12000 m^3	0.01
5-9	18000 m^2	21000 m^3	0.001
9a patient class areas and Class 9c	1000 m^2	-	0.01

Several new definitions are also included in the proposed legislation:

Individual risk *- the frequency at which an individual may be expected to sustain a given level of harm from the realisation of a specified hazard.*

Societal risk *- frequency and the number of people suffering from a specified level of harm in a given population from the realisation of specified hazards.*

Reportable fire *- a fire that would be reported to the fire brigade.*

For inclusion in NCC Guide - If a fire is reported to the fire authorities, they are required to respond and therefore the number of reportable fires corresponds to the number of fires attended by the fire authorities. It should be noted that a large proportion of fires occur and are dealt with by occupants and the fire brigades are not called. These small fires that are extinguished by occupants or self-extinguish are not defined as reportable fires.

Withstand *- for the purposes of A8.3(a) means that in response to an imposed fire action the following conditions must not occur:*

i. *Fire spread more than 5m above an opening in the façade through which flames are venting.*

ii. *Fire Spread more than 2m beyond the extent of flames from a burning item adjacent to the structure such as a vehicle, waste bin, collection of combustible rubbish depending on the use and access to adjacent areas*

iii. *Ignition and propagation as the result of the imposed heat flux from a fire in an adjacent building or potential building on an adjoining allotment (embers are likely to be present and therefore piloted ignition should be considered if combustible materials are present).*

iv. *Ignition and fire propagation within cladding materials and building cavities.*

v. *Release of flaming droplets.*

vi. *Release of significant quantities of debris (criteria should be developed during the PBDB process having regard for the proximity of other property and the requirements of the emergency services. The risk to life of occupants evacuating the building from falling debris should be evaluated under A8.2).*

vii. *Structural failure*

The term untenable conditions are not defined in the proposed legislation; however, AFEG defines untenable conditions as: "*Environmental conditions associated with a fire, in which human life is not sustainable*" (ABCB, 2021). The selected tenability criteria that are used in the case study are specified in Section 4.4.4.2.

3.1.2 Development of the proposed legislation

The purpose of this section is to highlight how the legislation has been developed based on documentation received from the ABCB. To develop the proposed legislation, ABCB has undertaken or sponsored several studies on the quantification of fire safety and other NCC Performance Requirements.

A document prepared for the ABCB presents the process used to develop quantified risk-based Performance Requirements for fire safety. The process was based on several stages (ARUP, 2019):

- A number of reports, technical papers, and other documents related to the quantification of fire safety performance or risk tolerance methodologies and criteria were reviewed. The reviewed documents are presented in Appendix C of the referenced document. The review was conducted to gain an understanding of:
    - The basis of the risk tolerance approach applied to the NCC Performance Requirements. Those related to fire safety were of specific interest.
    - The application of risk tolerance criteria as well as the risk tolerance verification method to fire safety.
    - Evaluating risk for consolidated Performance Requirements in comparison to leaving the Performance Requirements in their current form.
    - If some parts of a building are designed to meet DtS provisions, how can the risk tolerance approach be used for only some Performance Requirements.
    - How the risk tolerance approach may affect the design of a building and its fire safety under NCC 2022, considering methods and data available to professionals and their expected skills.

- Variables to be considered in the proposed quantitative performance requirements were derived. Based on a series of issues identified during the research and review process, an issues matrix was developed to identify matters for consideration in relation to potential solutions and the quantification of fire-related Performance Requirements.

For the proposed legislation, the idea was to consolidate all fire safety-related Performance Requirements into two requirements with risk-based criteria, one for occupant safety and one for property protection. This was based on a review of the Performance Requirements and the following:

- Only a few Performance Requirements are currently addressed in many fire safety engineering designs or analyses.
- The Performance Requirements have not been quantified so far. Therefore, there has been an inconsistency in applying Performance Requirements to fire safety assessment and design.
- Consolidating all fire safety-related Performance Requirements into two requirements can encourage a holistic approach to fire safety design and assessment when verifying compliance between the NCC and the proposed design.

In the last stage, a text for inclusion was provided for a public comment draft. The proposed Part A8 presented and referenced in Section 3.1.1 contains quantified risk metrics for fire safety. Guidance on how to conduct a risk assessment is not provided in the proposed legislation.

3.2 Application to case study

As previously mentioned, the general objective of this thesis is to identify and evaluate the consequences of using QRA as a verification tool in comparison to existing verification methods currently in use in Australia. To identify the advantages and disadvantages of using QRA as a verification tool and to provide input on how to choose a method for analysis, a case study has been conducted to test and illustrate the application of the proposed Part A8 of NCC 2022. The case study is presented in Section 4 of this report.

3.3 Performance Solution as a benchmark

The building selected for use in the case study is, as previously mentioned, an already existing building. The fire safety measures specified are to support the proposed Performance Solution for the building. By using Performance Solutions, compliance with the BCA can be demonstrated by other means than prescriptive provisions. According to the Fire Engineering Report (FER) prepared for the building by RED Fire Engineers, the proposed Performance Solutions meets the Performance Requirements for the building.

Based on this, it could be expected that the provision of the same fire safety measures in the case study would lead to the risk-based criteria being met. Therefore, the proposed Performance Solutions will be used as a benchmark to determine whether the same fire safety measures also support meeting the proposed risk-based criteria in Part A8. The comparison is presented in Section 5 of this report.

4 Case study

As one of the specific objectives for this thesis, this case study tests and illustrates the application of Part A8 of BCA2022 as previously mentioned in Section 1.2. The following subsections present method selection, system definition, hazard identification, risk analysis, risk evaluation, and a sensitivity analysis.

The presentation structure of the case study is inspired by the risk management process described in Section 2.1.1. The case study will be presented as follows:

- Selecting a method
- System definition
- Hazard identification
- Risk Analysis
- Risk Evaluation
- Sensitivity Analysis

As previously mentioned in Section 3.3, the proposed Performance Solutions will be used as a benchmark to determine whether the same fire safety measures specified for the case study building also support meeting the proposed risk-based criteria in Part A8. The comparison is presented in Section 5 of this report.

4.1 Selecting a method

For this thesis, an event tree based QRA approach will be used. By using an event tree approach, the scenario is structured to answer the risk triplet's questions. This approach was used by Frantzich (1998) to conduct a risk analysis of a building. The methodology used to create the event tree for this case study is described in 4.4.3.2.

As previously mentioned in Section 2.2.8.2.3, the event tree approach is useful when examining a large number of scenarios and provides a rational method for quantitative risk analysis. Therefore, it is suitable for the fire safety design of a building where multiple fire scenarios are feasible. It is also possible to integrate commonly used fire safety tools into an event tree to help determine the probability of an event. Examples of such fire safety tools are hand calculations and Computational fluid dynamics (CFD).

Further, the event tree approach is one of the approaches deemed suitable during the design stage when conducting a risk assessment based on a previous evaluation by Rausand (2011).

A sensitivity analysis to identify important variables will be conducted instead of explicitly considering uncertainty in the variables. Frantzich (1998) suggests that a sensitivity analysis is done to complement the quantitative risk analysis in order to identify the variables that control the result.

4.1.1 Sensitivity analysis

A sensitivity analysis will be carried out to determine how the individual and societal risk is affected by varying reliabilities of selected fire protection systems and other methods to calculate frequency. In addition, a sensitivity analysis will be carried out to determine the societal risk for the building based on the assumption that a sprinkler-controlled fire leads to no occupants being exposed to untenable conditions. The sensitivity analysis is further described in Section 4.6.

4.1.2 Uncertainty analysis

No uncertainty analysis will be carried out for the case study. Instead, uncertainties will be managed by the use of conservative inputs.

4.2 System definition

The following subsections contain a description of the building analysed and the conditions applicable to the building for this case study.

4.2.1 Building description

The building used for this case study is an already existing 4-storey residential building, with suggested fire safety measures to support the Performance Solutions for the building. Table 13 shows the building characteristics.

Table 13: Building characteristics

Occupancy	Basement	Class 7 - Carpark
	Ground Floor	Class 2 – Residential
	Level 1 to Level 2	Class 2 – Residential
DtS minimum construction type	Type A	
Height	Effective height: Approximately 6.4 m (measured as the vertical distance between the lowest floor included in the determination of rise in storeys and the floor of the topmost storey (ABCB, 2019)) Rise in Storeys: 3 Total number of storeys: 4	

The floor plan for Level 1 is shown in Figure 12 below. Refer to Appendix A for drawings.

Figure 12: Floor plan for Level 1

The following departures from the BCA (ABCB, 2019) DtS provisions and relevant Performance Requirements have been identified for the building based on the FER prepared by RED Fire Engineers for the subject building (Refer Table 14). The FER includes suggested fire safety measures to support the Performance Solutions for the building. The purpose of the usage of Performance Solutions are to achieve compliance with the Performance Requirements by other means than a DtS solution (ABCB, 2019).

As previously mentioned in Section 1.4, the proposed Performance Solutions meets the Performance Requirements for the building according to the Fire Engineering Report (FER) prepared for the existing building by RED Fire Engineers.

Table 14: Departures from DtS provisions for the building

Item	Description of DtS departures	DtS Provisions	Relevant Performance Requirements
1	a) Single exit to serve the basement carpark greater than 50 m2 in floor area.	D1.2	DP4, EP2.2
	b) Distance of travel to an exit in the basement carpark to be up to 33 instead of 20 m.	D1.4(c)(i)	
2	Distance of travel to exceed DtS Provisions as per the following: a) From the residential apartments on the ground floor to an exit to be 24 m instead of a maximum of 20 m. b) From the level 1 residential apartments to an exit to be 19.5 m in lieu of a maximum of 6 m. c) From the level 2 residential apartments to an exit to be 13 m in lieu of a maximum of 6 m.	D1.4(c)(i)	DP4, EP2.2
3	a) Fire-isolated stair to discharge internally into the ground floor corridor which has an unimpeded path of travel to an open space of less than 20 m but the corridor is not open for at least 2/3 of its perimeter.	D1.7(b)(ii)	DP5, EP2.2
	b) Rising and descending stair flights connected within the fire isolated stairway without a smoke separation.	D2.4	
4	Fire services test drains to be located within the fire-isolated exit stair.	C3.9	CP2, CP8, DP5
5	Omission of fire hose reel in the smoke lobby in the basement.	E1.4	EP1.1
6	a) Omission of sprinkler heads to the top of the lift shaft. b) Omission of sprinkler heads within full-height of shower cubicles	E1.5, Spec E1.5	EP1.4
7	a) Lightweight gauge steel construction to loadbearing internal walls (excluding shaft walls) on the topmost storey instead of being concrete/masonry.	C1.1, Spec C1.1 Clause 3.1(d)	CP1, CP2
	b) Installation of fire grade plasterboards to internal walls between apartments not to continue to underside of the roof covering due to the truss hangers fixed directly to frame.	C1.1, Spec C1.1 Clause 3.7(a)	
8	Non-fire-rated access hatch at the top of the fire-isolated stair instead of a fire-rated access hatch.	C1.1, Spec C1.1 Clause 2.7	CP2, CP8, DP5

The Guide to the BCA (ABCB, 2019) presents the intent of each relevant performance requirement, as shown in Table 15.

Table 15: Intent of relevant performance requirements

Relevant Performance Requirement	Intent of performance requirement
CP1	To set requirements for structural stability during a fire.
CP2	To avoid fire spread within and between buildings.
CP8	To provide fire protection of openings and penetrations in building elements to resist the spread of fire.
DP4	To ensure that sufficient exits are provided with the number and dimensions of exits provided being appropriate to the travel distances, characteristics, and the number of occupants, etc.
DP5	To ensure that the fire-isolated exits must be appropriate to the number of storeys connected, fire safety systems installed, the function of the building, etc.
EP1.1	This requirement states that a fire hose reel system must be provided to the degree necessary appropriate to the size of the fire compartment, the function or use of the building, other fire safety systems installed in the building, and the fire hazard.
EP1.4	This requirement sets out the criteria for automatic fire suppression systems, such as a sprinkler system. When implementing, the likely size and intensity of a fire should be taken into consideration.
EP2.2	Requires that occupants are given time to evacuate before the onset of untenable conditions.

4.2.2 Occupant characteristics

As previously mentioned, the building used for this case study is an already existing 4-storey residential building. To ensure a similar number and distribution of occupants for the case study as those specified in the Fire Engineering Report for the already existing building, the number and distribution of occupants are based on the Fire Engineering Report prepared by RED Fire Engineers. Table 16 shows the number and distribution of occupants for the building.

Table 16: Number and distribution of occupants for the building

Characteristic	Residential areas	Carpark
Number and distribution	Apartment distribution: Average of 2 persons per bedroom/study/flexi room in each unit (SOU) Ground: 46 occupants Level 1: 46 occupants Level 2: 30 occupants	Carpark – 30m^2 per occupant (BCA Table D1.13) (ABCB, 2019) Basement: 10 occupants

The following assumptions are made regarding the state of occupants in the building for this case study.

To determine the probability of the occupants being awake and asleep, fire statistics have been used. NFPA (2021) presents statistics on reported apartment fires by the time of day between 2015 and 2019. Based on the presented statistics, 20% of fires happen between 2200-0600. Therefore, 80% of fires can be considered to happen during the daytime. For the case study, it will be assumed that all occupants are awake during the day and asleep during the night.

No consideration is taken to mobility impaired or intoxicated occupants. This is further discussed in Section 6.4.

Occupants are expected to be familiar with the building and therefore able to respond to cues and/or alarm signals and locate escape routes (BSI, 2019).

4.2.3 Occupant evacuation

The development of fire and smoke in an enclosure has the potential of not only causing harm to the occupants in the enclosure but also those located in other areas of the building. If fire or smoke spreads throughout a building, there is a risk to the health of other occupants if they are unable to egress before critical conditions arise. Occupants unable to egress before the onset of untenable conditions are at risk of dying unless the fire department responding to the fire rescues them in time. (Yung, 2008)

To determine whether the occupants inside and outside the compartment of fire origin can egress before the onset of untenable conditions, the Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET) can be calculated. By comparing ASET with RSET, it is possible to determine if occupants are able to egress before the onset of untenable conditions. This is further expanded upon in Section 4.4.4.1.

Egress strategies that can be selected for use include simultaneous, phased, progressive evacuation, and stay put. Simultaneous evacuation means an immediate evacuation of all occupants of the building on the sounding of the alarm system. A phased egress strategy includes the phased movement of people, where the people directly at risk evacuate before others. Progressive evacuation includes progressive movement of people directly at risk and monitoring of the situation before making the decision to evacuate additional occupants. The stay-put strategy includes the evacuation of people directly at risk while other occupants stay inside a fire-resistant compartment. (BSI, 2019)

For this case study, a full evacuation strategy is adopted, and occupants are therefore expected to evacuate the building upon activation of the building occupant warning system. The occupants are assumed to egress through the corridor and via the fire-isolated stair. No consideration is made to potential queuing before entering the stair, this is further discussed in Section 6.4. This strategy is adopted for both the SOU and corridor fire scenarios.

4.2.4 Fire Safety Measures

Based on the identified departures from the DtS provisions, a number of fire safety measures have been proposed to support the proposed Performance Solution for the building used for this case study. Fire safety measures considered for use in this analysis are presented below, together with a comparison between fire safety systems for the residential levels of the case building and that of a DtS building, as well as a comparison between the case building basement and that of a DtS building.

Active fire safety measures are specified in Table 17 below. Active systems which were decided not to be included in the analysis are in *italics*. The reasons for excluding these active systems from the analysis are discussed in Section 6.5. The fire safety measures, required standards, and coverage are based on the Fire Engineering Report prepared by RED Fire Engineers for the subject building.

Table 17: Active Systems

Active Systems		
System	**Standard**	**Coverage**
Automatic sprinklers	AS 2118.1:2017	Throughout the building
Smoke detection	AS 3896:2014	Public corridors and internal spaces
Heat detection	AS 7240.5:2018	Lift shaft
Smoke alarm (interconnected)	AS 1670.1:2018	SOUs
Fire hydrant system	AS 2419:2005	In accordance with BCA Clause E1.3 and AS 2419-2005 or subject to Regulation 129 Application
Fire hose reels	BCA E1.4	Basement in accordance with BCA E1.4, with the exception of the smoke lobby in the basement
Fire extinguishers	AS 2444:2001	Located in accordance with BCA E1.6 and AS 2444, i.e., within 15m of all areas and within 4m from an exit on each level
Building Occupant Warning System (BOWS)	Clause 7 of BCA E2.2a	Throughout the building, including sounders in the SOUs. BOWS operate on activation of the sprinkler system, smoke, or heat detection

Other fire safety measures suggested for the building that has been included in the analysis are:

- Automatic door-closers
- Management in use policy to clear public corridors of combustible furniture

The following occupant behaviour related to fire detection and the use of fire extinguishers has also been included in the analysis:

- Manual (occupant) fire detection
- Manual (occupant) use of fire extinguisher

A comparison between fire safety systems for the residential levels and the design of the basement for the case building and that of a DtS building is shown in Table 18 and Table 19. The comparison is based on the FER produced by RED Fire Engineers.

Table 18: Comparison between fire safety systems for residential levels of the case building and that of a DtS building

Fire Safety System	DtS Solution	Performance Solution
Smoke alarm in SOUs	Yes	Yes
Smoke detectors in public corridors and internal spaces	Yes	Yes
Fire-rated internal walls between SOUs and SOU walls bounding the public corridors	Yes	Yes
Self-closing fire doors protecting doorways of SOU walls boundary public corridors	Yes	Yes
Medium temperature smoke seals on SOU entry doors	No	Yes
Sprinkler system in the building	No	Yes
Sound pressure level of building occupant warning system	100 dbA outside the SOU entry doors	75 dBa at the bedhead in SOUs
Separation of stair connecting all floors	Non-fire-isolated open stair	Fire-isolated stair

In addition, a smoke lobby is provided outside of the fire-isolated stair on ground floor, which would not be the case in a DtS building.

Table 19: Comparison between the design of the basement in the case building and that of a DtS building

Design under DtS Solution	Design under Performance Solution
• Two non-fire-isolated exit stairs separated by a minimum distance of 9 m and a distance of up to 60 m as per BCA Clause E1.5 (ABCB, 2019) • Heat detectors on the basement as no sprinkler system is required by BCA Clause E1.5 as the carpark accommodates not more than 40 vehicles (ABCB, 2019).	• Single fire-isolated exit stair with a travel distance of up to 33 m from the furthest point to the fire isolated stair door • Smoke lobby outside of the fire-isolated stair with self-closing smoke doors. Two entries provided on opposite sides of the lobby. • Automatic sprinkler system • Carpark vehicle entry door connected to the fire detection system and to automatically open upon fire detection

4.3 Hazard identification

To identify potential hazards for the building, statistics have been gathered during the conducted literature review. This section presents statistical data for apartment buildings in Australia and the USA. The presented data is used to determine potential fire locations in apartment buildings. To help determine potential fire locations, the following have been studied: common areas of fire origin inside apartment buildings, common areas of fire origin resulting in occupants being injured or dying, common items first ignited, and common activities performed by people injured or dying as a result of a fire. A summary of important findings is located at the end of this section.

The most common area of fire origin for apartment buildings is inside apartments based on statistics from the New South Wales Fire Brigade, as shown in Figure 13. As shown in the figure, 76.9% of fires originating in apartment buildings did so inside an apartment.

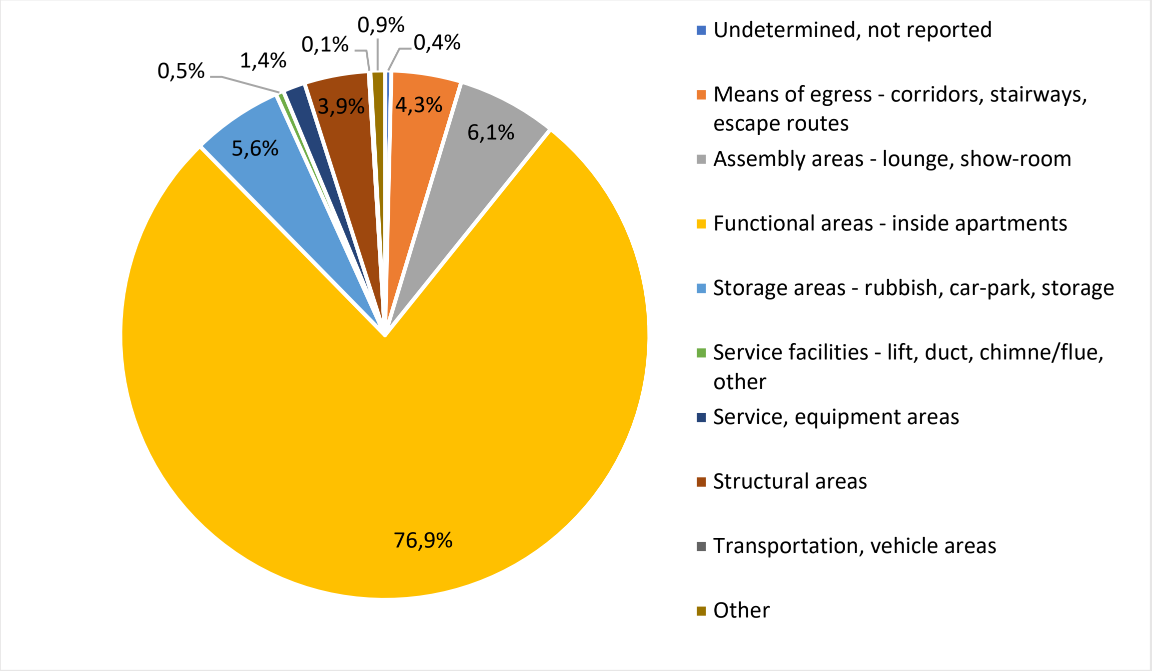


Figure 13: Area of fire origin in apartment buildings (NSWFB, 2007)

For residential fires in Australia, the most common room of fire origin inside an apartment is the kitchen or cooking area with 49,0% of reported fires followed by sleeping room for under five persons with 10,5% of reported fires for the year 2006/2007, as shown in Figure 14.

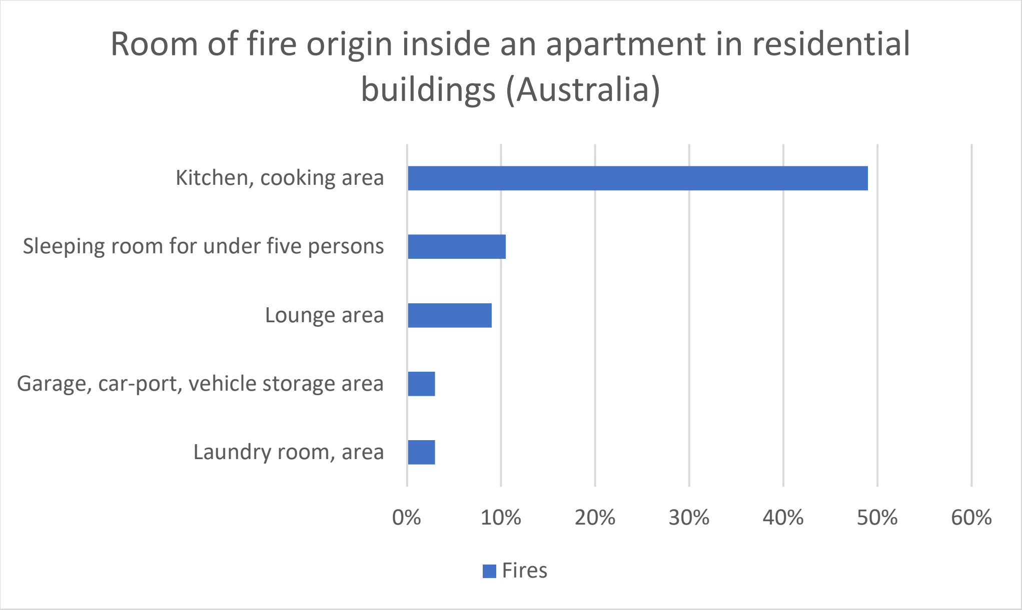


Figure 14: Room of fire origin for residential buildings in Australia (NSWFB, 2007)

The leading areas of origin in apartment fires between 2015 and 2019 in the USA was the kitchen or cooking area with 69%, followed by the bedroom with 4% of fires, as shown in Figure 15.

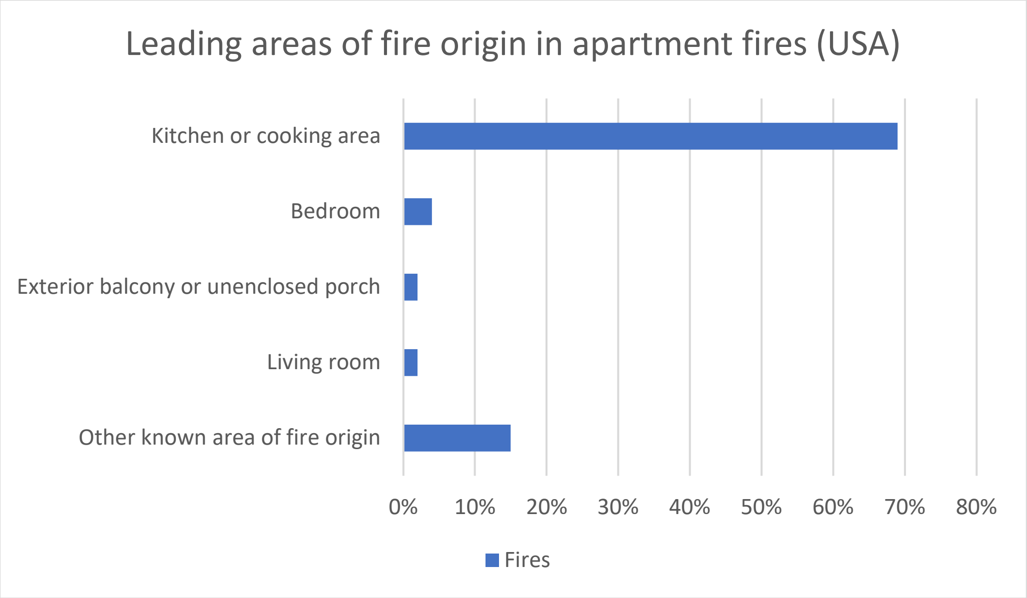


Figure 15: Leading area of fire origin apartment fires in the USA (NFPA, Home Structure Fires, 2021)

Based on the presented statistical data from Australia and the USA in Figure 14 and Figure 15, it can be determined that the most common area of fire origin inside an apartment is the kitchen, followed by the bedroom.

The kitchen or cooking areas also constitute the leading area of fire origin in apartment buildings resulting in injuries in the USA, as shown in Figure 16. However, more common areas for fire ignition causing deaths are the bedroom and the living room, as shown in Figure 17.

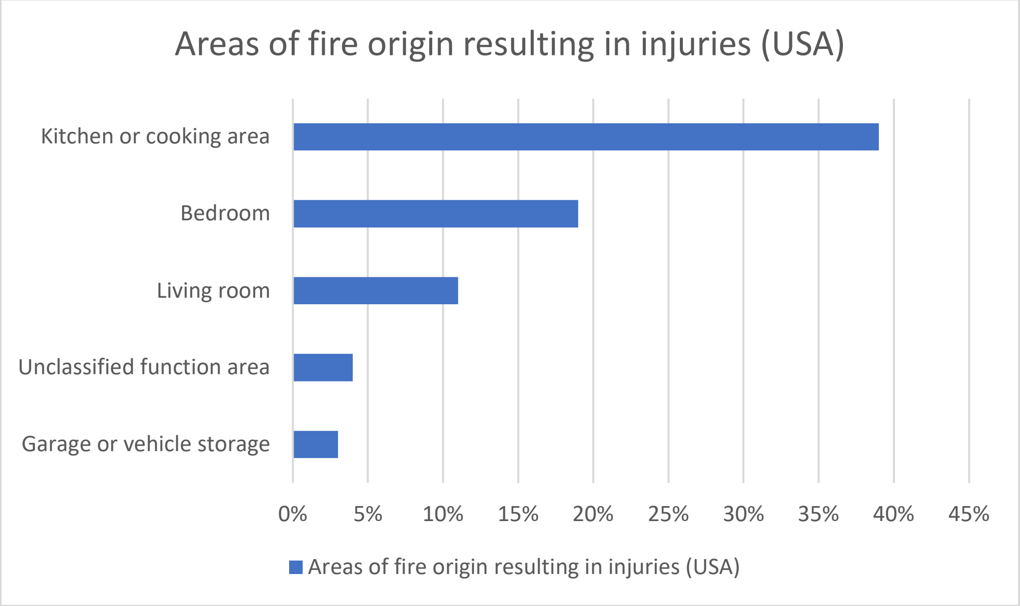


Figure 16: Leading areas of fire origin in home structure fires resulting in injuries in the USA (NFPA, Home Structure Fires, 2021)

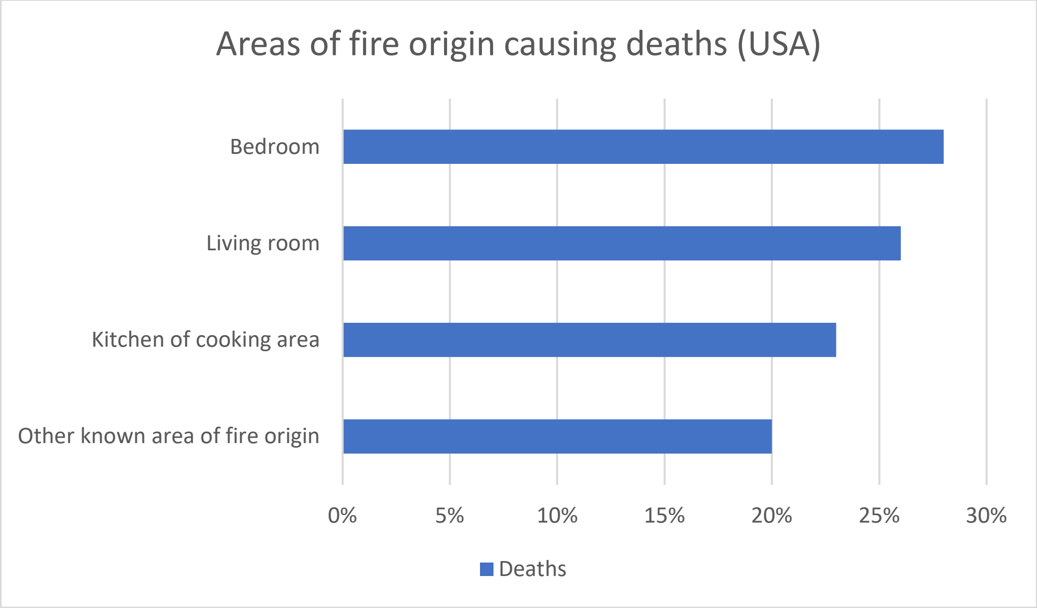


Figure 17: Areas of fire origin causing deaths in apartment buildings in the USA (NFPA, Home Structure Fires, 2021)

Based on the presented statistics in Figure 16 and Figure 17, it can be determined that the leading areas of fire origin resulting in injuries are the kitchen followed by the bedroom, while the leading areas of fire origin resulting in deaths are the bedroom followed by the living room.

Additional statistics from the US were studied to identify common first items to be ignited during a fire. The statistics show that the leading items ignited, resulting in deaths, are upholstered furniture followed by mattress or bedding, as shown in Figure 18.

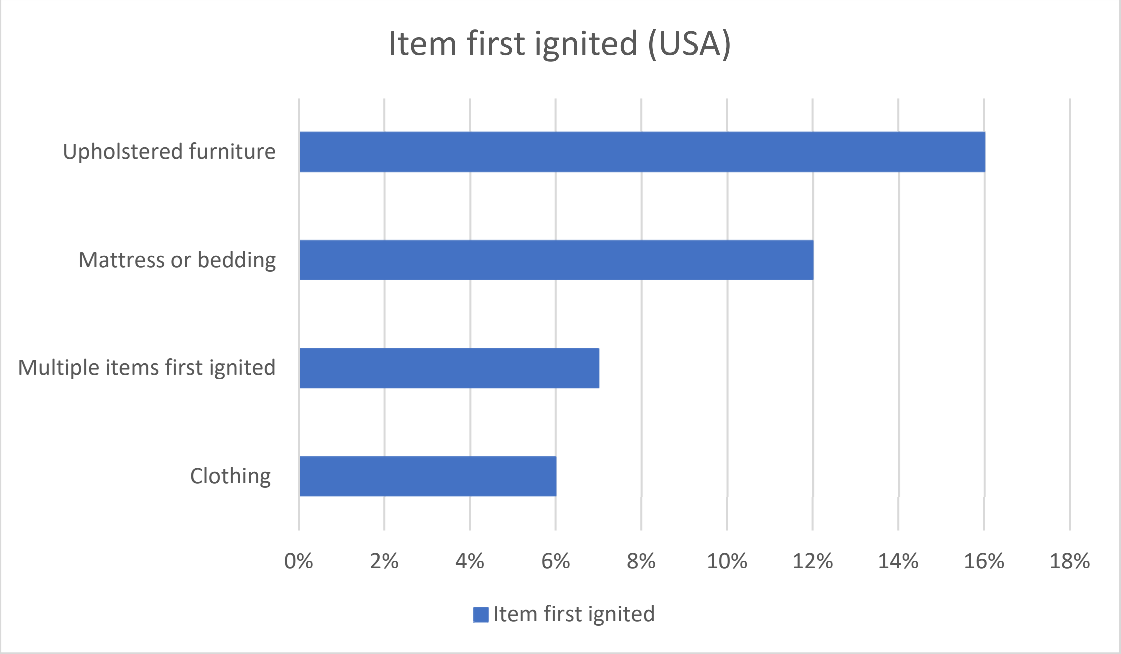


Figure 18: Item first ignited, leading to the highest percentage of deaths in the USA (NFPA, Home Structure Fires, 2021)

To determine the location of people being affected by a fire, statistics from the USA were analysed. NFPA presents data on the percentage of deaths and injuries for home fires in relation to the activity performed. The three most common activities performed are shown in Figure 19.

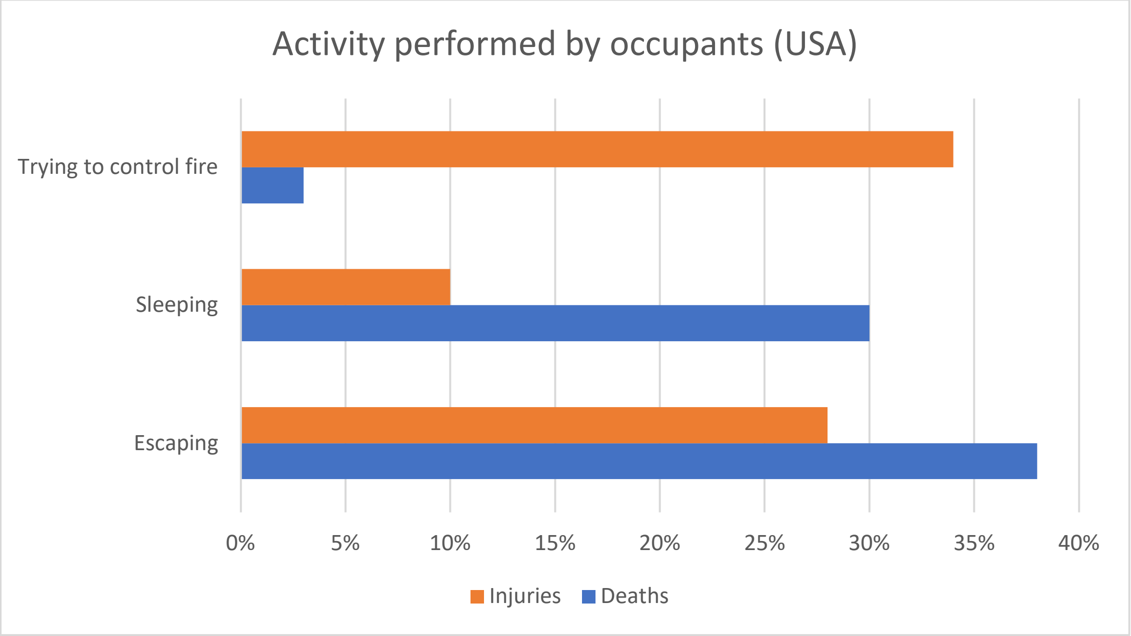


Figure 19: Activity performed by occupants during home fires in the USA (NFPA, Home Structure Fires, 2021)

Based on the statistics presented in Figure 19, it can be determined that the highest percentage of deaths occurs for egressing occupants, followed by sleeping occupants, while the highest percentage of injuries occurs for occupants fighting the fire followed by occupants trying to escape.

4.3.1 Summary of findings

The conducted hazard identification shows the following:

- The highest percentage of fires occur inside apartments, as shown in Figure 13.
- The most common room of fire origin inside an apartment is the kitchen, followed by the bedroom, as shown in Figure 14 and Figure 15.
- The most common room or area of origin resulting in injuries is the kitchen or cooking area, followed by the bedroom, as shown in Figure 16. However, the most common room or area of fire origin resulting in deaths in the bedroom, followed by the living room, as shown in Figure 17.
- The four most common items first ignited during a fire are upholstered furniture, mattress or bedding, multiple items, or clothing, as shown in Figure 18.
- The three most common activities performed by people becoming injured or dying as a result of a fire are trying to control the fire, sleeping, or escaping. The highest percentage of deaths was seen for people escaping from a fire, while the highest percentage of injuries was seen for people trying to control a fire.

The conducted hazard identification is used as input for the scenario definition presented in Section 4.4.3.

4.4 Risk Analysis

4.4.1 Fire statistics

In many countries, it is common to record details of a fire every time the fire brigade is called to a building fire. These statistics can be used to estimate the frequency of fire occurring in different types of buildings. (Hasofer, Beck, & Bennetts, 2007) In addition, fire statistics can be used to determine relevant fire scenarios.

Yung (2008) presents the probabilities of different fire types in non-sprinklered apartment buildings in Australia based on analysis of fire statistics, as shown in Figure 20.

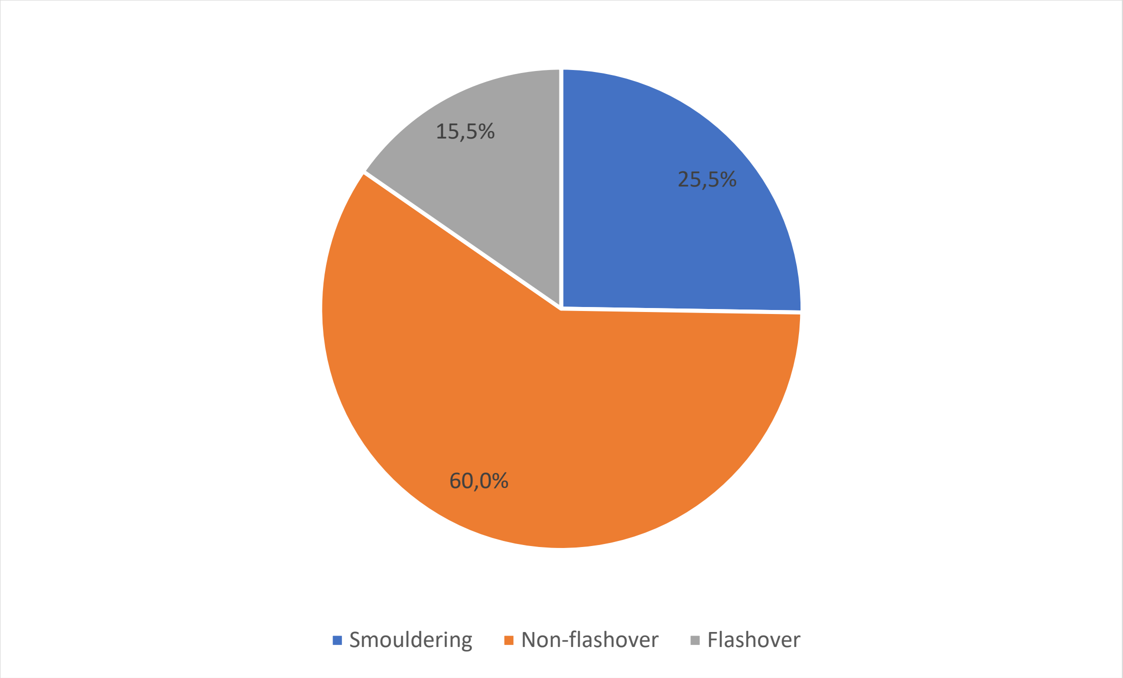


Figure 20: Probabilities of different fire types in apartment buildings in Australia

4.4.2 Fire frequency

To be able to estimate and quantify fire risk, it is important to gather relevant data on fire frequency. Based on fire statistics data, a quantitative estimate of fire frequency can be calculated as a function of floor area per annum. Several methods to calculate frequency are presented below. One is based on the generalization of a model proposed by Barrios (Xin & Huang, 2013), and two of them are based on a data study conducted for the ABCB by ARUP and The University of Queensland (UQ) (ARUP, 2021) on the frequency of fires in Australia. For this thesis, the frequency used for the analysis is based on the total number of square meters multiplied by the frequency per square meter per year from the data study. The other calculated frequencies are used during the sensitivity analysis located in Section 4.6.

To calculate the frequency of fire as a function of the floor area per annum, a generalization of a model proposed by Barrios can be used. The equation proposed by Barrios is shown in Equation 3.

$$\mathrm{f(A) = c_1A^r + c_2A^s} \qquad \textbf{Equation 3}$$

The following parameters shown in Table 20 are used for residential buildings in the generalized Barrios model.

Table 20: Parameters (Xin & Huang, 2013) used for residential buildings in the generalized Barrios model

c_1	c_2	r	s
0.010	5*10^-6	-1.83	-0.05

The model can be used to calculate the ignition frequency in a building with a floor area between 100 m^2 and 20000 m^2. (Hasofer, Beck, & Bennetts, 2007).

Using the Barrios model with an estimated total SOU and corridor area of approximately 2946.5 m^2, the frequency of fire per year and area can be calculated as:

$\mathrm{f} = 0.010 \cdot 2946.5^{-1.83} + 5 \cdot 10^{-6} \cdot 2946.5^{-0.05} = 3.36 \cdot 10^{-6}$ year^{-1}m^{-2}

The fire frequency per year can now be calculated as:

$\mathrm{f} = 3.36 \cdot 10^{-6} \cdot 2946.5 = 0.00989$ year^{-1}

In the data study conducted for the ABCB by ARUP and The University of Queensland (UQ) (ARUP, 2021), fire frequency is calculated as a function of floor area per annum and a function of unit per year. The data study is based on fires reported to the Australian Incident Reporting System (AIRS) database between the financial years 2011/2012 to 2018/2019. The AIRS database contains information about every fire that has been attended by the different fire and rescue services in Australia. The data study maps all fires reported to the AIRS database to the different building classifications specified in the NCC.

Based on the data study, the average fire frequency per square meter per year for apartment buildings in Australia between financial years 2011/12 to 2018/19 is $\mathrm{f} = 9.6 \cdot 10^{-6}$ year^{-1}, with a minimum of $\mathrm{f} = 8.5 \cdot 10^{-6}$ year^{-1} and a maximum of $\mathrm{f} = 1.2 \cdot 10^{-5}$ year^{-1}.

By multiplying this frequency with the corridor and SOU area, the frequency of fire in an SOU or corridor per year can be estimated. For the subject building, the total SOU and corridor area is approximately 2946.5 m^2. The frequency of having a fire in an SOU or corridor per year can therefore be estimated to an average of $\mathrm{f} = 0.02825$ year^{-1}, with a minimum frequency per year of $\mathrm{f} = 0.02504$ year^{-1} and a maximum frequency of $\mathrm{f} = 0.03536$ year^{-1}.

The data study also suggests that the fire frequency can be estimated as the number of fires per unit. The average frequency per unit for apartment buildings between financial years 2011/2012 to 2018/2019 is $\mathrm{f} = 1.04 \cdot 10^{-3}$ year^{-1} with a minimum of $\mathrm{f} = 9.24 \cdot 10^{-4}$ year^{-1} and a maximum of $\mathrm{f} = 1.25 \cdot 10^{-3}$ year^{-1}. Based on a total of 24 units in the building, the average frequency can then be estimated to be $\mathrm{f} = 0.02496$ year^{-1}, with a minimum frequency of $\mathrm{f} = 0.022176$ year^{-1} and a maximum frequency of $\mathrm{f} = 0.03$ year^{-1}. Table 21 shows a summary of the different calculated frequencies based on the different models.

Table 21: Summary of calculated frequencies

Model used to calculate frequency	Calculated frequency	Calculated minimum frequency for Data study	Calculated maximum frequency for Data study
Barrios	0.00989 year^{-1}	-	-
Frequency per square meter (Data study)	0.02825 year^{-1} (average)	0.02504 year^{-1}	0.03536 year^{-1}
Frequency per unit (Data study)	0.02496 year^{-1} (average)	0.022176 year^{-1}	0.03 year^{-1}

As previously mentioned in this section, the frequency used for this thesis will be based on the total number of square meters multiplied by the average frequency per square meter per year from the data study. Therefore, a frequency of 0.02825 fires per year will be used.

4.4.3 Scenario definition

4.4.3.1 Fire scenarios

A fire scenario can be described as a successive number of fire events connected by the success or failure of fire protection measures. Examples of fire protection measures with the potential to affect fire events are automatic sprinkler systems, alarms, or occupant evacuation. An event tree for a fire risk assessment can be created based on five consecutive fire events: the initial fire, fire growth, smoke spread, occupant evacuation, or fire department response. The reason for this is that before a fire can cause harm to the occupants of a building, each of these events must occur. In addition, each event can only happen if the fire safety measures put in place for that event fail. The number of potential fire scenarios can be numerous. (Yung, 2008)

Three types of fires can occur upon the ignition in an enclosure; these are smouldering fires, flaming fires (non-flashover), and flashover fires (Hasofer, Beck, & Bennetts, 2007). For this case study, only flaming and flashover fires will be considered.

The Australian Fire Engineering Guidelines (AFEG) provide guidance on identifying and defining fire scenarios. Events related to a fire scenario can, according to the guidelines, be considered in relation to the different sub-systems listed in the AFEG and mentioned in Section 2.2.4.1. (ABCB, 2021)

Based on the conducted hazard identification showing that the highest number of fires occur inside apartments, a fire starting inside of an SOU is selected to be used for the case study. While the percentage of fires originating in areas used as means of egress such as corridors are quite low, as shown in Figure 13, the consequence of a fire could be severe. As described in the hazard identification summary located in Section 4.3.1, the highest percentage of deaths and a high percentage of injuries occur when occupants are escaping, which is shown in Figure 19. A fire starting in a corridor is therefore also used for the case study. Due to the potential high fire load in the carpark, a fire occurring in the basement carpark was considered to be included in the analysis. The decision was, however, made not to include a fire in the basement due to the relatively low percentage of fires starting carparks compared to apartments in residential buildings. This is further discussed in Section 6.2.

Other fire locations were also considered to be selected for the analysis but were decided to be left out. The reason for this is that the percentage of fires for each other location in residential buildings is relatively low compared to the percentage of apartment fires. In addition, the percentage of fires resulting in injuries and deaths is quite low for fires in other areas of residential buildings fires compared to fires occurring in an apartment.

For the subject building, the assumption will be made that the occupants of the building will be home inside their apartments for 24 hours a day. The consequence of this is that it can be assumed that occupants being located inside their apartments 24 hours a day will be exposed to higher individual risk compared to occupants dividing their time between different enclosures.

Using these two fire locations, it can be expected that one of the fires has a higher probability of occurring but lower consequence (a fire inside of an SOU) and that one fire has a lower probability of occurring but higher consequence (a fire located in the corridor).

The occupants will also be expected to try to escape from the apartments via the corridor in case of fire inside an SOU or the corridor, as previously mentioned in Section 4.2.3. Therefore, the number of occupants exposed to untenable conditions can be expected to be higher compared to the use of a ‘stay put’ policy.

The probability of each fire scenario occurring in the event tree is calculated based on the relative probability of each scenario happening. This is based on the statistics presented in Figure 21 below, which was also presented during the hazard identification conducted in Section 4.3. The relative probability is calculated as shown in Equation 4 and Equation 5.

$$\text{P(SOU fire)} = \frac{\text{P(fire in SOU)}}{\text{P(fire in corridor)+P(fire in SOU)}}$$ **Equation 4**

$$\text{P(corridor fire)} = \text{1-P(SOU fire)}$$ **Equation 5**

The relative probabilities are therefore calculated as:

$$\text{P(SOU fire)} = \frac{0.769}{0.043+0.769} = 0.947$$

$$\text{P(corridor fire)} = 1\text{-}0.947 = 0.053$$

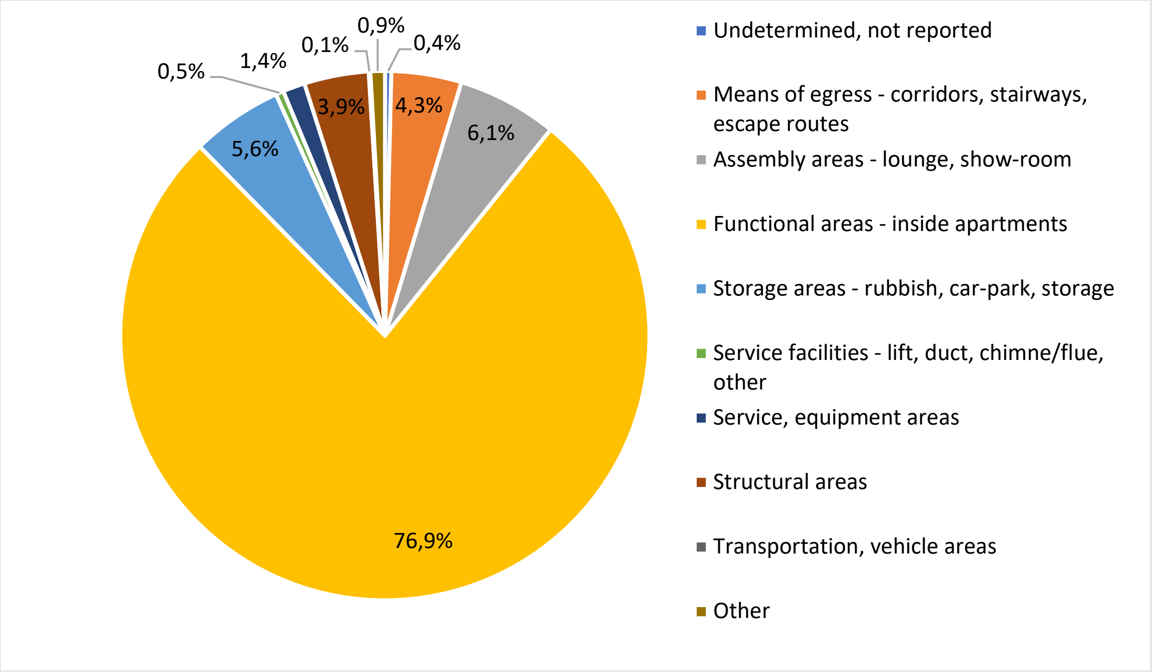


Figure 21: Area of fire origin in apartment buildings (NSWFB, 2007)

4.4.3.2 Event tree methodology

The methodology used to create the event tree for this case study is inspired by the five major fire events and their barriers suggested by Yung (2008) and outlined previously: the initial fire, fire growth, smoke spread, occupant evacuation, and fire department response. In addition, the specified fire safety measures described Section 4.2.4 for the subject building were considered for inclusion as barriers in the event tree.

The event tree for this case study was created based on an initial fire event followed by intermediate events expected to happen in chronological order for each scenario. For the event tree used, the initial event is the initial fire, followed by if the fire occurs during the day or night. The time of the day will influence whether occupants can be expected to be asleep or not and therefore impact the expected order of events. After that, the tree is split into the location of the fire: at an SOU or the public corridor. The fire locations for the event tree were based on the hazard identification conducted previously. While only a small number of fires occur in corridors, it was determined that a fire starting in a corridor could have severe consequences for the occupants on the same level in the building. After that, additional intermediate events were added to the event tree based on the order in which they are expected to happen, resulting in 119 scenarios.

Two block diagrams were created to identify possible ways for a fire to spread for inclusion in the event tree, as shown in Figure 22 and Figure 23 below. The block schemes were based on the two different evaluated fire scenarios.

Three different ways were identified for fire spread outside of an SOU. These were via an open door, or a window, or via penetrations. Simplifications have been made for the event tree in relation to fire spread outside of an SOU as follows:

- If the door to the SOU is closed, it will be assumed that the entire fire enclosure achieves its Fire Resistance Level (FRL), smoke seals perform as designed, and that no fire spread will occur via penetrations. Based on this, fire and/or smoke spread has been evaluated to occur from an SOU to the corridor only if the door is open, and from an SOU to another floor via a window.
- If a fire has spread via a window to another floor, no evaluation will be made regarding the potential of that fire to spread into the corridor or to another SOU on the same floor.
- The probability of a fire spreading upwards to an additional (a third) floor after already spreading to a second floor via a window is very low (0.001-0.003%) (Korhonen & Hietanemi, 2005). This event has therefore not been included in the event tree.

Fire or smoke spread from the corridor to another SOU, or the lift shaft is not included in the event tree analysis. The reason for this is because lift shafts are not to be used during emergency evacuation, and fire/smoke spread from the corridor to another SOU is superseded by the probability of direct fire/smoke spread from one SOU to another.

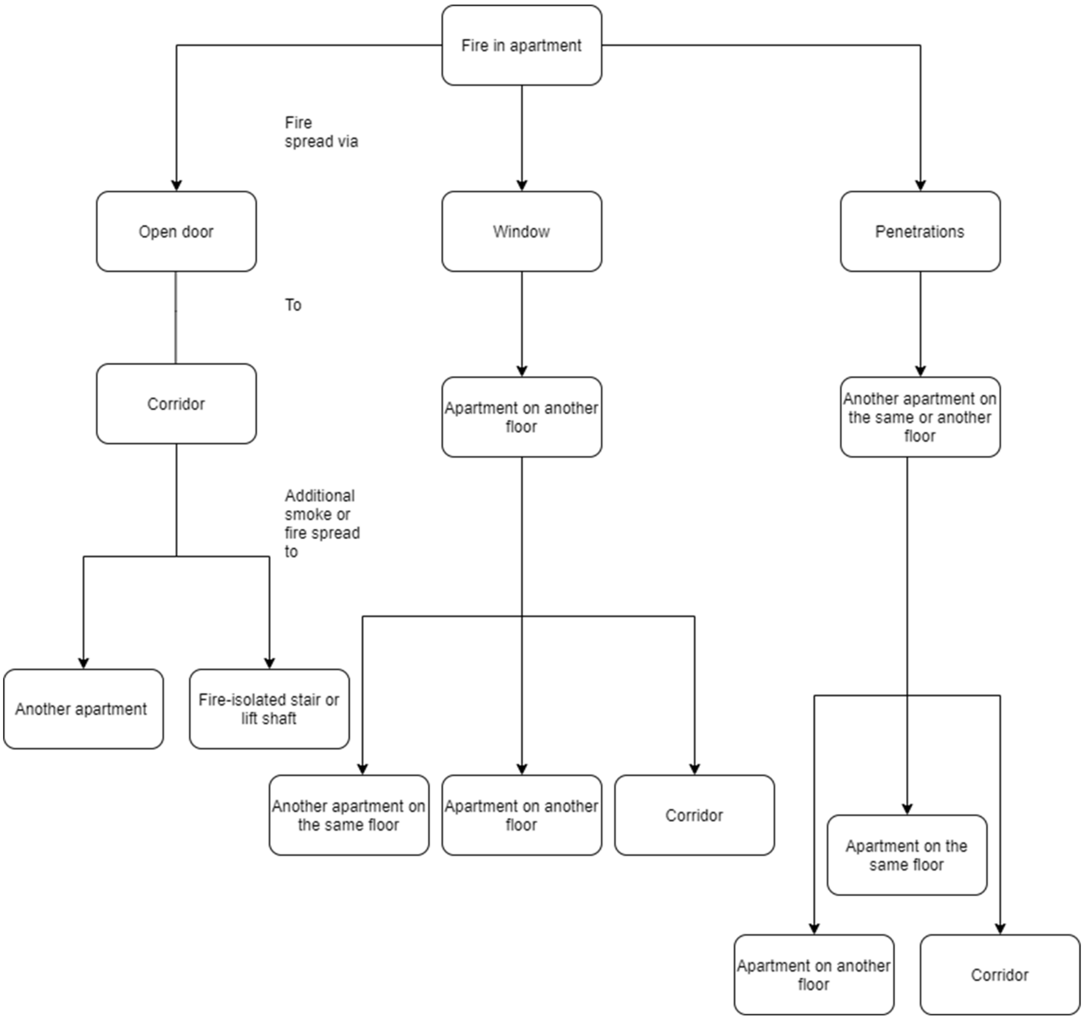


Figure 22: Block diagram for fire starting in an apartment

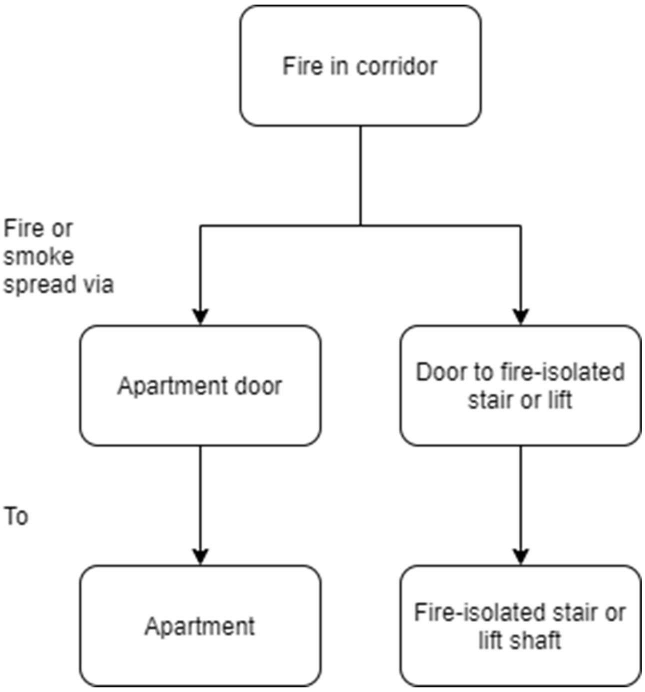


Figure 23: Block diagram for fire starting in a corridor

The potential consequences of an initial fire depend, in addition to passive and active fire safety systems, on the occupants and their behaviour. According to AFEG (ABCB, 2021), scenarios for occupant detection should be developed when using an event tree approach. Occupants can be expected to detect a fire by vision, smell, or other sensory responses. In addition, occupants can also be expected to detect a fire in response to an alarm or warnings issued to them by other occupants (ABCB, 2021).

The ability to detect a fire will also depend on whether the occupants are awake or asleep. Since the statistics used for this case study are based on fires that have been attended by the different fire and rescue services in Australia, small fires extinguished at an early stage by occupants or self-extinguished are not assumed to be included in the data. However, portable fire extinguishers are part of the specified fire safety measures for the subject building. Therefore, the use of portable fire extinguishers will be included in the event tree analysis.

The event tree was modeled in an excel sheet using the excel add-in PrecisionTree version 8.0 (Palisade, 2021). Table 22 shows the events included in the event tree and a description of each event. The event tree created for the analysis of the case building is presented in Appendix B.

Table 22: Description of each event in the event tree

Event	Description
Fire location	Location of fire origin, SOU, or corridor.
Day/Night	Time of day. It is assumed that occupants are awake during the day and asleep during the night.
Sprinkler system control fire	An automatic sprinkler system has been installed and operate to AS 2118.1:2017 standard.
Smoke detection and BOWS in corridor activate	Smoke detection has been installed and operate according to AS 3896:2014 standard. BOWS have been installed and operate according to Clause 7 of BCA E2.2a.
Smoke alarm activates	Smoke alarms have been installed and operate according to AS1670.1:2018 standard.
Apartment door closed	The door is closed during the fire; the door was installed to achieve the prescribed Fire Resistance Level (FRL), and smoke seals perform as per the design.
Smoke spread to stair	Smoke spread to stair hindered if the door is closed during the fire; the door was installed to achieve the prescribed FRL, and smoke seals perform as per the design.
Fire spread via a window to one more floor	Flames venting out of a SOU window to the storey above, igniting combustible material in an SOU on that storey.
Manual detection	Occupants detect fire.
Manual use of an extinguisher	Occupants choose to use a fire extinguisher to fight the fire.
Manual extinguishment	Occupant succeeds in using a fire extinguisher to extinguish the fire.
Combustible furniture present in the corridor	Is there any combustible furniture present in the corridor? Yes or no.

Probabilities were assigned to the different events based on the literature study conducted in Section 2, time of day, and engineering judgements as presented in the paragraph below. The assigned probabilities are shown in Table 23.

One of the management procedures in use for the building is to keep the corridors free of combustible furniture as mentioned in Section 4.2.4. This was included in the event tree for the corridor scenario. Due to the difficulty of determining the probability of the corridors being free from combustible material, a conservative probability of 50% was used. For a DtS building, the stair separating all floors are not required to be fire-isolated as mentioned in 4.2.4. Due to the stair for a DtS building being open, it is expected that fire or smoke will spread to the stair if the door to an SOU is open for a fire starting inside in an SOU or a fire starting in a corridor. The probability of this happening has therefore been assumed to be 100% for a DtS building.

Table 23: Assigned probabilities for event tree analysis

Event	Assigned probability of success	Reference
Fire in SOU	0.947	Bukowski et al. (2002) and Section 4.2.4
Fire in corridor	0.053	Bukowski et al. (2002) and Section 4.2.4
Day	0.2	(NFPA, Home Structure Fires, 2021)
Night	0.8	(NFPA, Home Structure Fires, 2021)
Sprinkler system control fire	0.92	(ABCB, 2020)
Smoke detection and BOWS in corridor activate	0.81	Section 2.2.10
Smoke alarm activates	0.75	Zhang et al. (2014)
Apartment door closed	0.9	Bukowski et al. (2002)
Fire or smoke spread to the stair (on the floor of fire origin)	0.1 (based upon the probability of automatic door-closers failing)	Bukowski et al. (2002)
Fire spread via window to one more floor	0.002	(Korhonen & Hietanemi, 2005)
Manual detection	1 (Awake)	Hasofer et al. (2007)
	0.1 (Sleeping)	Hasofer et al. (2007)
Manual use of an extinguisher	0.15	Ghosh (2009)
Manual extinguishment	0.8	Ghosh (2009)
Combustible furniture present in the corridor	0.5	Based on engineering judgement

4.4.3.3 Design fires

Building regulations around the world often require that objectives related to the life safety of the occupants and the structural stability of the building are met. To be able to carry out a fire engineering evaluation, design fires need to be specified for the subject building (ABCB, 2021).

When creating a design fire, several considerations need to be made. A simple way of constructing a design fire curve can be done by dividing the fire curve into three phases: the growth phase, the steady phase, and the decay phase. (Karlsson & Quintiere, 2000)

During the initial growth phase of a fire, the fire is almost always accelerating. In the growth phase, the fire can be described mathematically by the t-squared fire:

$$\dot{Q} = \propto \cdot t^2$$

Karlsson & Quintiere (2000) presents values for different fire growth rates according to NFPA 204M and recommended common fire growth rates for different types of occupancies, as shown in Table 24 and Table 25.

Table 24: Values of α for different Growth Rates

Growth rate	α (kW/s^2)	Time to reach 1055 kW (s)
Ultra-fast	0.19	75
Fast	0.047	150
Medium	0.012	300
Slow	0.003	600

Table 25: Typical Growth Rates recommended for various types of occupancies

Type of occupancy	Growth Rate
Dwellings, etc.	Medium
Hotels, nursing homes, etc	Fast
Shopping centers, entertainment centers	Ultra-fast
Schools, offices	Fast
Hazardous industries	Not specified

If the fire is not extinguished during the growth phase, the fire will either become fuel controlled or ventilation controlled. The growth of a fuel-controlled fire is dependent on the geometry and characteristic of the fuel. If there is not enough oxygen available, a fire might become ventilation controlled. (Karlsson & Quintiere, 2000)

During the decay phase of a fire, the energy release rate declines. Usually, the fire brigade is expected to start firefighting and rescue operations within the first 10 to 30 minutes of a fire. Due to this, the fire is often not assumed to transition from the steady phase into the decay phase. (Karlsson & Quintiere, 2000)

Different materials in an apartment can be represented by different growth rate values. The simple design fire described above is not detailed enough to account for the growth rate of each individual material located inside the fire enclosure. A more detailed design fire curve can be created when more detailed information is known regarding the materials and furniture used in a fire enclosure. (Karlsson & Quintiere, 2000)

Specification E2.2b of the BCA (ABCB, 2019) presents a maximum heat release rate (HRR) for un-sprinklered buildings. For a class 2 residential building, a maximum heat release rate of 5 MW is specified. Staffansson (2010) also present a peak HRR for dwellings of 5 MW. Based on these sources, a fire with a maximum HRR of 5 MW will be used for the SOU in the case study.

A fire in the corridor could be caused by the ignition of combustible furniture or another item placed inside the corridor. Management policies are in place to remove combustible furniture as mentioned in Section 4.2.4. For the fire located in a corridor, it is assumed that a fire starts in a rubbish bag briefly left in the corridor. The maximum heat release rate (HRR) for a fire in the corridor fire will therefore be based on a fire in a rubbish bag. The heat release rate for a fire in the rubbish bag will be assumed to be 350kW (Karlsson & Quintiere, 2000).

For this case study, two different design fires will be created. The first design fire with a maximum HRR of 5 MW will be used in the SOU fire scenario, and the second design fire with a maximum HRR of 350 kW will be used in the corridor fire scenario. Based on recommended growth rate for dwellings as presented in Table 25, a medium fire growth will be used. Table 26 shows a summary of the parameters of the created design fires.

Table 26: Parameters of the created design fires

Fire location	Maximum HRR	Fire growth rate
SOU	5 MW	0.012 kW/s^2 (medium)
Corridor	350 kW	

4.4.3.4 Summary of inputs and parameters

A summary of inputs and parameters for each fire scenario is shown in Table 27 and Table 28 below. The inputs and parameters are based on Sections 4.2.4.

Table 27: Fire scenarios

Fire Scenario	Maximum HRR	Fire growth rate	Fire duration	Refer to Section
SOU	5 MW fire	0.012 kW/s^2 (medium t-squared fire)	3600 s	4.4.3.3
Corridor	350 kW (fire corresponding to one rubbish bag)			

Table 28: Probability of event success

Event	Assigned probability of success	Reference	Refer to Section
Fire in SOU	0.947	Bukowski et al. (2002) and Section 4.2.4	4.4.3.1
Fire in corridor	0.053	Bukowski et al. (2002) and Section 4.2.4	4.4.3.1
Day	0.2	(NFPA, Home Structure Fires, 2021)	4.2.3
Night	0.8	(NFPA, Home Structure Fires, 2021)	4.2.3
Sprinkler system control fire	0.92	(ABCB, 2020)	2.2.10.1

Smoke detection and BOWS in corridor activate	0.81	Zhang et al. (2014) and Section 2.2.10	2.2.10
Smoke alarm activates	0.75	Zhang et al. (2014)	2.2.10.1
Apartment door closed	0.9	Bukowski et al. (2002)	2.2.10.1
Fire or smoke spread to the stair (on the floor of fire origin)	0.1 (based upon the probability of automatic door-closers failing)	Bukowski et al. (2002)	2.2.10.1
Fire spread via window to one more floor	0.002	(Korhonen & Hietanemi, 2005)	2.2.10.3
Manual detection	1	Hasofer et al. (2007)	2.2.10.2
	0.1	Hasofer et al. (2007)	2.2.10.2
Manual use of an extinguisher	0.15	Ghosh (2009)	2.2.10.2
Manual extinguishment	0.8	Ghosh (2009)	2.2.10.2
Combustible furniture present in the corridor	0.5	Based on engineering judgement	4.4.3.2

4.4.4 Consequence analysis

To determine the consequences, several scenarios have been modeled based on many of the scenarios in the event tree sharing the same initial and intermediate events. It was therefore possible to model a select number of scenarios to help determine the ASET for the occupants and consequence for each scenario or endpoint in the event tree. For the consequence analysis, it was decided to model a fire occurring in each of the different Sole Occupancy Units (SOUs) based on the door to the SOU being open and the sprinkler system either controlling the fire or failing. For the corridor fire, modeling was done to determine the consequences during a sprinkler-controlled fire, and a fire where the sprinkler system fail. This is further described in Appendix C together with a conducted ASET-RSET analysis.

4.4.4.1 Calculation methods and computer programs

Different models are available when performing fire simulations for an enclosure. Examples of models that can be used are algebraic models in the form of hand-calculations, zone models, and Computational Fluid Dynamics (CFD) models. When selecting which model or models to use, a determination needs to be made regarding whether a specific scenario can be analyzed by the selected model. (NRC, 2012)

Since the geometries involved in the selected scenarios for the subject building are of a simple character (SOUs and adjoining corridor), a zone model can be used to calculate fire environment variables. A zone model can be described as a model which uses zones of an enclosure to calculate the fire environment variables.

In a zone model, an enclosure can be divided into a hot upper layer and a cool lower layer. Each zone is considered to be uniform since all fire environment variables, such as smoke concentration, temperature, etc., are considered to be well-mixed. While the usage of a zone model requires more computational time compared to hand calculations, the overall time required can be considered to be low. By using a zone model, the temperature, visibility, and heat flux can be calculated. Examples of zone models are Consolidated Fire Growth and Smoke Transport Model (CFAST) and MAGIC. (NRC, 2012)

The Available Safe Egress Time (ASET) and the Required Safe Egress Time (RSET) have been calculated to determine whether the occupants inside and outside the apartment of fire can egress before the onset of untenable conditions. By comparing ASET with RSET, it is possible to determine if occupants are able to egress before the onset of untenable conditions. The occupants can be expected to be able to egress in time if the available safe egress time exceeds the required safe egress time, as shown in Equation 6.

$$\mathrm{RSET} < \mathrm{ASET} \qquad \textbf{Equation 6}$$

The ASET values are based on the time until the first tenability criteria are met. For this case study, CFAST version 7.3.0 is used to help determine smoke spread and time to untenable conditions for the specified fire scenarios. Three different apartments were modeled on floor Level 1 of the building, which is the floor with the longest extended travel distance. The apartments modeled represent the apartment with the smallest area, largest area, and a mid-sized apartment. In addition, the apartments modeled are located near, at medium distance, and far away from the fire-isolated stair. Figure 24 shows the modeled corridor marked in yellow and apartments marked in red on floor Level 1.

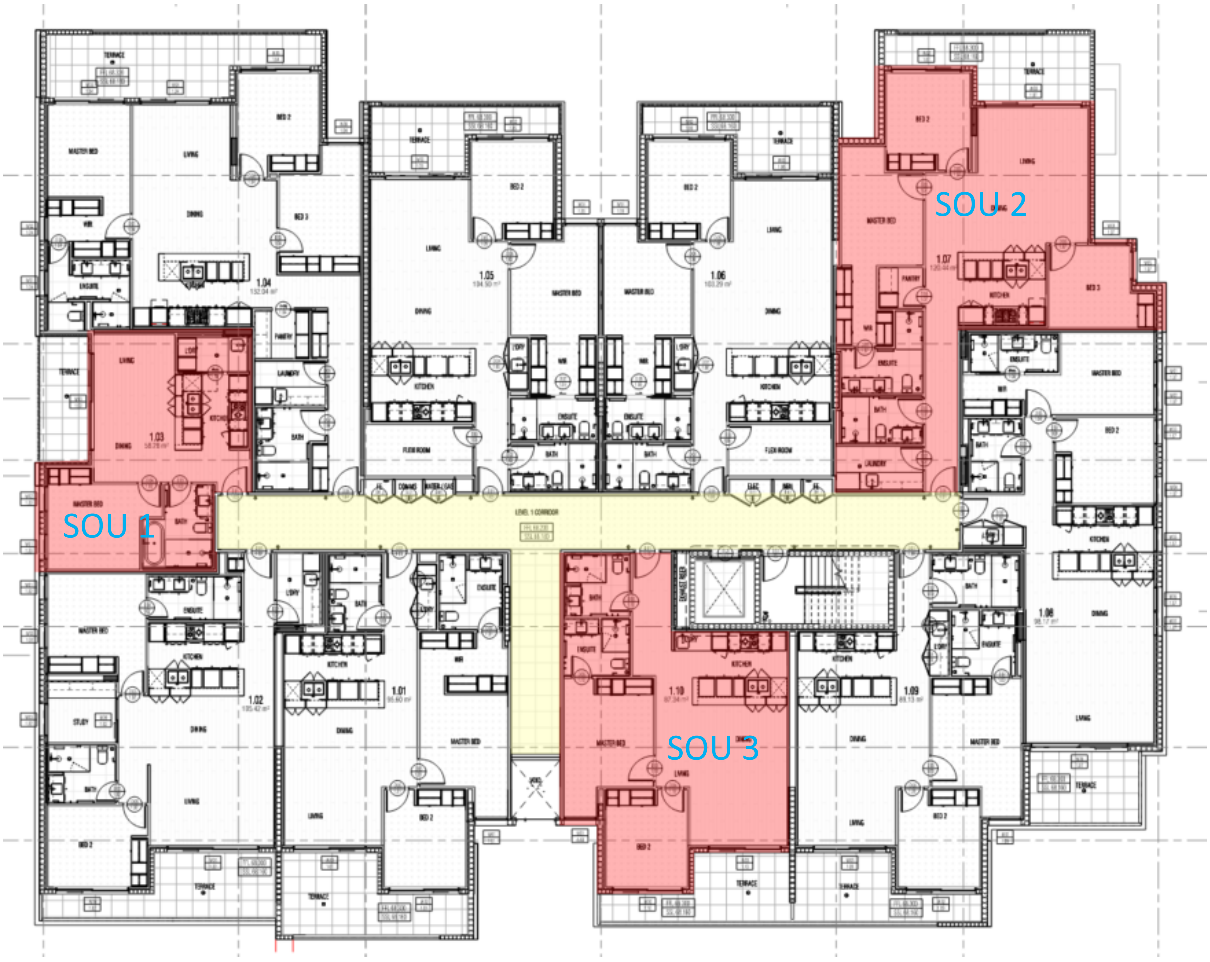


Figure 24: Modelled corridor and apartments on floor Level 1.

The apartments will be referred to as SOU 1, SOU 2, and SOU 3, in order of distance to the fire-isolated stair. The apartment furthest away from the stair will be called SOU 1, and the apartment close to the stair will be called SOU 3.

The geometry of the SOUs has been simplified in that they have been modeled with the same volume as in the drawings of the subject building. However, the internal layout of the SOUs has not been modeled. Modeling of the smoke spread is further detailed in Appendix C. Figure 25 shows a snapshot of the model.

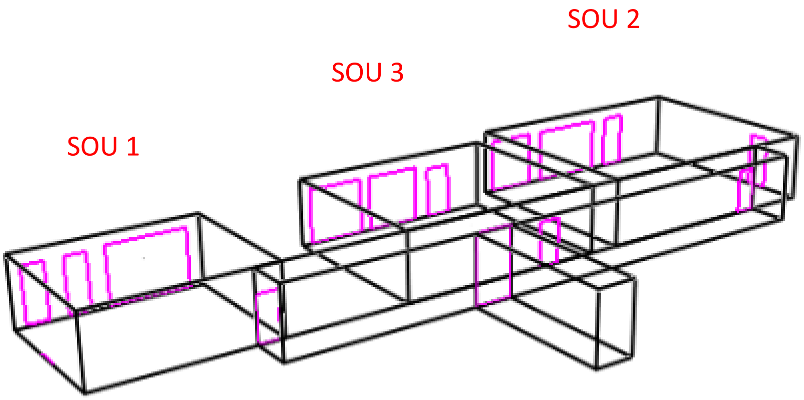


Figure 25: Example of CFAST model of floor Level 1 corridor and selected SOUs

To determine the concentration of toxic gases at a specific time during a fire, the fractional effective dose (FED) method (Purser, 2000) can be used. By using the FED method, the incapacitating or lethal dose received by occupants can be estimated. In addition, the FED method can also be used to determine a combined estimate of the exposure to radiant and convective heat.

A simplified approach to determining tenability conditions in relation to toxicity also exists. The simplified approach is based on it being unlikely that the tenability criteria for all toxic gases are exceeded if the visibility does not fall below 10 m (Spearpoint, 2008). For this case study, the simplified approach to determining tenability conditions in relation to toxicity is used as described in Section 4.4.4.2. The ASET analysis is further described in Appendix C.

Hand calculations have been used to determine the RSET for building occupants. The total evacuation time consists of the detection time, the alarm or warning time, the pre-travel time, and the movement time (BSI, 2019). The RSET is described by Equation 7 below.

$$t_{RSET} = t_{det} + t_a + t_{pre} + t_{trav}$$ **Equation 7**

The inputs used for the egress calculations are shown in Table 29.

Table 29: Inputs for egress calculations

Variable	Occupants awake and familiar in the enclosure of origin	Occupants awake and familiar outside of enclosure of origin	Occupants asleep and familiar in the enclosure of origin	Occupants asleep and familiar outside of enclosure of origin
Detection and alarm/warning time	Smoke below 5% of ceiling height (Eaton, 1991)	Based on calculated detection time	Based on calculated detection time	Based on calculated detection time
Pre-travel time	30 seconds (Ministry of Business, Innovation & Employment, New Zealand, 2014)	60 seconds (Ministry of Business, Innovation & Employment, New Zealand, 2014)	60 seconds (Ministry of Business, Innovation & Employment, New Zealand, 2014)	300 seconds (Ministry of Business, Innovation & Employment, New Zealand, 2014)
Travel time	Travel speed of 1 m/s (horizontal travel)	Travel speed of 1 m/s (horizontal travel)	Travel speed of 1 m/s (horizontal travel)	Travel speed of 1 m/s (horizontal travel)

The RSET analysis is further described in Appendix C, which also contains the ASET-RSET analysis for the building. The number of occupants per SOU varies between two, four, and six for the building. For the consequence analysis, four occupants per SOU have been assumed.

4.4.4.2 Tenability criteria

As previously mentioned, this case study uses a combination of hand calculations and computer programs to determine if the occupants are exposed to untenable conditions through an ASET-RSET analysis. The following tenability criteria shown in Table 30 have been selected for use in this thesis based on the Fire Engineering Design Guide (Spearpoint, 2008).

Table 30: Tenability criteria

Measurement	Criteria 1: Smoke layer above 2.1 m	Criteria 2: Smoke layer below 2.1 m
Upper layer temperature	Not applicable	Not to exceed 60°C
Lower layer temperature	Not to exceed 60°C	Not to exceed 60°C
Radiant heat	Not to exceed 2.5 kW/m2 at 2.1 m above floor level.	Not to exceed 2.5 kW/m2 at 2.1 m above floor level.
Visibility	-	Visibility not to fall below: 10 m generally 5 m in small rooms 5 m where occupants are standing in queue for a short period of time.
Toxicity	-	Visibility not to fall below: 10 m generally 5 m in small rooms 5 m where occupants are standing in queue for a short period of time.

According to the Fire Engineering Design Guide, a visibility of 10 m corresponds to an optical density of 0.1, visibility of 5 m corresponds to an optical density of 0.2, and radiant heat of 2.5 kW/m^2 corresponds to a smoke layer temperature of 200°C (Spearpoint, 2008). It should be noted that the time until untenable conditions will be based on the shortest time to reach one of the tenability criteria for the case study. The selection of tenability criteria is discussed in Section 6.6.

4.4.5 Individual risk

Part A8.2 specifies an upper and lower tolerable limit for individual risk as previously presented in Section 3.1.1. The individual risk is calculated based on Equation 2.

Since the building occupants are assumed to be inside their SOUs for 24 hours a day, the occupants inside the apartment of fire origin can be expected to be exposed to the maximum individual risk for the building. The scenario leading to the maximum individual risk is caused by a fire occurring in an SOU during the night, detector failure, failure to detect the fire manually, and sprinkler failure. The maximum individual risk can therefore be calculated as shown in Equation 8.

$$\text{IR}=\text{f(fire)} \cdot \text{P(fire in SOU)} \cdot \text{P(night)} \cdot \text{P(smoke alarm failure)} \cdot \text{P(no manual detection)} \cdot \text{P(sprinkler failure)} \qquad \textbf{Equation 8}$$

Based on the presented calculation, the individual risk can be calculated as:

$\text{IR} = 0.02825 \cdot 0.947 \cdot 0.2 \cdot 0.25 \cdot 0.9 \cdot 0.08 = 9.63 \cdot 10^{-5}$

Where the frequency of a fire occurring in an apartment building is $f = 0.02825$.

The individual risk has also been calculated for a DtS building. For a DtS building, no sprinkler system or smoke seals are required. Therefore, the calculated individual risk for a DtS building can be estimated to be:

$\text{IR} = 0.02825 \cdot 0.947 \cdot 0.2 \cdot 0.25 \cdot 0.9 = 1.20 \cdot 10^{-3}$

It should be noted that no consideration has been taken to the omission of smoke seals to doors for the DtS building.

The calculated individual risk is evaluated in Section 4.5.

4.4.6 Societal risk

Part A8.2 specifies an upper and lower tolerable limit for societal risk as previously presented in Section 3.1.1. For societal risk, an FN-curve has been created based on the method of sorting triplets in order of increasing consequence.

To calculate the societal risk, the developed event tree was used in combination with the ASET/RSET comparison presented in Appendix C. The events included in the event tree are shown in 4.4.3.2.

As previously mentioned in Section 4.4.4.1, many of the scenarios in the event tree share the same initial and intermediate events. It was therefore possible to model a select number of scenarios to help determine the consequence for each scenario or endpoint in the event tree. For the consequence analysis, it was decided to model a fire occurring in each of the different Sole Occupancy Units (SOUs) based on the door to the SOU being open and the sprinkler system either controlling the fire or failing. For the corridor fire, modeling was done to determine the consequences during a sprinkler-controlled fire, and a fire where the sprinkler system fail. This is further described in Appendix C.

To determine the ASET for the occupants of the building, a CFAST model was developed to be able to determine the time until untenable conditions as previously mentioned in Section 4.4.4. Hand calculations were performed to determine the RSET for the occupants of the building as previously mentioned in Section 4.4.4. An ASET-RSET comparison was then conducted to determine the number of occupants exposed to untenable conditions for the different scenarios. Detailed calculations for the ASET-RSET analysis are shown in Appendix C.

Scenarios have been created in the event tree based on a fire spreading via the window of an SOU to the floor above, and for fire or smoke to spread to the fire-isolated stair in case of a corridor fire or if an SOU door is open during a fire in an SOU. This was done to account for occupants located on another floor than the floor of fire origin. The number of occupants per SOU varies between two, four, and six for the building. For the consequence analysis, four occupants per SOU have been assumed. Table 31 shows the number of occupants assumed to be exposed to untenable conditions, in addition to those exposed on the floor of fire origin. Fire spread from an SOU to one floor above is expected to expose occupants in an SOU on the floor above to untenable conditions. Fire or smoke spread from the corridor to the fire-isolated stair is assumed to expose the occupants on other floors of the building to untenable conditions. This is discussed in Section 6.5. For sprinkler-controlled scenarios, all occupants located on another floor than the floor of fire origin are expected to evacuate the building without being exposed to untenable conditions.

Table 31: Additional occupants exposed to untenable conditions for sprinkler failure scenarios on other floors than fire origin

Scenario	Additional occupants exposed to untenable conditions
Fire spread from SOU to one floor above	4
Fire or smoke spread from corridor to fire-isolated stair	76

The FN curve showing the societal risk for the building is shown in Figure 26, and a comparison between the case building and a DtS building is shown in Figure 27.

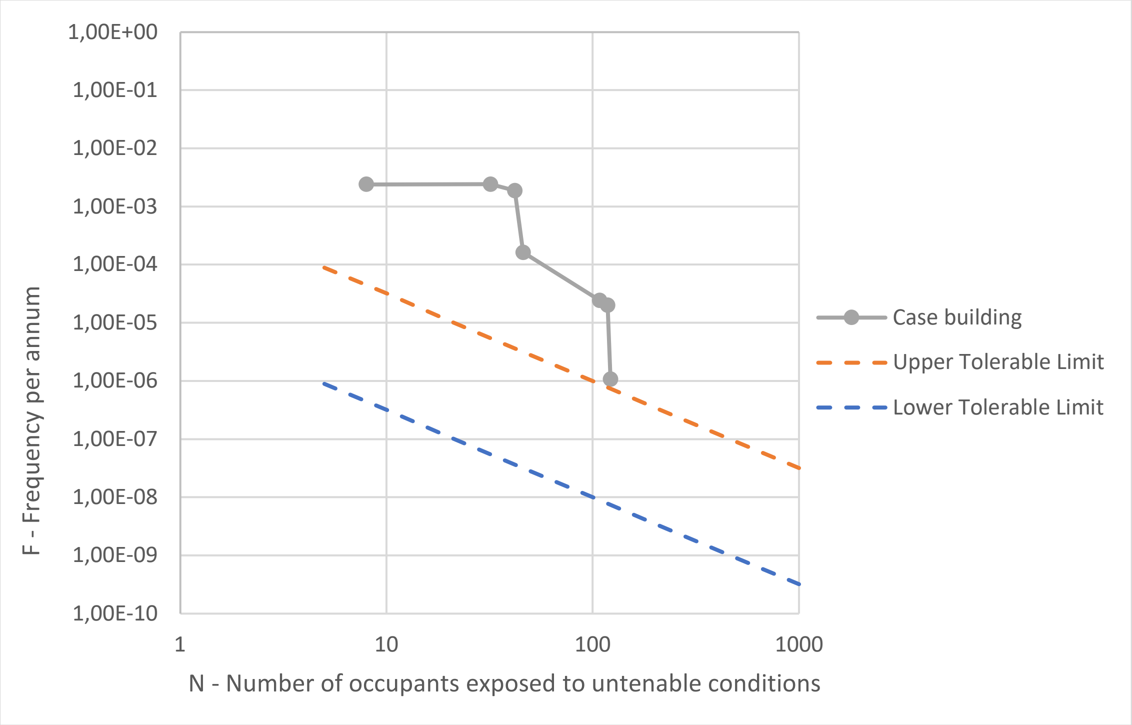


Figure 26: Societal risk for the case building in comparison with criteria

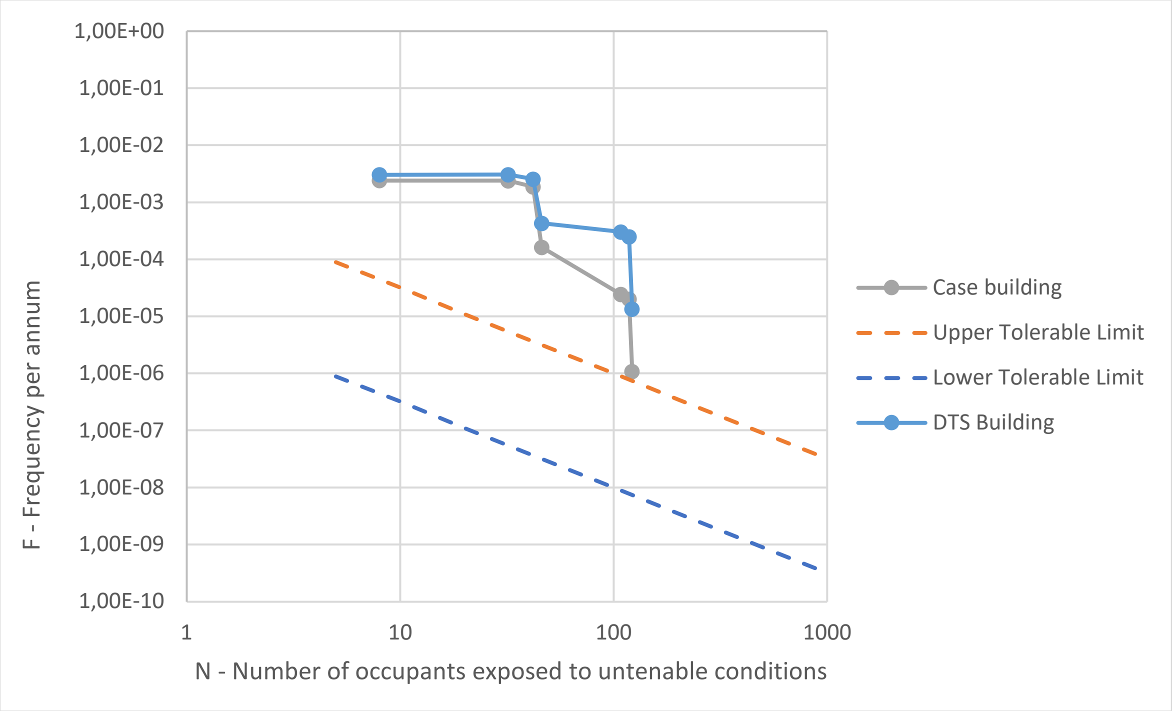


Figure 27: Societal risk for the case building and a DtS building in comparison with criteria

The calculated societal risk is evaluated in Section 4.5.

4.4.7 Fire spread between buildings

Part A8.3 requires the following criteria to be met in relation to fire spread between buildings (ABCB, 2019):

"A building must avoid the spread of fire between buildings such that:

The probability of a reportable fire in a building causing heat fluxes greater than the values listed in Table 8.3a must not exceed 0.001 at the stated distance from the boundary on an adjacent allotment or at the distances between buildings on the same allotment; and

The probability of a building not being able to withstand the heat flux in Table 8.3a for a period of 30 minutes must not exceed 0.01."

Assessment

An assessment has been made to determine the risk of fire spread between buildings. Only sprinkler-failure scenarios have been considered since sprinkler activation can be expected to cool the fire enclosure and reduce the radiation emitted from openings. Due to limited probability data, worst-case scenarios have been assumed from both emitted and received radiation to estimate the probability of fire spread between buildings.

4.4.7.1 Emitted radiation

In case of sprinkler failure, it is expected that the fire will become fully developed. As presented in Section 4.4.1, the probability of a flashover fire in a non-sprinklered apartment building is estimated to be 15.5%. Based on this, the probability of a reportable fire causing becoming large enough is calculated as:

$$\mathrm{P} = \mathrm{P(flashover)} \cdot \mathrm{P(sprinkler\ failure)} = 0.155 \cdot 0.08 = 0.0124$$

However, the expected heat flux also needs to be calculated to determine the probability of a reported fire to cause heat fluxes greater than the values listed in Table 8.3a. To calculate the heat flux emitted through a window from an enclosure with a fully developed fire, a conservative temperature of 900°C based on a full-scale fire test (NIST, 1998) and an emissivity of 1 (Spearpoint, 2008) have been used.

The computer program 'TRA' version 1.8.2 (Fire Engineering Software, 2016) was used to determine the heat flux emitted from the building to the adjacent boundary. In addition, the emitted heat flux was calculated 1 m from the boundary, 3 m from the boundary, and 6 m from the boundary.

The shortest distance to an adjacent boundary is from the building is 3 m. The SOUs located closest to the adjacent boundary are located on the ground floor. To determine the heat flux emitted from the subject building, two different scenarios were modeled:

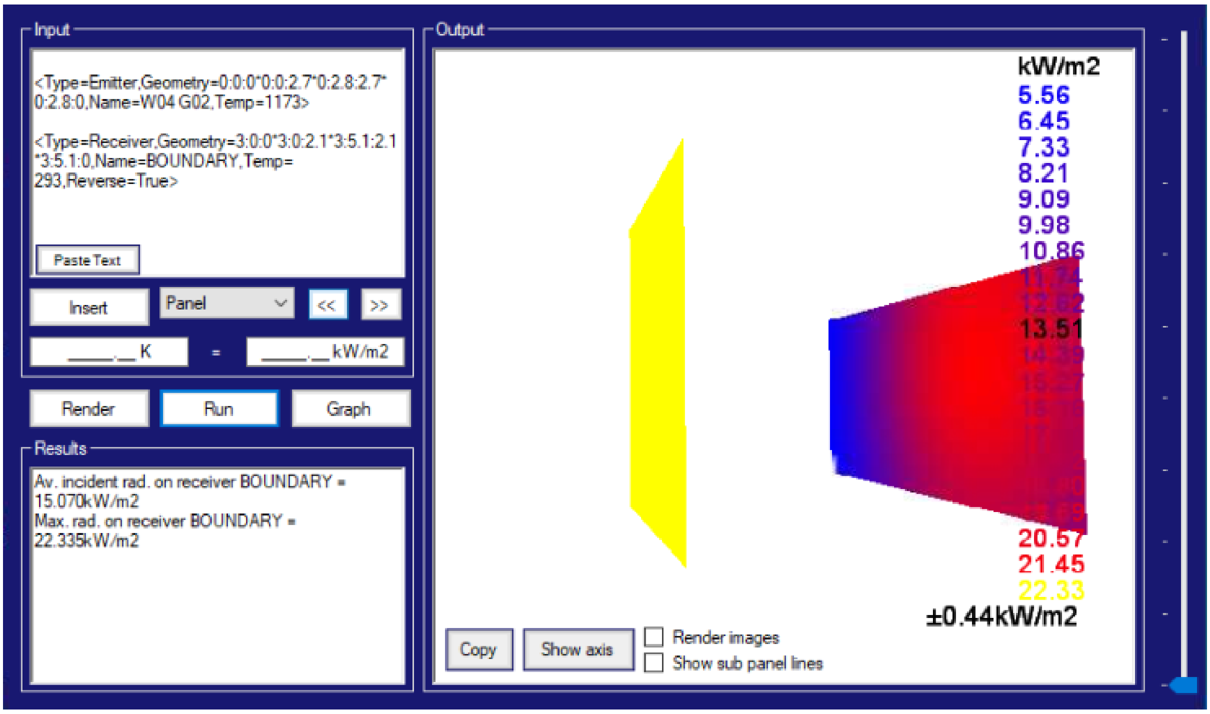
- Fire in a single SOU
- Horizontal fire spread involving all SOUs in an entire floor

Table 32 shows the scenarios used for this analysis.

Table 32 Scenarios used for the analysis of fire spread between buildings

Scenario	Openings	Measurement of modeled openings	Distance to boundary
SOU (900°C and 1200°C)	1 SOU opening	2.7 m wide x 2.7 m high	3 m
Horizontal fire spread involving entire storey (ground floor) (900°C)	8 SOU openings on same storey	2.3 m wide x 1 m high	8.1 m
		8.95 m wide x 2.7 m high	3 m
		2.6 m wide x 2.7 m high	4.6 m

In addition to using a conservative temperature of 900°C for 1 SOU opening, an even more conservative temperature of 1200°C has been used for the single SOU fire scenario. It should be noted that the second scenario involving all SOUs on an entire floor can be considered a very conservative assumption. Even the probability of a fully developed fire occurring in two SOUs on the same floor at the same time is expected to be very low. A third scenario involving vertical fire spread to SOUs on three storeys was also considered. Due to the limited fuel load in an apartment, the fire on the ground floor can be assumed to be in the decay phase or extinguished when a fire on the second floor becomes fully developed. Figure 28 and Figure 29 show examples of the setup for the different scenarios at a distance of 3 m from the boundary.



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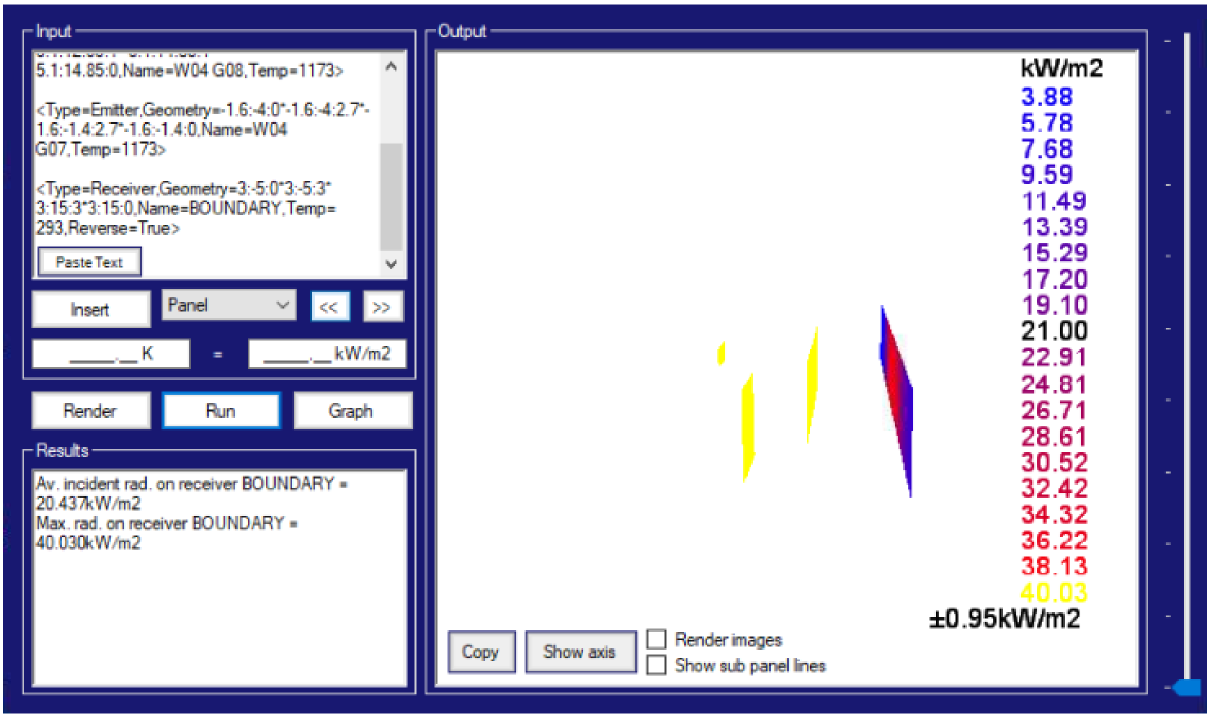
0:2.8:0,Name=W04 G02,Temp=1173>

<Type=Receiver,Geometry=3:0:0*3:0:2.1*3:5.1:2.1
*3:5.1:0,Name=BOUNDARY,Temp=
293,Reverse=True>
```

```
Av. incident rad. on receiver BOUNDARY =
15.070kW/m2
Max. rad. on receiver BOUNDARY =
22.335kW/m2
```

Figure 28: Example of 1 SOU opening at a distance of 3 m to the boundary



```
5.1:14.85:0,Name=W04 G08,Temp=1173>

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1.6:-1.4:2.7*-1.6:-1.4:0,Name=W04
G07,Temp=1173>

<Type=Receiver,Geometry=3:-5:0*3:-5:3*
3:15:3*3:15:0,Name=BOUNDARY,Temp=
293,Reverse=True>
```

```
Av. incident rad. on receiver BOUNDARY =
20.437kW/m2
Max. rad. on receiver BOUNDARY =
40.030kW/m2
```

Figure 29: Example of 8 SOU openings on the same storey at a distance of 3 m to the boundary

Table 33 shows the calculated radiation from the subject building to a building located at a specified distance.

Table 33: Calculated radiation received at a distance

Scenario	Openings	Heat flux received on boundary	Heat flux received 1 m from boundary	Heat flux received 3 m from boundary	Heat flux received 6 m from boundary	Criteria met?
Maximum heat flux permitted by Table 8.3a of Part A8		80 kW/m2	40 kW/m2	20kW/m2	10kW/m2	
Fire in SOU (900°C)	1 SOU opening	22.4 kW/m2	13.9 kW/m2	6.7 kW/m2	3.1 kW/m2	Yes
Fire in SOU (1200°C)	1 SOU opening	44.7 kW/m2	34.6 kW/m2	16.7 kW/m2	7.7 kW/m2	Yes
Horizontal fire spread involving entire storey (900°C)	6 SOU openings on same storey	40.1 kW/m2	29.8 kW/m2	17.9 kW/m2	9.9 kW/m2	Yes

Given the compartment size, existing openings, fuel load, and calculated heat fluxes, the probability of a fully developed fire in the building reaching an intensity such that the radiant heat at the boundary exceeds the values listed in Table 8.3a can be assumed to be under 0.001. The criteria are therefore considered to be met.

4.4.7.2 Received radiation

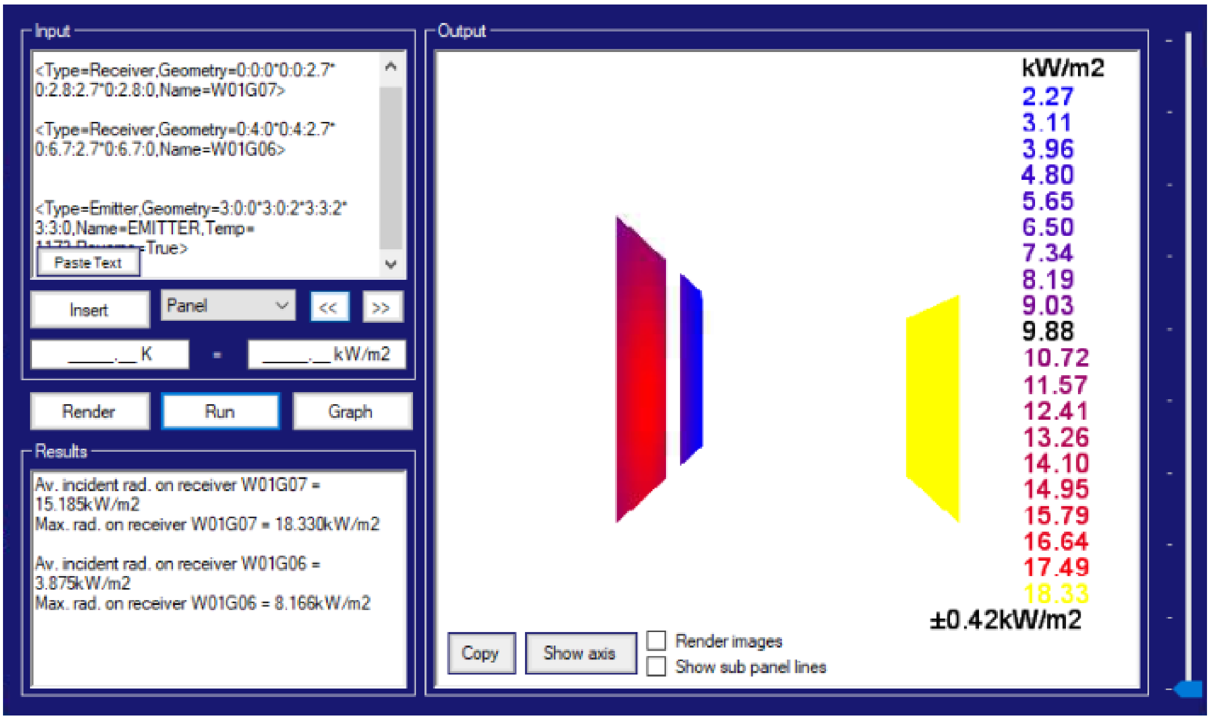
The definition of **withstand** applicable to this scenario is: *"Ignition and propagation as the result of the imposed heat flux from a fire in an adjacent building or potential building on an adjoining allotment (embers are likely to be present and therefore piloted ignition should be considered if combustible materials are present)"*.

The shortest distance to the building from the adjacent boundary is 3 m from the ground floor. The construction on the ground floor is therefore required to withstand a radiant heat flux of 20kW/m^2 for 30 minutes. The specified period of 30 minutes is interpreted to include all phases in enclosure fire development.

The façade of the building is of non-combustible construction; however, there is a risk that the windows in the SOUs 3 m from the boundary break. The windows in the building are double-glazed.

The computer program 'TRA' version 1.8.2 (Fire Engineering Software, 2016) was used to determine the possible radiative heat flux received from the adjacent boundary to the SOU located 3 m from the boundary.

A calculation was conducted based on a conservative temperature of 900°C based on a full-scale test (NIST, 1998) and an emissivity of 1. If the received radiation is calculated based on an assumed large window with a size of 3 m wide and 2 m high, the maximum received heat flux can be estimated to be approximately 18.3 kW/m^2. The configuration is shown in Figure 30.



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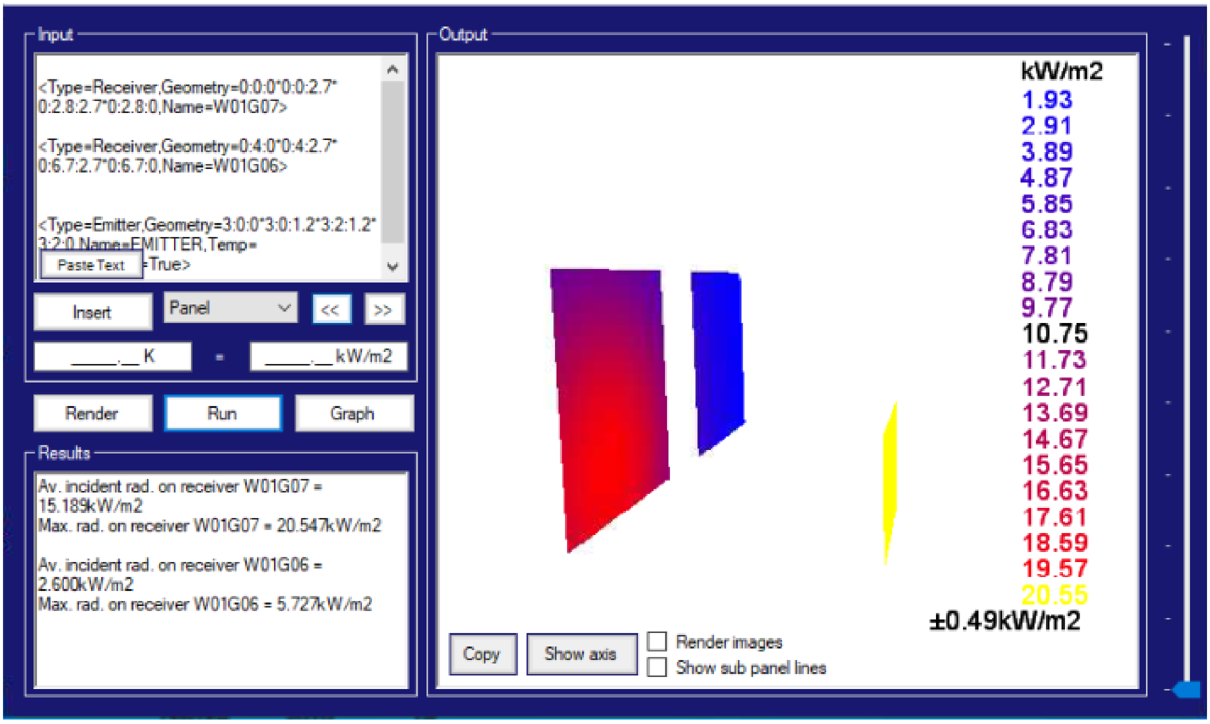
[illegible]=True>
```

```
Av. incident rad. on receiver W01G07 =
15.185kW/m2
Max. rad. on receiver W01G07 = 18.330kW/m2

Av. incident rad. on receiver W01G06 =
3.875kW/m2
Max. rad. on receiver W01G06 = 8.166kW/m2
```

Figure 30: Calculation of radiation received at openings in the SOU located 3 m from the boundary based on a temperature of 900°C

The received heat flux was also calculated from the boundary based on an emitter consisting of a window with an assumed size of 2 m wide and 1 m high and an even more conservative temperature of 1200°C with an emissivity of 1. Based on this case, the maximum received heat flux is estimated to be approximately 20.5 kW/m^2. It should be noted that a temperature of 1200°C is a very conservative assumption and that this is an unlikely case. The configuration is shown in Figure 31.



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<Type=Receiver,Geometry=0:0:0*0:0:2.7*
0:2.8:2.7*0:2.8:0,Name=W01G07>

<Type=Receiver,Geometry=0:4:0*0:4:2.7*
0:6.7:2.7*0:6.7:0,Name=W01G06>


<Type=Emitter,Geometry=3:0:0*3:0:1.2*3:2:1.2*
3:2:0,Name=EMITTER,Temp=
=True>
```

```
Av. incident rad. on receiver W01G07 =
15.189kW/m2
Max. rad. on receiver W01G07 = 20.547kW/m2

Av. incident rad. on receiver W01G06 =
2.600kW/m2
Max. rad. on receiver W01G06 = 5.727kW/m2
```

Figure 31: Calculation of radiation received at openings in the SOU located 3 m from the boundary based on a temperature of 1200°C

Babrauskas (1998) presents data based on several tests of glass breakage during fires for both small and large windows. Several factors affect the probability of glass breakage during fires; some examples are windows size, window thickness, and glass defects. Based on a study conducted by Cohen and Wilson, it was determined that both panes in double glazed windows fall out at a heat flux of between 20 kW/m^2 to 30 kW/m^2 during external fires. A conservative value of 20 kW/m^2 has been assumed for the purpose of this assessment.

Based on the presented data, calculated heat fluxes, and uncertainties related to e.g., compartment size, opening size, and fuel load, it is hard to determine if the probability of the building being able to withstand a heat flux of 20 kW/m2 for 30 minutes exceed 0.01. Therefore, the criterion is considered not to be met. It should be noted that openings located at a distance of 3 m or more from the boundary are not required to be protected in accordance with Clause C3.2 of BCA 2019 Amendment 1.

4.4.8 Fire spread via the external façade

4.4.8.1 Flames venting through an opening

Part A8.3 requires the following criteria to be met in relation to burning items adjacent to the structure (ABCB, 2019):

> *"The probability that the external façade of a building cannot withstand the following exposures from reportable fires must not exceed 0.001:*
>
> - *flames venting through an opening from an enclosure fire within the building."*

Assessment

The building is provided with an automatic sprinkler system, as detailed previously. Therefore, it is unlikely that flames will vent through an opening from an enclosure within the building unless the sprinkler systems fail. In addition, a large fire is required for flames to vent through an opening. As presented in Section 4.4.1, the probability of a flashover fire in a non-sprinklered apartment building is estimated to be 15.5%. Based on this, the probability of a large enough fire occurring for flames to vent out through an opening is calculated as:

$$\mathrm{P(large\ enough\ fire)} = \mathrm{P(flashover\ fire\ )} \cdot \mathrm{P(sprinkler\ failure)} = 0.155 \cdot 0.08 = 0.0124$$

Korhonen and Hietanemi (2005) conducted a study where they looked at the fire safety of wooden facades in residential multi-storey buildings. In the study, they determined the probability of fire spread from an apartment to another apartment above by flames venting out from an opening. Based on the study, the authors present the probability of fire spread via a window to the floor above for both wood and non-combustible façades on multi-storey residential buildings. For a non-combustible façade, the estimated probability of fire spreading to the floor above was 0.02. However, the authors note that based on statistics for fires in residential multi-storey buildings, the frequency of fire spread via an opening to an apartment above is a factor of ten less. Therefore, the suggested probability of a fire spreading to another floor can be estimated to be 0.002. The probability of the external façade not being able to withstand flames venting through an opening from an enclosure fire within the building can is therefore calculated as:

$$\mathrm{P} = \mathrm{P(large\ enough\ fire)} \cdot \mathrm{P(fire\ spread\ to\ floor\ above)} = 0.0124 \cdot 0.002 = 0.0000248$$

The calculated probability is ≤ 0.001. The criterium is therefore considered to be met.

4.4.8.2 Burning items adjacent to the structure

Part A8.3 requires the following criteria to be met in relation to burning items adjacent to the structure (ABCB, 2019):

> *"The probability that the external façade of the building cannot* ***withstand*** *the following exposure from reportable fires must not exceed 0.001:*
>
> - *Burning items adjacent to the structure such as a vehicle, waste bin, collection of combustible rubbish depending on the use and access to adjacent areas."*

Assessment

The definition of **withstand** applicable to this scenario is: *"Fire Spread more than 2m beyond the extent of flames from a burning item adjacent to the structure such as a vehicle, waste bin, collection of combustible rubbish depending on the use and access to adjacent areas".*

Based on the use and access to adjacent areas of the building, the possible burning items adjacent to the building which could spread to the façade are cars entering or exiting the basement carpark and potentially waste bins and burning items. The façade of the building is non-combustible; and the probability of the façade fire spread more than 2m beyond the extent of flames from a burning item adjacent to the structure such as a vehicle, waste bin, or collection of combustible rubbish is therefore considered to be low enough not to exceed the criteria. However, calculations have been made to demonstrate that the windows won't break, which is more conservative than the specified criteria. The windows used in the openings are double-glazed panels.

The computer program 'TRA' version 1.8.2 (Fire Engineering Software, 2016) was used to determine the heat flux emitted from a vehicle located in front of the ramp down to be basement carpark. To model the radiation from both the front and the side of a vehicle, two emitters were created. A temperature of 820 °C, an emissivity of 1.0 was used for both emitters. A size of 5.1 m wide x 2.1 m high was used for the first emitter, and a size of 2 m wide x 2.1 m high was used for the second emitter. The configuration is shown in Figure 32.


```
1093,Reverse=True>

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2:5.1:2.1*2:5.1:0,Name=EMITTER2,Temp=
1093,Reverse=True>

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2.7:8.6:2.5*-1.5:8.6:2.5*-
1.5:8.6:0,Name=WINDOW01G08,Temp=293>

er,Geometry=-5.8:5.5:0*-
```

```
Av. incident rad. on receiver WINDOW01G08
= 5.177kW/m2
Max. rad. on receiver WINDOW01G08 =
5.956kW/m2

Av. incident rad. on receiver WINDOW02G08
= 3.523kW/m2
Max. rad. on receiver WINDOW02G08 =
5.789kW/m2
```

Figure 32: Calculation of radiation received at openings on the ground floor from vehicle fire near in front of ramp down to carpark

The maximum heat flux emitted to the SOU windows adjacent to the ramp has been calculated to 5.79kW/m^2 and 5.96 kW/m^2, as shown in Table 34.

Table 34: Maximum heat flux received from a vehicle fire adjacent to the building

Scenario	Openings	Maximum heat flux received on openings
Vehicle fire	W01 in G.08	5.96 kW/m^2
	W02 in G.08	5.79 kW/m^2

Examples of other potential burnings items potentially being adjacent to the building are waste bins and combustible rubbish. Therefore, a radiation calculation was made to determine the heat flux radiated from a burning rubbish bag with a heat release rate of 350kW and a diameter of 1 m at a distance of 2 m from the building. For this, Modak's simple method was used, as shown in Equation 9 (Karlsson & Quintiere, 2000).

$$\dot{Q}'' = \frac{\chi_r \dot{Q}}{4\pi R_0^2}$$ **Equation 9**

Where R_0 is the distance to the target from the centre of the flame, χ_r is the fraction total of energy radiated (usually 0.6 for high-sooting fuels), and $\dot{Q}$ is the heat release rate. The radiation emitted towards the building from a distance of 2 m then becomes:

$$\dot{q}'' = \frac{0.6 \cdot 350}{4\pi \cdot 2.5^2} = 2.67 \text{ kW/m}^2$$

Babrauskas (1998) presents data based on several tests of glass breakage during fires for both small and large windows. Several factors affect the probability of glass breakage during fires; some examples are windows size, window thickness, and glass defects. Based on one study, it was determined that double glazed windows fall out (in both panes) at a heat flux of between 20 kW/m^2 to 30 kW/m^2 during external fires. A conservative value of 20kW/m^2 has been assumed for the purpose of this assessment.

Given that the calculated radiant heat flux is up to 5.96 kW/m^2 (below breaking point for glazing), and that the façade is non-combustible, it can be assumed that the probability of a fire occurring adjacent to the structure reaching an intensity required for fire to spread more than 2 m beyond the extent of flames is less or equal to 0.001. The probability that the external façade of the building cannot withstand the exposure from a burning item adjacent to the structure is therefore assumed to be less or equal to 0.001. It should be noted that demonstrating that the windows won't break is more conservative than the specified criteria, as previously mentioned in this assessment.

4.4.8.3 Fire occurring on a balcony

Part A8.3 requires the following criteria to be met in relation to a fire on the balcony (ABCB, 2019):

"The probability that the external façade of the building cannot ***withstand*** *the following exposure from reportable fires must not exceed 0.001:*

- *A fire occurring on a balcony."*

Assessment

The definition of **withstand** applicable to this scenario is: *"Fire Spread more than 2m beyond the extent of flames from a burning item adjacent to the structure such as a vehicle, waste bin, collection of combustible rubbish depending on the use and access to adjacent areas".*

Therefore, for the building to meet this requirement, fire cannot spread more than 2m beyond the extent of flames in the case of a fire occurring on a balcony. For this to happen, the fire would have to spread on the façade of the building. Several of the balconies in the building are separated by non-combustible façade material. In addition, the rest of the façade of the building is also non-combustible. It is further assumed that the wall achieves the prescribed Fire Resistance Level (FRL). Based on this, the probability that the façade cannot withstand exposure from a fire occurring on a balcony is considered to be low enough to not exceed 0.001. The criterion is therefore considered to be met.

4.4.9 Fire spread within the building

4.4.9.1 Fire spread outside of an SOU

Part A8.3 requires the following criteria to be met in relation to fire spread outside of an SOU (ABCB, 2019):

“A building must avoid the spread of fire within the building such that when a reportable fire occurs, the probability of fire spread does not exceed 0.01 to spread outside of an SOU for Class 2, 3 and 4 buildings.”

Assessment

Fire spread outside of an SOU can either happen through the SOU door being open, compartmentation failure, or via a window in the SOU breaking, causing fire to vent through the opening to another floor. Therefore, a large fire is required for fire spread through compartmentation failure or an opening to another floor is to occur. For this assessment, compartmentation failure is expected to happen when the SOU door is open.

Based on the statistics presented on fire types in non-sprinklered apartment buildings in Australia, the probability of fire reaching flashover can be estimated to 15.5%, as shown in Section 4.4.1. For this to happen, the sprinkler system must fail. The probability of fire reaching flashover has been calculated as:

$$\mathrm{P} = \mathrm{P(flashover)} \cdot \mathrm{P(sprinkler\ failure)} = 0.155 \cdot 0.08 = 0.0124$$

The following probabilities have been assumed for the SOU door being open, fire spreading via a window to another floor, and compartmentation failure:

- SOU door open: 10% (Refer Section 2.2.10.1)
- Fire spreading via a window to another floor: 0.002 (Refer Section 2.2.10.3)
- Compartmentation failure: 50%

The probability of compartmentation failure is based on the probability of a large penetration being unprotected, which is the most conservative case. It should be noted that a probability of failure of 50% for the compartmentation is higher than the estimated probability of failure for gypsum and concrete walls. The probability of a fire spreading outside an SOU for each path of fire spread has therefore been calculated as:

$$\mathrm{P(Fire\ spreading\ via\ a\ window)} = 0.155 \cdot 0.08 \cdot 0.1 = 0.00124$$

$$\mathrm{P(SOU\ door\ open\ )} = 0.155 \cdot 0.08 \cdot 0.002 = 0.0000248$$

$$\mathrm{P(Compartmentation\ failure)} = 0.155 \cdot 0.08 \cdot 0.5 = 0.0062$$

The calculated probability of fire spread outside of an SOU is, therefore, ≤ 0.01. The criterium is therefore considered to be met.

4.4.9.2 Fire spread between storeys

Part A8.3 requires the following criteria to be met in relation to fire spread between storeys (ABCB, 2019):

“A building must avoid the spread of fire within the building such that when a reportable fire occurs, the probability of fire spread does not exceed 0.01 to spread between storeys.”

Assessment

Fire spread between storeys can either happen via flames venting out through a window or via floor failure. Therefore, a large fire is required if a fire is to spread via a window or floor failure is to occur. To calculate the probability of fire spread between storeys, a floor failure rate of 50% will be used. This is based on the probability of a large penetration being unprotected and is the most conservative case. The probability of a fire spreading outside an SOU has therefore been calculated as:

$$\mathrm{P} = \mathrm{P(flashover)} \cdot \mathrm{P(sprinkler\ failure)} \cdot \mathrm{P(floor\ failure)} = 0.155 \cdot 0.08 \cdot 0.5 = 0.0062$$

The calculated probability of fire spread between storeys is, therefore, ≤ 0.01. The criterium is therefore considered to be met.

4.4.9.3 Fire spread beyond floor area and volume

Part A8.3 requires the following criteria to be met in relation to fire spread beyond floor area and volume (ABCB, 2019):

"A building must avoid the spread of fire within the building such that when a reportable fire occurs, the probability of the fire spread does not exceed:

- *the values in Table 8.3b* (Refer Table 35)

Table 35: Fire spread limits

Building classification	Floor area	Volume	Maximum probability of spread beyond specified floor area and volume
5, 9b	3000 m^2	18000 m^3	0.01
6, 7, 8, 9a, 9c	2000 m^2	12000 m^3	0.01
5-9	18000 m^2	21000 m^3	0.001
9a patient class areas and Class 9c	1000 m^2	-	0.01

Assessment

The building contains a Class 7 carpark, and the maximum probability of fire spread beyond a floor area of 2000 m^2 and a volume of 12000 m^3 are therefore required to be demonstrated to be ≤ 0.01.

The area and volume of the basement carpark do not exceed the specified floor area and volume. This criterion is therefore not applicable to the case study building.

4.5 Risk Evaluation

Evaluations of the calculated risk levels and probabilities based on the conducted case study are shown in Sections 4.5.1, 4.5.2, 4.5.3 below. Sections 4.5.1 and 4.5.2 concerns Part A8.2, and Section 4.5.3 concerns Part A8.3.

4.5.1 Individual Risk

Table 36 shows the calculated individual risk for the building. The calculated individual risk is within the upper and lower tolerable limits for the case study building.

Table 36: Calculated individual risk for the building and comparison with individual risk criteria in Part A8.2

Fire location	Calculated individual risk per annum	Individual risk per annum (lower tolerable limit)	Individual risk per annum (upper tolerable limit)	Tolerable?	Refer to Section
SOU	9.63×10^{-5}	5×10^{-6}	5×10^{-4}	Yes	4.4.5

As previously mentioned in Section 3.1.1, Part A8 (ABCB, 2019) state that '*If the individual and / or societal risks presented by the proposed Performance Solution lie between the lower and upper allowable risks the proposed Performance Solution can be considered to have been satisfied if the following additional criteria is satisfied if it can be demonstrated that:- the individual and / or societal risk presented by the Performance Solution is less than or equal to that presented by a similar Deemed-to-Satisfy compliant reference building that is considered to represent a tolerable risk'.*

Table 37 shows a comparison between fire safety systems for residential levels of the case building and that of a DtS building.

Table 37: Comparison between fire safety systems for residential levels of the case building and that of a DtS building

Fire Safety System	DtS Solution	Performance Solution
Smoke alarm in SOUs	Yes	Yes
Smoke detectors in public corridors and internal spaces	Yes	Yes
Fire-rated internal walls between SOUs and SOU walls bounding the public corridors	Yes	Yes
Self-closing fire doors protecting doorways of SOU walls boundary public corridors	Yes	Yes
Medium temperature smoke seals on SOU entry doors	No	Yes
Sprinkler system in the building	No	Yes
Sound pressure level of building occupant warning system	100 dbA outside the SOU entry doors	75 dBa at the bedhead in SOUs
Separation of stair connecting all floors	Non-fire-isolated open stair	Fire-isolated stair

Table 38 shows the calculated individual risk for the case study building compared to that of a DtS building. The individual risk for a DtS building is calculated in Section 4.4.5.

Table 38: Comparison of calculated individual risk for selected fire location and individual risk criteria in Part A8.2

Fire location	Calculated individual risk per annum	Calculated individual risk per annum (DtS Building)	Individual risk per annum (lower tolerable limit)	Individual risk per annum (upper tolerable limit)	Tolerable?	Refer to
SOU	9.63×10^{-5}	1.20×10^{-3}	5×10^{-6}	5×10^{-4}	Yes	4.4.5

The calculated individual risk for the case building is lower than that of a DtS building. Based on the calculations, the building design, therefore, meet the required criteria for individual risk, and that the risk level is considered to be tolerable. This is further discussed in Section 6.1.

4.5.2 Societal Risk

Figure 33 shows the societal risk for the case building and the criteria set out in Part A8 of the proposed legislation. The societal risk for the case building exceeds the upper tolerable limit, which means that the societal risk level for the case building is not considered to be tolerable.

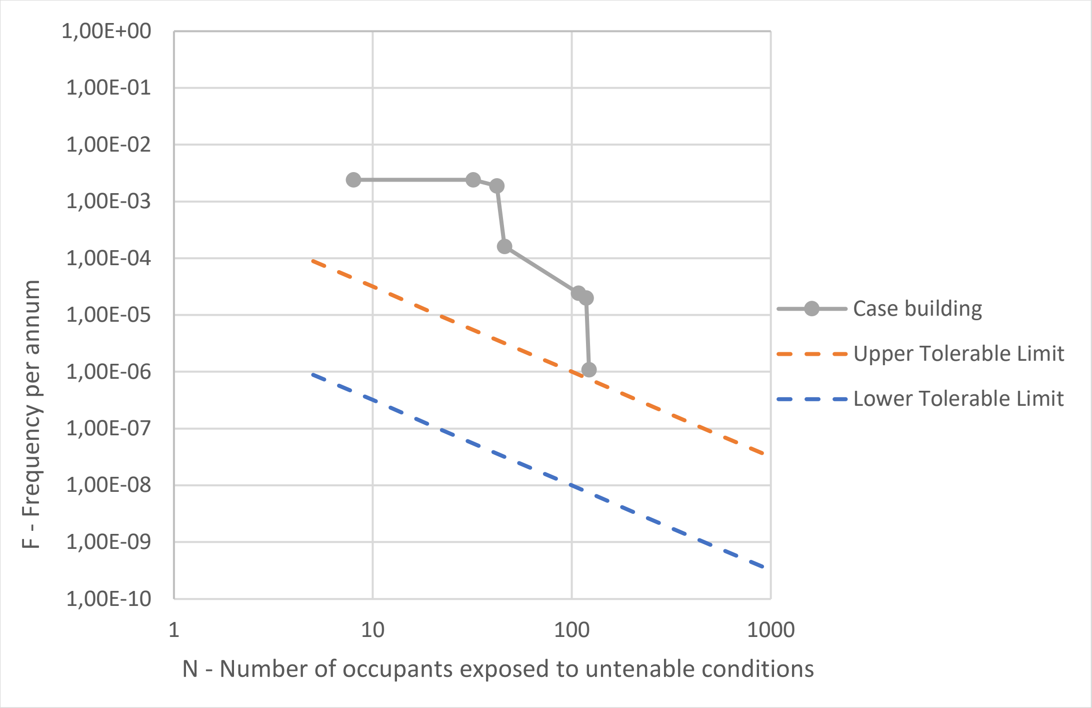

Figure 33: Societal risk for the case building in comparison with criteria

As previously mentioned in Section 3.1.1, Part A8 (ABCB, 2019) states that '*If the upper tolerable limits (individual or societal) are exceeded by the proposed Performance Solution the individual or societal risk criteria have not been satisfied and modifications to the proposed solution will be required*'.

This means that based on the resulting societal risk for the building, the proposed legislation would require the building to be redesigned. This has not been done due to the analysis being conducted on an already existing building with specified fire safety measures.

However, a comparison has been made with a DtS Building. As previously mentioned in this section, a modified event tree was used together with the consequence analysis to determine the risk level for DtS building.

Table 39 shows a comparison between fire safety systems for residential levels of the case building and that of a DtS building.

Table 39: Comparison between fire safety systems for residential levels of the case building and that of a DtS building

Fire Safety System	DtS Solution	Performance Solution
Smoke alarm in SOUs	Yes	Yes
Smoke detectors in public corridors and internal spaces	Yes	Yes
Fire-rated internal walls between SOUs and SOU walls bounding the public corridors	Yes	Yes
Self-closing fire doors protecting doorways of SOU walls boundary public corridors	Yes	Yes
Medium temperature smoke seals on SOU entry doors	No	Yes
Sprinkler system in the building	No	Yes
Sound pressure level of building occupant warning system	100 dbA outside the SOU entry doors	75 dBa at the bedhead in SOUs
Separation of stair connecting all floors	Non-fire-isolated open stair	Fire-isolated stair

A comparison of the estimated societal risk for the case building in comparison with a DtS building and the specified criteria is shown in Figure 34.

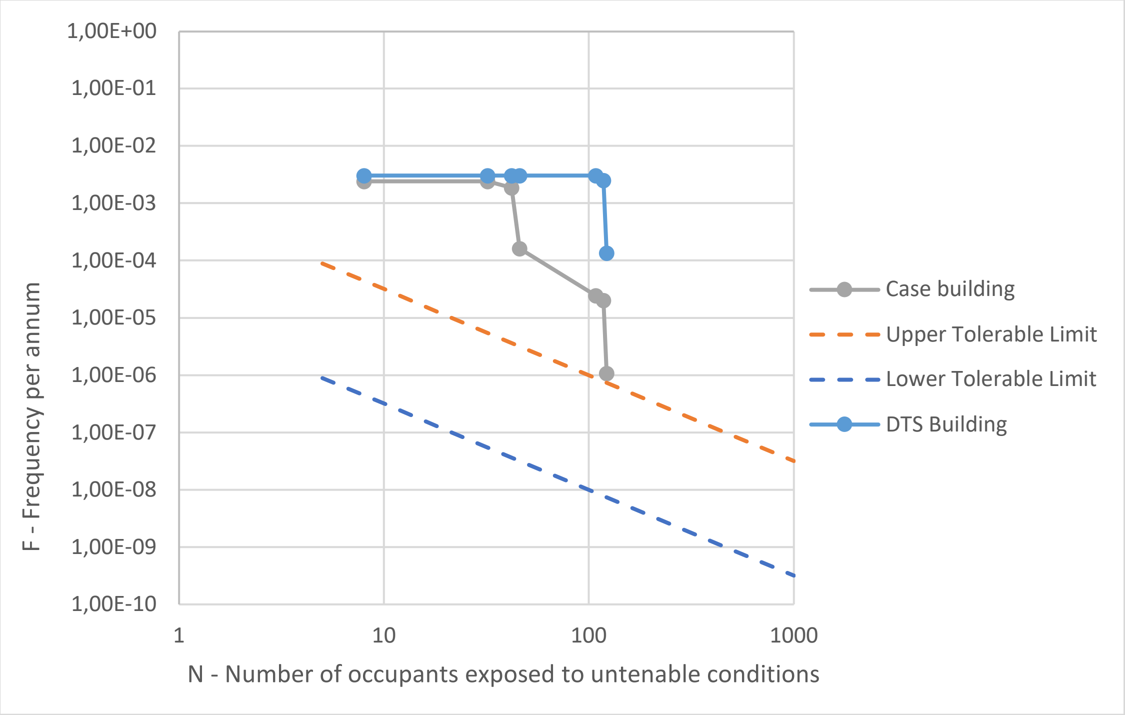

Figure 34: Societal risk for building in comparison with criteria and a DtS Building

The results show that neither the case study building nor a DtS building meets the risk criteria for societal risk. This means that the societal risk level for both the case building and a DtS building is not considered to be tolerable. This is further discussed in Section 6.1.

4.5.3 Spread of fire

Table 40 shows the calculated probabilities compared to the criteria set out in Part A8.3 for Class 2 buildings of the proposed legislation based on the assessments conducted in Sections 4.4.7, 4.4.8, and 4.4.9 of this thesis. The case study building is determined to meet the criteria of Part A8.3 except for Part A8.3(a)(ii) related to the probability of the building being able to withstand the heat flux listed in Table 8.3a of the proposed legislation for 30 minutes. It should be noted that Part8.3(b)(iii) is not applicable to the building. This is further discussed in Section 6.1.

Table 40: Comparison of calculated probabilities and Part A8.3

Section	Description	Calculated probability	Criteria	Tolerable?	Refer to Section
(a)(i)	Probability of a reportable fire in a building causing heat fluxes greater than the values listed in Table 8.3a of Part A8 at the stated distance from the boundary on an adjacent allotment or at the distances between buildings on the same allotment	≤0.001	≤0.001	Yes	4.4.7
(a)(ii)	The probability of a building not being able to withstand the heat flux in Table 8.3a of Part A8 for a period of 30 minutes	-	≤0.01	No	4.4.7
(a)(iii)	The probability that the external façade of a building cannot withstand the following exposures from reportable fires				
(a)(iii)(A)	Flames venting through an opening from an enclosure fire within the building	0.0000248	≤0.001	Yes	4.4.8
(a)(iii)(B)	Burning items adjacent to the structure such as a vehicle, waste bin, collection of combustible rubbish depending on the use and access to adjacent areas	≤0.001	≤0.001	Yes	4.4.8
(a)(iii)(C)	A fire occurring on a balcony	≤0.001	≤0.001	Yes	4.4.8
(b)(i)	Spread of fire outside of an SOU for Class 2, 3 and 4 buildings	≤0.01	≤0.01	Yes	4.4.9
(b)(ii)	Spread of fire between storeys	0.0062	≤0.01	Yes	4.4.9
(b)(iii)	The values in Table 8.3b	Not applicable	≤0.01	Not applicable	4.4.9

4.6 Sensitivity analysis

A sensitivity analysis has been carried out to determine how the individual and societal risk is affected by varying reliabilities of selected fire protection systems. In addition, a sensitivity analysis has also been carried out to determine the societal risk for the building based on the assumption that a sprinkler-controlled fire leads to no occupants being exposed to untenable conditions, as well as a combination of using the Barrios model to calculate the frequency of initial fire and the assumption that a sprinkler-controlled fire leads to no occupants being exposed to untenable conditions.

The individual risk for the different scenarios has been calculated based on the reliability of failure for the systems listed in Table 41 and by the use of Equation 8. The varying reliabilities are based on the minimum and maximum reliability identified during the literature review, except for the lower selected reliability for smoke alarms. Because the standard value used for smoke alarm reliability is the lowest found during the literature study, the sensitivity analysis has only been conducted for the maximum identified value. Table 41 shows the fire protection systems selected for analysis and the evaluated values of reliability.

Table 41: Fire protection systems selected for sensitivity analysis and evaluated values of reliability

System	Selected varying reliability values (minimum and maximum), %	Standard value, %	Reference
Automatic sprinkler system	87	92	(ABCB, 2020)
	97		(BSI, 2019)
Smoke alarm	-	75	-
	79		(Bukowski, Budnick, & Schemel, 2002)
Self-closing doors	85	90	(BSI, 2019)
	95		(BSI, 2019)

Figure 35 shows the calculated individual risk for the sensitivity analysis in comparison to the standard values used. The calculated individual risk for the sensitivity analysis based on varying reliability and frequency is also shown in Table 42 and Table 43. It should be noted that the provision of self-closing doors does not affect the calculated individual risk in the building. The individual risk has therefore not been calculated for varying reliability related to self-closing doors.

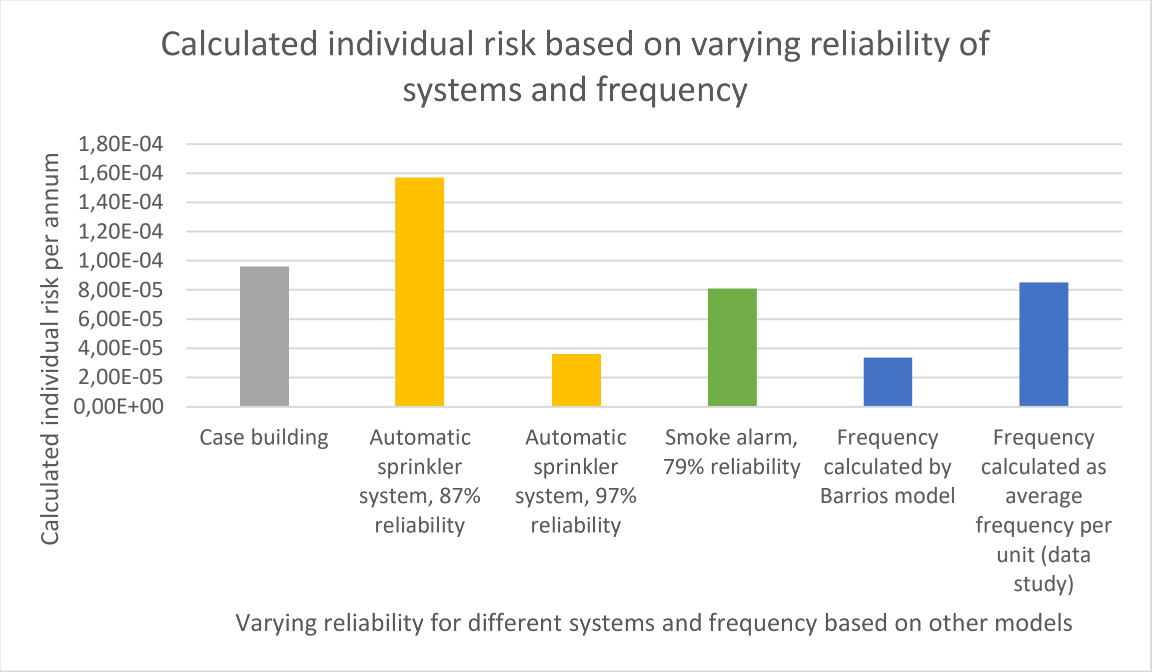

Figure 35: Calculated individual risk based on varying reliability and frequency

Table 42: Calculated individual risk based on varying reliability

System	Reliability, %	Calculated individual risk
Automatic sprinkler system	87	1.57×10^{-4}
	97	3.61×10^{-5}
Smoke alarm	79	8.1×10^{-5}

Table 43: Calculated individual risk based on varying frequency

Model to calculate frequency	Calculated individual risk
Barrios model	3.37×10^{-5}
Average frequency per unit (data study)	8.51×10^{-5}

The performed calculations for individual risk for the different scenarios are shown below.

$IR_{\text{Sprinkler 87\%}} = 0.02825 \cdot 0.947 \cdot 0.2 \cdot 0.25 \cdot 0.9 \cdot 0.13 = 1.57 \cdot 10^{-4}$

$IR_{\text{Sprinkler 97\%}} = 0.02825 \cdot 0.947 \cdot 0.2 \cdot 0.25 \cdot 0.9 \cdot 0.03 = 3.61 \cdot 10^{-5}$

$IR_{\text{Smoke Alarm 79\%}} = 0.02825 \cdot 0.947 \cdot 0.2 \cdot 0.21 \cdot 0.9 \cdot 0.08 = 8.10 \cdot 10^{-5}$

For the conducted sensitivity analysis, the variation in frequency used is shown in Table 44.

Table 44: Other frequencies used in the sensitivity analysis

Frequency model	Calculated frequency
Barrios	0.00989
Average frequency per unit (data study)	0.02496

The performed calculations for individual risk for the case study building based are calculated using Equation 8. The calculated individual risk for the different frequencies is shown below.

$IR_{barrios} = 0.00989 \cdot 0.947 \cdot 0.2 \cdot 0.25 \cdot 0.9 \cdot 0.08 = 3.37 \cdot 10^{-5}$

$IR_{avg.\ freq.\ per\ unit} = 0.02496 \cdot 0.947 \cdot 0.2 \cdot 0.25 \cdot 0.9 \cdot 0.08 = 8.51 \cdot 10^{-5}$

The sensitivity study shows that the calculated individual risk for the building lies within the lower and upper tolerable limits for the building for all scenarios analysed.

To determine the societal risk for the building based on the varying reliability and frequency values, the developed event tree was used. By varying the reliability of selected fire protection systems and frequency of fire initiation, the societal risk for the varying reliability and frequency values could be determined.

Figure 36 and Figure 37 show the societal risk based on the varying reliability of fire protection systems and frequency. Figure 38 shows the societal risk if the assumption is made that a sprinkler-controlled fire leads to no occupants being exposed to untenable conditions. A combination of the frequency calculated through the Barrios model and a sprinkler-controlled fire leading to no occupants being exposed to untenable conditions can be seen in Figure 39.

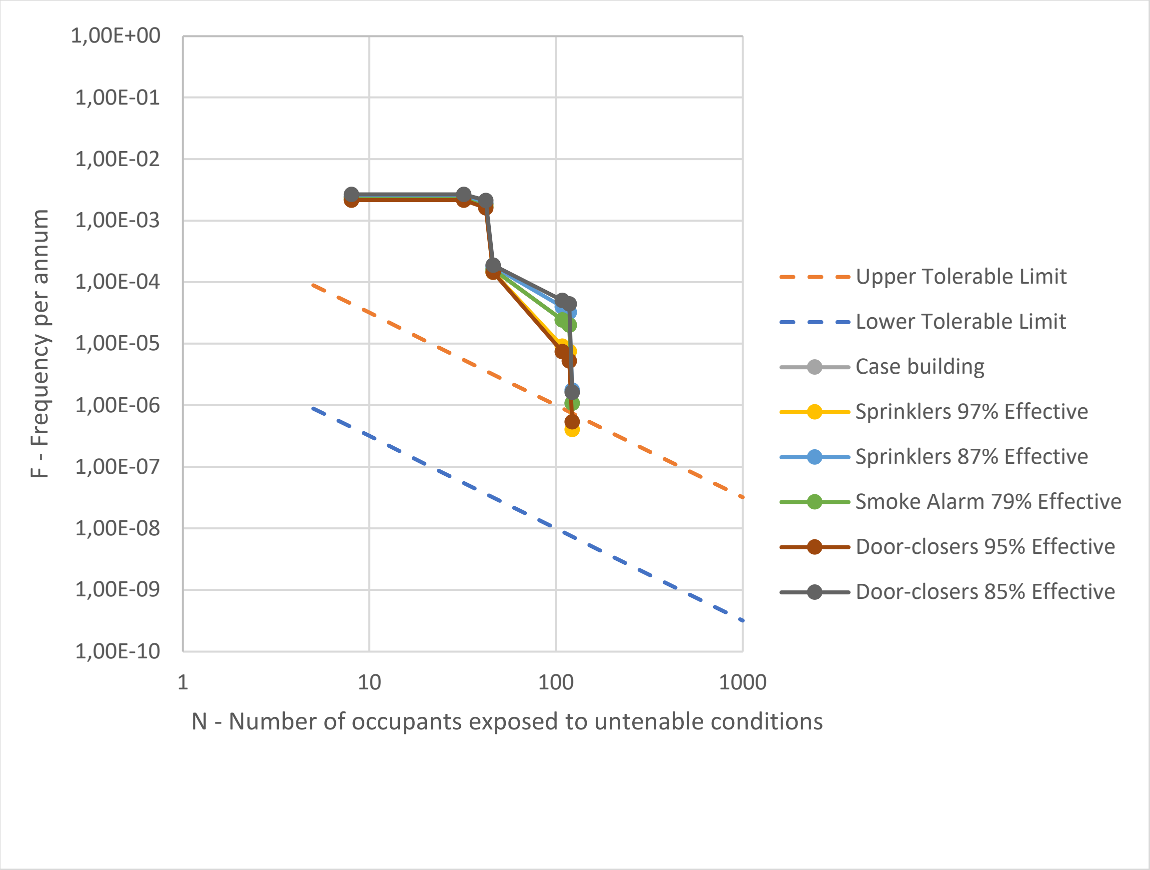

Figure 36: Societal risk based on different fire protection system reliability

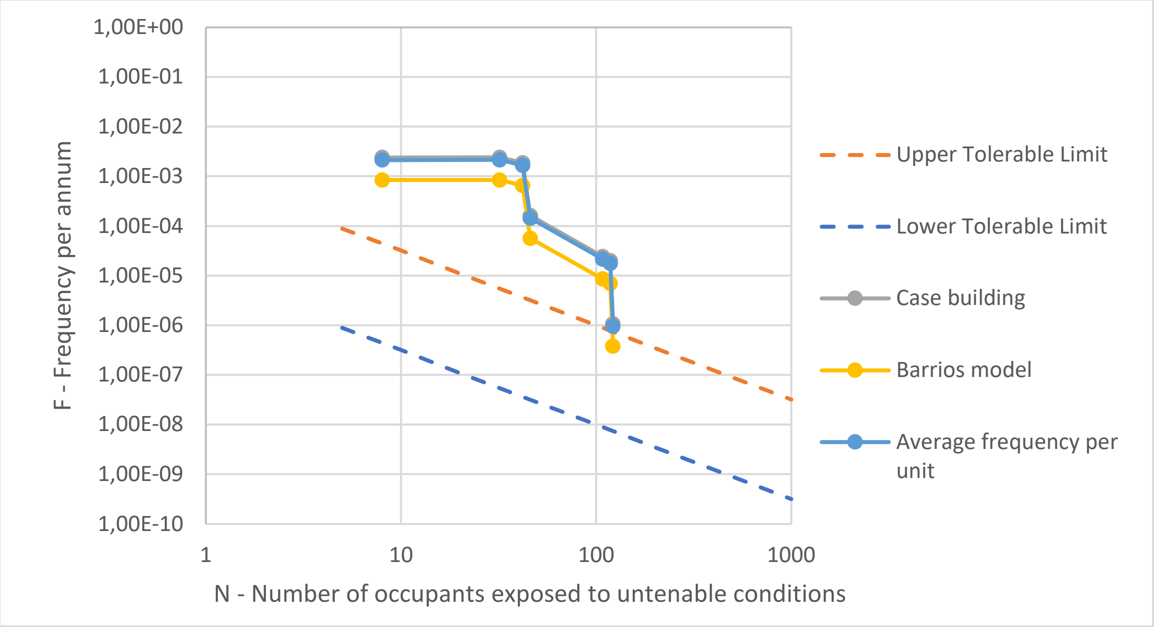

Figure 37: Societal risk based on calculated frequency via other methods

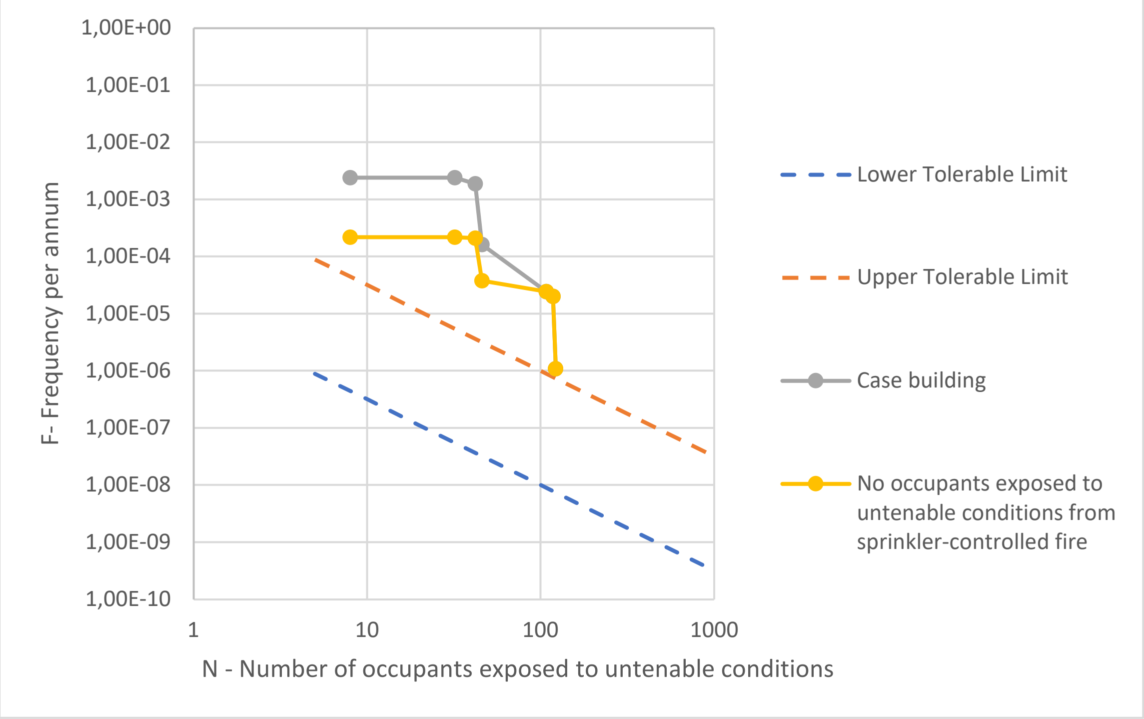

Figure 38: Societal risk based on the assumption that no are occupants being exposed to untenable conditions from a sprinkler-controlled fire

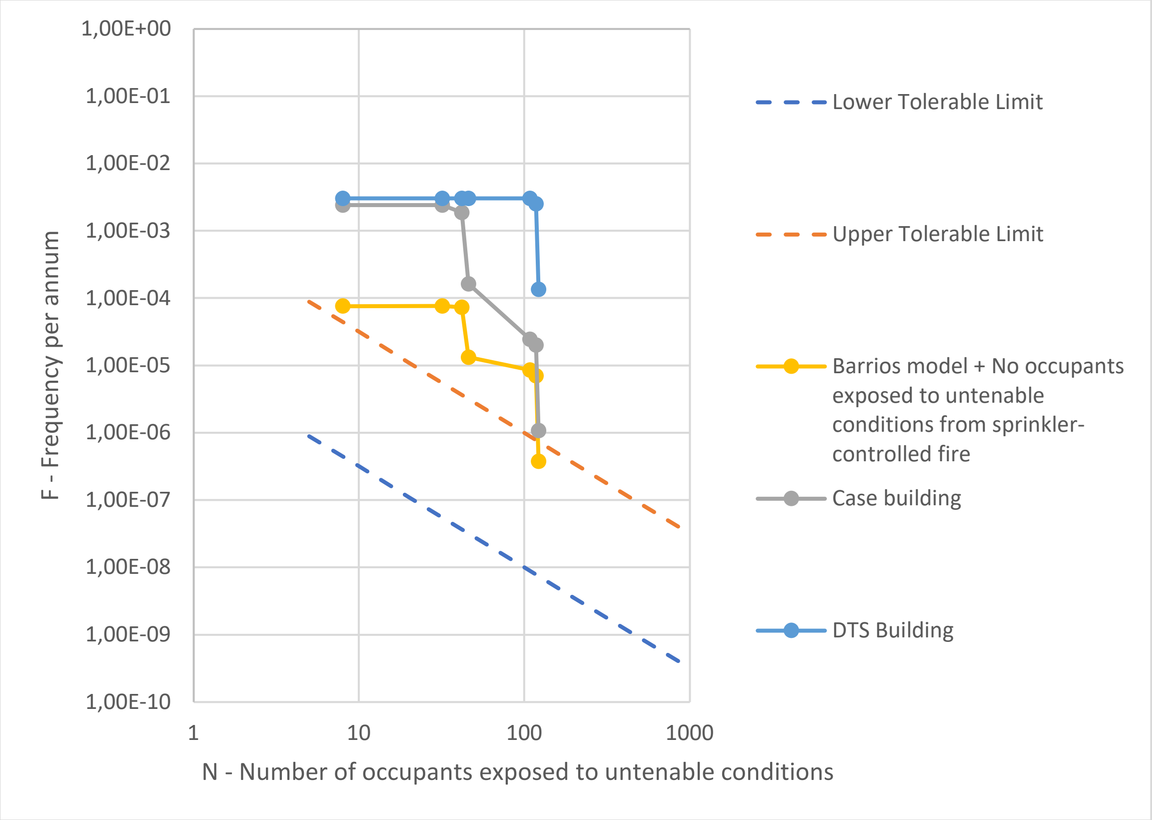

Figure 39: Societal risk based on frequency calculated through the Barrios model in combination with the assumption that no occupants are exposed to untenable conditions from a sprinkler-controlled fire

For societal risk, changing the reliability of the different selected fire protection systems, frequency of initial fires, and assuming that a sprinkler-controlled fire will lead to no occupants being exposed to untenable conditions only results in minor changes to the result. The same can be said for the combination of calculating frequency through the Barrios model and assuming a sprinkler-controlled fire leads to no occupants being exposed to untenable conditions.

5 Comparison to performance-based solution

Based on the result from the case study, the fire safety measures which was used to support the Performance Solutions were able to meet the risk-based criteria in the proposed Part A8 of BCA 2022, except for societal risk and Part A8.3(a)(ii). Part A8.3(b)(iii) is not considered to be applicable for the building.

Not meeting the societal risk levels specified in Part A8 might be caused by the use of conservative estimates for the probabilities and reliabilities for different intermediate events and the conservative tenability criteria used for the consequence analysis.

It should be noted that a DtS building also exceeds the upper tolerable limit for societal risk and would need to be modified according to the proposed legislation. If the societal risk of the case study building had been between the lower and upper tolerable limits and be equal to or lower than a DtS building, then the societal risk criteria for the building would have been satisfied.

The calculated individual risk for the case study building lies within the upper and lower tolerable limit of the risk criteria. Due to the individual risk being estimated to be higher for a DtS building, the case building is considered to meet the criteria for individual risk.

As mentioned, Part A8.3(b)(iii) is not considered to be applicable for the building as stated in Section 4.4.9. The reason for this is that the area and volume of the basement carpark do not exceed the specified floor area and volume listed in Table 8.3b, and the criterion is therefore not applicable for the case study building.

The case study building was determined to not meet Part A8.3(a)(ii) based on the assessment conducted in Section 4.4.7. The criterion specifies the requirement for the building to withstand a radiant heat flux of at least 20 kW/m^2 for 30 minutes. As previously mentioned in the case study, the windows on the building are double glazed. Based on the presented data, calculated heat fluxes, and uncertainties related to e.g., compartment size, opening size, and fuel load, it is hard to determine if the probability of the building being able to withstand a heat flux of 20 kW/m^2 for 30 minutes exceed 0.01. It should, however, be noted that openings at a distance of 3 m or more from the boundary do not need to be protected in accordance with Clause C.3.2 of the BCA.

6 Discussion

6.1 Results

Designing the building with the proposed fire safety measure supporting the Performance Requirements for the case building results in the risk-based criteria in Part A8 being met, except for the calculated societal risk and Part A8.3(a)(ii) related to the probability of the building being able to withstand the heat flux listed in Table 8.3a of the proposed legislation for 30 minutes.

Regarding the probability of the building being able to withstand a heat flux of 20kW/m^2 for 30 minutes exceeding 0.01, it should be noted that there is limited data regarding the probability of failure for glazing. Based on data for breakage during fires, calculated heat fluxes, and uncertainties related to compartment size, opening size, and fuel load, it could not be determined if the probability of the building being able to withstand a heat flux of 20 kW/m^2 for 30 minutes exceed 0.01. Therefore, the criterion was considered not to be met. It should be noted that openings located at a distance of 3 m or more from the boundary are not required to be protected in accordance with Clause C3.2 of BCA 2019 Amendment 1 (ABCB, 2019). The criteria could have been met by providing tempered glass, which did not show cracking for heat fluxes up to 29.2 kW/m2, according to a study (Babrauskas, 1998).

The estimated individual risk for the building lies within the upper and lower tolerable limits. However, due to the estimated individual risk for a DtS building being higher, the individual risk criteria are considered to be met. It should be noted that a DtS building exceeds the upper tolerable risk, as specified in Section 3.1.1.

The estimated societal risk for the building exceeds the upper tolerable limit of the risk criteria. This may be caused by the use of conservative estimates for the probabilities and reliabilities for different intermediate events and the conservative tenability criteria used for the consequence analysis. It should be noted that a DtS building also fails to meet the criteria for societal risk and would need to be modified according to the proposed legislation. If the societal risk of the case study building had been between the lower and upper tolerable limits and be equal to or lower than a DtS building, then the criteria would have been satisfied.

6.2 Fire scenarios and frequency of fires

The selected fire scenarios for the case study were based on the most probable fire location and a scenario that is expected to cause severe consequences potentially. Due to the potential high fire load in a carpark, a fire in the basement carpark was also considered as a scenario in this assessment. However, it was decided not to include a carpark fire scenario. The reason for this is that based on the hazard identification in Section 4.3, the number of carpark fires in residential buildings is relatively low compared to apartment fires. In addition, the number of injuries and deaths is quite low for carpark fires compared to fires in other areas of residential buildings. Further, it can be assumed that occupants being located inside their apartments 24 hours a day will be exposed to higher individual risk compared to occupants dividing their time between different enclosures.

To estimate the individual and societal risk for the different scenarios in the event tree, the average frequency of fires per square meter and year was used based on the data study conducted for the ABCB. The selected frequency for use in the case study is only based on the number of reported fires attended by the fire brigade and might therefore underestimate the frequency of fires for apartment buildings. This is not expected to affect the calculated probabilities for the proposed Part A8.3 but might affect the results concerning Part A8.2. The calculated frequency of fires for apartment buildings based on the Barrios model suggests an even lower frequency of fires per year. The frequency based on the number of units is also based on reportable fires attended by the fire brigade and might therefore also underestimate the frequency of fires for apartment buildings.

6.3 Modeling of fire scenarios

The fire scenarios were modeled on a 5 MW fire in the apartments and a 350 kW fire in the corridor (Refer Appendix C). The fire scenario for the apartments can be considered to be a worst credible-case fire and is therefore conservative. However, not every fire occurring in an apartment will have an HRR of 5 MW. A smaller fire would be expected to increase the time until untenable conditions for the occupants inside and outside the enclosure of fire origin.

Due to the openings located inside the SOUs, a lot of heat can be expected to be lost out of the openings when the windows break in the created CFAST model. Because of this, the windows are set to be closed during the duration of the fire scenario, and a small vent measuring 1 m wide and 0.1 m high was created near the bottom of each enclosure for ventilation. To ensure that enough oxygen is supplied during a fire, different sizes of ventilation openings were modeled. However, it was concluded that larger openings (up to 7 m wide and 0.1 m high) only had a minor impact on the modeling results. This is expected to create more realistic modeling scenarios.

Adiabatic compartment surfaces were used in the CFAST modeling. This means that the surfaces cannot absorb or lose heat. This should lead to more conservative results from the simulations. For the sprinkler-controlled scenarios modeled in CFAST, an automatic sprinkler system was modeled for each scenario. It should be noted that sprinklers in CFAST only impact the heat release rate of fire. Sprinkler activation in CFAST does not reduce the duration of a fire, which means that the consequences estimated in sprinkler-controlled scenarios are expected to be conservative.

6.4 Consequence analysis

The Available Safe Egress Time (ASET) was based on the modeling of a fire in three apartments of different sizes at varying distances to the fire-isolated stair on floor level 1, as shown in Figure 41. An average time to untenable conditions for an SOU fire was then calculated to determine the ASET for occupants. The lowest and highest ASET for an occupant within the enclosure of fire origin for a fire in an SOU was 76 s and 120 s for the sprinkler failure scenario, and 76 s and 124 s when the sprinkler systems control the fire, as shown in Table 46.

If the lowest ASET value had been used, a fire while the occupants are sleeping would result in occupants being exposed to untenable conditions for every SOU for both the non-sprinklered and sprinklered scenario. However, sprinkler activation in CFAST only affects the HRR of the fire, so it can be expected that the consequences would be lower for a sprinkler-controlled fire.

An average ASET was also calculated for occupants located outside of the enclosure of fire origin, as shown in Table 46. Because of the use of an average ASET, all occupants located outside of the enclosure of fire origin during a sprinkler failure SOU fire during daytime were determined to be exposed to untenable conditions. However, if the longest time to ASET had been used, the number of occupants exposed to untenable conditions would be lower.

Human behaviour in fire is hard to predict, and there can be large variations in pre-movement time for different persons. This is something that might affect the calculated RSET time, which is shown in Table 62. It should be noted that the pre-movement time for occupants can vary and be up to between 10 to 20 minutes for occupants who cannot see smoke (BSI, 2019).

For the case study, no consideration is taken to intoxicated or mobility impaired occupants, which are risk factors for fatal fires (Runefors, 2020). It is expected that intoxicated and mobility-impaired occupants will have a longer egress time or be unable to egress the building. In addition, no consideration is made to potential queuing before entering the stair. Should queueing occur in front of the stair, the RSET can be expected to be longer.

It is not always guaranteed that occupants will awake upon smoke alarm or smoke detection activation. Bruck (1999) studied to which extent adults and children will awaken to a smoke alarm with a dBa of 60 located in the hallway with the bedroom door left open. Based on the study, it was determined that all adults reliably woke up to the alarm, while only up to 35% of children reliably awoke to the alarm.

The building studied in the case study has sounders with a minimum sound pressure level of 75 dBa installed in the SOU bedrooms. It is hard to determine exactly how the provision of sounders with a higher minimum sound pressure will affect the number of children reliably becoming awake by the alarm. However, the percentage is expected to increase. The issue of using an ASET-RSET analysis in quantitative risk analysis in building classes with sleeping occupants is further discussed in Section 6.8.

6.5 Event tree

The event tree for this case study was created based on an initial fire event followed by intermediate events expected to happen in chronological order for each scenario. Several fire protection systems included in the performance solution for the building were included in the event tree analysis as previously specified in Section 4.4.3.2. In addition, intermediate events related to or affecting human behaviour were also included. These are presented and described in Section 4.4.3.2.

The active fire protection systems included in the performance solution but not in the event tree analysis are the heat detector to the top of lift shafts, provision of fire hose reels, and fire hydrants as previously specified in Section 4.4.3.2. The reason for this is as follows:

- Fire hose reels are provided to the basement level of the building and, therefore, are not included in the selected fire scenarios.
- The fire hydrant system is a provision to the fire brigade and therefore not included.
- The heat detector replaces a smoke detector (which would be required in a DtS building) at the top of the lift shafts. The provision of a heat detector instead of a smoke detector to the top of the lift shaft is not expected to change the result of the case study.

The omission of these fire protection systems from the event tree is therefore not expected to affect the calculated risk for the subject building.

Based on the conducted literature review for reliabilities and probabilities located in Section 2.2.10.2, fire hoses and fire extinguishing equipment prevented fire spread in 15% of all fires per year in Norway. This is based on all residencies being equipped with fire extinguishing equipment. In addition, a study from Sweden presented in the same section of this report states that fire extinguishers are used in 17% of recorded incidents. Clause E1.6 of the BCA requires portable fire extinguishers to be located outside of the SOUs, with a travel distance from an SOU to a fire extinguisher of a maximum of 10 m. It should be noted that the conditions in the case study building might differ from the buildings where the data for portable fire extinguisher usage was gathered during the literature study. Therefore, a conservative probability of fire extinguisher usage of 15% has been selected for use in the event tree analysis.

To account for occupants on other floors than fire origin being exposed to untenable conditions, intermediate events were added for fire spread to one more level via the window and fire or smoke spread to the fire-isolated stair. Fire spread to one more level was based on statistics (Korhonen & Hietanemi, 2005). While the probability of this happening is low, it was decided to be included in the event tree as a way to account for fire spreading to another floor than the floor of fire origin. Due to the low probability of fire spread via the window to one more level happening, the estimated societal risk for the building was basically unchanged in case of this event happening. The intermediate event added for fire or smoke spread to the fire-isolated stair has a large effect on the expected number of occupants being exposed to untenable conditions since it is assumed that all occupants in the building will be unable to egress the building via the fire-isolated stair. This is a conservative assumption since smoke spread upwards, and occupants located below the floor of fire origin are therefore expected to be able to egress the building in many cases.

6.6 Selected tenability criteria

For toxicity, a tenability criterion related to visibility was selected instead of, e.g., a fractional effective dose. In case of fire, it can be expected that the visibility will be limited for the occupants before they are exposed to a dose high enough for the conditions to become untenable. In addition, Kobes et al. (2010) state that many occupants tend to walk through smoke in case of a fire instead of sheltering in place inside their apartment. The use of visibility criteria for toxicity is therefore conservative. This is expected to cause an overestimation of the consequence and affect the calculated societal risk. Therefore, the usage of a conservative criteria for toxicity might partially explain the building exceeding the upper tolerable level for societal risk.

If FED had been used for tenability criteria, it would be expected that the time until untenable conditions or ASET would be longer compared to using visibility as tenability criteria for toxicity. It should, however, be noted that carbon monoxide (CO) prediction could result in a maximum error of approximately 500% (Melcher, Zinke, Trott, & Krause, 2016).

6.7 Sensitivity analysis

Based on the conducted sensitivity analysis, changing the reliability levels of different fire protection systems changes the individual and societal risk for the building up to a factor of ten. Depending on which system the reliability is changed for, the change in risk can therefore be substantial. Changing the reliability of smoke alarms mainly affects the individual risk level, which is expected based on the result of the case study.

Varying the frequency for the case building based on the different models presented to determine frequency shows that calculating frequency by using the Barrios model results in a lower frequency of initial fire compared to one of the models using the data study. As previously mentioned, the frequencies calculated by the use of the data study are expected to be underestimating the frequency of initial fire due to the omission of fires not reported to and attended by the fire brigade. However, the author has not been able to determine if and by how much the frequency, in that case, is underestimated. Based on this, it can be expected that using the Barrios model also results in an underestimation of the frequency.

The assumption that a sprinkler-controlled fire results in no occupants being exposed to untenable conditions also lower the estimated societal risk by about a factor of ten. This assumption mainly affects the risk level for scenarios leading to a lower number of consequences. The reason for this is that the reliability of automatic-door closers has a larger effect on whether fire or smoke is expected to spread to the fire-isolated stair, leading to the highest consequence for the building.

Combining the assumption of a sprinkler-controlled fire not leading to any occupants being exposed to untenable conditions and the calculated frequency using the Barrios model causes the biggest change in societal risk level. It should, however, be noted that the calculated individual risk is still within the acceptable limits and that the societal risk for the building is still above the upper tolerable limit.

6.8 QRA as a verification tool – advantages and disadvantages

Several challenges were encountered while conducting the quantitative risk assessment. One challenge was related to the scenario selection process. Selecting relevant scenarios to be evaluated for a building is dependent on being able to identify potential hazards. However, even if one manages to identify all potential hazards, it is not practical to evaluate every single possible scenario. Failing to select relevant scenarios might result in an incorrect estimation of risk. The scenarios determined to be evaluated by the author of this thesis represent one with a higher probability but a lower expected consequence and one with a lower probability but expected higher consequence. It is expected that these two scenarios be adequate to evaluate the risk for the building.

Several simplifications were made for the event tree analysis in relation to fire spread outside of an SOU as specified in paragraph 4.4.3.2. These simplifications might have contributed to the societal risk level for the building not being met. It should also be noted that a DtS building with the same simplifications performed worse and was not able to meet the societal or individual risk criteria, as shown in Section 4.4.5.

During the literature study, it was found that only limited data exists for Australian contexts, such as data related to human behavior in fire, probability failure data of different types of glazing, and data used for hazard identification (fire location, first item ignited, etc.). Therefore, data from other countries have been used to conduct the assessment. When selecting probability data, it is important to consider if and to what extent that data can be applied to, e.g., an intermediate event in the event tree. To determine to what extent the data can be used, it is important to, if possible, compare and see if similar conditions exist. It was not part of the scope of this thesis to determine if similar conditions exist for all the data used from other countries.

The question on how to select reliability and probability data for use in an analysis also needs to be asked. When selecting data, it is possible to select conservative or expected estimates for the probability or reliability of an event to happen or a system to operate or fail. When designing a building, conservative data values are usually preferred, and worst-case scenarios are applied in deterministic analysis. However, selecting conservative data values for a probabilistic analysis might result in a too conservative estimation of risk, resulting in the risk criteria not being met. As previously discussed, this can probably be seen in the evaluation of societal risk for the case study building, where a less conservative frequency estimation and consequence analysis resulted in a lower societal risk for the building, and the suggested building design came closer to meeting the required criteria. Therefore, less conservative or expected values should be used in an analysis if deemed appropriate.

Based on the resulting societal risk for the building, the proposed legislation would require the building to be redesigned. However, this has not been done due to the analysis being conducted on an already existing building with specified fire safety measures. Redesigning the building is expected to be a potentially time-consuming and expensive process. This is expected to be the case for large and complex event trees.

Another challenge to selecting data is related to uncertainty. It is not always clear which uncertainties exist for the different data gathered for probabilistic analysis. This might lead to the under or overestimation of the probability or reliability of an event.

When conduction an ASET-RSET analysis for any type of building class with sleeping occupants, uncertainties exist in relation to whether the occupants are awake or asleep. For example, there might be occupants sleeping during the day due to them working night shifts. It could also be the case that not all occupants are asleep during the night.

These uncertainties lead to large variations in the egress time for the occupants located in the building and make it hard to estimate the number of occupants exposed to untenable conditions correctly. Because of this, an ASET-RSET analysis may not be appropriate to use when analysing a building with sleeping occupancies. Due to these uncertainties, it is important to design a robust fire safety strategy for the building.

The author’s opinion is that using Quantitative Risk Assessment for evaluating fire safety in buildings can be expected to lead to a more holistic fire safety design for a building compared to just evaluating specific selected performance requirements for the identified departures from deemed-to-satisfy provisions. A more robust fire safety design may also result as a consequence of the QRA due to the evaluation of potentially a large number of scenarios and by considering the probability of success for different fire protection systems.

6.9 Proposal for selecting a QRA method

When selecting a QRA method, it is important to consider the circumstances that exist for the building that is being analysed. This also means that it might not be adequate to use a single method but that a combination of methods needs to be used. As presented in Section 2.2.8.1, Cadena Gomez (2021) reviewed different methodologies for conducting a Quantitative Risk Assessment. Based on the author's review, the SFPE Guide is considered the best performing guideline, i.e., the most appropriate to use in fire risk analysis out of all guidelines in general.

The author of this thesis did not follow a specific guideline but used an event tree based QRA approach. Based on the author's experience from building the case study, the event tree method proved to be useful since it made it possible to arrange the different fire scenarios in a chronological order to consider the failure or success of different intermediate events and barriers such as fire protection systems in the analysis. It is also possible to integrate commonly used fire safety tools into event tree to help determine the probability of each event. In addition, the approach made it possible to link the consequence analysis to different scenarios. These experiences gained during the study are consistent with the information gathered during the literature study, which was used as a basis for selecting the method as presented in Section 4.1.

Based on this, it is therefore proposed that an event tree based QRA approach is used when conducting a QRA for a building. The event tree approach is one of the approaches deemed suitable during the design stage when conducting a risk assessment (Rausand, 2011).

During the case study, an ASET-RSET analysis was also conducted for the consequence analysis. While the author does believe that an ASET-RSET analysis is a useful method for use during a QRA, the author does not recommend its use for any occupancy with sleeping occupants. These include Class 2 buildings, Class 3 buildings, and Class 9c Aged Care buildings. Instead, it is suggested that other methods are used to determine the consequences for these tenancies.

6.10 Difficulty in interpreting the legislation

The author considers the legislation hard to interpret with regards to the probability of a building to ‘withstand’ a specified heat flux or exposure. The reason for this is that some conditions within the definition of ‘withstand’ are open to interpretation since the BCA does not provide explanatory information.

6.11 Future challenges

While some of the challenges discussed above might be addressed in the near future, additional challenges may rise, e.g., electric car fires or mass timber building fires. It can be questioned if the current data available for these upcoming challenges are reliable.

7 Conclusions

The following conclusions can be made from this study based on the questions presented in the problem definition in Section 1.3.

- What are the consequences of using QRA as a verification tool? What are the advantages and disadvantages of using QRA as a verification tool? What difficulties arise? What happens to robustness?
- How has the proposed legislation been developed, and how is it being applied? What potential difficulties are encountered during the application of the proposed legislation?
- How would one select which QRA method to use?

Using QRA for evaluating fire safety in buildings is expected to lead to a more holistic fire safety design for a building compared to just evaluation specific selected performance requirements for the identified departures from deemed-to-satisfy provisions.

A more robust fire safety design may result as a consequence of using QRA for evaluating fire safety due to the evaluation of potentially a large number of scenarios and by considering the probability of success for different fire protection systems.

Evaluating fire safety by the use of QRA comes with several challenges, including limited availability of data, selection of scenarios, and uncertainties related to available data.

The legislation was developed through a process containing several stages, including a review of documents, the derivation of variables to be considered, development of an issues matrix, consolidation of all fire safety-related Performance Requirements into two requirements, and providing a text for inclusion in a public comment draft. The first part of the legislation, Part A8.1 specify the application of Part A8.2 and A8.3. The two last parts of the, Part A8.2 and A8.3 applies to the interpretation of a number of specified Performance Requirements that relate to departures from the Deemed-to-Satisfy provisions. The legislation is considered to be hard to interpret in some cases since explanatory information is not provided.

Based on the findings in the literature study, the SFPE Guideline is, in general, the most appropriate framework to use. It is proposed to use an event tree based QRA approach when conducting a QRA for a building.

8 Further work

Further research into the areas mentioned below would provide benefits to similar studies conducted in the future.

Based on the literature review, it was found that only limited data exist for Australian contexts. Access to more complete data would contribute by reducing the uncertainty of selected probability and reliability data. Additional data which would be of use are, e.g., data related to human behavior in fire, probability failure data of different types of glazing, and data used for hazard identification for Australian contexts (fire location, first item ignited, etc.).

Examples of previous case studies conducted are a single storey retail building, an eight-storey residential aged case building, a single-storey primary school building, and a five-storey building with a primary school, café, and entertainment tenancies. Additional case studies with sensitivity analyses are suggested to be conducted to determine how the probability or reliability of different fire protection systems affect the risk level of the building. Most calculated risks are acceptable in the case study of this report largely because of the provision of sprinklers. One suggestion is, therefore, to conduct a case study on a residential building without sprinklers.

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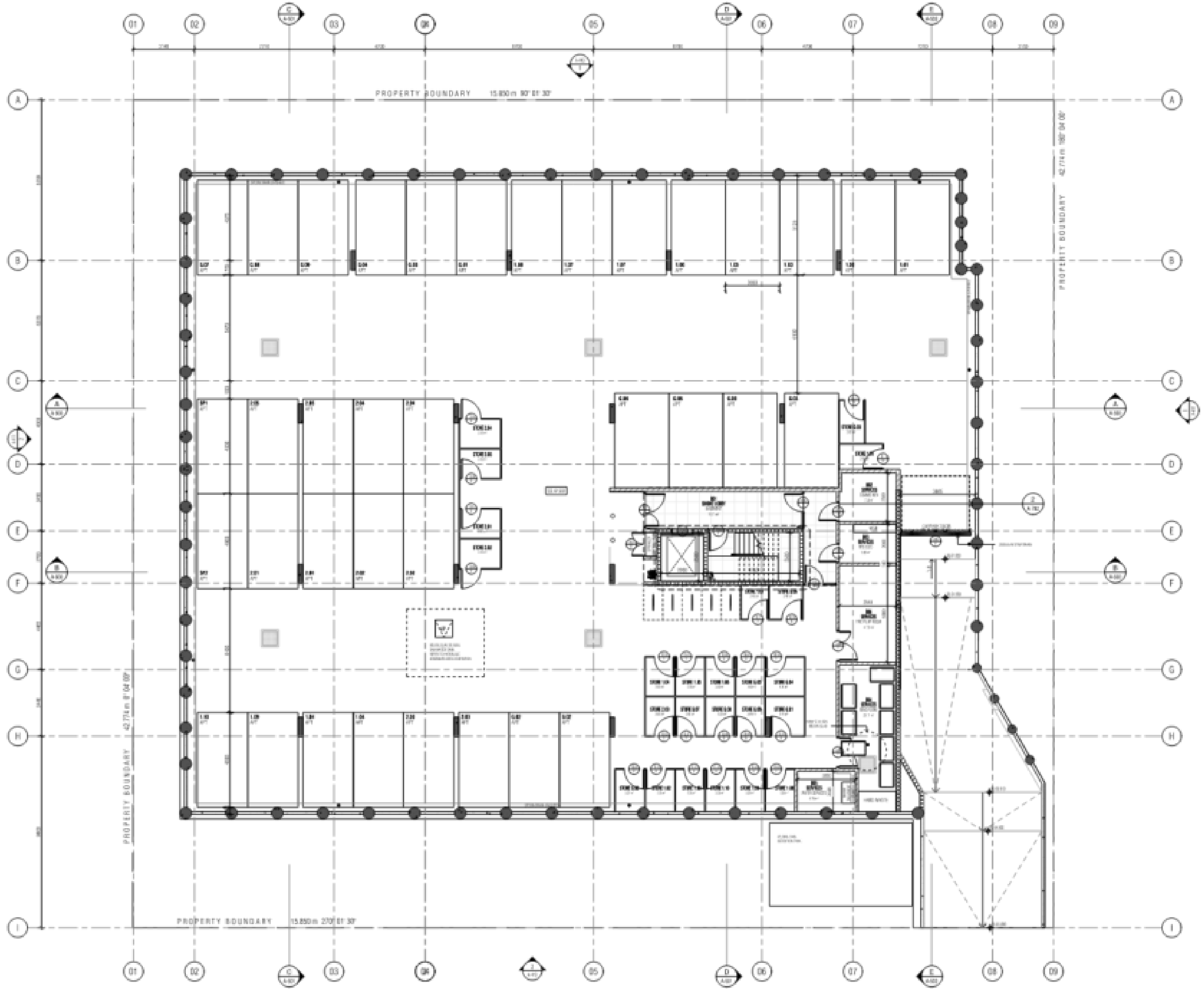
Appendix A. Drawings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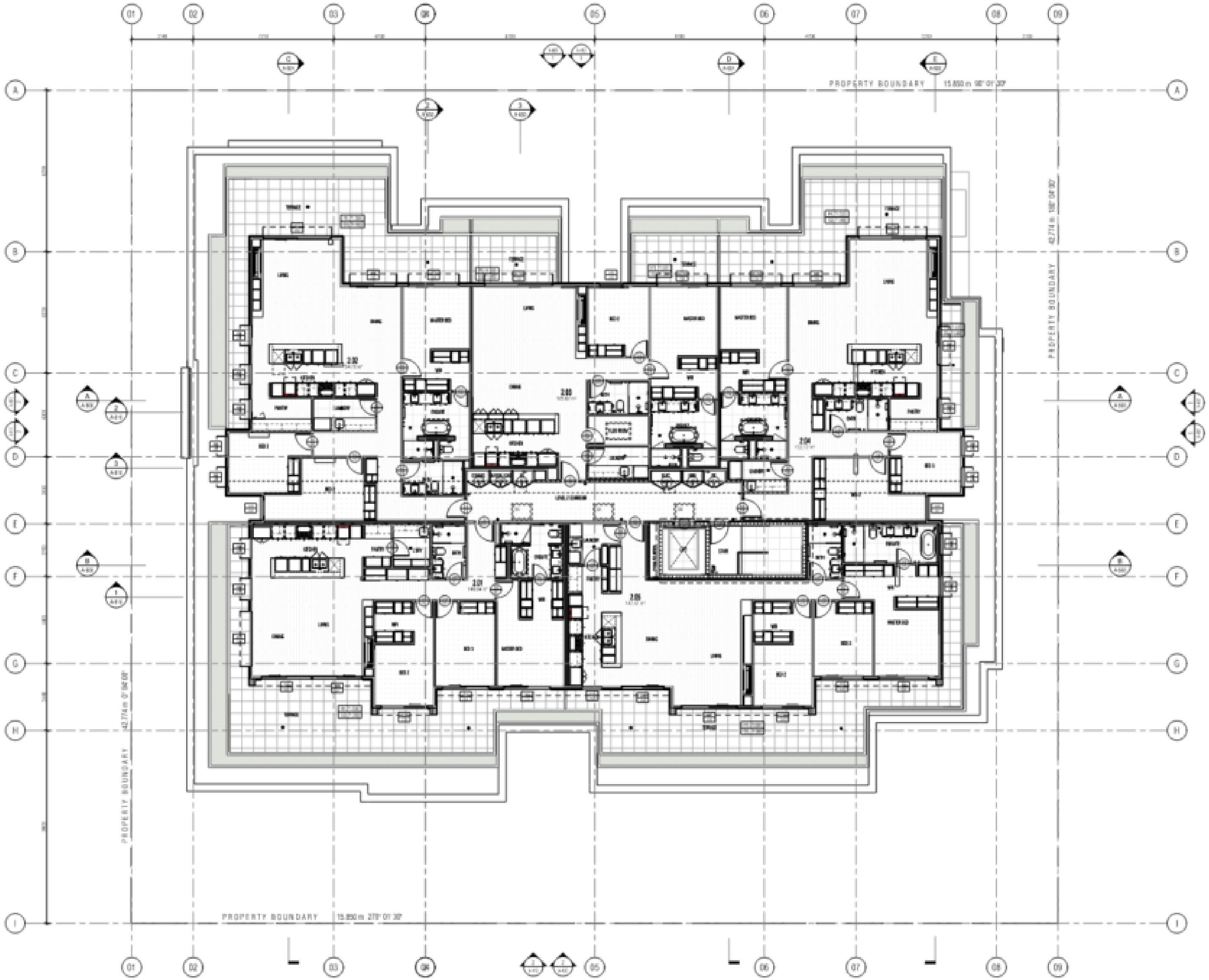
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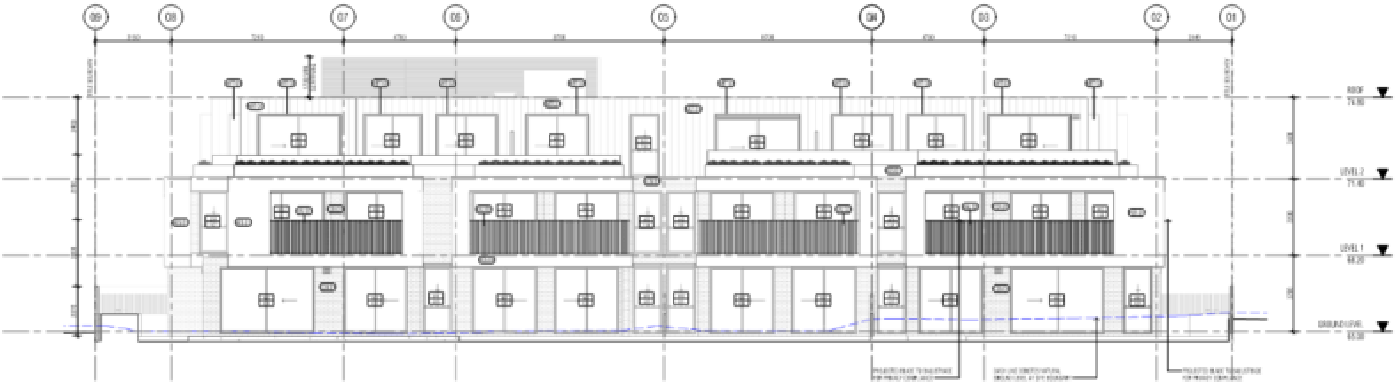

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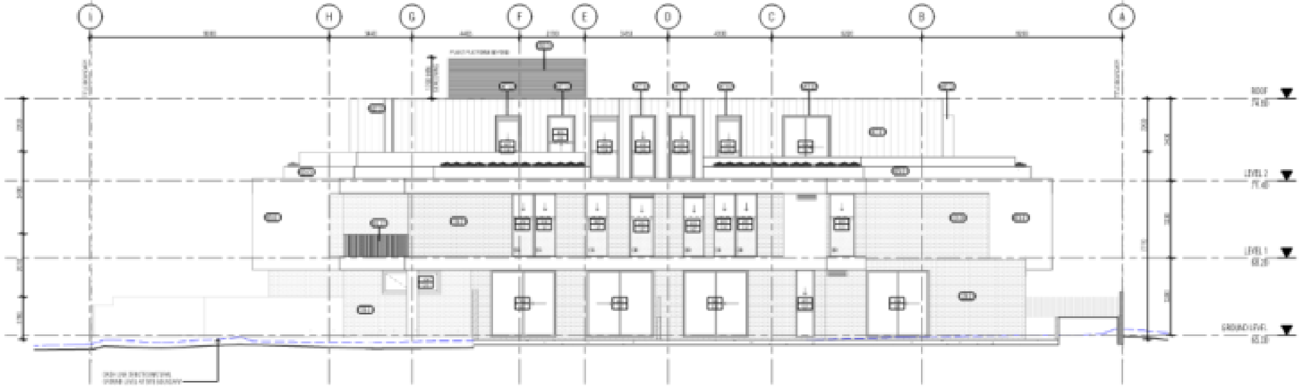
2 ELEVATION SOUTH
SCALE 1 : 100



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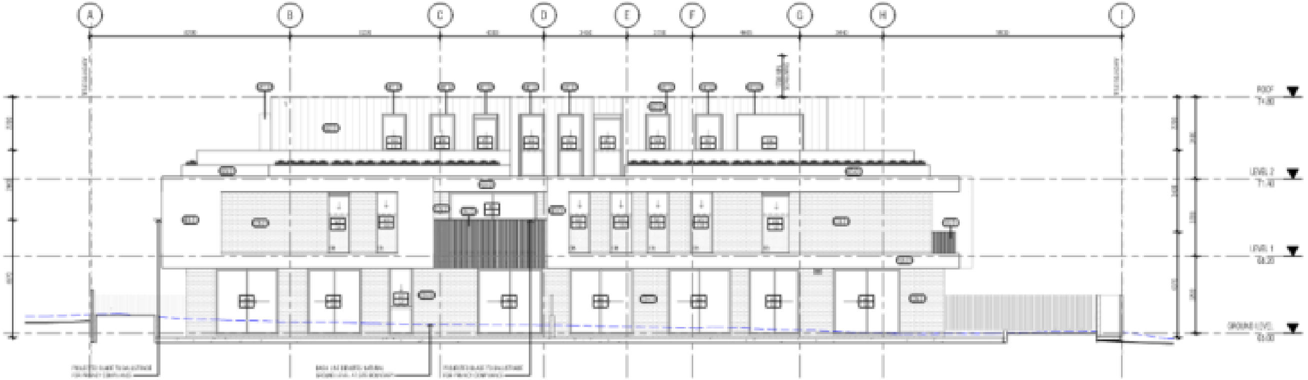

2 ELEVATION_WEST
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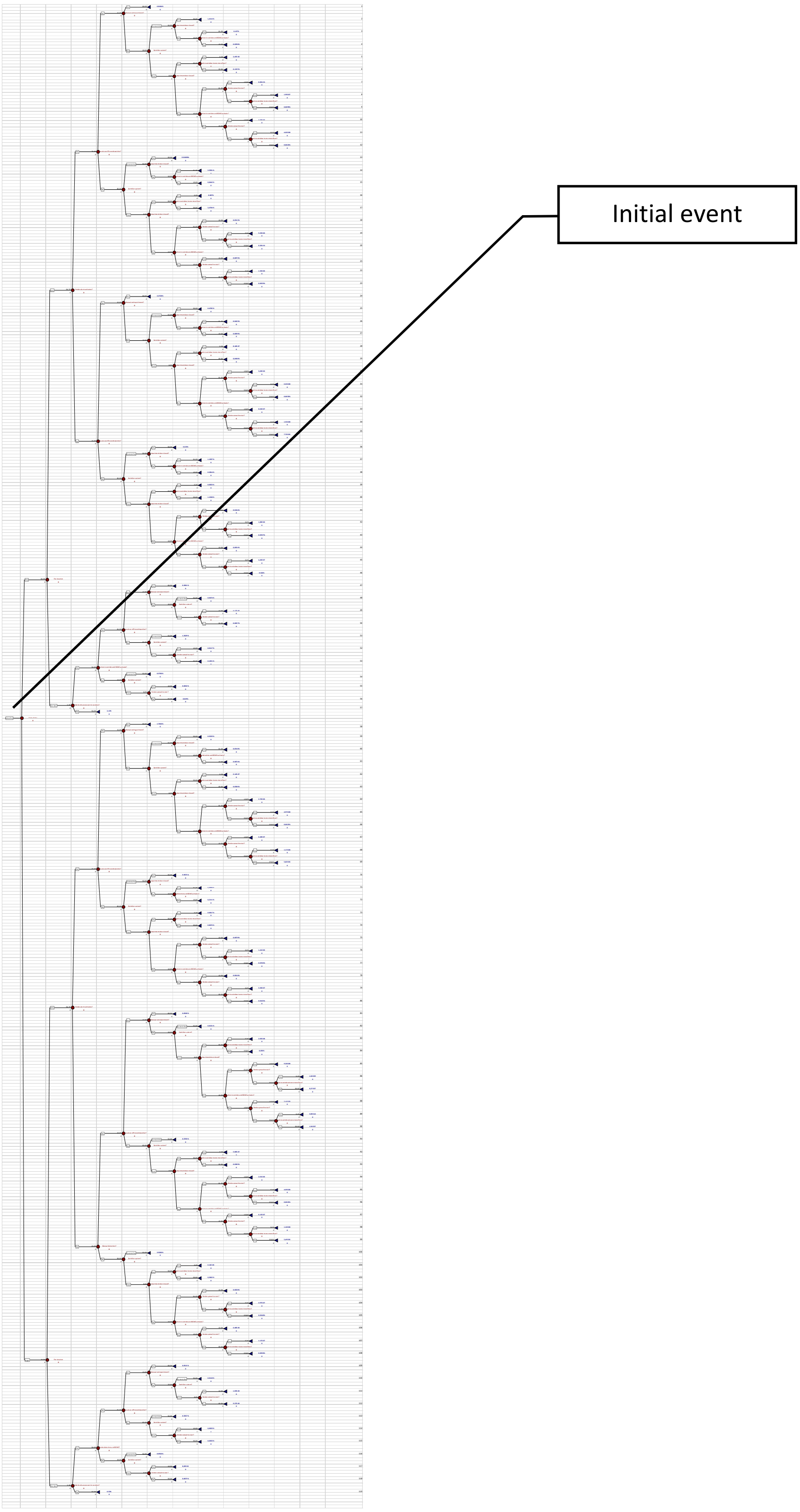
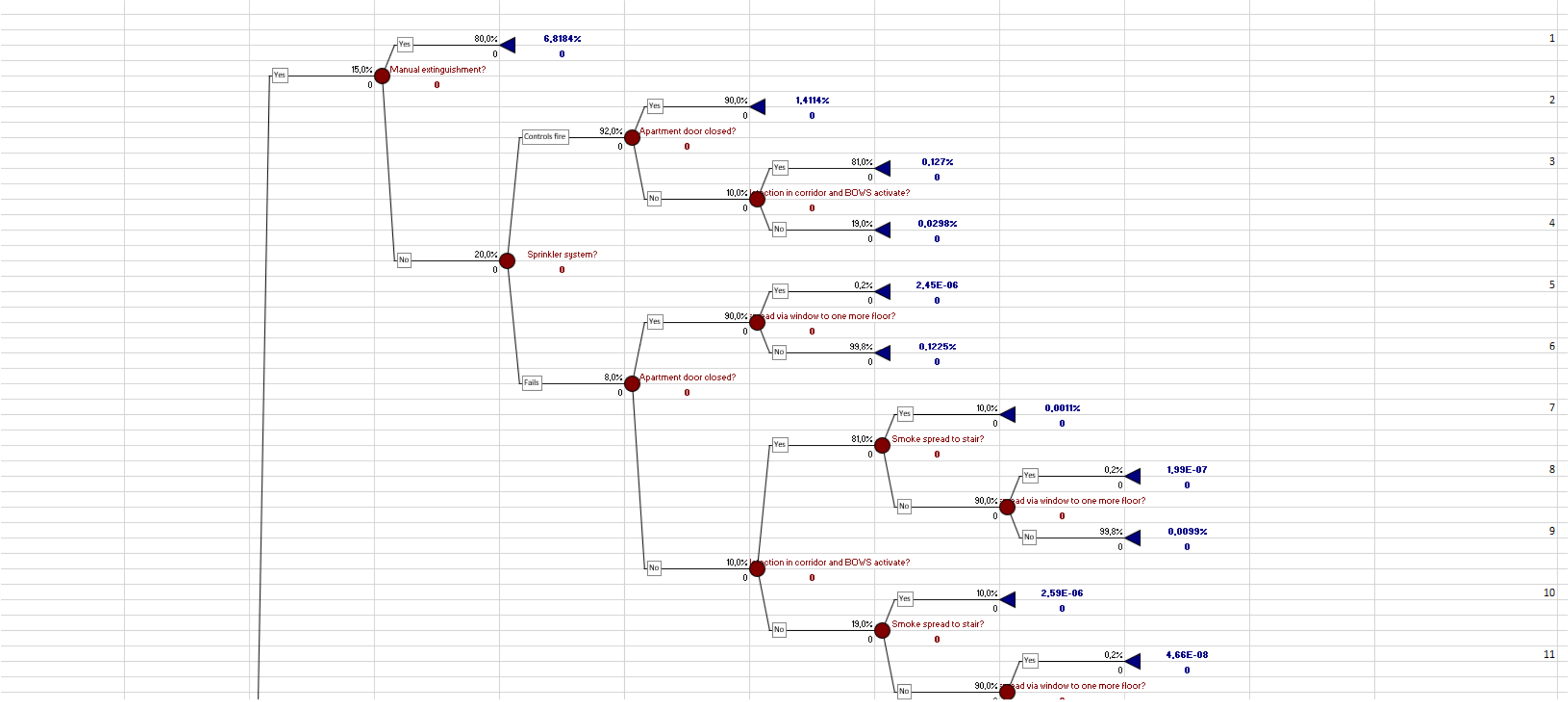
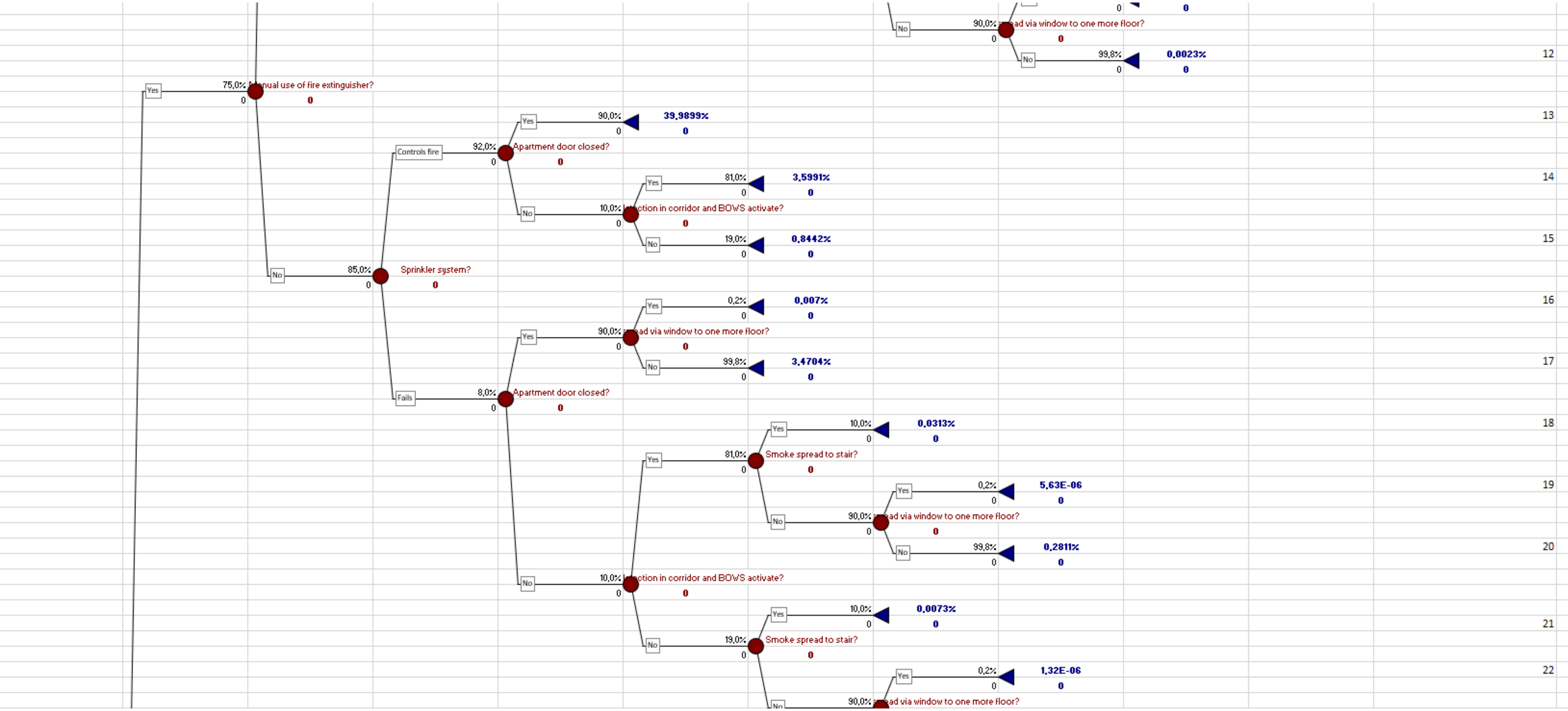
Appendix B. Event tree

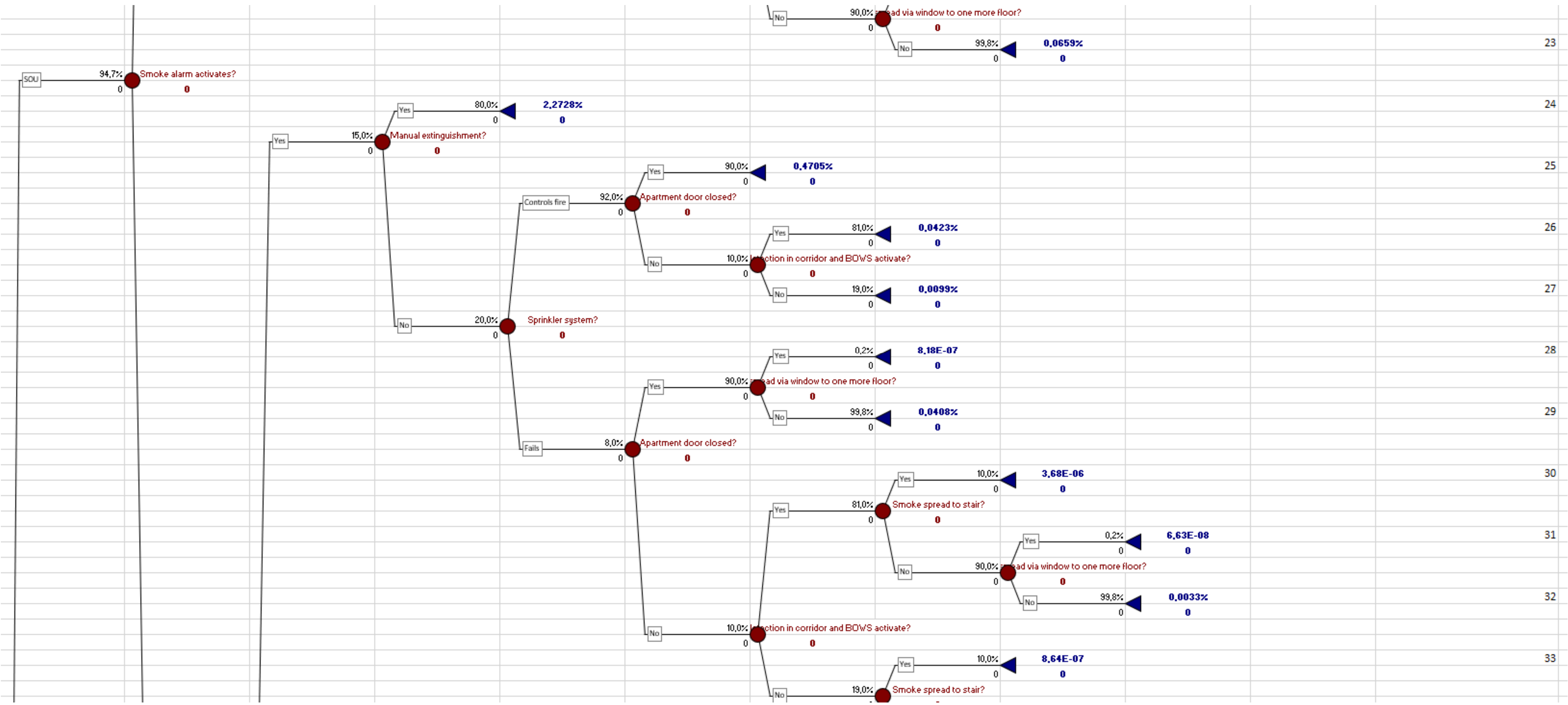
Event tree overview

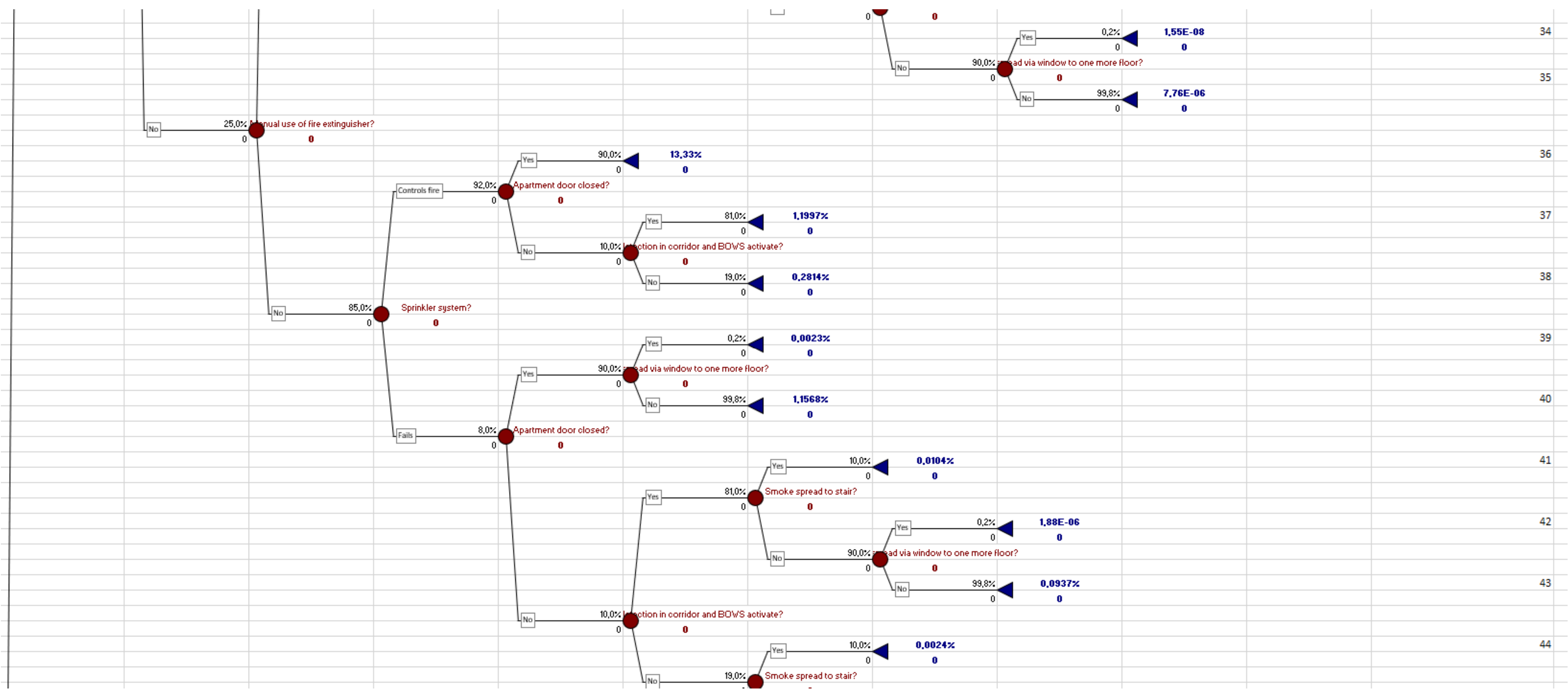


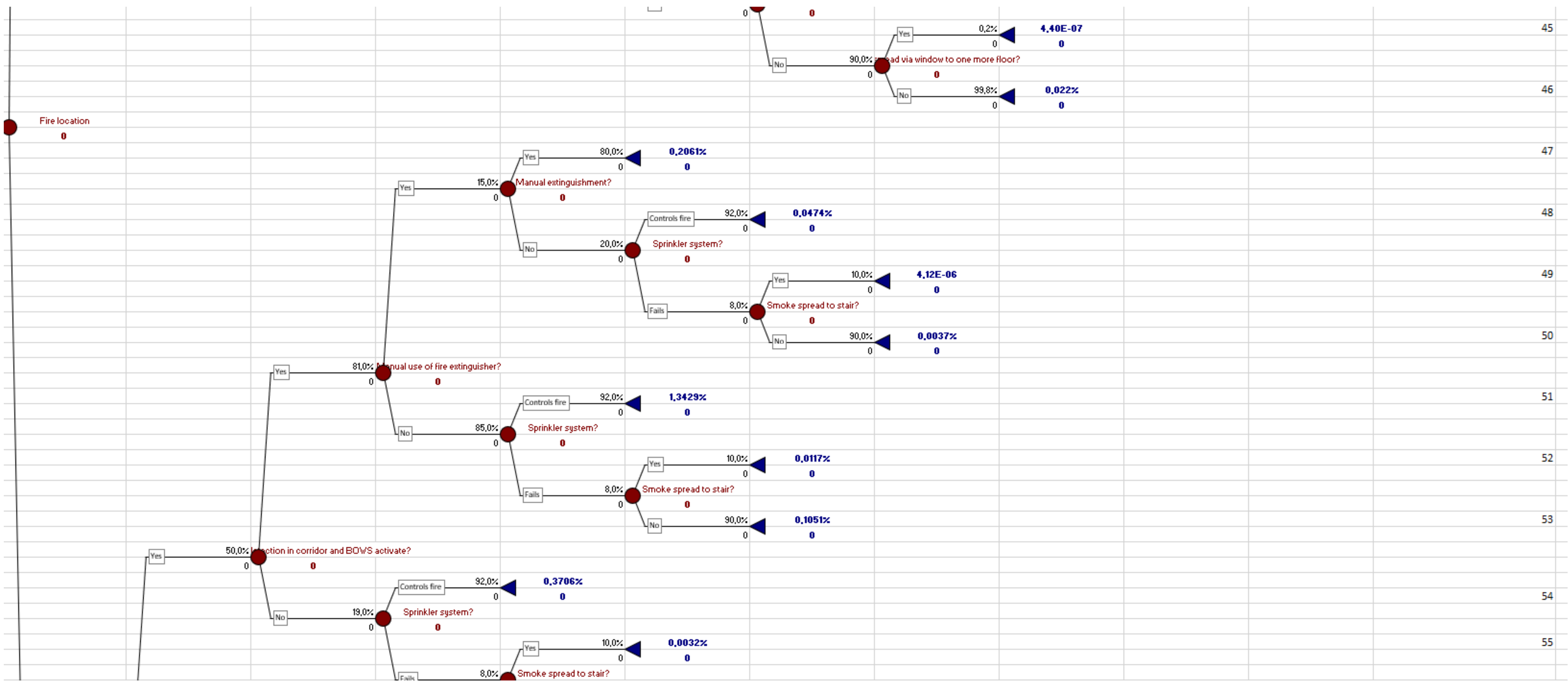
Detailed event tree

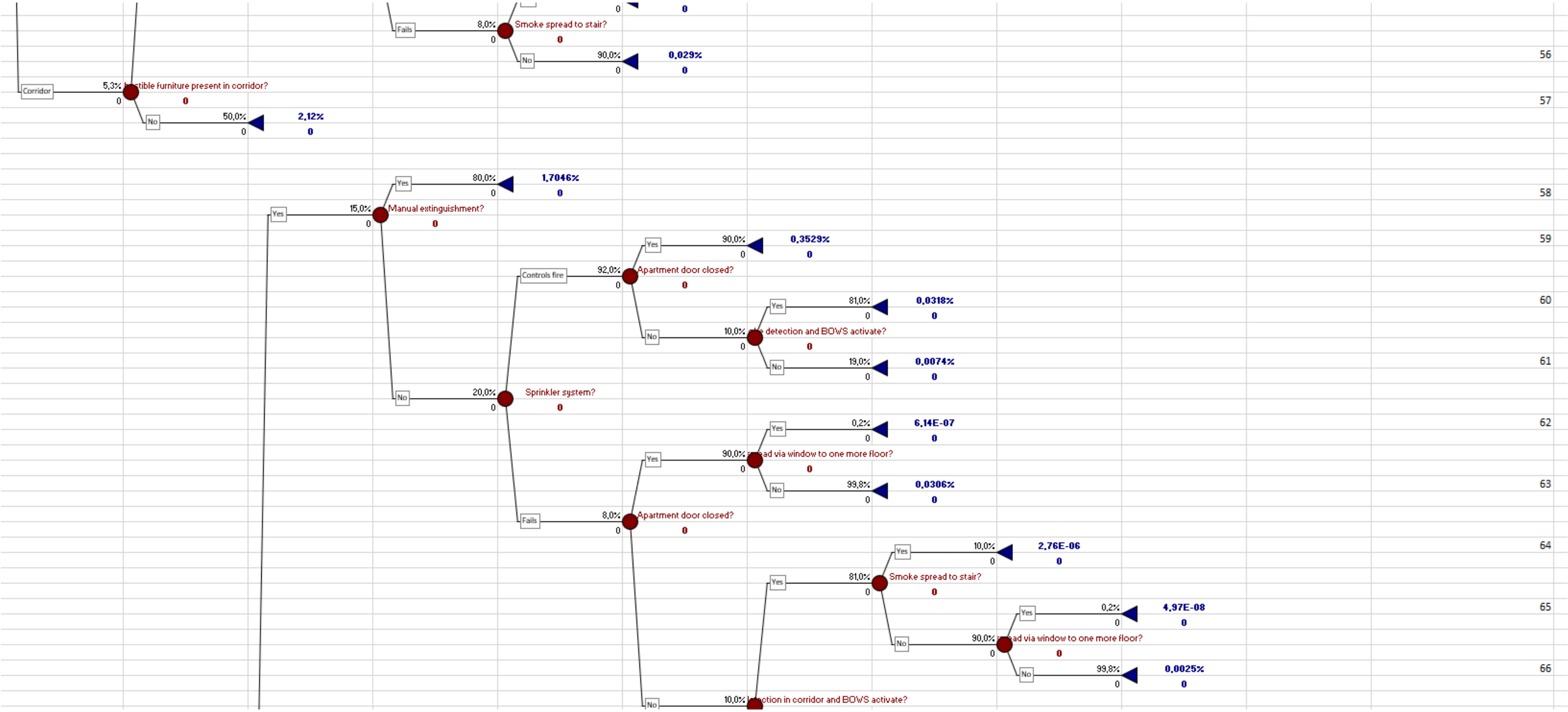



0
0
No
90,0%
ad via window to one more floor?
0
0
No
99,8%
0
0,0023%
0
12
Yes
75,0%
nual use of fire extinguisher?
0
0
Yes
90,0%
0
39,9899%
0
13
Controls fire
92,0%
0
Apartment door closed?
0
Yes
81,0%
0
3,5991%
0
14
No
10,0%
ction in corridor and BOWS activate?
0
0
No
19,0%
0
0,8442%
0
15
No
85,0%
0
Sprinkler system?
0
Yes
0,2%
0
0,007%
0
16
Yes
90,0%
ad via window to one more floor?
0
0
No
99,8%
0
3,4704%
0
17
Fails
8,0%
0
Apartment door closed?
0
Yes
10,0%
0
0,0313%
0
18
Yes
81,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
5,63E-06
0
19
No
90,0%
ad via window to one more floor?
0
0
No
99,8%
0
0,2811%
0
20
No
10,0%
ction in corridor and BOWS activate?
0
0
Yes
10,0%
0
0,0073%
0
21
No
19,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
1,32E-06
0
22
No
90,0%
ad via window to one more floor?

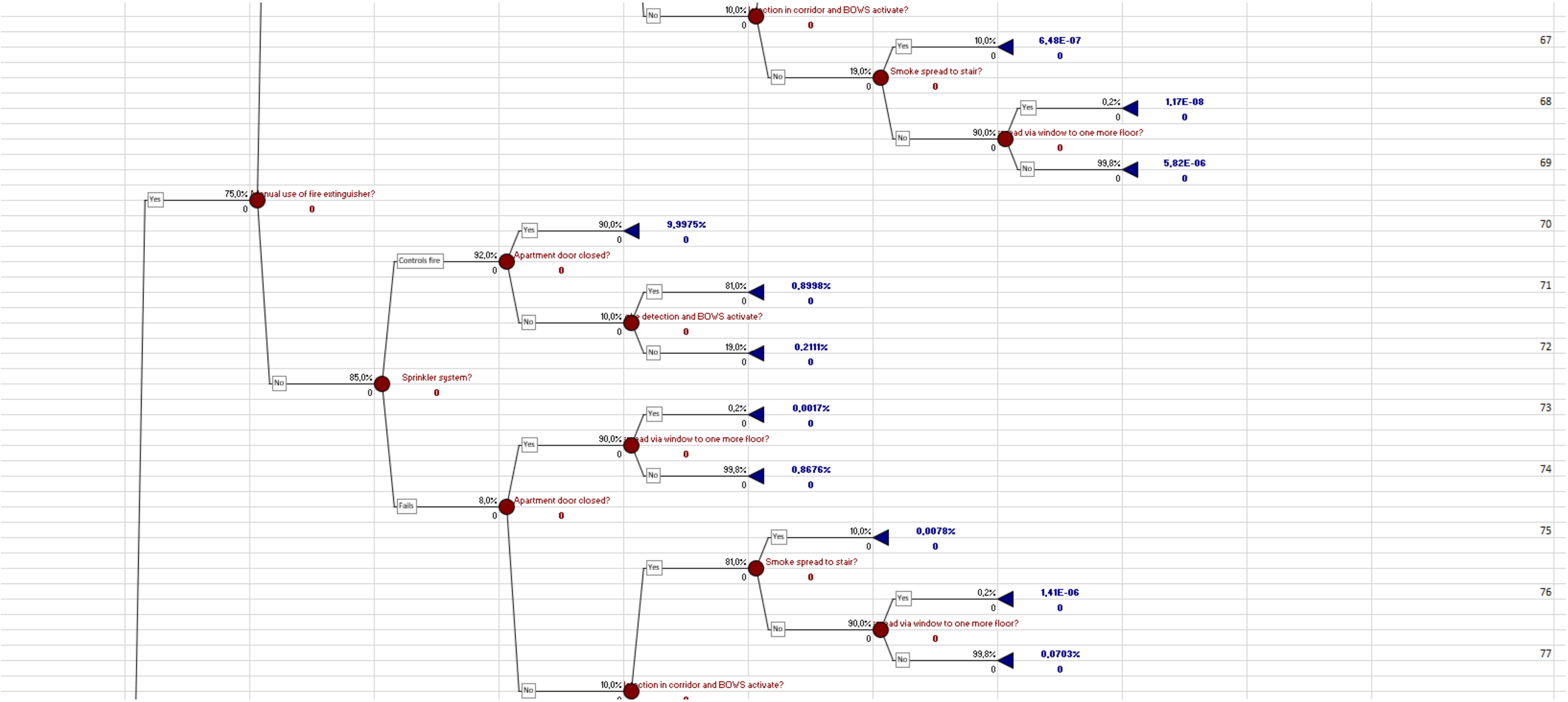

No
90,0%
ad via window to one more floor?
0
0
No
99,8%
0
0,0659%
0
23
SOU
94,7%
0
Smoke alarm activates?
0
Yes
80,0%
0
2,2728%
0
24
Yes
15,0%
0
Manual extinguishment?
0
Yes
90,0%
0
0,4705%
0
25
Controls fire
92,0%
0
Apartment door closed?
0
Yes
81,0%
0
0,0423%
0
26
No
10,0%
0
ction in corridor and BOWS activate?
0
No
19,0%
0
0,0099%
0
27
No
20,0%
0
Sprinkler system?
0
Yes
0,2%
0
8,18E-07
0
28
Yes
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,0408%
0
29
Fails
8,0%
0
Apartment door closed?
0
Yes
10,0%
0
3,68E-06
0
30
Yes
81,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
6,63E-08
0
31
No
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,0033%
0
32
No
10,0%
0
ction in corridor and BOWS activate?
0
Yes
10,0%
0
8,64E-07
0
33
No
19,0%
Smoke spread to stair?

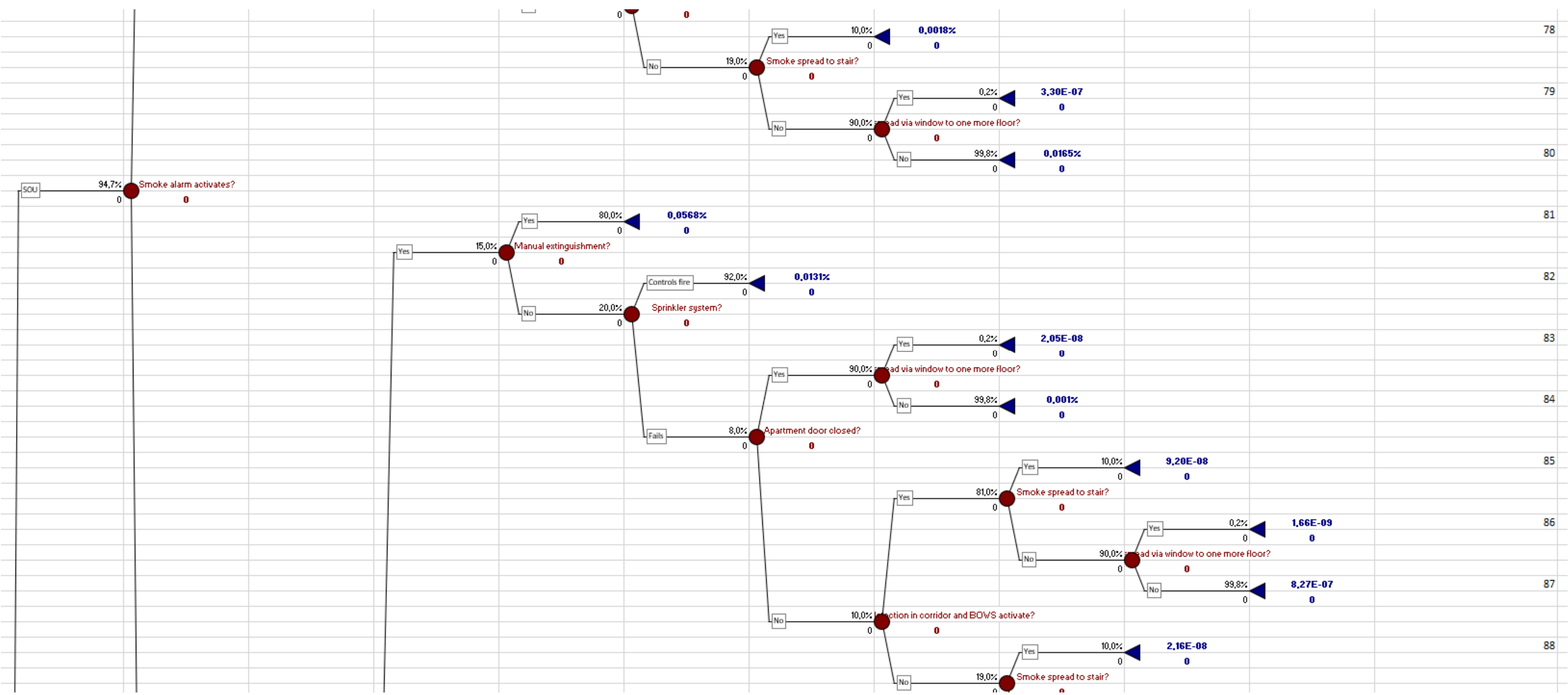

0
0
Yes
0,2%
0
1,55E-08
0
34
No
90,0%
ad via window to one more floor?
0
0
35
No
99,8%
0
7,76E-06
0
No
25,0%
nual use of fire extinguisher?
0
0
Yes
90,0%
0
13,33%
0
36
Controls fire
92,0%
Apartment door closed?
0
0
Yes
81,0%
0
1,1997%
0
37
No
10,0%
ction in corridor and BOWS activate?
0
0
No
19,0%
0
0,2814%
0
38
No
85,0%
Sprinkler system?
0
0
Yes
0,2%
0
0,0023%
0
39
Yes
90,0%
ad via window to one more floor?
0
0
No
99,8%
0
1,1568%
0
40
Fails
8,0%
Apartment door closed?
0
0
Yes
10,0%
0
0,0104%
0
41
Yes
81,0%
Smoke spread to stair?
0
0
Yes
0,2%
0
1,88E-06
0
42
No
90,0%
ad via window to one more floor?
0
0
No
99,8%
0
0,0937%
0
43
No
10,0%
ction in corridor and BOWS activate?
0
0
Yes
10,0%
0
0,0024%
0
44
No
19,0%
Smoke spread to stair?


0
0
Yes
0,2%
0
4,40E-07
0
45
No
90,0%
ad via window to one more floor?
0
0
No
99,8%
0
0,022%
0
46
Fire location
0
Yes
80,0%
0
0,2061%
0
47
Yes
15,0%
0
Manual extinguishment?
0
Controls fire
92,0%
0
0,0474%
0
48
No
20,0%
0
Sprinkler system?
0
Yes
10,0%
0
4,12E-06
0
49
Fails
8,0%
0
Smoke spread to stair?
0
No
90,0%
0
0,0037%
0
50
Yes
81,0%
0
nual use of fire extinguisher?
0
Controls fire
92,0%
0
1,3429%
0
51
No
85,0%
0
Sprinkler system?
0
Yes
10,0%
0
0,0117%
0
52
Fails
8,0%
0
Smoke spread to stair?
0
No
90,0%
0
0,1051%
0
53
Yes
50,0%
0
ction in corridor and BOWS activate?
0
Controls fire
92,0%
0
0,3706%
0
54
No
19,0%
0
Sprinkler system?
0
Yes
10,0%
0
0,0032%
0
55
Fails
8,0%
Smoke spread to stair?



0
0
Fails
8,0%
0
Smoke spread to stair?
0
No
90,0%
0
0,029%
0
56
Corridor
5,3%
0
tible furniture present in corridor?
0
No
50,0%
0
2,12%
0
57
Yes
80,0%
0
1,7046%
0
58
Yes
15,0%
0
Manual extinguishment?
0
Yes
90,0%
0
0,3529%
0
59
Controls fire
92,0%
0
Apartment door closed?
0
Yes
81,0%
0
0,0318%
0
60
No
10,0%
0
e detection and BOWS activate?
0
No
19,0%
0
0,0074%
0
61
No
20,0%
0
Sprinkler system?
0
Yes
0,2%
0
6,14E-07
0
62
Yes
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,0306%
0
63
Fails
8,0%
0
Apartment door closed?
0
Yes
10,0%
0
2,76E-06
0
64
Yes
81,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
4,97E-08
0
65
No
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,0025%
0
66
No
10,0%
ction in corridor and BOWS activate?


No
10,0%
0
ction in corridor and BOWS activate?
0
Yes
10,0%
0
6,48E-07
0
67
No
19,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
1,17E-08
0
68
No
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
5,82E-06
0
69
Yes
75,0%
0
nual use of fire extinguisher?
0
Yes
90,0%
0
9,9975%
0
70
Controls fire
92,0%
0
Apartment door closed?
0
Yes
81,0%
0
0,8998%
0
71
No
10,0%
0
detection and BOWS activate?
0
No
19,0%
0
0,2111%
0
72
No
85,0%
0
Sprinkler system?
0
Yes
0,2%
0
0,0017%
0
73
Yes
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,8676%
0
74
Fails
8,0%
0
Apartment door closed?
0
Yes
10,0%
0
0,0078%
0
75
Yes
81,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
1,41E-06
0
76
No
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,0703%
0
77
No
10,0%
ction in corridor and BOWS activate?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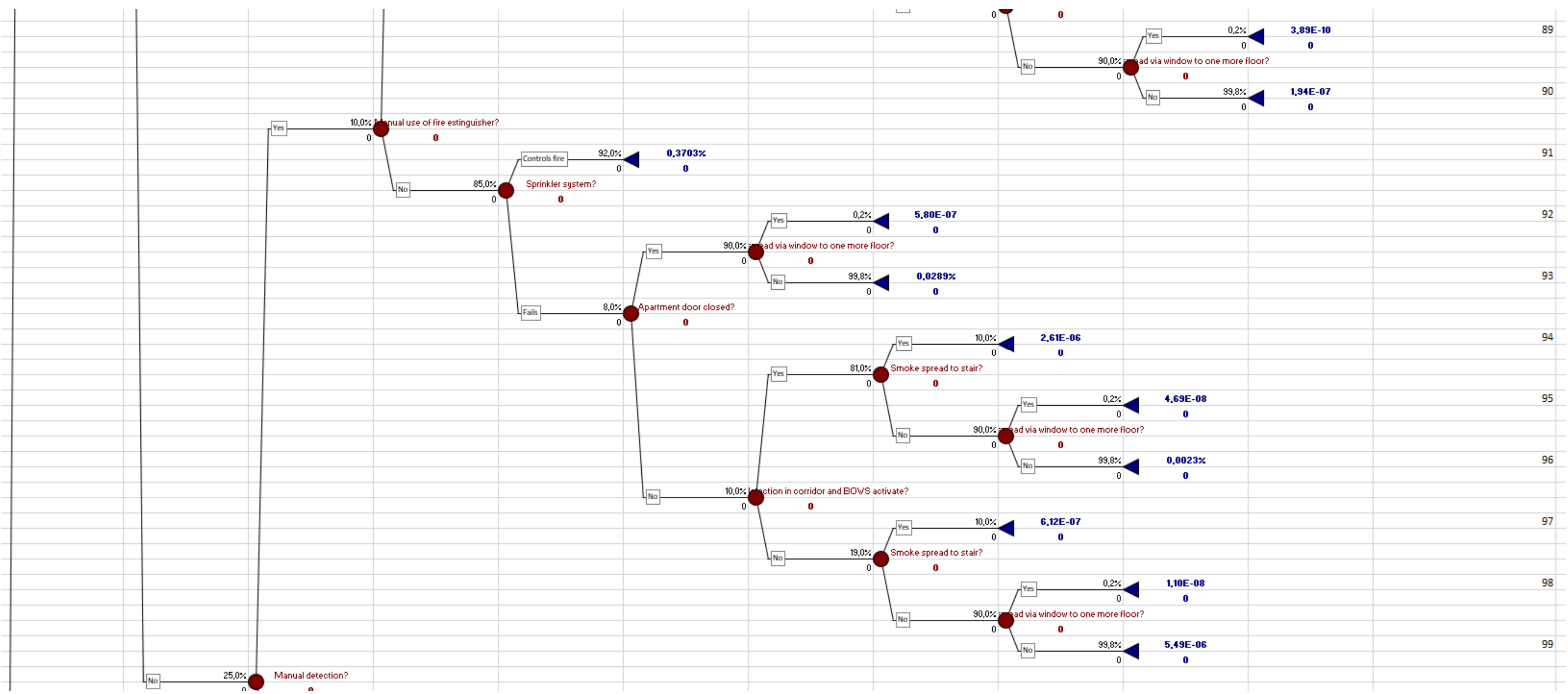
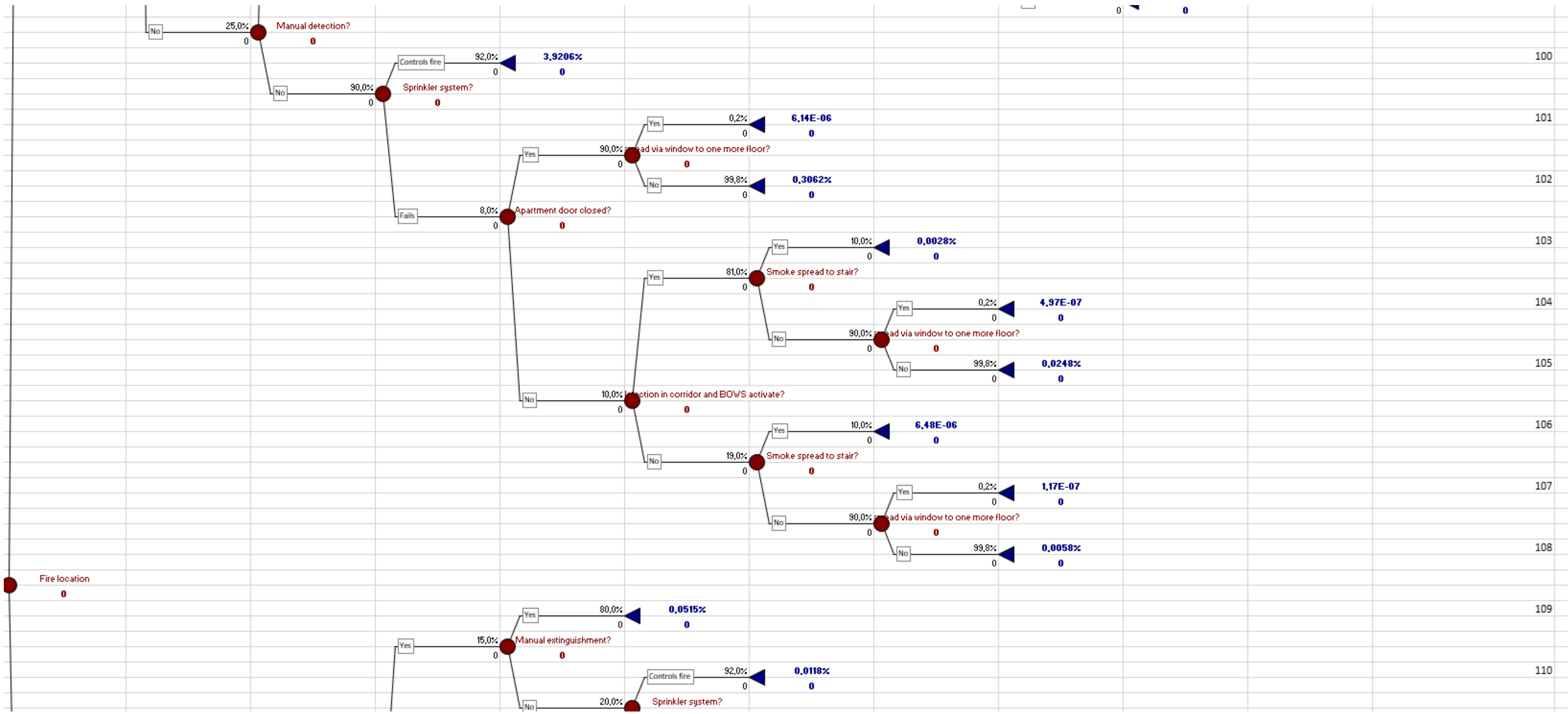
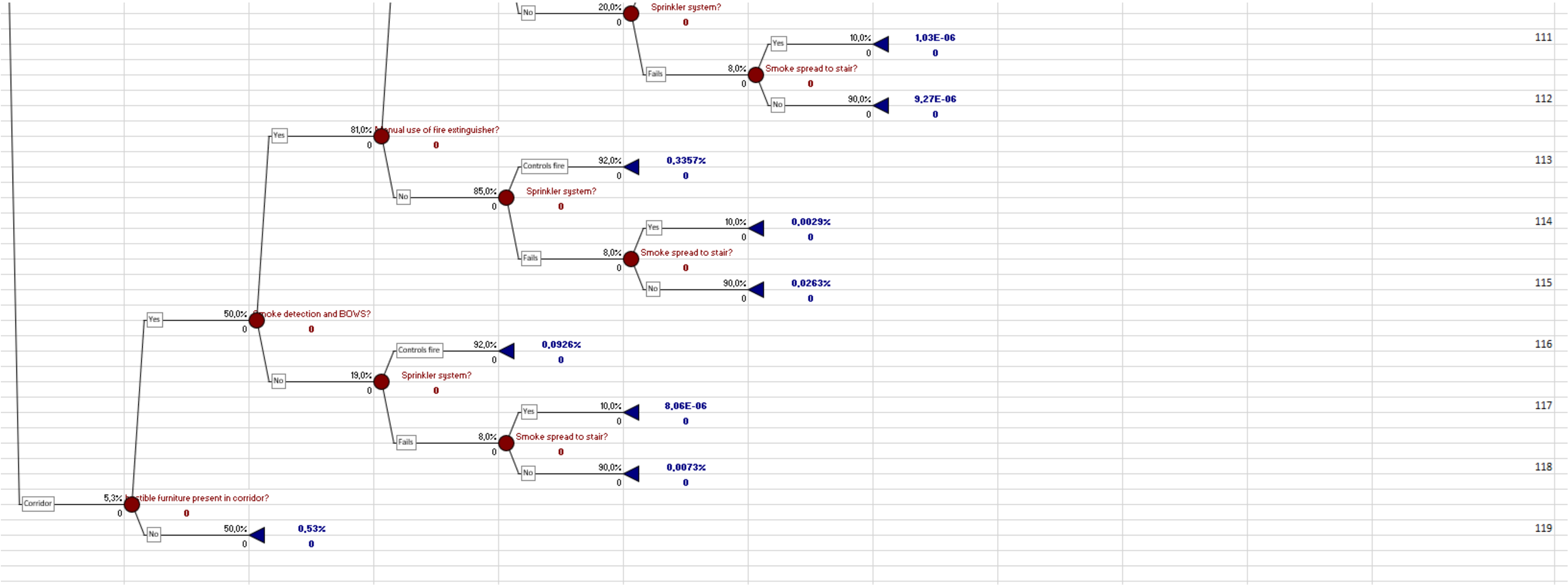
0
Yes
10,0%
0
0,0018%
0
78
No
19,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
3,30E-07
0
79
No
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,0165%
0
80
SOU
94,7%
0
Smoke alarm activates?
0
Yes
80,0%
0
0,0568%
0
81
Yes
15,0%
0
Manual extinguishment?
0
Controls fire
92,0%
0
0,0131%
0
82
No
20,0%
0
Sprinkler system?
0
Yes
0,2%
0
2,05E-08
0
83
Yes
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,001%
0
84
Fails
8,0%
0
Apartment door closed?
0
Yes
10,0%
0
9,20E-08
0
85
Yes
81,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
1,66E-09
0
86
No
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
8,27E-07
0
87
No
10,0%
0
ction in corridor and BOWS activate?
0
Yes
10,0%
0
2,16E-08
0
88
No
19,0%
0
Smoke spread to stair?
0



0
0
Yes
0,2%
0
3,89E-10
0
89
No
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
1,94E-07
0
90
Yes
10,0%
0
nual use of fire extinguisher?
0
Controls fire
92,0%
0
0,3703%
0
91
No
85,0%
0
Sprinkler system?
0
Yes
0,2%
0
5,80E-07
0
92
Yes
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,0289%
0
93
Fails
8,0%
0
Apartment door closed?
0
Yes
10,0%
0
2,61E-06
0
94
Yes
81,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
4,69E-08
0
95
No
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,0023%
0
96
No
10,0%
0
ction in corridor and BOWS activate?
0
Yes
10,0%
0
6,12E-07
0
97
No
19,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
1,10E-08
0
98
No
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
5,49E-06
0
99
No
25,0%
Manual detection?


No
25,0%
0
Manual detection?
0
Controls fire
92,0%
0
3,9206%
0
100
No
90,0%
0
Sprinkler system?
0
Yes
0,2%
0
6,14E-06
0
101
Yes
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,3062%
0
102
Fails
8,0%
0
Apartment door closed?
0
Yes
10,0%
0
0,0028%
0
103
Yes
81,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
4,97E-07
0
104
No
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,0248%
0
105
No
10,0%
0
ction in corridor and BOWS activate?
0
Yes
10,0%
0
6,48E-06
0
106
No
19,0%
0
Smoke spread to stair?
0
Yes
0,2%
0
1,17E-07
0
107
No
90,0%
0
ad via window to one more floor?
0
No
99,8%
0
0,0058%
0
108
Fire location
0
Yes
80,0%
0
0,0515%
0
109
Yes
15,0%
0
Manual extinguishment?
0
Controls fire
92,0%
0
0,0118%
0
110
No
20,0%
Sprinkler system?


No
20,0%
0
Sprinkler system?
0
Yes
10,0%
0
1,03E-06
0
111
Fails
8,0%
0
Smoke spread to stair?
0
No
90,0%
0
9,27E-06
0
112
Yes
81,0%
0
nual use of fire extinguisher?
0
Controls fire
92,0%
0
0,3357%
0
113
No
85,0%
0
Sprinkler system?
0
Yes
10,0%
0
0,0029%
0
114
Fails
8,0%
0
Smoke spread to stair?
0
No
90,0%
0
0,0263%
0
115
Yes
50,0%
0
oke detection and BOWS?
0
Controls fire
92,0%
0
0,0926%
0
116
No
19,0%
0
Sprinkler system?
0
Yes
10,0%
0
8,06E-06
0
117
Fails
8,0%
0
Smoke spread to stair?
0
No
90,0%
0
0,0073%
0
118
Corridor
5,3%
0
tible furniture present in corridor?
0
No
50,0%
0
0,53%
0
119

Appendix C. ASET-RSET analysis

Modeling

For this thesis, the ASET was determined based on the spread of smoke in the subject building. The smoke spread in case of fire was assessed using CFAST 7.3.0. Three different apartments were modeled on floor Level 1 of the building, which is the floor with the longest extended travel distance. The apartments modeled represent the apartment with the smallest area, largest area, and a mid-sized apartment. In addition, the apartments modeled are located near, at medium distance, and far away from the fire-isolated stair.

Figure 40 shows the modeled corridor marked in yellow and apartments marked in red on floor Level 1.

Figure 40: Modelled corridors and apartments on floor Level 1.

The apartments will be referred to as SOU 1, SOU 2, and SOU 3, in order of distance to the fire-isolated stair. The apartment furthest away from the stair will be called SOU 1, and the apartment close to the stair will be called SOU 3.

The geometry of the SOUs has been simplified in that they have been modeled with the same volume and opening size as in the drawings of the subject building. However, the internal layout of the SOUs has not been modeled. Figure 41 shows a snapshot of the model.

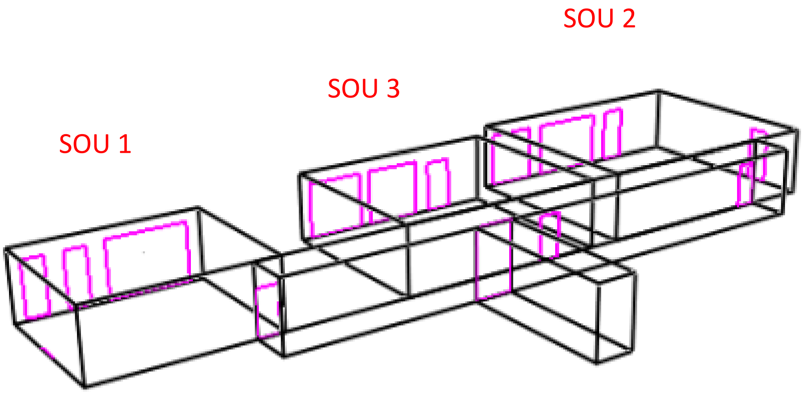


Figure 41: Example of CFAST model of floor Level 1 corridor and selected SOUs

The following general parameters were used for the model.

Simulation time	3600 s
Temperature	20°C
Humidity	50 %
Pressure	101325 Pa

The window openings in the SOUs are assumed to be closed for the fire scenarios. Instead, a small ventilation opening will be added at the floor level for each scenario. The modeled opening will be 1 m wide and 0.1 m high. No smoke leakage is expected to occur via the SOU windows when they are closed. Adiabatic compartment surfaces have been used for all compartments. Table 45 shows the fire properties used for the CFAST simulation.

Table 45: Fire properties

Variable	Value	Reference
Heat release rate (SOU fire)	5 MW	(ABCB, 2019) (Staffansson, 2010)
Heat release rate (Corridor fire)	350 kW	(Karlsson & Quintiere, 2000)
Heat of combustion	20 MJ/kg	(Ministry of Business, Innovation & Employment, New Zealand, 2014)
Chemical formula	$CH_{1.8}$, $O_{0.3}$, $N_{0.05}$ (GM21 Polyurethane)	(Khan, Tewarson, & Chaos, 2016)
Soot yield	0.07	(Ministry of Business, Innovation & Employment, New Zealand, 2014)
CO yield	0.04	(Ministry of Business, Innovation & Employment, New Zealand, 2014)
Radiative fraction	0.35	(Ministry of Business, Innovation & Employment, New Zealand, 2014)

Available Safe Egress Time (ASET)

Table 46 shows the ASET for a fire in the corridor and the minimum and maximum ASET for three different SOUs on floor Level 1.

The ASET values used for the ASET-RSET comparison are based on the shortest time until one of the tenability criteria is met. If two criteria are met at the same time, the time when they are met will be used for the analysis as long as no other criteria are met before.

Several scenarios have been modeled based on many of the scenarios in the event tree sharing the same initial and intermediate events to determine the consequences. It was therefore possible to model a select number of scenarios to help determine ASET for the occupants and the consequence for each scenario or endpoint in the event tree. The following fire scenarios were modeled for the consequence analysis:

- Fire in SOU 1 –sprinkler fails – door open
- Fire in SOU 1 –sprinkler controls fire – door open
- Fire in SOU 2 – sprinkler fails – door open
- Fire in SOU 2 - sprinkler controls fire – door open
- Fire in SOU 3 – sprinkler fails – door open
- Fire in SOU 3 – sprinkler controls fire – door open
- Corridor fire – sprinkler controls fire
- Corridor fire – sprinkler fails

Table 46: ASET for different fire scenarios

Fire scenario	ASET for occupants in fire enclosure of origin	ASET for occupants in another enclosure	Average ASET for occupants in fire enclosure of origin	Average ASET for occupants in another enclosure
Fire in SOUs– Sprinkler failure – Door open	76 s (SOU1), 120 s (SOU2), 98 s (SOU3)	157 s (SOU1), 198 s (SOU2), 178 s (SOU 3)	98 s	177 s
Fire in SOUs – Sprinkler-controlled fire– Door open	76 s (SOU1), 124 s (SOU 2), 99 s (SOU3)	167 s (SOU1), 224 s (SOU2), 195 s (SOU3)	99 s	195 s
Fire in the corridor – Sprinkler failure	-	99 s	-	99 s
Fire in the corridor – Sprinkler-controlled fire	-	99 s	-	99 s

Table 47 to Table 54 shows the time until untenable conditions for the different fire scenarios.

Table 47: Time until untenable conditions for SOU 1 (sprinkler failure)

Fire scenario	Measurement	Criteria 1: Smoke layer above 2.1 m	Criteria 2: Smoke layer below 2.1 m
SOU fire – SOU 1 – Sprinkler failure – Door open Conditions in SOU	Upper layer temperature	Not applicable	98 s
	Lower layer temperature	Does not exceed 60°C	193 s
	Radiant heat	Does not exceed criteria	186 s
	Visibility	-	76 s
	Toxicity	-	76 s
SOU fire – SOU 1 – sprinkler failure – door open Conditions in corridor	Upper layer temperature	Not applicable	170 s
	Lower layer temperature	Does not exceed 60°C	255 s
	Radiant heat	Does not exceed criteria	292 s
	Visibility	-	157 s
	Toxicity	-	157 s

Table 48: Time until untenable conditions for SOU 1(sprinkler-controlled fire)

Fire scenario	Measurement	Criteria 1: Smoke layer above 2.1 m	Criteria 2: Smoke layer below 2.1 m
SOU fire – SOU 1 – Sprinkler-controlled fire - Door open Conditions in SOU	Upper layer temperature	Not applicable	99 s
	Lower layer temperature	Does not exceed 60°C	342 s
	Radiant heat	Does not exceed criteria	Does not exceed criteria
	Visibility	-	76 s
	Toxicity	-	76 s
SOU fire – SOU 1 – sprinkler-controlled fire – door open Conditions in corridor	Upper layer temperature	Not applicable	281 s
	Lower layer temperature	Does not exceed 60°C	447 s
	Radiant heat	Does not exceed criteria	Does not exceed criteria
	Visibility	-	167 s
	Toxicity	-	167 s

Table 49: Time until untenable conditions for SOU 2 (sprinkler failure)

Fire scenario	Measurement	Criteria 1: Smoke layer above 2.1 m	Criteria 2: Smoke layer below 2.1 m
SOU fire - SOU 2– Sprinkler failure – Door open Conditions in SOU	Upper layer temperature	Not applicable	120 s
	Lower layer temperature	Does not exceed 60°C	228 s
	Radiant heat	Does not exceed criteria	230 s
	Visibility	-	120 s
	Toxicity	-	120 s
SOU fire - SOU 2– Sprinkler failure – Door open Conditions in corridor	Upper layer temperature	Not applicable	208 s
	Lower layer temperature	Does not exceed 60°C	300 s
	Radiant heat	Does not exceed criteria	344 s
	Visibility	-	198 s
	Toxicity	-	198 s

Table 50: Time until untenable conditions for SOU 2 (sprinkler-controlled fire)

Fire scenario	Measurement	Criteria 1: Smoke layer above 2.1 m	Criteria 2: Smoke layer below 2.1 m
SOU fire– SOU 2 Sprinkler failure – Door open Conditions in SOU	Upper layer temperature	Not applicable	124 s
	Lower layer temperature	Does not exceed 60°C	522 s
	Radiant heat	Does not exceed criteria	Does not exceed criteria
	Visibility	-	124 s
	Toxicity	-	124 s
SOU fire - SOU 2– Sprinkler failure – Door open Conditions in corridor	Upper layer temperature	Not applicable	557 s
	Lower layer temperature	Does not exceed 60°C	633 s
	Radiant heat	Does not exceed criteria	Does not exceed criteria
	Visibility	-	224 s
	Toxicity	-	224 s

Table 51: Time until untenable conditions for SOU 3 (sprinkler failure)

Fire scenario	Measurement	Criteria 1: Smoke layer above 2.1 m	Criteria 2: Smoke layer below 2.1 m
SOU fire – SOU 3 – Sprinkler failure – Door open Conditions in SOU	Upper layer temperature	Not applicable	107 s
	Lower layer temperature	Does not exceed 60°C	211 s
	Radiant heat	Does not exceed criteria	210 s
	Visibility	-	98 s
	Toxicity	-	98 s
SOU fire – SOU 3 – Sprinkler failure – Door open Conditions in corridor	Upper layer temperature	Not applicable	190 s
	Lower layer temperature	Does not exceed 60°C	279 s
	Radiant heat	Does not exceed criteria	319 s
	Visibility	-	178 s
	Toxicity	-	178 s

Table 52: Time until untenable conditions for SOU 3 (sprinkler-controlled fire)

Fire scenario	Measurement	Criteria 1: Smoke layer above 2.1 m	Criteria 2: Smoke layer below 2.1 m
SOU fire – SOU 3) – Sprinkler failure – Door open Conditions in SOU	Upper layer temperature	Not applicable	111 s
	Lower layer temperature	Does not exceed 60°C	421 s
	Radiant heat	Does not exceed criteria	Does not exceed criteria
	Visibility	-	99 s
	Toxicity	-	99 s
SOU fire – SOU 3 – Sprinkler failure – Door open Conditions in corridor	Upper layer temperature	Not applicable	404 s
	Lower layer temperature	Does not exceed 60°C	522 s
	Radiant heat	Does not exceed criteria	Does not exceed criteria
	Visibility	-	195 s
	Toxicity	-	195 s

Table 53: Time until untenable conditions for corridor fire (sprinkler failure)

Fire scenario	Measurement	Criteria 1: Smoke layer above 2.1 m	Criteria 2: Smoke layer below 2.1 m
Corridor fire– Sprinkler failure	Upper layer temperature	Not applicable	106 s
	Lower layer temperature	Does not exceed 60°C	154 s
	Radiant heat	Does not exceed criteria	201 s
	Visibility	-	99 s
	Toxicity	-	99 s

Table 54: Time until untenable conditions for corridor fire (sprinkler-controlled fire)

Fire scenario	Measurement	Criteria 1: Smoke layer above 2.1 m	Criteria 2: Smoke layer below 2.1 m
Corridor fire– Sprinkler-controlled fire	Upper layer temperature	Not applicable	108 s
	Lower layer temperature	Does not exceed 60°C	192 s
	Radiant heat	Does not exceed criteria	670 s
	Visibility	-	99 s
	Toxicity	-	99 s

Required Safe Egress Time (RSET)

Hand calculations have been used to determine the RSET for building occupants. The total evacuation time consists of the detection time, the alarm or warning time, the pre-travel time, and the movement time (BSI, 2019). The RSET equation below is described by Equation 10 below.

$$t_{RSET} = t_{det} + t_a + t_{pre} + t_{trav}$$ **Equation 10**

The inputs used for the egress calculations are shown in Table 55.

Table 55: Inputs for egress calculations

Variable	Occupants awake and familiar in the enclosure of origin	Occupants awake and familiar outside of enclosure of origin	Occupants asleep and familiar in the enclosure of origin	Occupants asleep and familiar outside of enclosure of origin
Detection and alarm/warning time	Smoke below 5% of ceiling height (Eaton, 1991)	Based on calculated detection time	Based on calculated detection time	Based on calculated detection time
Pre-travel time	30 seconds (Ministry of Business, Innovation & Employment, New Zealand, 2014)	60 seconds (Ministry of Business, Innovation & Employment, New Zealand, 2014)	60 seconds (Ministry of Business, Innovation & Employment, New Zealand, 2014)	300 seconds (Ministry of Business, Innovation & Employment, New Zealand, 2014)
Travel time	Travel speed of 1 m/s (horizontal travel)	Travel speed of 1 m/s (horizontal travel)	Travel speed of 1 m/s (horizontal travel)	Travel speed of 1 m/s (horizontal travel)

The computer model program CFAST was used to determine the time to detection for the SOU smoke alarms, the corridor smoke detectors, and sprinkler activation time. The sprinklers are assumed to have an RTI of 50 $(m \times s)^{1/2}$ and an activation temperature of 68°C. Table 56 and Table 57 show the calculated detection times for the scenarios.

It should be noted that the manual cue/detection time for occupants being awake inside the enclosure of fire origin based on smoke below 5% of ceiling height was met within 15– 26s. Based on the simulations, the smoke alarm inside the SOUs detects a fire after 15-16s. Therefore, a 16 s detection time has been used for occupant being awake inside the enclosure of fire origin.

Table 56: Detection and activation times for fire in an SOU

Scenario	Detection time in SOU	Detection time in the corridor (sprinkler failure in SOU)	Sprinkler activation time
SOU 1 fire	15 s	108 s	92 s
SOU 2 fire	16 s	152 s	94 s
SOU 3 fire	16 s	129 s	93 s

Table 57: Detection time for a fire in the corridor

Scenario	Detection time in the corridor	Sprinkler activation time
Corridor fire	34 s	96 s

The average detection time for a fire in an SOU is shown in Table 58.

Table 58: Average detection time for a fire in an SOU

Scenario	Detection time in SOU	Detection time in the corridor (sprinkler failure in SOU)	Sprinkler activation time
SOU fire	16 s	130 s	93 s

The calculated combined detection and pre-movement time for the building occupants are shown in Table 59 and Table 60. The calculations are based on the fire being detected by a smoke detector in an SOU or corridor.

Table 59: Calculated combined detection and pre-movement time for building occupants for sprinkler failure scenarios

Fire Scenario	Occupants awake and familiar in the enclosure of origin	Occupants awake and familiar outside of enclosure of origin	Occupants asleep and familiar in the enclosure of origin	Occupants asleep and familiar outside of enclosure of origin
SOU fire (excluding travel time) (smoke detection)	46 s (including a detection time of 16 s)	190 s	76 s	430 s
Corridor fire (excluding travel time) (smoke detection)	-	94 s	-	334 s

Table 60: Calculated combined detection and pre-movement time for building occupants for sprinkler-controlled fire scenarios

Fire Scenario	Occupants awake and familiar in the enclosure of origin	Occupants awake and familiar outside of enclosure of origin	Occupants asleep and familiar in the enclosure of origin	Occupants asleep and familiar outside of enclosure of origin
SOU fire (excluding travel time) (smoke detection)	46 s (including a detection time of 16 s)	153 s	76 s	393 s
Corridor fire (excluding travel time) (smoke detection)	-	94 s	-	334 s

The travel time for the occupants can be expected to differ based on the location of the SOUs in relation to the fire-isolated stair or exit. To determine the consequence for occupants located in apartments with varying distances to a stair or exit, the travel time will be calculated for each SOU on floor Level 1. Based on a travel speed of 1m/s, the travel time from the different SOUs on floor Level 1 vary between 2.6-19.5s. It should be noted that any occupant travel inside the SOUs is assumed to be included in the pre-movement time.

Table 61: Travel time between SOUs and fire-isolated stair on floor Level 1

SOU	Travel distance (m)	Calculated travel time (s)
1.01	13.1	13.1
1.02	18.2	18.2
1.03	19.5	19.5
1.04	15.2	15.2
1.05	9.9	9.9
1.06	2.6	2.6
1.07	5.6	5.6
1.08	6.5	6.5
1.09	4.2	4.2
1.10	4	4

Table 62 shows the calculated RSET for each SOU on floor Level 1 based on Table 59 to Table 61.

Table 62: Calculated RSET for each SOU on floor Level 1

Fire Scenario	SOU	RSET for occupants awake and familiar in the enclosure of origin [s]	RSET for occupants awake and familiar outside of enclosure of origin [s]	RSET for occupants asleep and familiar in the enclosure of origin [s]	RSET for occupants asleep and familiar outside of enclosure of origin [s]
SOU fire (Sprinkler failure)	1.01	59.1	203.1	89.1	443.1
	1.02	64.2	208.2	94.2	448.2
	1.03	65.5	209.5	95.5	449.5
	1.04	61.2	205.2	91.2	445.2
	1.05	55.9	199.9	85.9	439.9
	1.06	48.6	192.6	78.6	432.6
	1.07	61.6	195.6	81.6	435.6
	1.08	52.5	196.5	82.5	436.5
	1.09	50.2	194.2	80.2	434.2
	1.10	50	194	80	434
SOU fire (Sprinkler-controlled fire)	1.01	59.1	166.1	89.1	406.1
	1.02	64.2	171.2	94.2	411.2
	1.03	65.5	172.5	95.5	412.5
	1.04	61.2	168.2	91.2	408.2
	1.05	55.9	162.9	85.9	402.9
	1.06	48.6	155.6	78.6	395.6
	1.07	61.6	158.6	81.6	398.6
	1.08	52.5	159.5	82.5	399.5
	1.09	50.2	157.2	80.2	397.2
	1.10	50	157	80	397
Corridor fire	1.01	-	107.1	-	347.1
	1.02		112.2		352.2
	1.03		113.5		353.5
	1.04		109.2		349.2
	1.05		103.9		343.9
	1.06		96.6		336.6
	1.07		99.6		339.6
	1.08		100.5		340.5
	1.09		98.2		338.2
	1.10		98		338

ASET-RSET comparison

Table 63 shows the consequences based on the ASET-RSET analysis for the different simulated fire scenarios on the floor of fire origin based on smoke alarms and detectors working. The number of occupants per SOU varies between two, four, and six for the building. For the consequence analysis, four occupants per SOU have been assumed. For cases where a fire starts in the corridor or spread to the corridor and no smoke detection/ bows activation or sprinkler activation occur, it has been assumed that occupants outside of the enclosure of fire origin on the floor of fire origin will become exposed to untenable conditions. This is a conservative assumption since a common response of people is to warn others (Nystedt, 2003).

Table 63: Consequences for the different fire scenarios based on the ASET-RSET analysis

Fire scenario	Location of occupants	Time of day	ASET for occupants	RSET for occupants	Number of occupants exposed to untenable conditions
SOU fire (Sprinkler failure)	Inside enclosure of fire origin	Day	98 s	48.6 – 65.5 s	0
		Night		78.6 – 95.5 s	0
	Outside enclosure of fire origin	Day	177 s	192.6 – 209.5 s	42
		Night		432.6 – 449.5 s	42
SOU fire (Sprinkler-controlled fire)	Inside enclosure of fire origin	Day	99 s	48.6 – 65.5 s	0
		Night		78.6 – 95.5s	0
	Outside enclosure of fire origin	Day	195 s	155.6 – 172.5 s	0
		Night		395.6 – 412.5 s	42
Corridor fire (Sprinkler failure)	Outside enclosure of fire origin	Day	99 s	96.6 – 113.5 s	32
		Night		336.6 – 353.5 s	46
Corridor fire (Sprinkler-controlled fire)	Outside enclosure of fire origin	Day	99 s	96.6 – 113.5 s	32
		Night		336.6 – 353.5 s	46