De ontwikkeling van een probabilistisch risicobeoordelingsmodel voor het kwantificeren van personenveiligheid in gebouwen in geval van brand

The Development of a Full Probabilistic Risk Assessment Model for Quantifying the Life Safety Risk in Buildings in Case of Fire

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Ghent, June 2019
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Introduction

Common symbols and abbreviations used throughout the dissertation are listed below. Specific symbols which are not listed may be used locally and in a specific context. As these symbols are locally explained and not used further in the dissertation, they have been omitted from the lists below.

Roman Symbols

A	Building surface area	[m²]
A_{max}	maximum fire area	[m²]
A_o	Area or weighted area of opening	[m²]
A_T	Total internal enclosure surface area	[m²]
b	slope of the best fit	[-]
C	concentration	[ppm]
c	constant	
D	exposure dose for incapacitation	[%COHb]
E	load effect	
F	frequency	[1/year]
H_o	height of the opening	[m]
h	convective heat transfer coefficient	$W/(m^2K)$
h_L	smoke layer height	m
F	frequency	[-]
f_s	fire frequency	[1/year]
$\dot{m}_f$	mass loss rate of fuel	[kg/s]
$\dot{m}_a$	mass loss rate of air	[kg/s]
N	number of fatalities	[-]
P_f	probability of failure	[-]
Q	heat Release Rate	[kW]
Q_{Act}	heat Release Rate at sprinkler activation	[kW]
q	the radiant flux from the fire or smoke layer	[kW/m²]
R	resistance effect in case of fire	[min]
r	stoichiometric fuel-to-air ratio	[-]

T	temperature	[K]
T_{skin}	skin temperature	[K]
t	time	[s]
t_{iconv}	the time to incapacitation due to convective heat transfer	[min]
t_{irad}	the time to incapacitation due to radiative heat transfer	[min]
V	coefficient of variation	[-]
V_X	coefficient of variation of the parameter X	[-]
V_{CO2}	multiplicity effect of inhaled CO2	[-]
V_E	volume of air breathed each minute	[l/min]
w	Weighting function	
v	the walking speed	[m/s]
y_x	yield of specific smoke production component x	[kg/kg]

Greek Symbols

α	Fire growth coefficient	[kW/s^2]
$\beta\alpha$	Coefficients for response surface modelling	[-]
Δ	Difference between two values	
δ_s	safety factor	[-]
δ_i	Error term	[-]
ε	emissivity	[-]
ε_{reg}	regularization parameter	[-]
λ_{ig}	yearly fire ignition frequency	[1/(year·m^2)]
λ	Failure rate	[1/year]
μ	mean value	
μ_X	mean value of the parameter X	
σ	standard deviation	
Φ	equivalence ratio	[-]

Acronyms

ALARP	As Low As Reasonably Practicable
ASET	Available Safe Egress Time
CDF	Cumulative Density Function
CFD	Computational Fluid Dynamics
DET	Deterministic
DOE	Design of Experiments
EDK	Erica Dawn Kuligowski
EDM	Evacuation Decision model
EE	Elementary effect
ERI	Early Risk Injury
ERL	Early Risk to Life
ETA	Event tree Analysis
FDS	Fire Dynamics Simulator
HRR	Heat Release Rate
HRRPUA	Heat Release Rate Per Unit Area
HSE	Health and Safety Executive
FCE	Fire Cost Expectation
FED	Fractional Effective Dose
FFM	Fire Field Modelling
FID	Fractional Incapacitation Dose
FORM	First Order Reliability Method
FSE	Fire Safety Engineering
FTA	Fault Tree Analysis
HRR	Heat Release Rate
IMLS	Interpolation Moving Least Squares
IR	Individual Risk
ISO	International Organization for Standardization
LHS	Latin Hypercube Sampling
LN	Lognormal
MC	(crude) Monte Carlo
OAT	One at a time
OGS	Optimal Grade Spread
OH	Ordinary hazard
PADM	Protection Action Decision Model

PBD	Performance Based Design
PCE	Polynomial Chaos Expansion
PDF	Probability Density Function
PRA	Probabilistic Risk Assessment
RSM	Response Surface Modelling
RSO	Relative safety level for occupants
SA	Sensitivity analysis
SHC	Smoke and Heat Control
SPLR	Sprinkler
SSE	Sum of Squared Errors
QRA	Quantitative Risk Assessment
RSET	Required Safe Egress Time

SAMENVATTING

Het doel van brandveiligheid in publieke gebouwen is om de gevolgen voor de gezondheid, eigendom, continuïteit van activiteiten, milieu en erfgoed in geval van brand zo optimaal als mogelijk te beperken. Om deze doelstellingen te bereiken worden brandveiligheidsmaatregelen geïmplementeerd dewelke zowel de kans op het ontstaan van brand als de mogelijke effecten ervan verminderen. De keuze van maatregelen wordt meestal bepaald door overheidsinstellingen via regelgeving. Historisch gezien zijn twee belangrijke wettelijke nalevingsmethoden ontwikkeld, namelijk prescriptieve en performantiegerichte ontwerpmethodieken. Prescriptieve ontwerpen worden in principe ontwikkeld op basis van ervaringen uit eerdere brandincidenten die specifieke veiligheidskwesties aan het licht brengen. In een prescriptief regelgevingssysteem voor brandveiligheid wordt impliciet aangenomen dat wanneer alle regels van de wet worden toegepast, het niveau van brandveiligheid aanvaardbaar is. Voorgeschreven codes zijn zeer praktisch voor het ontwerp van gebouwen en vallen binnen de beoogde scope van de reglementering. Toenemende architecturale creativiteit, functionele vereisen, verbeterde bouwtechnieken en materiaalwetenschappen hebben echter geleid tot ontwerp en constructie van gebouwen die niet altijd kunnen worden uitgevoerd binnen de bestaande regels voor brandveiligheid.

Naarmate het domein van Fire Safety Engineering zich ontwikkelde, veranderden meer en meer landen hun brandveiligheidswetgeving om gebouwen te ontwerpen in termen van doelstellingen en prestaties. Reguleringsvormen zijn daarbij objectief, waarbij prestatie-gebaseerde en risico-geïnformeerde methoden het meest worden toegepast. In deze regelgeving wordt het acceptabele veiligheidsniveau expliciet en dient het veiligheidsniveau door analyse aangetoond te worden. Deze methodieken zijn al toegepast in een aantal wettelijke kaders (bijv. VK, Zweden, Nieuw-Zeeland en Australië). Het voordeel is dat deze regelgevingen flexibiliteit, innovativiteit en kosteneffectiviteit bevorderen. Het nadeel is dat de kwalitatieve of beschrijvende aard van de prestatie-eisen soms worden bekritiseerd vanwege het feit dat ze anders kunnen worden geïnterpreteerd en dat er geen kwantificeerbare of verifieerbare prestatie-eisen en criteria zijn. Bovendien vertrouwt de methode op de professionele en ethische competentie van de brandveiligheidstechnicus. Om deze redenen hebben bepaalde landen aanpassingen gedaan om de onduidelijkheid van deze regelgevingen te

verminderen, waarbij een verschuiving werd toegepast van een totale performantiegerichte regelgeving naar een "prescriptief" performantiegerichte kader. In een poging om een uniformer veiligheidsniveau te bereiken, werden specifieke scenario's en parameters geïntroduceerd die in de analysemethodiek dienen te worden toegepast. Afhankelijk van het project kunnen sommige brandscenario's en belangrijke invloedsfactoren niet worden geïdentificeerd en geadresseerd. Bovendien wordt de effectiviteit van de geïmplementeerde veiligheidssystemen vaak niet kwantitatief in rekening genomen.

Omdat de bovengenoemde methoden tekortkomingen vertonen, bestaat er een algemene consensus dat een meer holistische benadering noodzakelijk is, waarin de gebouwconfiguratie, gebruikers, inhoud, veiligheidssystemen en procedures samen worden geanalyseerd. Risicogebaseerde methodieken bieden een manier om te evolueren naar een dergelijke holistische benadering. Daarom wordt in dit proefschrift een probabilistische risicobeoordelingsmethodologie ontwikkeld om het risico voor personenveiligheid te kwantificeren in het kader van brandveiligheidsontwerp.

Om deze vraagstelling aan te pakken, worden in deze thesis verschillende bestaande risicoconcepten en -modellen geanalyseerd. De sterke en zwakke punten worden onderzocht, zodat de beste onderdelen van elk in de methodologie kunnen worden opgenomen. Op basis van de literatuurstudie wordt een deterministisch en probabilistisch kader ontwikkeld. In het deterministisch deel wordt de nadruk gelegd op de ontwikkeling van een holistische benadering van meerdere submodellen om de verschillende invloedsfactoren van veiligheidssystemen, ontwerpscenario's, evacuatie, rookverspreiding en gevolgenmodellering te combineren tot één geheel. Om rekening te houden met de onzekerheid van ontwerpparameters en de betrouwbaarheid van veiligheidssystemen, wordt een probabilistisch kader ontwikkeld. De methode bestaat uit meerdere probabilistische technieken die het veiligheidsniveau kwantificeren door een kans op overlijden, individueel en groepsrisico. De kern van de methode bestaat uit een methodologie met responsoppervlakken in combinatie met steekproeftechnieken en convergentiemethoden voor betrouwbaarheidsanalyse. Het resultaat is een computationeel efficiënt model voor een nauwkeurige kwantificering van de prestaties van brandveiligheidsontwerpen. Om het rekenmodel verder te optimaliseren, is een vereenvoudigd model voorgesteld. De belangrijkste verschillen met het vereenvoudigde model zijn de toegepaste submodellen voor analyse van rookverspreiding en evacuatie. Voor rookverspreiding wordt een zonemodel voorgesteld in plaats van een veldmodel. Voor evacuatie wordt een intern netwerkmodel ontwikkeld in plaats van een continu model.

De uitgebreide en vereenvoudigde probabilistische modellen worden onderworpen aan een gedeeltelijke verificatie- en validatieanalyse. Op basis van een reeks testen blijkt het model een goede modelleringsnauwkeurigheid te hebben met betrekking tot de methodologie van het responsoppervlak. De testen die werden toegepast voor het vereenvoudigde submodel van het evacuatienetwerk zorgden ook voor een voldoende modelleringsnauwkeurigheid.

Na de validatie en verificatie wordt de toepasbaarheid van de methodologie getest op verschillende case studies. Er zijn twee case studies gekozen, namelijk een eenvoudige en een meer complexere gebouwconfiguratie. De vereenvoudigde en uitgebreide QRA-methode wordt getest in beide casestudies en er wordt een vergelijking gemaakt tussen de resultaten. De resultaten tonen aan dat beide methoden kunnen worden toegepast op de eenvoudige en uitdagende casestudies. De berekende foutverschillen voor de meer uitdagende case study geven aan dat de eenvoudige methode slechts een ruwe schatting geeft van de gevolgen voor de bestudeerde gevallen. Vanuit een ingenieursperspectief gezien, is een positief aspect van deze foutenmarge dat de vereenvoudigde methode over het algemeen conservatievere resultaten oplevert dan de meer accurate methode. Daarom kan bij het ontwerpen van brandtechnologie een eerste schatting worden gemaakt op basis van de vereenvoudigde methode. In het geval dat de resultaten op de grens van aanvaardbaarheid liggen kan de beslissing worden genomen om de uitgebreide methode toe te passen.

Het uiteindelijke doel van het proefschrift was om het brandveiligheidsniveau van een gebouwontwerp te kwantificeren en het berekende veiligheidsniveau te evalueren aan de hand van een vooraf gedefinieerd acceptabel risicocriterium. Daarom wordt een voorstel gedaan voor een acceptabel sociaal risiconiveau. Het voorgestelde aanvaardbare risicocriterium wordt getest voor een case study van een winkelcentrum. De case study is ontworpen volgens het vereiste regelgevingskader voor brandveiligheid in drie landen: België, Zweden en Nieuw-Zeeland. De Belgische configuratie wordt gekenmerkt door grotere uitgangsbreedtes, een rook- en warmteafvoerinstallatie (RWA) en een sprinklerinstallatie. De Zweedse en Nieuw-Zeelandse configuratie worden gekenmerkt door kleinere uitgangen en enkel een sprinklersysteem. De resultaten geven aan dat de Belgische case conservatiever is dan de Zweedse en Nieuw-Zeelandse cases. Het veiligheidsniveau van de laatste twee cases is vergelijkbaar en vereist een verbeterde redundantie van het sprinklersysteem om aan het voorgestelde aanvaardingscriterium te voldoen.

SUMMARY

The aim of fire safety in buildings is to reduce the consequences for life, property, continuity of operations, environment and heritage as much as reasonably possible in case of fire. In order to achieve these objectives, fire safety measures are implemented to reduce the probability and mitigate the possible effects of fire. The choice of measures is often defined by governmental institutions through regulatory frameworks. Historically, two main regulatory compliance methods have been developed, namely prescriptive and performance-based design approaches. Prescriptive designs are in principle developed based on trial and error experiences from past fire incidents revealing particular issues in safety. In a prescriptive fire safety regulatory system it is implicitly assumed that when all the rules of the regulation are applied, the fire safety level is acceptable. Prescriptive codes are very practical for the design of buildings within the intended scope of the regulation. However, advancements in architectural creativity, functional demands, structural engineering as well as material sciences have led to design and construction of buildings that cannot be covered within these existing fire safety related codes.

As the field of Fire Safety Engineering has evolved, more and more countries changed their fire safety legislation proceeding to design buildings in terms of objectives and performance. Regulatory formats are objective-based, with commonly used performance-based and risk-informed methods, where the acceptable safety level assumption becomes explicit and the safety level must be demonstrated. These methods have already been applied in some legal frameworks (e.g., UK, Sweden, New-Zealand and Australia.). The advantage is that these codes promote flexibility, innovativeness and cost-effectiveness. The disadvantage is that the qualitative or descriptive nature of the performance requirements is sometimes criticized for being subject to interpretations and for lacking quantifiable or verifiable performance requirements and criteria. Furthermore, the method relies upon the professional and ethical competence of the fire safety engineer. Due to these reasons, some countries have made efforts to reduce the ambiguity of these codes and introduce a shift from a total performance-based code to a “prescriptive” performance-based framework by specifying scenarios and parameters to be implemented in the analysis, in an attempt to achieve a more uniform safety level. However, depending on the case, some fire scenarios and important

influence factors might not be addressed. Moreover, the effectiveness of the implemented safety systems is often not considered quantitatively.

As the aforementioned methods show shortcomings, there is a consensus that a holistic approach is necessary, in which the building configuration, user, content, safety systems and procedures are analysed together Risk-based methods provide a way to evolve towards such a holistic approach. Therefore, in this dissertation a probabilistic risk assessment methodology is developed to quantify the life safety risk of occupants in the context of fire safety design.

In order to tackle the challenges, several existing risk concepts and models are analysed. Strengths and weaknesses are investigated to incorporate the best parts into the methodology. Based on the literature study, a deterministic and probabilistic framework is developed. In the deterministic framework focus is put on the development of a holistic approach of multiple submodels to combine the different influence factors from safety systems, design scenarios, evacuation, smoke spread and consequence modelling into one framework. In order to take into account the uncertainty of design parameters and reliability of safety systems, a probabilistic framework is developed. The method consists of multiple probabilistic techniques that quantify the safety level through a probability of fatality, individual and societal risk. The core of the method consists out of a response surface methodology in combination with sampling techniques and convergence methods for reliability analysis. The outcome is a computationally efficient model for accurate quantification of the performance of fire safety designs. In order to further optimize the computational model, a simplified model has been proposed. The main differences from the simplified model are the applied submodels for smoke spread and evacuation analysis. For smoke spread, a zone model is proposed instead of a field model. For evacuation, an in-house network model is developed instead of a continuous model.

The full probabilistic and the simplified models are subjected to a partial verification and validation analysis. Through a set of test cases, the model proves to have a good modelling accuracy with respect to the response surface methodology. The test cases applied for the simplified evacuation network submodel also provided a good modelling accuracy.

After the validation and verification, the applicability of the methodology is tested on different case studies. Two case studies are chosen, namely a simple and a more challenging building configuration. The simplified and comprehensive QRA method are tested on both case studies and a comparison is made between the results. The results show that both methods can be applied to the simple and challenging case studies. The observed error differences for

the more challenging case study indicate that the simple method only provides a rough estimate of the consequences for these types of cases. From an engineering perspective, a positive aspect of these relative errors of the simplified method is that it in overall yields more conservative results. Therefore, in fire engineering design, a first estimate can be made based on the simplified method. In case the results are on the border of acceptability, the decision can be made to apply the comprehensive method.

The final objective of the thesis is to quantify the fire safety level of a building design and to evaluate the calculated safety level against a predefined acceptable risk criterion. Therefore, a proposal is made for an acceptable societal risk level. The proposed acceptable risk criterion is tested for a shopping mall case study. The case study is designed according to the required fire safety regulatory framework of three countries: Belgium, Sweden and New Zealand. The Belgian case is characterized by larger exit widths, a smoke and heat control (SHC) and sprinkler system. The Swedish and New Zealand cases are characterized by smaller exits and a sprinkler system. The results indicate that the Belgium case is more conservative than the Swedish and New Zealand cases. The safety level of the latter two cases is similar and requires an improved redundancy of the sprinkler system to meet the proposed acceptable limit.

CHAPTER I

INTRODUCTION

I.1 Context of the research topic

The aim of fire safety in buildings is to reduce the consequences for life, property, continuity of operations, environment and heritage as much as reasonably possible in case of fire [1]. In order to achieve these objectives, fire safety measures can be implemented to reduce the probability and mitigate the possible effects of fire. The choice of measures is defined by governmental institutions and is incorporated in their regulatory framework. Sources have been found from the 17th century and onwards, indicating development of regulations based on experience and rules of good practice. These guidelines were applied to traditional building layouts like row houses. Initially, the aim of these codes was to ascertain a minimum safety level while keeping the impact low [2]. During the past decades, modern building design has become more and more influenced by fire safety considerations [3]. Regulations, standards and guidelines have been developed and extended in such a way that the impact of these requirements has become increasingly significant in the decision making process [4,5]. This increased impact is mainly due to the higher cost of fire safety measures (up to 10% of building cost [6]), technological advancement in industry, and architectural developments. The consequence is that building fire safety regulations receive increasingly more attention from different stakeholders. Therefore, more and more governmental institutions have their current regulatory framework reviewed by fire safety and law experts, and look into the possibility of adapting their code to overcome the limitations of the regulations [7–9].

Historically, two main regulatory compliance methods have been developed, namely, prescriptive codes and performance based design (PBD) codes [10–14]. Prescriptive designs or "deemed-to-satisfy" methods are principally developed based on trial and error experiences from past fire incidents revealing particular issues in safety to the occupants, the fire fighters and the community (e.g., Great Fire of London [15], Innovation fire [2], WTC attacks [16], nightclub fires [17], Grenfell façade fire [18], etc.). In a prescriptive fire safety regulatory system, it is implicitly assumed that when all the rules of the regulation are applied, the fire safety level is acceptable [10], [19]. These methods are typically applied in civil law regulatory frameworks [7] (e.g., Belgium, USA, Germany, France and the Netherlands) because they facilitate the implementation and enforcement in this type of legislation [2]. Prescriptive codes are very practical for the design of buildings within the intended scope of the regulation. However, with the advancements in architectural creativity, functional demands, structural engineering, as well as material sciences, buildings are being designed with complex configurations, which cannot always be built in accordance with these existing codes. Prescriptive codes do not always provide a proper safety level for configurations outside the scope of the regulatory framework. Additionally, these codes might not always foresee the implications of new technologies that meet the 'requirements' yet perform substantially differently. An example of this is the relationship between fire resistance and cross laminated timber (CLT). Additionally, prescriptive fire safety regulations do not provide insight into the obtained fire safety level, and compliance with these code requirements does not ensure that all buildings are constructed to the same level of safety [20,21].

As the field of Fire Safety Engineering (FSE) has evolved, more and more countries changed their legislation regarding fire safety and have proceeded to design buildings in function of objectives and performance [9]. Developed regulatory formats are objective-based [22,23], with commonly used performance-based [19,24,25] and risk-informed [26,27] methods, where the implicit acceptable safety level assumption in prescriptive rules now becomes explicit by showing the verified safety level. These methods have also already been applied in several law frameworks [7] (e.g., UK, Sweden, New-Zealand and Australia.). The advantage is that these codes promote flexibility, equality, innovativeness and cost-effectiveness. Additionally, the actual safety level can be quantified [28]. The disadvantage is that the qualitative or descriptive nature of the performance requirements is sometimes criticized for being subject to interpretations and lacking quantifiable or verifiable performance requirements and criteria. Furthermore, the method relies upon the professional and ethical competence of the fire safety engineer. Typical PBD methods demand various input parameters for analysis of the different fire and evacuation scenarios. Some of these variables are the fire growth rate, the maximum Heat Release Rate (HRR), pre-evacuation time, affiliation, etc. [29–31]. The selection of appropriate values to each of these variables requires profound expertise in FSE. In traditional available safe egress time (ASET) versus required safe egress time (RSET) approaches, the choice of the input parameters will have an important influence on the outcome of the safety factor δ_s, defined as:

$$\delta_s = \frac{ASET}{RSET} \tag{II.1}$$

Two different FSE analyses of the exact same fire safety design with different input parameters will result in different safety factors [32]. For example, an engineer adopting non-conservative input values with a lower fraction on the cumulative distribution function (CDF) (Figure I.1) will obtain a higher safety factor than a FSE adopting conservative input values corresponding to a higher fractile of the CDF. The results obtained from these different input parameters will give a distorted view of the actual safety level [33].

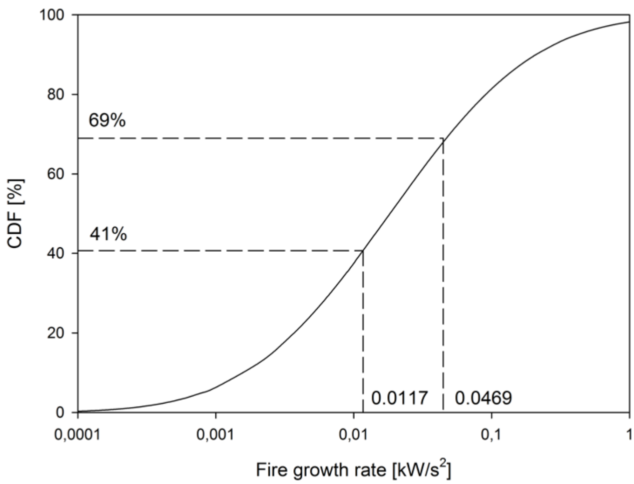

Figure I.1: Cumulative distribution function of the fire growth rate for warehouse occupancies [34].

Due to the reasons stated above, some countries have made efforts to reduce the ambiguity of these codes and shift from a total performance based code to a "prescriptive" performance based framework by specifying scenarios and parameters to be implemented in the analysis [35,36]. This leads to a significant reduction in variability in obtained safety levels. However, depending on the case, some fire scenarios and important influence factors might not be addressed. Moreover, the effectiveness of the implemented safety systems is most often not considered quantitatively. In traditional fire safety designs, reliability and efficiency are not incorporated in the design fire scenarios. Once a safety system is implemented, it is assumed to work and have the same reliability during the entire life span of the building. Modern PBD codes incorporate a robustness scenario [25,37,38] into their code to take the possible failure of active fire protection systems into account. In this scenario, the FSE needs to choose one system that fails and analyse the consequence in case of this failure. However, the safety system considered to be ineffective can be freely chosen by the FSE, which means that the engineer might choose a more favourable system to fail. Additionally, effectiveness is not always properly implemented. From inspections [39] it is observed that a significant portion of active safety systems have a reduced performance when activating on demand. This reduced effectiveness should be incorporated into the fire safety design. On the other hand, the positive effect of proper maintenance and inspection should be considered as well. Another disadvantage of defining a prescriptive format in a performance-based code is that the responsibility shifts back to the regulator and the code becomes less open to creativity and technological advancements.

As the aforementioned methods show shortcomings [27], there is a consensus that a holistic approach is necessary, in which the building configuration, user, content, safety systems and procedures are analysed together [9]. Risk-based methods provide a way to evolve towards such a holistic approach. More specifically, quantitative risk assessment (QRA) techniques provide an opportunity to determine the safety level in a representative manner because both the magnitude and likelihood of hazards versus safeguards can be determined [40–41]. One of the main advantages of risk-based probabilistic methods is that they take uncertainties into account [5] (in addition to the deterministic quantification of scenarios and consequences), whereas in deterministic performance based designs uncertainty is generally dealt with by using safety factors [42,43].

I.2 Research scope

The aim of this study is to develop a probabilistic risk assessment (PRA) methodology to quantify the life safety risk of occupants in the context of the creation of a fire safety design. The goal is to objectify prescriptive and performance-based design methods by taking the uncertainty of design parameters and the reliability of safety systems into account. This is achieved by means of implicitly linking the degree of conservative values of the input parameters to the output results, through probabilistic methods. The final goal of the thesis is to develop a methodology that serves as a guideline for fire safety engineers to determine the safety level of various types of fire safety designs for different types of buildings.

Based on the scope of this research, the main objective can be divided into different sub-objectives. The first sub-objective is to analyse and situate current state-of-the-art risk analysis methods. The purpose is to generate a reference level for further analysis. The second sub-goal is to propose a generic quantitative risk analysis method that is able to evaluate fire safety designs. The method should be able to analyse complicated building configurations and take the different important aspects of fire safety design into account. More in particular, fire and evacuation scenarios should be quantified objectively, and the effectiveness of safety systems needs to be considered. The method should be capable of comparing the level of safety of prescriptive and performance-based design provisions, to verify performance-based designs with a pre-defined reference level and to compare different alternative solutions to each other. The third sub-goal is to develop a simplified version of the methodology that enables to provide a first estimate of the fire safety level. The aim of the simplified method is to analyse relatively quickly challenging projects and to distinguish between conservative fire safety design options and projects which are not on the safe side. The latter will be analysed more in depth with the advanced method. The fourth objective is to validate the methodology and apply the model to multiple case studies in order to test the feasibility and practicality of the QRA-model.

I.3 Outline

This thesis contains 9 chapters, grouped into two major parts:

- In **Part A,** Chapter I to V, state-of-the-art methods are analysed and the generic QRA-framework and simplified method is developed;
- in **Part B**, Chapter VI to VIII, the generic QRA-method is subjected to validation and testing. The results are compared with proposed acceptable risk levels.

After the general introduction in the current **Chapter I**, a literature study is conducted in **Chapter II,** focusing on different risk analysis tools for life safety in case of fire, more specifically on the analysis of existing quantitative methods that contain both fire and evacuation analyses. An overview is provided of current use of risk assessment methods and their added value in FSE. **Chapter III** describes the deterministic framework. The objective is to develop a combination of sub-models that provides consequence outputs for the probabilistic analysis. In **Chapter IV** the probabilistic framework is presented. The objective of the framework is to develop a methodology that provides a representative quantification of the safety level while considering the significant parameters. This is the core of the research. The final goal of the chapter is to design a methodology that guides the fire safety engineer through the probabilistic analysis to determine the safety level of various types of fire safety designs for different types of buildings. In **Chapter V,** a simplified model is proposed to serve as a pre-analysis tool to determine an initial estimate of the obtained safety level. The model essentially applies less complex submodels for the deterministic analysis, while maintaining the probabilistic framework.

The developed QRA-model is validated and tested in **part B**. The validation is executed in **Chapter VI**. Multiple parts of the probabilistic methodology are validated based on simplified and more complex case studies. The focus is on the error estimation of the different models. In **Chapter VII,** the method is tested on two case studies. First a simplified case study analysis is conducted as a proof of concept. Secondly, a more challenging case study is investigated to assess the validity, feasibility, and applicability of the method. In **Chapter VIII**, research regarding acceptability and comparison of safety levels of different countries is performed. A proposal is made for an acceptable societal risk level. The proposed acceptable risk criterion is compared with the result obtained in Chapter VII.

Finally, general conclusions and a summary of the research presented in this thesis are given in **Chapter IX**, along with suggestions for further research.

At the end of the thesis, several appendices are attached regarding studies performed during the research that give a wider view on the methods discussed in the main part of the thesis.

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CHAPTER II
RISK IN FSE

II.1 Introduction and objective

In chapter 2 of this thesis, a literature study is conducted on different risk analysis tools for life safety in case of fire. Many recent publications employ the term risk without providing a clear definition of its concept. This might be due to the fact that the term risk has wide-ranging meanings, interpretations, and methods in disparate disciplines, such as engineering, economics, politics, philosophy, etc. Hence, it is necessary to take a closer look at the term risk and its corresponding ideas, methodologies, and assumptions with a special focus on its application in FSE. In the following sections, an introduction into (fire) risk assessment will be provided. The focus is put on the analysis of existing quantitative methods that target both fire and evacuation analysis. First, a general introduction about risk and risk assessment is given. Next, the quantification of risk is discussed. Hereafter, a literature study is performed analysing different fire risk assessment models developed during the past 50 years. Finally, conclusions are drawn.

II.2 Risk

II.2.1 Definition of risk

The aim of building fire risk analysis is to gain insight into fire-related risks to better inform stakeholders about the wide range of decisions that must be taken as part of building design, construction, and operation. From a general point of view, it is very difficult to give a clear definition of risk. Many attempts have been made, but one unambiguous definition of the concept of risk is not available. Instead of trying to give one definition to the subject, other paths have been followed.

One of those approaches is followed in [1]. In order to cope with risk, an answer needs to be provided for the following three questions:

1. What can happen or what is the scenario?
2. How likely is it that it will happen or what is the probability?
3. If it does happen, what are the consequences or what is the damage?

By answering these questions for a specific case, the engineer will be able to get an idea of the possible risks related to the project. In [2] an in-depth analysis of different views on risk is discussed. In the above consideration of risk, fire is the hazard that may induce the loss or harm to that which is valued (e.g. life, property, business continuity, heritage, the environment, or some combination of these) [3].

From an engineering point of view it is practical to consider, for a particular scenario (question 1), risk in terms of likelihood (question 2) and consequences (question 3) of incidents that could expose people, property and the environment to the effects of fire. Likelihood is determined in terms of either frequency (how often can it happen?) or probability (what are the chances that this will happen?). This can be mathematically expressed as:

$$Risk \text{ or } R = F * C = Freq * Cons \qquad \text{(II.1)}$$

where R is the risk, F is the likelihood of an event and C are the consequences. As used in this chapter, risk is defined as the possibility of an unwanted outcome in an uncertain situation, where the possibility of the unwanted outcome is a function of three factors: loss of or harm to something that is valued, the event or hazard that may cause the loss or harm, and a judgment about the likelihood that the loss or harm will occur [1]. Specifically for fire safety, fire risk is the possibility of an unwanted outcome in an uncertain situation, where fire is the hazard that may induce the loss or harm to that which is valued (e.g., life, property, business continuity, heritage, the environment, or some combination of these). Building fire risk analysis, then, is the process of understanding and characterizing the fire hazard(s) in a building, the unwanted outcomes (relevant losses or harm) that may result from a fire, and the likelihood of fire and unwanted outcomes occurring.

The purpose of a fire hazard assessment is to identify possible sources of fire ignition and various conditions that may result from the fire without considering the likelihood of occurrence. Fire hazard assessments typically involve surveys of facilities or processes in order to obtain information such as potential ignition sources, potential fuel sources, arrangement of fuel packages, building and compartment configurations, and presence of fire safety features. Armed with this information, one assumes ignition or burning and estimates or predicts the fire growth, spread, and impact under a variety of fuel, compartment, and fire protection system configurations.

II.2.2 Risk assessment and risk management

Risk assessment is a part of the risk management process which consists of a risk analysis and a risk evaluation. The third step in risk management, risk reduction, is not included in a risk assessment (Figure II.1). The purpose of a risk assessment in general is to assess the risk. In this thesis, the final aim is to assess the risk of fire in buildings. The first step of the risk assessment is the risk analysis. This is a general term for a large family of different methodologies and models. According to the ISO definition, risk analysis is the "systematic use of information to identify sources and to estimate the risk". In other words, the analysis includes identification of all possible negative risk scenarios. Depending on the type of analysis, this includes a collection of quantitative information of frequencies, probabilities and consequences.

The second step in risk management is the risk evaluation process. Together with a risk analysis, an evaluation of the risk is always necessary. According to the ISO definition, risk evaluation is "the process of comparing the estimated risk against given risk criteria to determine the significance of the risk". This means that risks can be evaluated with a given acceptable minimum criterion (Discussed in Chapter 8). During the evaluation process, different alternative solutions can be compared to each other.

In short, the advantages of a risk assessment methods can be explained as follows:

- It describes qualitatively or quantitatively were the problems are in a design;
- It gives a measure of the safety level of a design which can be compared to a minimum safety level;
- It gives flexibility to the designer or architect;
- It gives the possibility to compare between different alternatives;
- It allows for optimisation of costs.

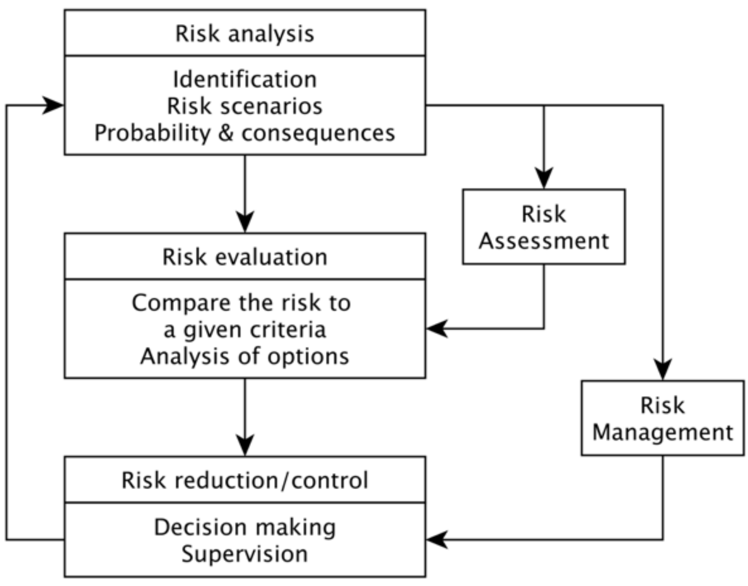

Figure II.1: Schematization of the risk assessment and management procedure. Taken from [4].

II.2.3 Measure of fire risk

In order to quantitatively asses the fire risk, it is essential to determine its measure. Philips [5] discusses that it is difficult to express risk to life in a way that can be understood by the community. This leads to the consideration of other metrics for risk. On the other hand, financial damage is the perfect metric for the property related risk. However, the primary focus of fire codes is life safety, which then requires that risk to life must include a measure of the value of human life. This considers the economic value of an individual as the present value of the stream of income that he or she expects to earn during the rest of his or her working life [5]. The concept that some people have less value to society than others has encountered great objection. Thus risk to life is usually assessed separately to avoid the difficulty of assigning a monetary value to human life. In most risk assessment models fire risk is measured separately using different comprehensive parameters. An example is the expected risk to life (ERL) and the fire cost expectation (FCE) [6]. ERL is defined as the expected number of deaths over the design life of a building, divided by the population of the building and the design life of the building. FCE is defined as the expected total fire cost, divided by the cost of the building and its contents. The ERL value and FCE value can be used for the decision making process [7].

Frantzich [8] divided life risk into two different types: the individual and the societal risk. This was done to make a distinction between the risk to an individual and to a group of people. Further, the suggestion was made to link the traditional safety factor obtained from ASET/RSET methods with a failure probability [9]. The former two types of risk quantification are explained in the following sections.

II.2.3.1 Individual risk

The principle of individual risk (IR) is defined as the probability of death or serious injury to which specific individuals are exposed, and this for a particular scenario. Typical individual risks of concern include general health risks (e.g., cancer, respiratory disease, heart disease, acute or chronic toxicity), safety risks (e.g., burns, asphyxiation, acute or chronic toxicity) associated with localized technological hazards (e.g., localized fire, explosion, chemical release), risks associated with accidents/unintended incidents (e.g., slips, falls, cuts from glazing). Individual risk can also be of concern when related to natural hazards and large technological events.

The individual risk can be expressed in several ways. The way of characterisation will depend on the way in which the risk information is intended to be used. As an example, the risk can be characterized using annual mortality and population figures. Often a time-based average, or an average based on age and gender, is used. In some cases, only specific target populations are considered (typically those considered vulnerable populations). Significant challenges exist in identifying populations of concern, hazards to which they are exposed, means to reflect the risk, data for analysis (historical) and data for prediction (e.g., see discussion in Stern and Fineberg [10]). In chapter VIII, an in-depth analysis is performed to define acceptable individual risk criteria.

II.2.3.2 Societal risk

Societal risk is often used when discussing risks associated with hazards or events that impact large geographical areas and therefore large numbers of people (e.g., natural hazards, such as earthquakes and cyclones, or large technological hazards, such as open air chemical releases). A widely cited representation of societal risk is the relationship between frequency and the number of people suffering from a specified level of harm in a given population as a result of the realization of specified hazards. In this way one can differentiate between high-frequency/low consequence events and high-consequence/low-frequency events. This is important because society tends to be less tolerant for high-consequence events (consequence aversion).

Societal risk is most often expressed in terms of the frequency distribution of multiple casualty events in an FN-curve. An example is given in Figure II.2. FN-curves were developed in the nuclear industry in the 1960s as a means for analysing and communicating the different levels and natures of risks, particularly those with the potential for high consequences, but with low frequencies [11]. The formula for the curve is given as:

$$1 - F_N(x) < \frac{C}{x^n} \tag{II.2}$$

where n is the steepness of the limit line and C the constant that determines the position of the limit line. A line with a steepness of n = 1 is called risk neutral. If the steepness n = 2, the criterion is called risk averse. In this case larger accidents are weighted more heavily and are thus only accepted with a relatively lower probability. In chapter VIII, an in-depth analysis is performed to define acceptable societal risk criteria.

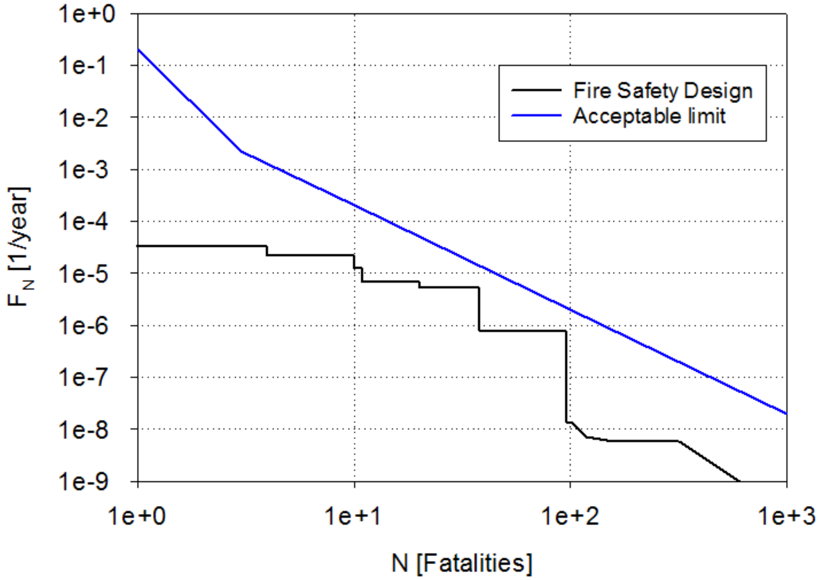

Figure II.2: Example of an FN-curve for a rail connection [12].

II.2.4 Risk models

Currently, no codes exist that outline detailed methodologies to execute a quantitative fire risk analysis. Some codes are under review to provide procedures [13]. Some basic guidance is provided in standards [14–16], engineering rules of good practice [7,17] and in literature studies [18–25]. These guidelines provide a good insight in how to structure a risk analysis. However, they often lack details or only focus on specific parts of the method or problem at hand. Therefore, in the last decades multiple quantitative risk analysis models have been developed. A summary is given in the following sections in which a distinction is made between single and multi-submodel systems, and integrated fire risk approaches. Single model systems consist out of one deterministic submodel while multi-model systems exist out of a combination of multiple deterministic submodels to quantify the risk level. Integrated fire risk approaches provide general guidelines and can also have multi-model systems, however, the focus is put on the framework and the sub-models are interchangeable.

II.2.4.1 Single-model systems

The first fire risk assessment models were developed in the 70s and consisted of single-model systems mainly based on statistical data for dwellings [26] and hospitals [27]. These methods, developed by Aoki and Beard, used stochastic techniques to determine the fire risk. In the same period, Ramachandran introduced a revolutionary approach in which he combined stochastic techniques and correlations for fire loss data to determine the financial and life safety risk in case of fire [28,29].

The COFRA method, developed in the 80's, systematically assesses the fire risk associated with individual, discrete spaces in telecommunication facilities by measuring and reporting fire risk values for life safety and network integrity. In this method, the focus is put on hierarchy levels of fire safety concepts, systems and components. During this period, Ramachandran presented his framework for fire growth and probabilistic fire ignition to assess property damage [30,31]. In later work (90s), his publications advocate non-deterministic risk assessment as a useful approach to the problem of fire safety [32,33].

At the end of 90s, fire risk ranking techniques were suggested for fire safety analysis [34]. In this method the fire safety level is a function of a list of fire safety attributes which are not directly measurable. Although these attributes are numerous, it can be said that a relatively small number of factors account for most of the problems, and it is possible to reduce the large number of parameters to make them easier to work with. Since the number of attributes that need to be handled is large, the mathematical operation will be complicated if they are all analysed in one operation. Instead, a hierarchy of three or more levels can be established in which similar attributes are grouped. Each group is then analysed, and the result is used for the analysis at the next level in the hierarchy. A weight is assigned to each attribute and criterion. To determine these weights, pairwise comparisons are done. To facilitate the assessment, surveyors evaluate each attribute in a linguistic score, and all scores provide a fuzzy set to determine an overall risk evaluation.

Several years later, further work was performed based on previous research of Ramachandran. Two risk assessment models were developed: the first based on the "Probability Tree Method" and the second based on the "Markov Analysis" method [35]. Both models incorporate fire test data in combination with the two zone model CFAST [36].

In the beginning of the 21th century research was done to incorporate Monte Carlo methods in statistical fire safety engineering [37]. Further research was done by Hostikka who utilized statistics to collect information and gain an understanding of elements affecting fire risk [23]. He compared the statistical data to that of other countries such as Canada. A fire risk assessment was made of residential buildings in China with the obtained statistical data. To this end the authors considered the risk of occupant deaths and the risk of the direct property loss. The occurrence of fire was determined by dividing the total residential building area by the number of fire ignitions. The risk of occupant deaths (resp. risk of direct property loss) was calculated by combining occurrence of fire and fire deaths (resp. direct property loss).

II.2.4.2 Multi-model systems

With the development of computer science, fire safety researchers were able to implement more complete and complex models, and especially multi-model systems, which can predict fire and occupant behaviour. These new systems permit a better estimate of risk for life than previous ones. These systems are mainly based on a sequence of several specific sub-models.

In the middle of the 80s, the National Fire Protection Association (NFPA) developed a probabilistic model called the Building Fire Simulation Model (BFSM) [38]. The model examined the interrelationships among fire development, spreading of combustion products and movement of people. Fire growth is defined by discrete steps representing the different observable phases of growth. The model developed by NFPA is a step-transition model to measure and compare the fire safety levels and building alternative configurations. The BFSM consists of five sub-models to quantify the risk level. These submodels were analytical models, hence needing few computational power.

In the following two decades, more quantitative fire risk analysis models were developed. The most known are FiRECAM [5,39], CESARE-Risk [40], FIERAsystem [41], CRISP [42], B-RISK [43], CUrisk [44], SCHEMA-SI [45], HAZARD [46], and other probabilistic methods [47].

In the 90s, the National Research Council of Canada (NRCC) developed FiRECAM (Fire Risk and Evaluation and Cost Assessment Model), a risk assessment and evaluation model tailored to the Fire Code of Canada. The main philosophy of FiRECAM is based on the work of Beck [48–51] and is developed for office and apartment buildings. FiRECAM calculates an estimate of the number of deaths and financial losses; these numbers are then combined with those of the probabilities of occurrence for various scenarios to provide information about the ERL and the FCE. ERL and FCE provide valuable information to anticipate the levels of human and financial risk for the entire building life. FiRECAM belongs to the modern generation of probabilistic assessment models and is built in a modular way.

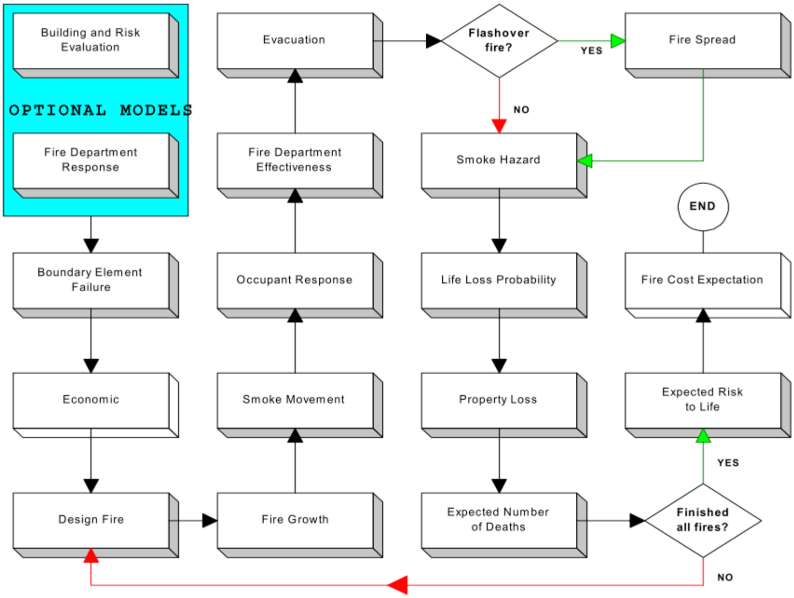

Figure II.3 Flowchart FiRECAM [52].

Closely related to FiRECAM is CESARE, which was developed in Australia for similar purposes [40,53,54]. It consists of a number of sub-models that simulate the dynamic interaction of fire growth, smoke spread, occupant response, and fire department intervention. Each of these models calculates a different set of simulations for fire growth, occupant behaviour, fire department response, and smoke hazards. The probabilistic approach is implemented by means of six design scenarios with according probabilities based on statistical data.

The National Institute of Standards and Technology (NIST) developed HAZARD to assess the fire hazard [47]. The methodology consists of a set of procedures combining expert judgment and calculations for estimating the consequences of a specified fire. The core of HAZARD is a sequence of procedures, implemented in a computer software, to calculate the development of hazardous conditions over time, to calculate the time needed by building occupants to escape under those conditions, and to estimate the resulting loss of life based on assumed occupant behaviour and tenability criteria. The centrepiece of HAZARD is a zone model of fire growth and smoke transport.

The CRISP model has a similar structure as the FiRECAM and CESARE models [4,55,56]. The model is developed to evaluate the risk of domestic houses. However, it is not limited to these types of buildings. It uses random methods to produce possible fire scenarios. The basic concept of the model is that a system may be treated as a collection of objects, which may interact in a number of ways. The model uses a zone-model for smoke spread and analytical models for evacuation and fire brigade intervention.

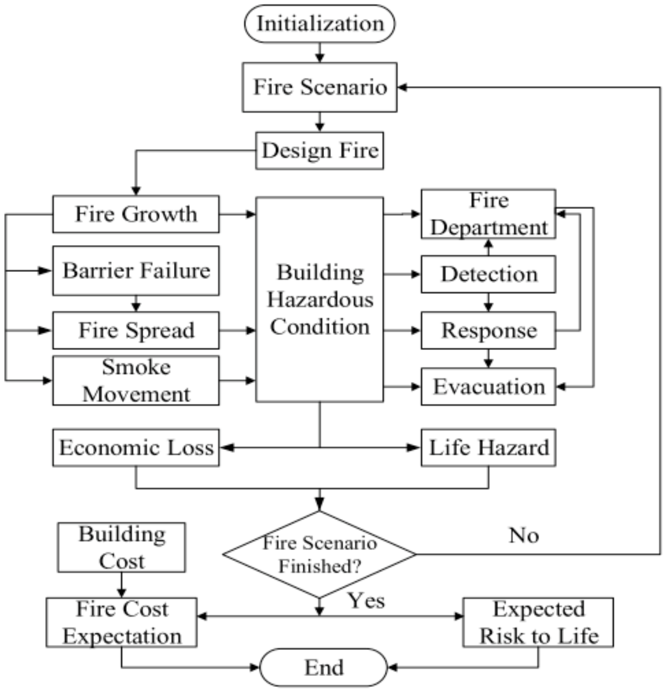

Figure II.4: A schematic representation of the model CURisk [57].

The FIERAsystem sub-model is developed by the same institute as the FiRECAM model. The model is developed to evaluate fire protection systems in industrial buildings, with a primary focus on warehouses and aircraft hangars [59]. The model uses similar sub-models as the FiRECAM model with different fire scenarios and the same way of using event trees.

The CUrisk model is developed to evaluate timber-framed commercial buildings [44]. The model uses a deterministic analysis of separate fire scenarios (based on event tree model) to calculate the smoke temperatures and toxic smoke concentrations. The approach uses a smoke spread, boundary failure, occupant response and evacuation model to determine the consequences. The model calculates the ERL and the expected risk injury (ERI). CUrisk uses Bayesian networks to simulate the fire spread process [59].

In France, the Scientific and Technical Centre for Buildings (CSTB) has been working on a system called SCHEMA-SI (Stochastic Computation and Hybrid Event Modelling Approach) [45,60]. This system is based on hybridization of two sub models. On one hand, a sub-model calculates the expansion of fire and smoke movements over time. This is a two-zone model named CIFI2009, also developed by the CSTB. On the other hand, discrete events, mainly representing human behaviour and operation of security systems, are modelled using specific Petri nets. CIFI2009 is a multi-compartment two-zone model that processes buildings with several compartments. The model uses Monte Carlo simulations to take the variability of system components into account. Thus, this simulation allows performing many experiments while varying, for example, the time of ignition, the location of occupants, and opening doors. CIFI2009 is validated for classical geometric shape compartments (rectangular).

B-RISK allows the user to perform Monte Carlo simulations by using randomly sampled parameters according to input distributions. In addition to the calculation of the fractional effective dose, reduced visibility is also taken as a hazard. However, these parameters are calculated for a fixed position in a specific room. While egress paths can be specified by the user, the life hazard of occupants calculated by using this method is problematic due to the high randomness of human behaviour [61].

From the above investigated risk models it is observed that most of the analysed methods use a combination of simple deterministic sub-models with low computational affordance to analyse a large number of scenarios. The majority of these risk models implemented similar techniques to analyse the life safety problem. The most important are analytical sub-models for e.g. fire spread, fire brigade intervention and consequence analysis, zone-models for smoke spread and hydraulic or network models for evacuation analysis. The probabilistic techniques used in the models are often a combination of event tree and simple sampling techniques (e.g. Monte Carlo, etc.). The output is presented in terms of fatalities, ERL or FCE. The scope of these models is mostly limited to simple office, commercial, and apartment buildings because of the simplified methods.

II.2.4.3 Integrated risk approaches

The main advantage of the above discussed risk models is the level of quantification in relation to the speed of execution. However, the disadvantages are the limited scope and the lack of accuracy of the sub-models (e.g. smoke spread, evacuation, etc.). Therefore, the focus of the research in the last decades shifted towards the development of more accurate techniques and probabilistic frameworks to provide for a more holistic approach.

Frantzich was one of the main founders for defining a probabilistic risk assessment framework in fire safety engineering [8,62]. His work was based on the combination of event tree scenarios and simplified deterministic techniques. Later on, he refined his technique by means of more accurate sub-models (e.g. FDS+EVAC) and probabilistic techniques (e.g. Monte Carlo and Latin Hypercube sampling) [63].

In [64,65], a generic QRA method was proposed to combine engineering and data driven approaches. The method is composed of multiple sub-models and is supported by state-of-the-art probabilistic techniques using Monte Carlo simulations. The model evaluates cost expectation and life safety. The advantage of the method is the level of interaction between the different sub-models over time. The disadvantage is the lower accuracy due to simplifications in the different submodels. In [28], an integrated QRA approach was presented to quantify the risk for people present in a tunnel in the context of a fire hazard in a railway tunnel. The model is composed of a smoke spread, an evacuation, and a consequence sub-model in combination with probabilistic techniques (bow-tie, limit state design, etc.). The methodology enables the user to determine the societal risk and to compare the different alternative solutions against each other, with predefined acceptable risk criteria. The advantage of the model is that it integrates more advanced submodels (e.g. field models, human behaviour, probabilistic toxicity analysis, etc.). The disadvantage is that it aims at passenger transport in tunnels and rail stations only.

In [66–68], a probabilistic response surface method (RSM) in combination with multiple sub-models was developed. The underlying mathematical technique for the RSM is based on Interpolating Moving Least Squares regression. The main sub-models used are the Fire Dynamics Simulator FDS [69] and its corresponding EVAC software [70]. The method shows promising results with respect to combining computational affording models (CFD, continuous evacuation models, etc.) and probabilistic techniques. However, the framework still shows some important shortcomings to analyse more complex designs. The main shortcomings are considered fourfold. Firstly, the method is only valid for simple geometries were evacuation and smoke spread are straightforward. In case of a more complex geometry, the number of volumes and manual actions in applying the model increases significantly. This will reduce the efficiency of the model. Secondly, the focus of the method is only on RSM for smoke spread, while other submodels such as evacuation could also benefit from the approach. Thirdly, evaluation of risk was considered based on a fixed location (e.g. toxicity analysis in front of a door) rather than occupant movement based. Fourthly, no extensive validation and testing was done for the RSM and several important parameters with respect to life safety (e.g. human behaviour, scenario analysis, etc.) were not considered.

More recently, Van Coile did extensive research on reliability and fire risk assessment of structural elements [71–73]. In his work he proposed a new framework which is included in the new BS 7974 [74]. The framework describes the necessary steps to be taken to perform a proper risk assessment. His work focuses also on risk acceptability and the role of the ALARP (As Low As Reasonable Possible) principle in fire risk engineering.

II.2.5 Uncertainty in risk analysis

In order to perform a QRA, the FSE needs to consider the different types of uncertainty related to the choice of the method and take actions to show the impact of these uncertainty and how to deal with it. Three types of uncertainty can be defined. These are parameter uncertainty, model uncertainty and completeness uncertainty [75].

The first type parameter uncertainty relates to the choice of the parameter value for specific input in the models used in the method. These can be ignition frequency, fire growth rates, system component failures, etc. Two types of parameter uncertainty exist, i.e. epistemic and aleatory uncertainties. Epistemic uncertainty is mainly related to the lack of data. This uncertainty can be reduced by obtaining more data through tests or keeping historical data. Aleatory uncertainty is more related to the randomness of an event.

The second type, model uncertainty, is related to the uncertainty generated by the assumptions and simplifications in the underlying methods of the model. This type of uncertainty is further discussed and analysed in Chapter VI.

Completeness uncertainty is related to whether all the significant phenomena and all the significant relationships and scenarios have been considered in the QRA. Examples of completeness uncertainty might be that some scenarios might be forgotten in setting up the event tree. Others can be that specific failure modes in fire safety systems might exist that are not taken into account. Specific phenomena (e.g. the effect of wind) might not be taken into account.

II.3 Reliability based design

When evaluating the reliability of a design one has to calculate the probability for the design to reach an undesired or unsafe state. Limit state design in fire safety engineering has been inspired by structural safety engineering because of the extensive experience with reliability analysis in the field. The general case of a limit state of a cross-section or construction element can be formulated in a limit state equation [76]:

$$\mathrm{g}(\mathbf{X}) = \mathrm{Z} = \mathrm{R} - \mathrm{E} = 0 \tag{II.3}$$

where R is the resistance and E is the load. The vector Z consists of n basic variables. For all the different variable an appropriate probabilistic distribution has to be chosen. In case a basic variable has a negligible variation or uncertainty, the variable can be considered as deterministic. The function is defined so that $\mathrm{g}(\mathbf{X}) > 0$ corresponds to a safe condition, while $\mathrm{g}(\mathbf{X}) < 0$ corresponds to failure. For life safety analysis this unsafe state would be reached when untenable conditions occur in the considered compartment or building before the egress has been completed. Such a limit state function is reached when the available safe egress (ASET) is equal to the required safe egress time (RSET). In mathematical form:

$$\mathrm{g}(\mathbf{X}) = \mathbf{ASET} - \mathbf{RSET} < 0 \tag{II.4}$$

When $f_x(x)$ is considered as the n-dimensional probability density function of the n basic variables X_i, then the probability of exceeding the limit state condition can be calculated:

$$P_f = \int_{g(\boldsymbol{X})<0} f_X(\boldsymbol{X}) d\boldsymbol{X} \tag{II.5}$$

Based on the philosophy of structural reliability approached, a third type of criterion can be considered, i.e. related to a probability of failure [7]. The failure probability can be estimated on system or on concept level. The former represents the reliability of fire safety systems (e.g. sprinkler system). The latter can be defined in terms of injury, fatality, monetary loss, etc. The period is typically one year or the lifespan of the building. In this thesis, when discussing the results, the concept of failure probability is defined as the probability of a fatality over a one-year period.

II.4 Conclusions

This part of the thesis provides a comprehensive review of available probabilistic risk assessment methods applied in the fire domain. Three important gaps are identified on the basis of this review:

- The importance of new models that can account for the stochasticity of the phenomenon (fire) and at the same time encompass the accuracy of deterministic approaches.
- The importance of optimization of computer time in order to support heavy all-round equations that can describe the phenomenon in its totality as well as support multi-room simulations
- The importance of standardization of data collection from experiments and real fire events. There is a need for a database to provide input for probabilistic assignment of fire parameters.

From the study it can be observed that the risk assessment community faces an important limitation in the availability of accurate data. State-of-the-art models with the ability to calculate risk with a high amount of detail are fed with inaccurate data. The EU with its member states does not have a common protocol for data collection. As mentioned above, adequate statistical data is a prerequisite for a full probabilistic risk assessment to quantify the overall life safety risk. Local conditions, political decisions and the absence of appropriate training dictates the type and form of the fire code, pushing probabilistic risk assessment to the periphery of risk science. The absence of this data at a local, national or trans-national level moves the focus of data collection to the risk assessor making it even more difficult.

Another important issue that arises from the review is the fact that although detailed and thorough risk assessment models exist, they are not used widely in practical applications (such as the design of new constructions). Only few official legislations and guidance documents advocate the use of probabilistic risk assessment for the design of new infrastructure.

II.5 Suggested approach

Based on the studied literature and the conclusions drawn from the investigation, the remainder of the thesis will focus on the development of a probabilistic risk assessment method that deals with the shortcomings discussed above. The goal of the method is to objectify designs by taking the probability of design parameters and the effectiveness of safety systems into account. The framework, that will be developed in chapters III and IV (Figure II.5), is a combination of deterministic and probabilistic techniques to assess the reliability of the design and quantify the risk level. The deterministic framework is a combination of analytical (fire spread, etc.) and numerical (detection time, smoke spread, evacuation, etc) interacting sub-models. These submodels give the possibility to analyse complicated building designs and analyse the effectivity of safety measures. The probabilistic framework is based on a combination of numerical sampling (e.g. LHS and Sobol sampling), RSM and reliability techniques to effectively quantify the life safety risk for individuals and occupant groups.

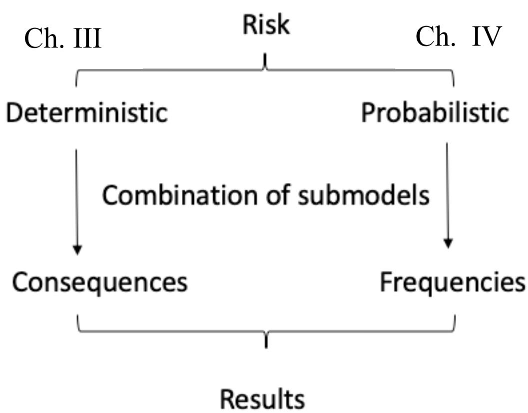

Figure II.5: Proposed approach for the PRA method.

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CHAPTER III
DETERMINISTIC FRAMEWORK

III.1 Introduction to the framework

In this chapter, the focus is on the deterministic part for the development of the framework to quantify the life safety risk to people in complex buildings in case of fire. The objective of the deterministic framework is to develop a combination of sub-models that provide explicit outputs for the probabilistic framework. The target of the deterministic models is to quantify the injury to occupants due to the effects of fire. In the following chapters, these models are developed and boundary conditions are set.

III.2 Problem description

The main problem for the development of the deterministic framework is to design a model that is able to accurately quantify the life safety level in case of fire. The challenge for developing such a framework is to choose or create different sub-models that provide representative results which are sufficiently accurate. Currently, multiple deterministic models exist for analysis of specific parts (fire spread, smoke spread, evacuation, toxicity effect, fire brigade intervention, etc.) of a fire with respect to life safety. These models do not define representative scenarios which should be taken into account for a specific problem. Further, they are normally not designed to efficiently interact with each other in one holistic risk model and if they are designed to interact, they are only applicable to a very small part of building types [1–3]. Therefore, research is needed to investigate and develop different model types and to design the most optimal models depending on the boundary conditions.

III.3 Objective

The main objective of the deterministic framework is to provide accurate life safety consequence outputs for deterministic design scenarios in case of fire. To achieve the challenge, the following objectives are set:

1. The model should consider the effectiveness of the safety systems.
2. The framework should assist in defining representative design scenarios for fire and evacuation modelling.
3. The framework needs to consider the most important boundary conditions and take into account the different influence factors in order to assess the life safety risk.
4. The models need to be compatible with each other for efficient interaction and analysis.
5. Keeping in mind that the probabilistic framework will demand multiple simulations, the deterministic method should be designed within computationally affordable limits.

III.4 Framework

In the following sections, the deterministic framework is presented. The framework is composed out of different models that interconnect with each other (Figure III.1). Based on the first objective, the safety system submodel is proposed. The model provides parameter inputs that relate to the effectiveness of the implemented safety systems. The efficacy is translated in event tree scenarios to determine the consequences. The reliability is determined based on fault tree techniques and provided as input for the probabilistic framework. For the second objective, the design fire and evacuation scenarios are defined. The model defines multiple fire and evacuation scenarios that provide time dependent parameters for further analysis in subsequent models. The design scenarios provide input for the Smoke Spread model, to analyse the smoke spread through the building. The Smoke Spread model provides input concentrations and visibility data for the evacuation model that, in its turn, provides toxic doses to the consequence model. The final result of the deterministic framework is a FED-value for each occupant in the considered design scenario. The results from the deterministic analysis output are provided as inputs for the probabilistic framework for further analysis to quantify the life safety risk level.

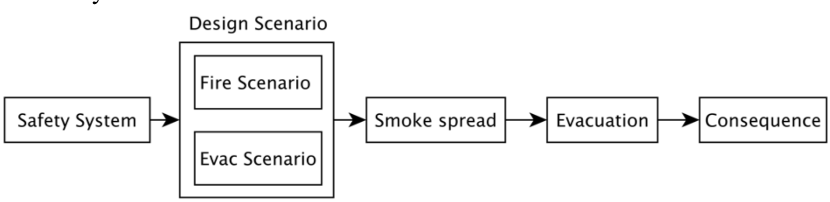

Figure III.1: Deterministic framework.

III.5 Safety System

The purpose of the safety system submodel is to quantify the effectiveness of the different safety systems. First a general description of the concept effectiveness is given. Second, methods to determine the effectiveness are elaborated. Third, the effectiveness of five types of safety systems is elaborated.

III.5.1 General

In order to quantify the effect of safety systems on fire safety designs, the term effectiveness is implemented in the model. The overall effectiveness of a fire safety system is, in engineering terms, the combination of efficacy and reliability [4–6]. The functional effectiveness gives a measure of whether the system will perform adequately for the chosen fire scenarios (e.g., control a fire for a sprinkler system). The reliability is a combination of the availability of the system and the operational reliability. The availability is the probability that the system is available (e.g., water supply) and the operational reliability is the probability that the system will work on demand (e.g., pump activation). In Figure III.2, a breakdown of effectiveness is given. Efficacy is typically determined by the considered fire scenarios (e.g., car vs. retail fire) and environmental factors (e.g., wind). The reliability mostly depends on proper design (e.g., NBN EN 12845), installation (testing) and maintenance (procedures).

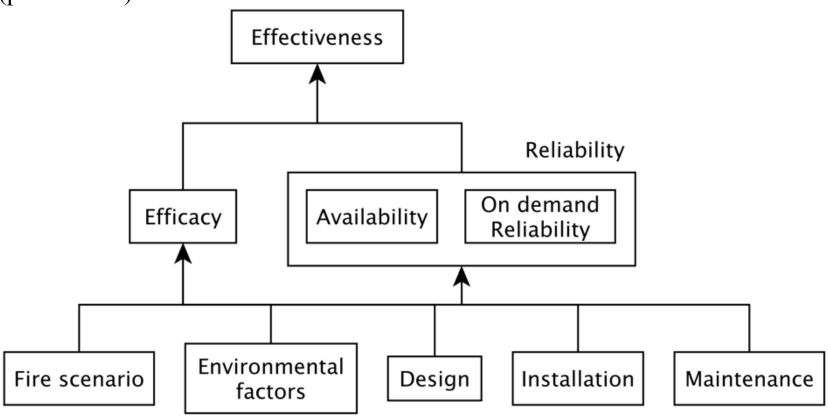

Figure III.2: Breakdown structure of effectiveness [4].

III.5.2 Methods to determine the effectiveness

Three methods are defined to determine the effectiveness of a fire safety system: the use of statistical data; fault tree analysis; and event tree techniques.

III.5.2.1 Statistical data

The application of statistical data in risk analysis is a powerful tool to quantify the effectiveness of safety systems. Based on past incidents, experiments, and testing data, frequencies can be obtained for both efficacy and reliability analysis. For instance, data on past incidents with sprinkler systems can define the level of mitigation in a frequentist approach. The same form of data can derive the reliability of a sprinkler system by defining the activation probability. Important for statistical data is to understand the scope and boundary conditions on how the data has been obtained.

III.5.2.2 Fault tree analysis

Fault tree analysis or FTA is a top-down deductive failure assessment method in which a failure of a system is analysed, using Boolean logic to combine lower event levels. It is based on the principle of “backward logic”: an event delves back into its possible causes and provides a structured method to quantify the frequency or probability of initiating events. The advantage of FTA, in case of fire, is that it provides a decomposition of the top initiating event into factors that contribute to the failure and ignition potential. The frequencies and probabilities used in the FTA can include a combination of equipment and human failure rate data, plant specific data, probabilities supported by deterministic modelling and subjective expert opinion probabilities. A general fault tree exists out of the following parts [7]:

- Initiating top event: an unwanted event or incident at the top of the fault tree that is traced down to more basic failures, using logic gates to determine its causes and likelihoods.
- Intermediate events: an event that propagates or mitigates a basic event during accident sequences, e.g., smoke detector failure.
- Basic events: a fault event that is sufficiently basic that no further development is judged necessary, e.g., equipment failure rates, human failure, and external events.
- Logic gate: a relationship between input events and a single output event. Most typical gates are “And” and “Or”. An “And” gate means that all underlying elements are necessary to initiate the event while an “Or” gate is used when the underlying elements can each individually initiate the top event.

An example of a fault tree is given in Figure III.3. The fault tree represents the fire triangle.

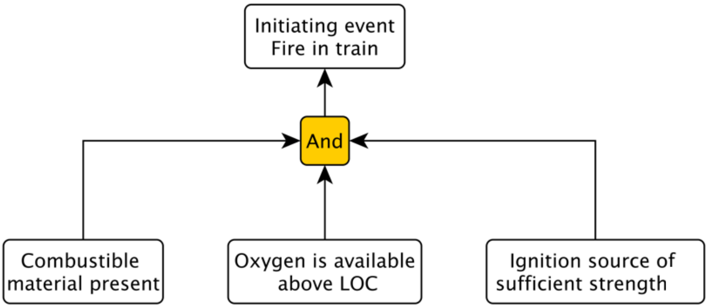

Figure III.3: General fault tree logic. Taken from [7].

FTA is an effective technique to determine the reliability of safety systems. It gives insight in the structure of the failure mechanism and provides an understandable deduction to basic events. The disadvantage of FTA is that it is difficult to use when only a limited amount of data are available.

III.5.2.3 Event tree technique

Event tree analysis or ETA is the most frequently used risk assessment technique for structuring fire loss scenarios. ETA brings the initiating event, sequences, incident outcomes, consequences, and frequencies together. It is based on the principle of "forward logic": from an event people look further into possible consecutive consequences. The advantage is that quantitative probabilities and consequences can be incorporated into a scenario. In order to successfully complete an event tree analysis, the engineer must identify the initiating source events, evaluate the performance of the different steps in the event tree, and evaluate incident outcomes and consequences. ETA has the following advantages [7]:

- It provides systematic organization of fire loss event stages.
- It orders events in time-related sequences.
- It identifies significant top fire loss events for subsequent FTA and probability modelling.
- It allows evaluation of fire detection and protection systems alternatives.
- It demonstrates the relationship between the success of fire performance systems and the potential fire incident outcomes, consequences and risk levels.

A typical ETA model consists of the initiating event, the intermediate or pivotal events and the outcomes. It is important that the event tree is structured following a timeline. The initiating event consists of a probability or a frequency. The intermediate events need probabilities for each branch in order to provide a final probability or frequency for every outcome. The consequences are determined for each outcome.

ETA is a very effective technique to determine the efficacy of safety systems. Like FTA, ETA gives insight into the structure of the failure mechanism and provides an easy-to-understand procedure. The disadvantage of ETA is that an extensive amount of information and statistical data needs to available. When this is not the case, expert judgement can provide a solution. Also, the number of possible outcomes can create problems concerning computational power. Grouping outcomes can provide an acceptable solution.

III.5.3 Sprinkler system

A sprinkler system is an active fire protection system consisting of a water supply system, providing adequate pressure and flowrate to a water distribution piping system, onto which fire sprinklers are connected. The purpose of the fire sprinkler system in the context of this thesis is to mitigate the fire conditions during evacuation and fire intervention. Different types of sprinkler systems exist, such as pre-action, wet-pipe, dry-pipe, and deluge systems [8]. The most used system in public buildings in Belgium is the wet pipe system. For the remainder of the thesis, the focus is on this system. Two types of wet-pipe sprinkler systems are typically implemented: these are the standard control mode fire and the ESFR (Early Suppression Fast Response) sprinkler.

In global terms, sprinkler performance in fires may depend on a series of different factors [6] such as building design (e.g., geometry, fire load, HVAC), other FSE-systems (e.g., SHC), sprinkler system design (e.g., characteristics, technology and redundant elements), lifespan (e.g., inspection, testing and maintenance) , and external factors (water supply).

The objective of the sprinkler system sub-model is to consider the effectiveness of this system. To this purpose, the reliability and efficacy need to be determined. The reliability will be determined based on available data. The efficacy, which reflects the mitigation effect, will be determined based on experimental data. Additionally, a sprinkler activation sub-model is implemented to determine the time to sprinkler activation.

III.5.3.1 Sprinkler reliability

III.5.3.1.1 General

The reliability of a sprinkler system is the measure of the probability that a fire protection system will operate as intended when needed [9]. Two general approaches have been used in previous studies to quantify sprinkler effectiveness: the component-based (FTA) methods; and the system-based (incident data) methods.

III.5.3.1.2 System based calculation

For the system based approach, extensive reliability literature studies have been done in past research [4–6,9–17]. Surveys from research give figures ranging from 38 to 99.5 % [16]. The wide range is partially due to the fact that the collection of statistics does not recognise whether or not the fire was large enough to activate the sprinkler system or if the sprinkler system failed to operate when the fire was large. U.S. statistics [13] indicate that the fire is too small to activate sprinkler heads in 44 to 87 % of the fires. The study gives operational reliability ranges between 75 % for educational facilities, 88 % for hotels, 90 % for health care buildings, 96 % for apartments, stores and offices, and 97 % for public assemblies.

Studies have reported that the main reason for sprinkler system failure, ranging from 33% to 100% of the reported failure, is that the system was shut off [4]. Inappropriate systems, lack of maintenance, and manual intervention are reported at frequencies from 5% to 33%.

Since fires are rare events, system-based studies often do not provide detailed information on specific types of sprinkler systems, specific sprinkler system configurations, or other present systems. Thus, it is difficult to estimate how system improvements such as electrical surveillance of the main valve, or improved inspection, maintenance, and testing practices, will improve system reliability from system-based studies. Therefore, it is suggested that, given the limited amount of information available, the recommended approach to estimate the reliability for a specific system is to determine the reliability for a general sprinkler system from system-based studies, and to modify the probability of failure or success using data from component-based approach. The relative contribution of each component to system effectiveness can be estimated from the component data, and then the effect of making a change to the sprinkler system should then be considered on a comparative basis with the base system, rather than on an absolute basis [6].

In order to estimate the reliability of a general sprinkler system, an in-depth analysis of multiple statistical studies was performed for sprinkler systems, designed and maintained according to proper standards [18]. Based on these studies, a system-based average is defined in Table III.1.

Table III.1: Reliability of sprinkler systems [18].

Assessing general reliability of sprinkler from literature [%]	
Miller [19]	95.8
Miller [18]	94.8
Powers [16]	96.2
Richardson [20]	96.0
Finucane et al [21]	96.9
Marryat [22]	99.5
Poon [18]	95.5
Average reliability	**96.1**

From the reference sprinkler system, upgrades can be implemented for various components [18]:

- Provision of a backup water tank for the sprinkler system
- Provision of a sprinkler valve alarm when turned off and flow monitoring alarm (to fire panel and fire brigade)
- Provision of a backup pump.
- Provision of subsidiary sprinkler valves serving each sprinkler zone
- Provision of end-of-line testing

The general impact on the sprinkler performance as a result of the above improvements on an upgraded system is depicted in the table below. The individual improvements to the Australian Building Code compliant system are given in the last column. With the above upgrades implemented, the overall improvement of the sprinkler operational reliability increased from about 95.5% to 99.5% [18].

Table III.2: Failure probability of key events for sprinkler operational failure. Taken from [18].

#	Event	BCA value [-]	Upgraded value [-]	Improvement (x times)
1.	No auxiliary water supply from water tank	1	0.00013	23
2.	No external water supply from mains	0.04268	0.000102	22
3.	Water supply cut off or local sprinkler valve turned off	0.0019	0.00450	0.95
4.	Water supply line to riser damaged	1.0E-06	0	1
5.	Sprinkler heads faulty	1.0E-06	1.0E-06	1
6.	Sprinkler heads do not issue water	0.04450	0.00450	9.9

III.5.3.1.3 Component based static calculation

In the static component-based approach, time independent fault trees are applied to calculate the failure reliability of the sprinkler system. To construct the fault tree, the different components of a sprinkler system have to be known. The main components are the water supply (e.g., town mains, storage tanks, and pressure tanks), power source (e.g., main town electricity network, generator, and UPS), pump sets (diesel or electrical), valves, piping, fire panel, and sprinkler heads. In the Figure III.4, an example layout of a simple sprinkler system is given.

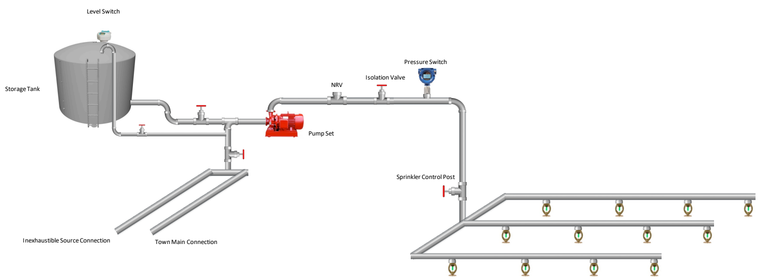

Figure III.4: Example of a sprinkler system.

Based on the top event, the FTA tree is developed (example in Figure III.5). The top event defines the sprinkler failure probability. Four intermediate events leading up to the top event are the failure of the water supply (e.g., town's main valve shut-off), water distribution (pipework failure), sprinkler head and panel failure. The advantage of this approach is that different system configurations can be considered. Simple systems are rewarded and complex systems are penalized. Secondly, additional safety measures such as electrical surveillance of the sprinkler valves can be reflected in the failure probability.

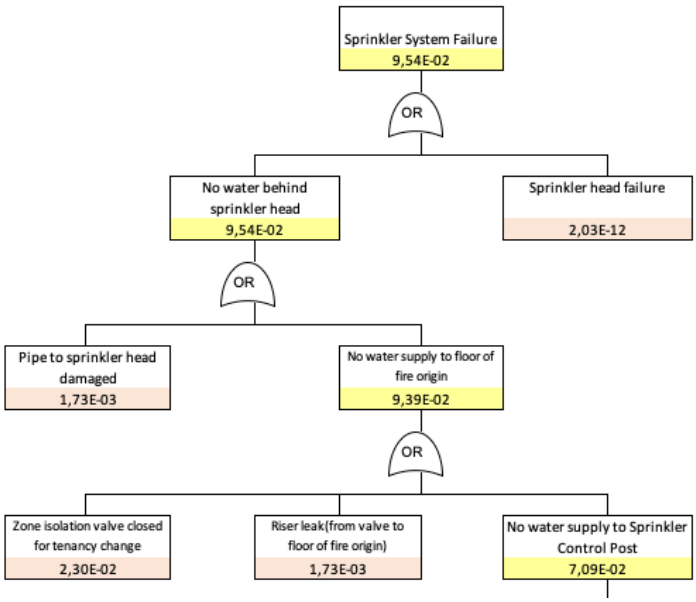

Figure III.5: FTA for part of a sprinkler system failure.

The approach discussed in documents from New Zealand insurer Marsh suggests to approach the reliability analysis as a failure probability distribution [4]. A PERT or triangular distribution is suggested with three parameters, i.e.

a is the lower value, b is the most likely value and c is the maximum. The PERT distribution is considered to be more accurate because the triangular distribution overestimates the tales [5]. The distribution parameters describe the failure probability in a global sense. The lower value should be considered for installations with poor maintenance and the higher values for installations with improved maintenance and quality [23].

The data used from Marsh cannot just be copied because differences in quality are expected for installation, inspection, maintenance, etc. New Zealand has a long tradition and extensive use of sprinkler systems. Additionally, the standard is slightly different. For example, the New Zealand standard NZS4541 [23,24] implements electrical surveillance of the sprinkler valves, which is not obliged in the European standard EN 12845 [25]. Studies [6] have shown that on average 73% of sprinkler failure is caused by the fact that the system had been shut off. Therefore, the additional failure rate needs to be implemented. Periodic inspection is different from the European standard. For different system parts, different inspection rates are required for the NZ standard [24]. Another difference is that every sprinkler system is directly connected to the fire services by a monitoring system [23]. This measure will not affect the direct reliability of the sprinkler system but it will reduce fire services intervention times. Therefore, the data obtained from Marsh needs adaptation to the considered conditions.

III.5.3.1.4 Component based time-dependent calculation

In addition to static components failure calculations, time dependent factors can be included. One of the most important factors affecting sprinkler reliability is maintenance and inspection. Grandison et al. suggested to express component reliability using an exponential time dependent function [26]:

$$R(t) = e^{-\lambda t} \tag{III.1}$$

where $R(t)$ is the reliability of the component at time t and λ is the failure rate. A failure rate of 0.00036 was found for standard sprinkler systems [26]. Using this correlation, the effect of increased periodical maintenance can be considered in the reliability calculation of the system. For the failure rate discussed above, a yearly or monthly maintenance will obtain a reliability of the sprinkler system (P_{ES}) of 93.71% for yearly or 99.46% for monthly maintenance. In the Figure III.6, the decreasing reliability of the system is visualised for both monthly and yearly maintenance.

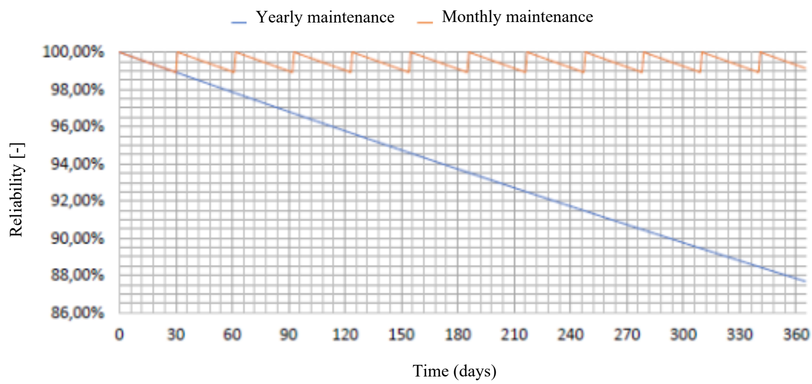

Figure III.6: Reliability of sprinkler system in function of maintenance.

For systems in parallel, the calculation procedure is different when both systems are active or when one system is in stand-by modus. For active systems, the standard binomial distribution is applicable for calculation of the reliability:

$$R(r \leq k \leq n) = \sum_{k=r}^{n} \binom{n}{k} R_x^k \, Q_x^{n-k} \tag{III.2}$$

Where n is the number of components, r is the number of failures which the system can withstand, k is the number of failure events and Q is the failure probability. For stand-by systems, the Poisson distribution needs to be applied. The system reliability R is:

$$R(0 \leq k \leq r) = \exp(-\lambda t) \sum_{k=0}^{r} \frac{(\lambda t)^k}{k!} \tag{III.3}$$

Where λ is the failure rate is.

III.5.3.1.5 Practical applications

Typical applications for public buildings in Belgium according to the NBN EN 12845 are between OH1-OH4 (restaurants, car parks, shopping mall, etc.). These applications only demand one pump set. For applications with higher risks a secondary redundant pump set is required. When calculating the reliability of the system, the additional backup pump can be used as compensating measure in order to increase the reliability of the system. It is important to notice that a redundant pump will increase the initial reliability but has no effect on the influence of proper maintenance and inspection over time on the reliability.

In general, it can be assumed that the reliability of sprinkler systems directly connected to the public water network will have a high reliability because no pump with power supply is necessary. Additionally, less valves with single point of failure are necessary in the system. Not only will the initial reliability increase, also the influence of proper maintenance and inspection over time will be lower. An example of this case with direct mounting on the water network is presented in Figure III.7. In this figure, the main contributors to unreliability are presented.

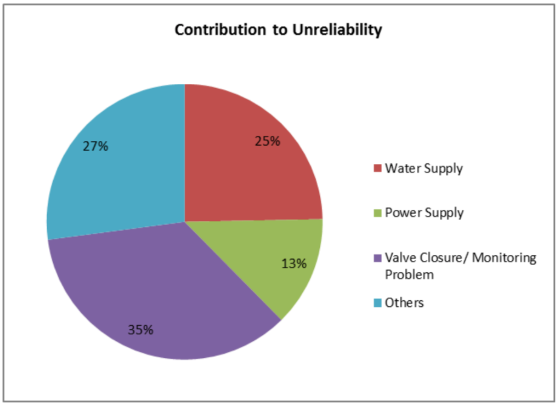

Figure III.7: Sprinkler system utilizing only town main and without pump.

III.5.3.2 Sprinkler efficacy

In this section, the efficacy of the sprinkler system is investigated. A distinction is made between the activation of the sprinkler and the effect of the sprinkler on the design fire after activation. First the activation time is determined that will give input to determine the effect on the fire scenario.

III.5.3.2.1 Sprinkler activation time

The sprinkler activation time is typically determined by means of a heat detector response model. Different response types methods exist to determine the activation time. The two main categories are analytical and numerical models.

The estimation of sprinkler activation by analytical models is done by fire plume and ceiling-jet models, which estimate the temperature and velocity of fire gases flowing past a detection device [27]. The heat transfer from fire to smoke and from smoke to sprinkler is calculated by means of explicit formulas. The advantage of analytical models is that they give a quick indication by means of hand calculations. The disadvantage is that they are less accurate and cannot take into account ventilation effects.

Numerical models, such as zone-models (CFAST, BRZANFFIRE, etc.) and field-models (e.g., FDS, SMARTFIRE, etc.), are used to take case specific features into account. Field models are more complex and are used when accuracy or special conditions (e.g., geometry, etc.) become significant.

For the purpose of the thesis it is assumed that sprinkler activation, represented by a ceiling jet model, is sufficiently accurate considering that other uncertainties are larger (e.g., evacuation into account). The ceiling jet model is a simple time dependent numerical model that determines the sprinkler activation time by iterating the temperature of the sprinkler bulb and the hot gas temperature. The model takes into account different fire, geometry, and sprinkler parameters. The Heat Release Rate (HRR) is considered one of the most sensitive parameters in the model [28]. For modelling the fire growth rate, two main fire size modelling approaches have been applied: the steady-state fire and the t^2 growing fire [29]. The former is used to obtain a crude estimate. The approach is implemented in the DetAct-QS model [30]. The latter is considered more accurate considering the detection in the initial stage of the fire. The approach is implemented in the DetAct-T2 model and discussed more in detail [29].

In order consider the effect of a growing fire on the time to sprinkler activation, Heskestad and Delichatsios [8] presented functional relationships to model the temperature and velocity of fires whose heat release rates grow according to the power-law relationship. They developed an analytical solution for the change in detector temperature. The approach and procedure is implemented in the model by means of Python code [31].

III.5.3.2.2 Sprinkler effect

The purpose of this section is to propose a method to quantify the effect of an activated sprinkler system on the fire scenario. This by modifying the HRR curve discussed in section 6.

III.5.3.2.2.1 Literature

In literature [4], the functional efficacy is often measured based on the number of sprinkler heads that should activate. However, this is not necessarily a proper measure of functional effectiveness, as an excessive number of sprinkler heads may open due to faults with the system or poor operational procedures.

The most common reason for sprinkler systems to operate ineffectively was that the water did not reach the fire, ranging from 19% to 55% of the reported cases. An inappropriate sprinkler system for the corresponding fire was the second most commonly reported reason, followed by an insufficient amount of released water.

For traditional design fires, the effect of the sprinkler system is taken into account by cutting the HRR off at the activation time (curve c in Figure III.8). This is considered a conservative approach because it is likely that control mode sprinkler extinguish the fire [15,32]. Lindsten concluded that fires are extinguished by a sprinkler system in 50% of the fire tests [33]. This percentage is also confirmed in Table III.3 In the other fire tests, the HRR was reduced or kept constant.

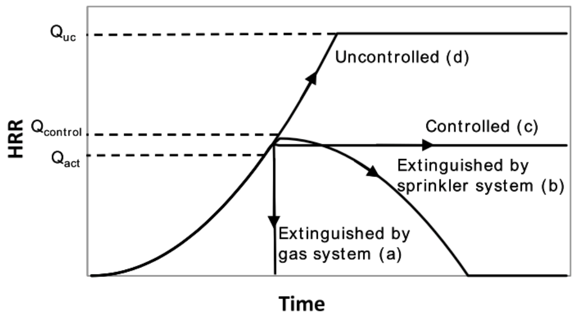

Figure III.8: Effect of suppression system on HRR. Taken from [8].

Table III.3: Sprinkler reliability studies [10].

System performance	Range
Sprinklers operate	95-97
Sprinkler control but do not extinguish	64-95
Sprinkler extinguish	48-96

The effect of sprinkler systems on different room configurations is investigated in several experiments [34]. Based on these experiments, an expression was developed in order to quantify the reduction of the heat release rate after sprinkler actuation [34]:

$$Q = Q_{Act} e^{0.0023t} \qquad \text{(III.4)}$$

Where:

Q	HRR rate at a given time after sprinkler actuation [kW]
Q_{Act}	HRR at sprinkler actuation [kW]
t	Time after sprinkler actuation [s]

The above defined design scenario should be applied to rooms with configurations with limited shielding of burning materials. In case of shielded fires, the HRR should be analysed more in-depth.

The effect of sprinkler system activation on the HRR curve is implemented in various regulatory frameworks. In New Zealand, a constant HRR after sprinkler activation is applied in the C/VM2 [35]. An exponential reducing HRR from activation onwards is applied in the UK in the PD7974-4 [36]. In Germany, a constant HRR is applied for the first 5 min and afterwards a linear reducing HRR is applied for 25 min until the fire is extinguished [37]. In Sweden, a constant HRR is utilized for the first minute after activation, afterwards, the HRR is kept constant at 1/3 of the HRR at sprinkler activation. The Netherlands apply a constant 50% reduction of the HRR after sprinkler activation. In France, the effect of sprinkler systems is not directly taken into account in the LCPP Guidelines [38].

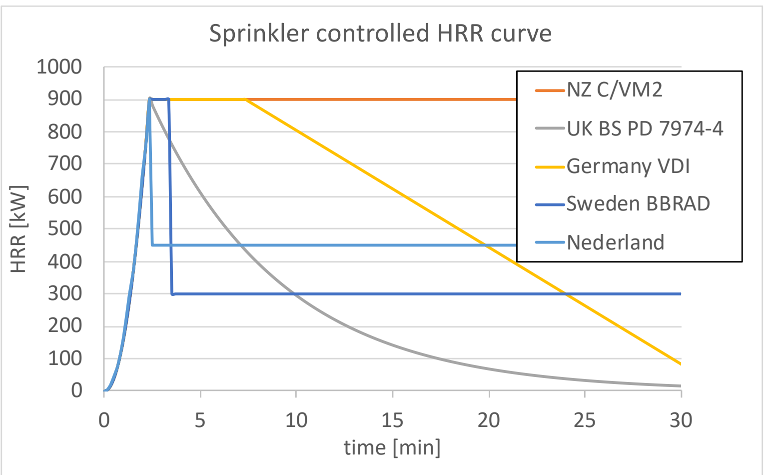

Figure III.9: The effect of sprinkler activation on the HRR and total heat load for different regulatory frameworks.

III.5.3.2.2.2 Effect of sprinkler system on soot production

The effect of sprinkler systems on smoke movement and soot production should be considered because the water droplets will cool down and partially inert the smoke [15,39]. The smoke will descend and the soot production will increase [40]. For small compartments, the former is more important and for larger compartments the second effect will take the overhand due to large distances from the fire [41]. The inertization gives rise to incomplete combustion, causing an increase in production of CO and other toxic products by up to a factor of 10 [39,42,43]. Other experiments showed that despite the elevated toxicity yields per unit fuel, the toxicity levels were still significantly lower when sprinkler systems operated, because the full mass loss rate decreases significantly.

III.5.3.2.2.3 Suggested sprinkler design fire scenarios

Based on the literature discussed above, the efficacy of the sprinkler system can be described by an event tree approach [5], i.e. the efficiency can be represented by multiple realistic fire scenarios:

- Sprinkler failure: effectiveness of the sprinkler is 0%. The HRR is not affected by the sprinkler system.
- Sprinkler shielded: efficacy of the sprinkler is reduced[1] so that the HRR is reduced to a fire in the largest shielding object.
- Sprinkler control mode: the efficacy of the sprinkler is considered cut off. In specific applications a reduction of the HRR after the cut-off can be applied as presented in Figure III.9.
- Sprinkler extinguishment: the sprinkler operates better than designed for and extinguishes the fire.

III.5.4 Fire Detection

III.5.4.1 General

A key aspect of fire protection is to identify a developing fire emergency in a timely manner, as well as to alert the building's occupants and fire emergency organizations. This is the role of the active fire detection and the alarm systems. Depending on the anticipated fire scenario, building and use type, number and type of occupants, and criticality of contents and mission, these systems can fulfil several main functions. The purpose of the fire detection sub-model is to determine the detection time between the start of the fire and the time at which the transmission of an alarm notification signal is sent to the control panel. From the control panel, different actions are taken, depending on the fire safety design. The system may activate the alarm, alert security and emergency services, shut down electrical and air handling equipment or special process operations, and it may be used to initiate automatic suppression systems. Different types of fire detection systems exist. The most important systems are smoke, heat, and flame detection. A description of different fire detection systems was elaborated in [44]. In the following sections, the focus is on smoke and heat detection. The reliability and efficacy of the fire detection system is

[1] The sprinkler standards typically take this into account in the form of a safety a factor by increasing the operational discharge area.

investigated considering that the system is in compliance with standard NBN S21-100 [45].

III.5.4.2 Reliability

Several system based studies have been performed to analyse fire detection system reliability [4,5,11,46]. A summary of reliability estimates are presented in the table below.

Table III.4: Smoke Detection System Reliability [11].

Occupancy	Property use	Mean Reliability	95% Up conf level	95% low conf level
Residential	Apartments	0.693	0.699	0.687
	Hotels/motels	0.778	0.793	0.764
	Dormitories	0.863	0.884	0.843
Commercial	Public assembly	0.679	0.698	0.659
	Stores & Offices	0.717	0.735	0.699
	Storage	0.682	0.7	0.663
	Industry	0.802	0.813	0.791
Institutional	Care of aged	0.849	0.866	0.833
	Care of young	0.84	0.863	0.816
	Educational	0.769	0.796	0.741
	Hospital & clinics	0.833	0.854	0.812
	Prisons and jails	0.842	0.859	0.825
	care of mentally handicapped	0.875	0.903	0.848

The results depicted in the table above show high failure rates for smoke detection systems. The reliability values are potentially low due to the share of smouldering fires in which ionization and heat detectors are more likely to fail. In other studies [47], failure rates are determined from testing and inspection for smoke and heat detectors for systems maintained according to the NFPA 72 [48]. The results are presented in Table III.5.

Table III.5: Smoke and heat detector failure rates and main cause of failure [48].

System type	Annual failure rate	Main cause
Photoelectric Smoke Detectors	0.0041	Alarm test failed
Ionization Smoke Detectors	0.0089	Failed sensitivity
Heat detector	0.0018	Alarm test failed

Besides the studies mentioned above, other research has been done regarding reliability analysis of smoke and heat detection systems. From these studies, the reliability rates varied between 60% and 94% [4].

III.5.4.3 Efficacy

In the next phase, the efficacy of the detection system is evaluated. For fire detection systems in general, the performance measure is that the system detects the fire in a timely manner and passes the signal to the main fire panel. According to [4], the efficacy is highly dependent on the design basis and fire scenario. Specifically, the selection of a detector type suitable for the fire scenario is important (Table III.6).

Table III.6: Failure probabilities for different detector types in multiple fire scenarios [4].

Detector type	Smouldering fire	Flaming fire
Ionisation	0.558	0.198
Photoelectric	0.041	0.04
Fusible link	0.999	10^{-8}

In this thesis, the functional effectiveness of the detection is considered as a measure of the time to a non-false detection. A distinction is made between smoke and heat detection.

Predicting smoke detector response to a growing fire requires calculating the time dependent evolution of the smoke concentration in the ceiling jet. Typically, the temperature rather than the smoke concentration is used to predict smoke detector response due to the availability of correlations for ceiling jet temperatures and the assumption that smoke concentration can be related to ceiling jet temperature. Using temperature to predict smoke detector activation is a conservative approach [49] because of delays due to heat transfer [29]. This makes them practical for engineering purposes. However, Davis et al. discussed that these methods are less realistic because they ignore differences in the production of smoke by burning materials that may completely invalidate a temperature/smoke prediction correlation [49]. Therefore, algebraic correlations for smoke and CO concentration in the ceiling jet in the presence of a smoke layer are developed [49]. The algebraic method is investigated by means of a case study in which the model is compared with the ceiling jet [30] and field model [50] described in the sprinkler sub-model.

The efficacy of the heat detection system is determined in the same way as the sprinkler activation method. The time to activation is obtained from implemented methods.

III.5.5 Fire Alarm system

The alarm can be triggered automatically by detection devices, if installed, such as smoke detectors, sprinklers, or heat detectors, or by an occupant activating a manual pull station. In the context of the thesis it is considered that detection devices are present in the building.

The main issue regarding the reliability of the alarm system is procedure implemented for the building. Typically, a delay is applied in order to avoid false alarm. After this delay the alarm should start automatically. However, two problems can occur: the first issue is whether the alarm is wrongly considered as false alarm, the second when the automatic alarm system is the pre-programmed to be overruled.

In [4], a differentiation was made between simple and complex systems. The reliability of this component for a simple system is relatively high, with an assumed expected value of 99.41% based on panel reliability. For variability, the distribution is set with one standard deviation giving an upper bound of 100% reliability. For complex systems the reliability of the system is assumed to be similar, to control components of a smoke management system such as a stairwell pressurisation system. The expected reliability of this system is 88%. The upper bound reliability is estimated as 98.4% and for variability this is set as 2 standard deviations from the mean.

The efficacy of the system is considered 100 % when the system is designed according to the standard NBN S21-100 [45] and when no time delay for alarm activation has been appointed.

III.5.6 Smoke and heat control

III.5.6.1 General

A smoke and heat control (SHC) system is an active fire protection system that mitigates the fire conditions and controls the effluents of the fire. The objective of the SHC system is two-fold. The first goal is to prevent fire spread by reducing temperatures and therefore reducing the chance of flashover. The second and main goal is to increase life safety of the occupants and assisting fire brigade by preventing accumulation of lethal concentrations and exposure to heat in the compartment of origin. Two basic approaches can be adopted at the design stage: either the smoke must be contained, or it must be extracted. Smoke containment may be achieved by use of physical barriers such as walls, smoke screens, downstands, etc. Containment may also be achieved by the use of pressurization systems to provide adequate pressure to resist the flow of the smoke entering a compartment or staircase. Smoke extraction, natural or mechanical, extracts smoke from the compartment of fire origin. The purpose is to maintain tenable conditions for evacuation or/and fire brigade intervention. For natural systems the size of the openings is determined and for mechanical systems the extraction rate is specified per units of volume. Depending on the geometry (e.g., inclined roof, etc.), environmental conditions (e.g., wind, etc.) and other fire safety systems (e.g., sprinklers, etc.) natural or mechanical systems are preferred [51,52]. In the next subsections, the focus is on different types of SHC systems. First, the standard SHC systems are discussed. Secondly, staircase pressurization system is investigated.

III.5.6.2 Smoke and heat ventilation

III.5.6.2.1 Reliability

Limited research has been done with respect to reliability of SHC systems. Zhao estimated SHC reliability using fault tree analysis [53]. The investigation concluded that zoned SHC have a reliability of between 52% and 62% for buildings with more than 5 and less than 20 floors. In Figure III.10, the top level of the designed fault tree developed in this research is depicted. In order to use the discussed reliabilities, the design is considered to be designed according to the NBN S21 208-1 [54] or standard 12101-5 [55].

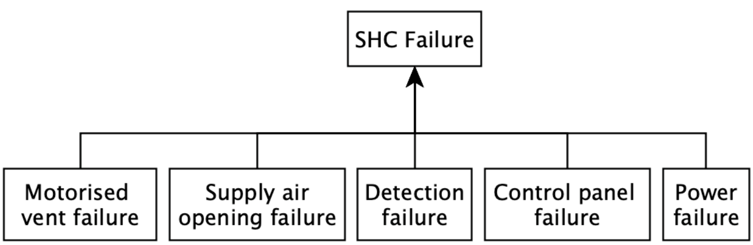

Figure III.10: Smoke control system fault tree [53].

Klote reviewed the reliability of five smoke management systems with increasing system complexity [56]. The research showed that the reliability of the system declined rapidly based upon the assumption that there was no redundancy in the system's design (i.e. any single failure would be critical). The results of the research is shown in Table III.7.

Table III.7: Smoke System Reliability [56].

Case	# of HVAC fans	# of other components	Reliability
1	3	0	0.97
2	0	3	0.83
3	3	9	0.56
4	5	18	0,31
5	5	54	0.03

Twelve existing buildings were inspected for reliability of their fire protection systems in Denmark [57]. The research concluded that all twelve buildings had deficiencies that can result in a situation where parts of the system will be non-functional. One of the reasons for the high failure rate is because at that moment only smoke detection and sprinkler systems are being inspected properly by an independent accredited company. Maintenance and inspection are not properly performed on SHC systems.

III.5.6.2.2 Effectiveness

The effectiveness of the smoke and heat control system is determined by analysing deterministic fire scenarios with the Smoke Spread model discussed in section 6.

III.5.6.3 Pressurization system

The objective of staircase or compartment pressurization is to prevent smoke infiltration through openings into the zone of overpressure. Staircases for high rise buildings are equipped with pressurization systems in order to provide safe escape for longer evacuation times. The code requirements for these systems typically demand a pressure difference to the adjacent floors or a minimum air inflow velocity into the fire floor by upper and lower bounds. Meinert summarized different code requirements in [58,59].

III.5.6.3.1 Design

The purpose of the pressurization system is to generate an overpressure in the staircase to avoid smoke infiltration in case of fire. A typical design consists of a fan inlet, a shaft to distribute the air flow, one or multiple dampers to distribute the smoke and pressure relief dampers (Figure III.11).

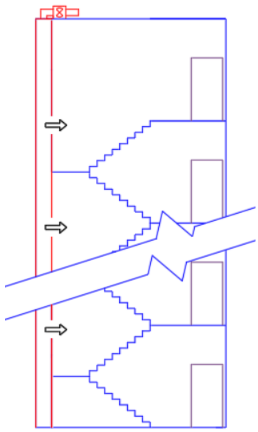

Figure III.11 Schematic representation of pressurization systems.

Based on experiments and rules of good practice, several standards have been developed in different countries [AUS/NZ], [60,61]. The overpressure in the staircase should be provided between a lower and an upper limit. The lower limit is to avoid smoke entrance in the staircase, typically a minimum of 20 Pa is used to obtain a minimum of 1 m/s air velocity when the doors open. The upper limit is set to avoid that staircase doors cannot be opened due to high pressures. Typically a maximum of 60-80 Pa is used [4,60–62]. This boundary condition leads to the necessity for the sectioning of stairwells by means of multiple injection points for heights greater than approximately 30 m. Noise levels are not considered one of the key performance criteria. In this thesis it is assumed that the design corresponds to the Belgian legislation [63] or European standard [60].

III.5.6.3.2 Reliability

Limited research has been done with respect to reliability of pressurization systems. Zhao assessed the reliability of pressurization systems by fault tree analysis [53]. The research concluded failure rates in the order of 90 %.

Based on the design of pressurization system, a fault tree can be developed to determine the reliability of the system. In Figure III.12, an example is given. The top-level failure components are detection system, door and staircase, damper, fan, and control panel. From literature it was observed that the main failure mode is the failure of the fan and dampers [64].

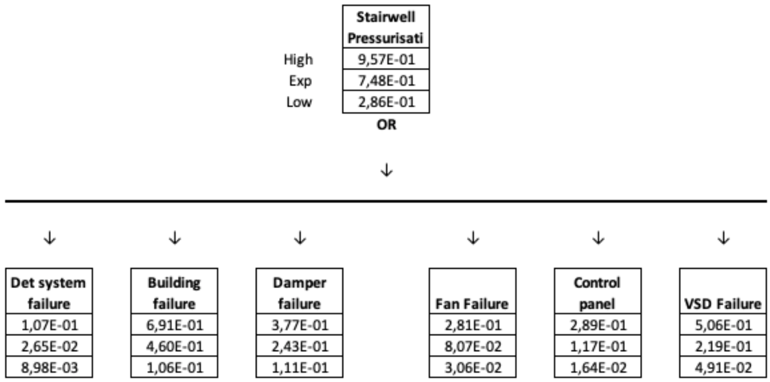

Figure III.12: Efficacy

The system is considered efficient when no smoke enters the staircase in case of fire. This is assumed to happen when sufficient pressure is provided across the smoke barrier. The NFPA 92A provides different pressure values necessary to overcome smoke entrance under closed doors conditions. The minimum pressure requirement in a fully sprinklered building is only 12.5 Pa because temperatures are not expected to increase beyond 93°C due to cooling and lesser likelihood of smoke generation.

Table III.8: Proposed min design pressure differences across smoke barriers. Adapted from [8].

Building type	Ceiling Height [m]	Design pressure [Pa]
Sprinklered	Any Height	12.4
Sprinklered	2.7	24.9
Sprinklered	4.6	34.8
Sprinklered	6.4	44.8

This means that the efficacy of the system can be defined as the probability of obtaining the necessary pressure difference at the level of the incident floor. Therefore, an event tree needs to be developed that considers the different evacuation and fire scenarios. The output provides, for every design scenario, different levels of smoke leakage flow coupled with a probability of occurrence. These can be classified in non/minor toxicity (< 50 ppm CO), medium toxicity (< 1000 ppm) and high toxicity (> 1000 ppm). 1000 ppm is the level of CO toxicity an average healthy adult male can withstand during half an hour of exposure before becoming unconscious.

The multiple deterministic scenarios can be analysed by the smoke spread model for staircases. The model is discussed in section 8.

III.5.7 Fire compartmentation

The performance of passive fire protection systems is typically taken as a given, providing they have not been compromised during commission. Their effectiveness can however vary widely depending on the nature of the fire scenario, the design of the system, and damage to the system. Passive systems are arguably more vulnerable to other trades or occupants compromising them, to physical damage, etc. in ways other systems are not. These systems are not always installed or inspected correctly, and ongoing maintenance is difficult.

From inspections in public buildings it was observed that there are many shortcomings with respect to passive fire protection [65]. Especially shortcomings related to doors, ducting, and piping are frequently found in buildings. During these inspections, 92% of the analysed buildings had one or more shortcomings related to doors and 88% of the buildings had one or more shortcomings related to ducting and piping.

For the purpose of the thesis, the effectiveness is considered optimal when no failure occurs. Therefore, the focus is only on the reliability of the systems. Two approaches are analysed in order to determine the reliability of the fire compartmentation concept: the system based approach and the component-based approach.

III.5.7.1 System based calculation

For the system based approach, the results obtained in [4] can be implemented. Depending on the type of building and whether a sprinkler system operates (Table III.9), fire spread to other parts of the building can be reported. In this way, different design fires can be developed.

Table III.9: Probability of fire spread to other parts of the building. Taken from [4].

Extend of flame damage	SPLR apartments	Non-SPLR apartments	SPLR offices	Non-SPLR offices
Confined to object of origin	0.69	0.46	0.68	0.47
Confined to area of origin	0.20	0.25	0.21	0.23
Confined to room[1] of origin	0.06	0.11	0.06	0.08
Confined to fire cell[2] of origin	0.02	0.02	0.01	0.01
Confined to floor of origin	0.01	0.04	0.01	0.04
Confined to structure of origin	0.02	0.1	0.02	0.15
Extend to structure of origin	0	0.02	0	0.02

[1] Partitioned part in the fire cell

[2] Fire cell as in compartment

III.5.7.2 Component based calculation

When the component-based approach is applied, every type of wall, openings or specific penetrations needs to be considered in terms of fire spread. A fault tree towards each surrounding compartment needs to be taken into account (Figure III.13).

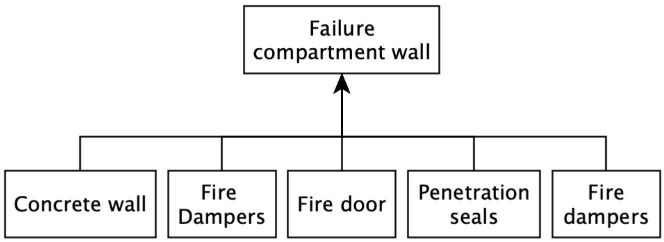

Figure III.13: FTA for fire separation.

In Table III.10, the data obtained from [4] and the British standard [66] is presented. This data can be implemented in the event tree model.

Table III.10: Reliability data for passive fire protection systems. Adapted from [4] and [66].

Component	Operational reliability
Masonry wall	0.95
Drywall	0.95
Reinforced concrete	0.99
Self-closing Fire door	0.9
Probability of fire door being blocked open	0.3
Probability of self-closing doors failing to close on demand	0.2
Penetration seals	0.999
Fire dampers	0.997

III.6 Design Fire Scenario

In this part of the method, the fire scenario is developed for further analysis in the subsequent deterministic models. Design fires have been widely investigated in the past [67–69]. Based on the research, the design fire is divided into four sub-categories (Figure III.14): location, ignition, fire spread, and effluents. The amount of smoke production is determined by the smoke spread model. The most important input data required to define the fire scenarios are the building configuration, occupation and environmental conditions.

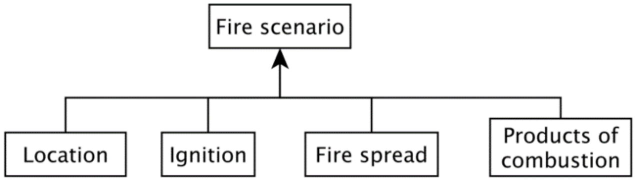

Figure III.14: Model for developing design fire scenarios.

In Figure III.15, a timeline is presented for a general fire and evacuation scenarios. The purpose of the timeline is to give a visual representation of both scenarios. It is important to remark that only the initial phase of the fire, until evacuation of self-reliant persons has finished, is analysed in the context of the thesis.

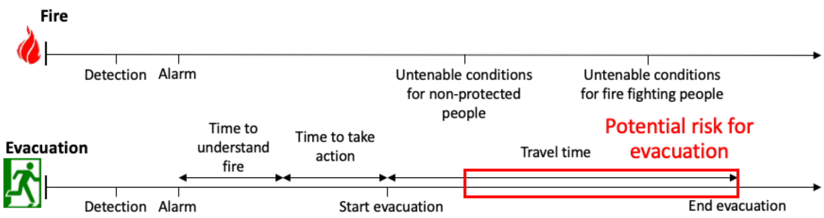

Figure III.15: Timeline for the fire and evacuation scenario.

III.6.1 Location

The location of the fire can be determined based on the building layout and functionality. The purpose is to choose fire locations which give a proper representation of the possible fire locations in the building. Important aspects are the size of the room and compartment. A fire in a smaller storage room will behave differently from a fire in an open landscape office. For larger rooms, multiple fire locations might be necessary to give a proper representation. When concealed spaces are present, the additional fire risk should be taken into account.

III.6.2 Ignition

For the quantitative estimation of fire risks, one of the most sensitive parameters is the fire ignition frequency. Correlations to determine the fire frequency are mostly derived from relevant building stock and fire statistics. The probability of a building catching fire has been known to depend on factors such as occupancy type and building size [70,71]. In general, it is assessed that the larger the building and the more human interaction, the higher the fire frequency. A literature review is performed of nine fire frequency data studies in Appendix A [72–80]. In the first eight studies, the frequency is determined based on occupancy type and surface area. In the last study, the frequency is based on occupancy type and building volume. In four of the nine studies, correlations that represent the ignition frequency per unit area are developed. In Figure III.16, these four correlations are presented for retail premises. The results show a significant difference for the different correlations depending on the surface area. Based on the literature discussed above, it is suggested to consider the correlations in which the frequency per unit area depends on the surface area, because it can be assumed that larger buildings will have higher general safety measures and procedures (e.g., material housekeeping) that reduce the overall fire frequency. Therefore, the larger the building, the smaller the likelihood of a fire to take place per unit floor area per year. Based on this assumption, the four correlations provided in [75,76,79,80] can be applied for retail spaces. It is suggested to apply the average of the four curves (yellow curve) and the outer boundaries as uncertainty. The older data provided in [74] is not taken into account. It is important to emphasize that the frequency should be calculated per building and not per compartment.

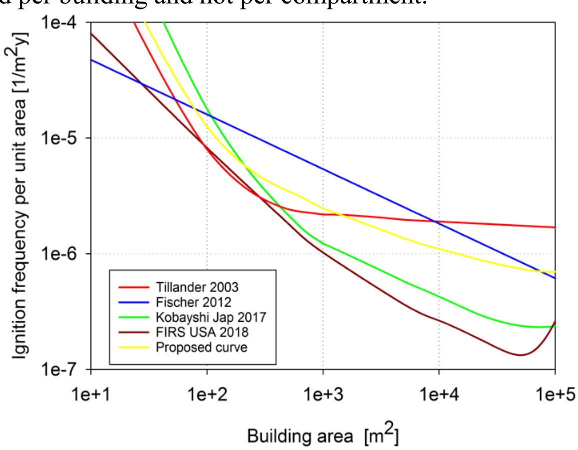

Figure III.16: Ignition frequency per unit area for a retail building.

III.6.3 Fire Spread

III.6.3.1 Initial Fire growth

From ignition onwards, the initial fire spread is modelled by using a t^2 fire. A quadratic fire spread is the most common approach to model primary fire growth [8]. In [8], several examples of quadratically growing fires are presented. The fire growth is expressed by the parameter α and typically represented by a log-normal distribution for applications in QRA. In Table III.11, parameters for different occupancy types are presented [81]. The expected fire growth parameter and 95th percentile values are included to give a proper interpretation of the physical meaning of the distributions.

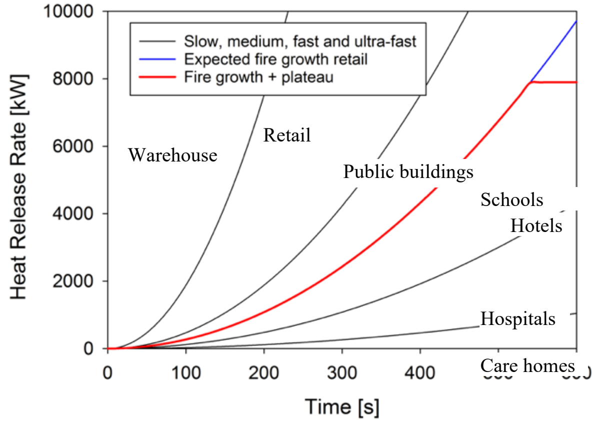

Figure III.17: t^2 fire growth application and location of 95-percentile of different building types

Table III.11: Log-normal parameters of the distribution of fire growth parameters for each occupancy group in the other sampled building fires. Adapted from [81].

Occupancy group	μ_{log}	σ_{log}	E(α) [kW/s²]	α_{95} [kW/s²]	α_{EC}[kW/s²]
Care homes	-7.7	1.1	0.001	0.003	0.012
Educational	-7.2	0.8	0.001	0.003	0.012
Hospitals	-7.1	1.3	0.002	0.007	0.012
Hotels	-7.7	2.1	0.004	0.014	0.012
Offices	-7.1	1.8	0.004	0.016	0.012
Schools	-7.3	2.0	0.005	0.019	0.012
Public buildings	-6.2	1.9	0.012	0.045	0.046
licensed premises	-6.6	2.2	0.016	0.053	-
Retail	-5.4	1.9	0.027	0.101	0.046
Factories	-5.9	2.2	0.03	0.100	-
Warehouse	-4.0	1.9	0.107	0.405	-

Albrecht suggested to apply an incubation period to account for the initial smouldering combustion [82], because it can significantly impact the course of events in life safety analysis, such as the reduction of the pre-movement time due to occupant reactions to fire cues (visible smoke, smell, etc.) or the activation of smoke detectors [37] and connected systems such as smoke and heat exhaustion. However, based on the literature [81], the incubation period is indirectly taken into account through the values reported in Table III.11.

The fire is considered to grow until under-ventilated conditions occur or until the fire is considered to reach its maximum surface area limited by building configuration, fuel load, fire safety systems, firefighting, etc. It is considered here that under-ventilated conditions occur in smaller rooms (e.g., storage, office, etc.) mainly due to flashover and that the time to flashover is determined by the expected HRR for flashover:

$$\dot{Q}_{FO} = 610 \left(h_k A_T A_o \sqrt{H_o}\right)^{1/2} \qquad \text{(III.5)}$$

Where:

h_k	Effective heat transfer coefficient [kW/m^{2}K]
A_T	Total internal enclosure surface area [m^2]
A_o	Area or weighted area of opening [m^2].
H_o	Height of opening [m]

It is important to mention that this formula is only valid for vertical openings and not horizontal openings. When multiple openings A_o are present, the weighted average is calculated according to the method discussed in [83]. These can be fixed openings, doors, broken windows, etc. The probability of (fire)doors being open is discussed in part 5. Just like door openings, air supply by means of window breakage is implemented in the model. In order to determine the breaking point and surface area of failure of windows, an analysis of past experiments is performed (Appendix B). Based on the literature study, critical gas temperatures at the window pane and associated fraction of glass fallout are suggested in Table III.12 for different window types and their corresponding thicknesses. It should be noted that, depending on the frame and fixation type, better or worse conditions can be expected. The values suggested are averaged and recommended by literature [84].

Table III.12: Suggested critical gas temperatures and fall out fraction for different window types and thicknesses.

Glass type	Thickness [mm]	% fallout [-]	Gas temp. [°C]	Radiative heat flux [kW/m^2]	Ref.
Single float glass	4	50%	360	-	[85]
	6	50%	450	30	[86]
Single tempered glass	6	100%	Flashover	43	[84]
Double layered glass	4	50%	375	25	[87]
	6	50%	600	35	[88]
Triple layered glass	4	20%	475	30	[87]

In case of large rooms, the peak HRR is based on statistical data determined from the combination of maximum fire size and HRRPUA [81]. The values applied for these parameters in the QRA are presented in Table III.13. The convective part of the heat release rate (and not the heat flux) is taken as 0.8 and reduced to 0.5 in case of a sprinklered fire [55,89].

Table III.13: Log-normal parameters characterizing the distribution of the fire damage area for different occupancy groups [81,90].

Occupancy group	μ_{log}	σ_{log}	E(α) [kW/s^2]	α_{95} [kW/s^2]	μ_{HRRPUA} [kW/m^2]	σ_{HRRPUA} [kW/m^2]
Care homes	-0.64	1.44	1	6	250	15
Educational	-0.08	1.28	2	8	250	15
Hospitals	-0.29	1.52	2	9	250	15
Hotels	0.78	1.7	9	36	250	15
Offices	0.69	1.89	12	45	275	15
Schools	1.17	1.84	18	66	250	15
Public buildings	0.56	2.24	22	70	250	15
licensed premises	0.83	2.14	23	78	450	50
Retail	1.68	1.91	34	124	500	50
Factories	1.8	1.92	38	142	500	50
Warehouse	2.87	2.13	170	586	1750	250

After the peak, the fire conditions remain constant until 70% of the fuel is consumed [91]. Only an average value is used for the fuel load, because preliminary sensitivity analysis showed that the fire load by itself has no significant influence on this problem and hence will be modelled deterministically using the mean value for the further analysis. These results correspond to in [92]. The fire load determines the duration of the fire, but the thresholds for life safety are usually reached already during the growth phase of the fire.

III.6.3.2 Secondary fire spread

In case of small rooms or compartments, secondary fire spread can be considered. From the fully developed fire onwards, fire spread to other rooms is considered to occur. Two methods can be used: statistical models and deterministic models. In case the statistical approach is used, the data presented in Table III.9 can be implemented. For the deterministic approach the failure barrier model from CUrisk can be applied [93].

III.6.4 Products of combustion

The chosen design fire must include estimations of the generation of combustion products from the fire. Especially species such as CO, HCN, CO_2, hydrocarbons, and soot are of interest [83]. These species are important because they have a significant impact on life safety by affecting occupants, property, equipment and operations. In the next sections these species are identified and investigated. First, the most important factors affecting production of combustion products are defined. Second, a literature study is performed to provide reliable data. Third, a suggestion is done for implementing and quantifying toxic species in the risk model.

III.6.4.1 Factors affecting products of combustion

Several factors affect the combustion process. The most important are the combustion process (i.e., smouldering or flaming), the air supply with respect to the fuel that is present and the retardation of the combustion reaction due to involvement of chemical agents [83].

The first factor includes the difference between smouldering and flaming combustion. For smouldering scenarios higher yields can be expected (see tables below) than for flaming fires, because flaming fires are expected to have better mixing oxygen and fuel. Therefore, smouldering has more incomplete combustion.

Table III.14: Suggested yield values for different types of fires. Adapted from [83].

Fire type	y_{CO} [g/g]	y_{CO_2} [g/g]	y_{O_2} [g/g]	y_{soot} [g/g]
Post-flashover, primary wooden fuels	0.3	1.1	0.9	-
Enclosure fires	0.2	1.5	1.8	-
Smouldering fires	0.5	-	-	0.15

Table III.15: Suggested yield of soot for different types of material. Yields are for well-ventilated conditions [83].

Material	y_{soot} [g/g] Flaming	y_{soot} [g/g] Smouldering
Cellulosic	0.01-0.025	0.01-0.17
Plastic	0.01-0.17	0.01-0.19

In the remainder of the thesis the focus is on flaming fires because of their higher frequency and risk factor in non-sleeping premises. Statistically, 92% of the fires in residential and public buildings are flaming fires [4]. Smouldering fire scenarios should be considered for buildings with sleeping functions and concealed spaces such as false ceilings without automatic detection.

The second important factor is the effect of the ventilation conditions during the combustion process. For flaming fires, an important yield determinant is the fuel/air ratio, represented by the following formula [94]:

$$\phi = \frac{\dot{m}_f/\dot{m}_a}{r} \tag{III.6}$$

Where:

ϕ	equivalence ratio [-]
m_f	mass loss rate of fuel [kg/s]
m_a	mass flow rate of air [kg/s]
r	stoichiometric fuel-to-air ratio [-]

The ratio gives an indication of whether the fire is fuel-controlled ($\phi < 1$) or ventilation-controlled ($\phi > 1$). Depending on the fire conditions, the soot and toxicity yields will vary. As mentioned in 4.2.1.3, under-ventilated fires that occur due to insufficient oxygen supply or inertization give rise to incomplete combustion, which causes higher soot and toxic product yields. The increase of soot and toxicity production can be expressed as function of the equivalence ratio, which can cause variations up to a factor of 50 [43,95–97]. A correlation of the CO yield dependence on the equivalence ratio for wood is given in Figure III.18. A similar phenomenon is observed for the CO yield from plastics and textiles, with different values but the same order of magnitude.

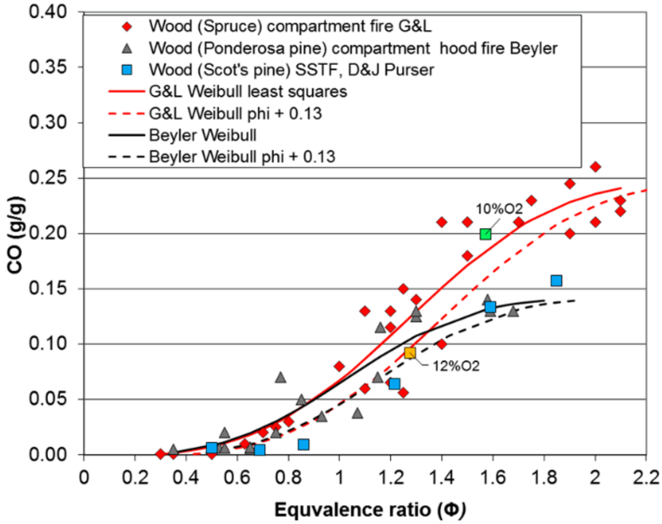

Figure III.18: Data points and fitted curves for CO yield (g/g) as function of equivalence ratio (ϕ) for wood. Taken from [98].

Similar to CO production, the production of HCN, for fuels containing nitrogen, grows with increasing equivalence ratio. An example of HCN yield dependence on the equivalence ratio for wood is given in Figure III.19.

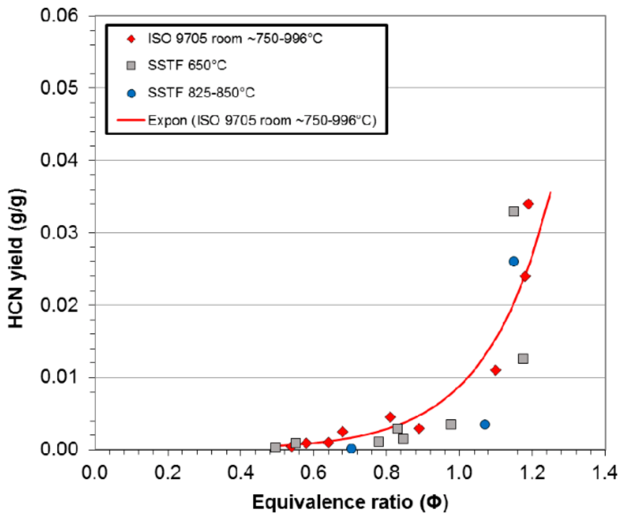

Figure III.19: HCN-yield as a function of equivalence ratio (ϕ) for Polyamide 6.6. Taken from [98].

Another correlation of the CO_2 yield as function of ϕ for PS is depicted in the figure below. Similar values for CO_2-yield are obtained for PE, PMMA, polyamide, etc. For wood lower values are expected because the stoichiometric maximum is 1.47 g/g.

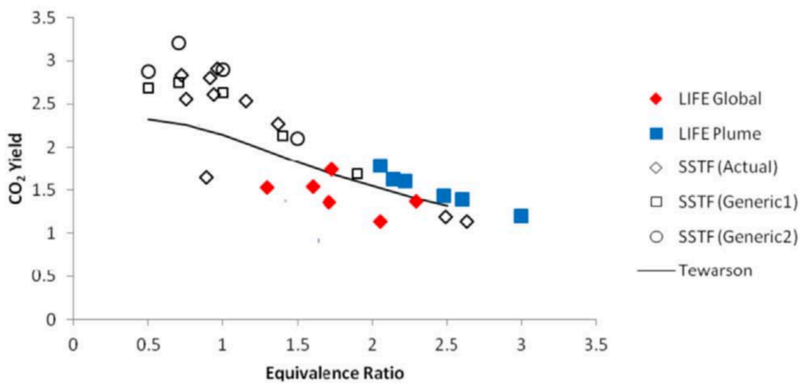

Figure III.20: CO_2-yield as a function of equivalence ratio (ϕ) for PS. Taken from [97].

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \quad \text{(III.7)}$$

The effect of incomplete combustion should be taken into account for the different design scenarios. The effect of under ventilated-fires in small rooms, false ceilings, sprinkler systems and shielded fires, should be conservatively incorporated in the products of combustions yields. On the other hand, the positive effect of smoke and heat control systems should be considered, because lower equivalence ratios can be expected. These values are between 0.2 - 0.8, while in normal fires the probability of having partial incomplete combustion will be higher. It is suggested to delay the transition from fuel-controlled to ventilated-controlled for concepts in which smoke and heat control systems are implemented.

The third factor is the type of chemical agents present in the fire. Different fires will give different products of combustion. In general, when different materials are decomposed there tends to be a set of basic organic and inorganic substances which are produced. These are common to most materials. An additional set of substances related to the specific chemistry of the material and sometimes unique to that material or class of materials can be produced as well.

Traditional fuels such as wood, paper, PE, etc. produce mostly CO and CO_2 as toxic products, while other products, such as polyamide, also produce HCN due to presence of nitrogen in the fuel. In order to illustrate the possible different combustion products in various materials, an illustration is given in Figure III.21 which discusses the different toxic species that contribute to the overall toxic potency of different materials for a well-ventilated fire in ISO 19706 [14].

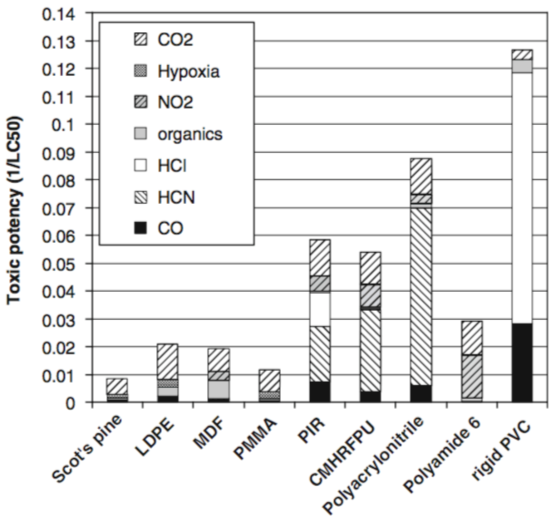

Figure III.21: Toxic potencies ($1/LC_{50}$[2]) for well-ventilated conditions [43].

An additional important consideration of toxicity yields is the elemental ratio of CO to HCN, because, depending on the ratio, one will become more important than the other. HCN is 25 times more toxic than CO. For example, considering a furniture fire which has both a high carbon (50-60%) and nitrogen (~ 9%) content in the fuel, the toxicity of the developing fire will be first dominated by HCN and next by CO, once it starts to become under-ventilated. When the compartment goes to flashover, then the entire room surface fuels the fire. The materials of the entire surface could be mainly cellulosic. The carbon will then still be around 50-60% and the nitrogen will now be only around 1% of the greater burning fuel package. So, the toxicity of the effluent plume flowing from the enclosure down the corridor may be dominated by CO rather than HCN. Therefore, the combination of fuel type and ventilation conditions is significant for the choice of yield components.

[2] LC_{50}: The concentrations of a combustion product in air that kills 50% of the test animals during the observation period.

III.6.4.2 Products of combustion in literature

Prediction of the generation of soot and combustion products is mostly based on experiments rather than the fundamental theory of the complex combustion reactions [83]. Literature which discusses parameters for products of combustion has been analysed. From codes it is observed that only a small number of countries directly implement these parameters (Table III.16). The research shows that several of these codes consider various toxicity parameters under different ventilation conditions.

Table III.16: Toxicity parameters for different regulatory codes.

Country	Code reference	Soot [g/g]	CO [g/g]	CO_2 [g/g]	ΔH_C [MJ/kg]
New Zealand	C/VM2	0.07/0.14[1]	0.04/0.4[1]	1.5	20
Sweden	BBRAD	0.06/0.1[2]	0.06/0.1[2]	2.5	20
UK	BS PD 7974-2	0.025-0.17[3]	0.013/0.25[1]	-	20
France	LCPP	0.05	-	-	25
Germany	vfdb TB 04-01	0.08/0.13	0.05/0.16	1.7	19-32
Belgium	NBN S21-208-2	0.22[4]	-	-	24

1 Pre- and post-flashover fire.

2 Related to the robustness or the standard scenario

3 Depending on the material ratio

4 Only for car parks

Extensive research has been done to obtain products of combustion yields [99–101]. Most of this research provides toxicity yields for specific materials. This means that, to determine a general distribution, the specific fuel distribution should be known in order to establish the joint density function. This is considered not practical and would shift the problem of this research. In other research [82] distributions for production of soot, CO and HCN were proposed for a general case in the application of a case study in QRA. However, no scientific background was given for the development of the distributions. In [102], a more extensive study has been done to develop a dataset for products of combustion. The main results are presented in Table III.17. The suggested distributions indicate results for well-ventilated conditions. No suggestions are made for under-ventilated conditions.

Table III.17: Toxicity distribution parameters developed in [102].

Country	Distribution	Par 1 (μ, α)	Par 2 (β, σ)	units
Soot	Weibull	1.67	0.02	g/g
CO	Gamma	0.0541	0.095	g/g
CO_2	Lognormal	1.8	1.47	g/g
HoC	Lognormal	16.8	27	MJ/kg

III.6.4.3 Suggested products of combustion for design fire scenarios

Based on the discussed factors and literature review [97,98], two scenarios with corresponding parameters are implemented in the model and presented in Table III.18. The suggested parameters are considered normally distributed variables. For CO_2 a fuel load of 50% wood and paper and 50% plastic and textiles (weight based) are assumed. The mean and standard deviation are calculated considering a uniform distribution between the lower and upper end of the over- and under-ventilated phase. For the HCN-yield parameters, a 20% fuel type configuration containing nitrogen is considered. For every project or building type, this fuel ratio should be reviewed.

Table III.18: Suggested distributions of products of combustion for fuel and ventilation-controlled fires.

Ventilation type	Ventilation type	μ	σ	units
Well ventilated	Soot	0.07	0.03	g/g
($0 < \phi < 1$)	CO	0.04	0.01	g/g
	CO_2	1.9	0.03	g/g
	HCN	0.001	0.0003	g/g
Under ventilated	Soot	0.2	0.05	g/g
($\phi > 1$)	CO	0.15	0.03	g/g
	CO_2	1	0.2	g/g
	HCN	0.005	0.001	g/g
Any	HoC	20	5	MJ/kg

During the fire growth phase, when the fire makes a transition from fuel controlled to ventilation controlled, the fire can be expected to be ventilation controlled when oxygen levels drop due to lack of sufficient air supply or because a part of the flame will be present in the smoke layer. This type of modelling may point out the benefits of SHC systems with well-ventilated fires.

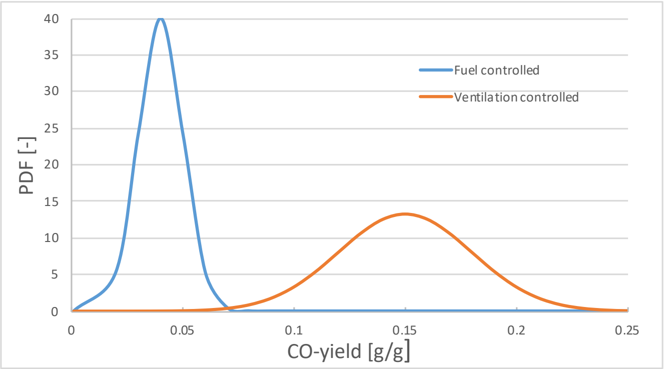

Figure III.22: Suggested CO-yield for ventilated and fuel-controlled fire.

III.7 Design Evacuation Scenario

In this part of the method, the evacuation scenario which is analysed in the deterministic models, is developed (part 9) .For every fire scenario, at least one evacuation scenario should be analysed. In an evacuation scenario, three parts can be considered from the initial cues onwards: recognition, response and evacuation (Figure III.23). The recognition and response are coupled in the pre-movement part. The occupants are considered to be, in either one of three states the normal, investigating, and evacuation state [103].

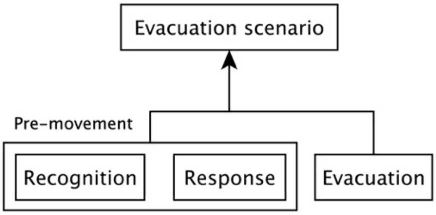

Figure III.23: Model for developing design evacuation scenarios.

III.7.1 Pre-evacuation time

In order to determine the pre-evacuation time, a simplified model is applied. It consists of one phase in which the cue processing, situational assessment and response selection and action are implicitly taken into account by a pre-defined pre-movement time distribution. In this approach a pre-movement time is implemented for each occupant individually. The input is obtained from a randomly generated value on the distribution.

The shape parameters of the distribution depend on the type of perceived cues. A lognormal Probability Density Function (PDF) is linked to each cue type. Given a particular cue, a random value on the PDF is generated and coupled to the corresponding agent. It is considered that more intense cues (e.g., visible smoke) have PDFs with lower mean and smaller standard deviation than less intense cues (e.g., standard alarm). Examples are given in Table III.19. Additionally, Lovereglio presented a pre-evacuation data base for use in egress simulations [104].

Table III.19: Pre-evacuation time Probability Density Functions.

Warning sources	Mean [s]	STD [s]	Ref
Flame/smoke	10	5	[8]
Alarm	60/120	10	[35]
Voice alarm	30/60	10	[35]
Fire departments	5	2	-

III.7.2 Evacuation

After the recognition and the decision to start the evacuation, the occupants need to decide how and to where they will evacuate. Occupants can use stairs or evacuation lifts and evacuate towards exits or safe places where they will wait for the fire brigade. Depending on the type of building, different features need to be taken into account. An example is a dancing hall. A representative evacuation scenario might be a scenario in which a large fraction of the occupants are intoxicated. In schools, the age of the occupants is an important factor. The evacuation of elderly homes will need to take into account the limited mobility of the people.

Another important part in the development of evacuation scenario is the incorporation of familiarity/affiliation towards exits. The purpose of the occupant exit choice modelling is to determine the exit choice for every occupant in the building during emergency evacuation. In the past, exit choice was mainly an optimization problem. Models were designed to assign agents to a certain exit depending on the shortest travel time. These algorithms give the shortest evacuation times. However, research has shown that people do not always know all available exits, or have a clear overview of the fastest route [105,106]. Methods can be based on statistical data obtained from experiments and on algorithms implemented in the model. Since familiarity mostly depends on the building configuration and procedures followed, it is suggested to use the combination of engineering experience and data available to determine a proper value for the familiarity. In Appendix C, a summary is presented of the available data.

III.8 Smoke spread model

The main purpose of the smoke spread sub-model is to analyse the spread of effluents of the fire. In order to define a suitable model, several important aspects about smoke spread modelling need to be investigated. First, the different types of smoke spread models are discussed. Second, important aspects of smoke spread modelling are discussed. Third, a concise review of current smoke spread models is conducted and specific features for the development of such models of research are discussed.

III.8.1 Methods of modelling approaches

In order to accurately assess the effects of a fire scenario, the spread of the fire itself as well the transport of the heat and by-products of the combustion, need to be simulated. The most traditional method to analyse fire scenarios is to utilize analytical or numerical simulation tools of varying accuracy, complexity, and numerical effort. Three approaches can be used: analytical calculations, zone modelling, and field modelling.

Analytical plume entrainment calculations represent the simplest approach for analysing the volume flow in the smoke layer [52]. By means of simple flow correlations, hand calculations can be performed to obtain a first indication of the smoke layer depth. The advantage of this approach is the speed and transparency. The disadvantage is the lack of accuracy. The model might be used to obtain a first estimate of the toxic potency within smaller compartments and single rooms.

Zone models can incorporate the basic principles of thermodynamics and conservation of mass. In these models the compartment is essentially subdivided into two ”zones,” the upper hot gas layer and the lower ambient air layer. The fire drives combustion products from the lower to the upper layer via the plume. The temperature within each layer is uniform, and its evolution in time is described by a set of ordinary differential equations derived from the fundamental laws of mass and energy conservation. The transport of smoke and heat from zone to zone is dictated by empirical correlations. Both layers are assumed to have homogeneous temperatures and mass concentrations, which limits the model applicability to simple compartment geometries, such as rectangular rooms with limited ceiling height [107].

Field models are the most advanced fire models. These are developed in computational fluid dynamics (CFD) packages containing multiple submodels such as combustion, turbulence, radiation, etc. CFD programs solve a system of partial differential equations. Additionally to the conservation of mass and energy in zone models, the conservation of total momentum is taken into account.

III.8.2 Important aspects of smoke spread modelling

The objective of the tool is to model the smoke spread in a building and provide a representative result with respect to the exposure of occupants to the effluents of the fire. In order to choose the most appropriate model, the main factors affecting the outcome in terms of fire effluent generation and transport need to be taken into account. From past research it has been concluded that both internal (e.g., safety systems, geometry, etc.) and external factors (e.g., wind, temperature, etc.) are important. The purpose of the remainder of this sub-chapter is to review and analyse smoke spread models.

III.8.3 Review of smoke spread models

For the purpose of the thesis, five smoke spread models have been analysed: two zone models, two field models, and one network model. The two zone models, CFAST [108] and BRANZFIRE [109,110] have been analysed for the simplified QRA-model. The two field models, FDS [50] and SMARTFIRE [111], have been studied for the comprehensive QRA model. The network model CONTAM [112] is investigated for analysing smoke spread in staircases.

CFAST is a two-zone fire model that predicts the thermal environment caused by a fire within a compartmented structure. Apart from the traditional features of zone-models, CFAST can take spill plumes and corner fires into account. Because the governing equations are relatively simple, CFAST simulations typically require a few tens of seconds of CPU time on typical personal computers.

BRANZFIRE is, similarly to C-FAST, a multizone fire model which integrates a flame spread and fire growth model for standard fire scenarios and scenarios with room lining materials [109]. Special features of BRANZFIRE is that it can take glass breakage and burning of wall linings into account.

FDS is the most widely used CFD packages for transient fire and smoke spread simulations. FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed ($Ma < 0.3$), thermally-driven flow, with emphasis on smoke and heat transport from fires. The tool is composed of multiple submodels of which turbulence (LES), combustion, and radiation models are the most important. The advantage of FDS is the applicability, transparency, transient analysis, number of possible submodels and well-documented technical, user, verification and validation guides. The disadvantage is the high computational power necessary to run simulations and that the underlying rectilinear mesh needs to be adjusted to the obstructions incorporated in the model.

SMARTFIRE is just like FDS a Fire Field Modelling (FFM) environment which has an unstructured-mesh finite volume approach. The main difference between FDS and RANS is the turbulence model, LES for FDS and RANS for SMARTFIRE.

CONTAM is a multizone indoor air quality and ventilation analysis computer program often used for ventilation and indoor air quality analysis. In the model, airflow and species transport are calculated between the rooms of a building and between the building and the outdoors. The so-called well-mixed assumption, in which each zone is characterized by a single contaminant concentration, is used to make the bulk analysis simpler and faster. The purpose of the model is to decouple the staircase geometries from the 3D field models so that the staircases can be analysed separately. Additionally, the model can determine the performance of the staircase pressurization systems by analysing the pressure differences across the staircase.

III.9 Evacuation model

The main purpose of the evacuation sub-model is to analyse the life safety threat to occupants during evacuation in case of fire, this by analysing the evacuation of the occupants from the building with fire conditions. In order to define a suitable model, several important aspects about evacuation modelling need to be investigated. Firstly, the different types of evacuation modelling are discussed. Secondly, important aspects of evacuation modelling are analysed. Thirdly, a review of current evacuation models is conducted and specific features of research for development of such models are discussed.

III.9.1 Functional boundary conditions

The choice of an evacuation (sub-)model for implementation in the QRA model depends not only on the criteria listed above, but also on the desired criteria set out by the FSE. Kuligowski suggested a series of important questions for the FSE to analyse before selecting a model [113]. Based on these research questions, the following boundary conditions are set. In this research the considered evacuation model should take into account:

- Input: input provided in terms of occupancy (e.g., people type, etc.) and environment characteristics (e.g., smoke information).
- Model: movement, main features and influence factors of human behaviour (affiliation, crowd, flow, group, etc.).

- Output: toxicity, temperature and radiation dose.
- Validation and verification: the implemented evacuation model should be sufficiently validated and verified. [114–118].

Based on these boundary conditions, the focus of the remainder of this chapter is on numerical evacuation models.

III.9.2 Methods of modelling approaches

To conduct an evacuation modelling, three approaches can be used: analytical calculations, numerical modelling, and multi-modelling [119].

Analytical calculations represent the simplest approach. By means of simple travel and flow correlations, hand calculations can be performed to obtain a first approximation of the evacuation time [8]. The advantage of this approach is its speed and lack of transparency. The disadvantage is the lack of detail and quantification of certain aspects of occupant and building characteristics.

Numerical models can be subdivided into network and spatial models. In network models each room or space is represented by a node and each node is connected with passageway or door connections. Spatial models represent the entire building layout by a grid or a continuous 3D-space. The advantage of these models is a higher accuracy level and the possibility to take into account more parameters compared to analytical models. The disadvantage is the higher computational cost.

Multi-model approaches combine analytical and numerical models, in order to use the benefits of both. The approach utilizes different evacuation models at the same time for the analysis of the evacuation scenarios. This approach is mostly used to design evacuation models for specific configurations (e.g., evacuation in road tunnels [119]).

III.9.3 Important aspects of evacuation modelling

The objective of the evacuation tool in this thesis is to model the evacuation of people from a building and provide a representative result with respect to the exposure of occupants to the effluents of the fire. In order to choose the most appropriate model, the main factors which affect the outcome in terms of exposure and evacuation time have to be considered. In the past, research has been conducted to define these critical factors for egress analysis [8,120–122]. From this research two main categories are defined: the occupant and the environment characteristics. The occupant characteristics are mainly represented by the physical and behavioural attributes. The environment characteristics are mainly represented by the architectural, procedural, organisational and environmental attributes [8].

III.9.4 Review of evacuation models

Comparison of different evacuation models has been conducted in past research [8,123–127]. Over 30 evacuation models have been investigated and compared for different characteristics and categories. Based on this research, the availability of the models and the boundary conditions discussed above, five evacuation models are considered appropriate for further analysis: STEPS [128], Pathfinder [129], BuildingEXODUS [126], FDS+EVAC [130] and JuPedSim [131]. The first four are the most commonly used evacuation models in countries with a performance based legislative framework [132]. The fifth model is a new and open source model. In the following sections, the main features and limitations of these models are analysed and discussed.

III.9.4.1 Common features

All five models have several common features. They can take into account complex geometry, e.g., turning stairs, complete stadia, stations, malls by means of different levels of simplification.

The basic time-dependent algorithm in the models is developed in the assumption that it is people's priority to get out of the model as quickly as they can, without the need to predefine exit routes, by analysing the provided known exits in the model. The principle is that once people are added to the model, they look for the closest exit within the compartment that leads to a place of relative safety. Once that exit is passed, the next exit will be pursued until the final system exit, which is the exit out of the considered geometry, is reached. If multiple exits are available, people select the exit depending on the shortest time to leave the compartment. In all the models, the walking speed of agents can be reduced by increased occupant and smoke density or inclined effects of surfaces (e.g., stairs). The models provide toxicity and the results can be requested for each participating person.

In the next sub-chapters, the evacuation models are further discussed individually. The focus is put on the implementation of human behaviour and fire scenarios.

III.9.4.2 STEPS

STEPS is a fine grid-based circulation and evacuation software that can model pedestrian movement in normal and emergency evacuations. The tool is an agent based model and takes into account aspects of human behaviour [128]. An example is the reduction of walking speeds (smoke and occupant density). Occupants also keep minimum distances between each other and can have different patience behaviour when queuing. Counter flows are allowed for and elevators can be used. Other behavioural aspects are implicitly taken into account, for example by defining a pre-movement time or a familiar exit choice. The effect of group behaviour and smoke blocking exits needs to be implemented manually in the model. The model has been validated against codes, fire drills and literature on past experiments [126]. STEPS is still updated and developed.

III.9.4.3 Pathfinder

Pathfinder is a continuous based evacuation model specifically designed for evacuation modelling in case of fire. Evacuation of agents is modelled based on steering behaviour [129]. Pathfinder moves occupants in continuous 3D space using a triangulated movement mesh (Figure III.24).This movement mesh represents areas where occupants can walk, and the triangulated geometry allows to accommodate arbitrary obstructions and curved paths with great accuracy. At each time step, every agent examines the surrounding environment and takes action based on its own perceptions and goals. At the moment, Pathfinder can only model exit familiarity by establishing the sequence of waypoints that lead to the occupant's exit which can be either the nearest exit or a user-specified exit. The model simulates counter flows, exit blockage, group effects and elevator use. Pathfinder has been validated against codes, fire drills or other people movement experiments/trials, literature on past experiments and other models [126]. Pathfinder has a practical user interface and the model is still updated and developed.

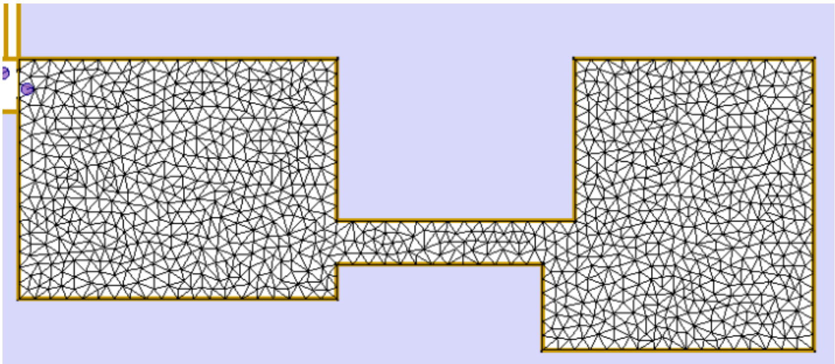

Figure III.24: Triangulated movement mesh [133].

III.9.4.4 BuildingEXODUS

EXODUS was originally designed primarily for use in transport systems such as aircrafts [134,135]. However, because of its modular format, it became clear that the model was suited for adaptation to other types of environment, such as buildings, and was therefore converted to building applications. BuildingExodus is a fine grid evacuation model for evacuation of multi-purpose buildings [126]. The model is considered one of the most advanced evacuation tools with respect to human behaviour modelling. It can model counter flows, reduced walking speeds, elevator use, exit blockage by smoke, group effects, adapted decision making due to environmental changes (e.g., smoke), impact of exit signs, incapacitation, crawling, etc. [106,136–139]. The model has been validated against fire drills, literature on past experiments and other models. Additionally, third party validation has been performed [126]. The model is still updated and developed.

III.9.4.5 FDS+EVAC

FDS+Evac is a continuous evacuation simulation module for FDS, developed and maintained by the research institute VTT in Finland [130]. The model is developed to be applied in combination with FDS and is called a social force model because the emphasis is on distances between occupant and objects. In the model, agents are guided to exit doors by the preferred walking direction vector field. An example of a vector flow field is given in Figure III.25.

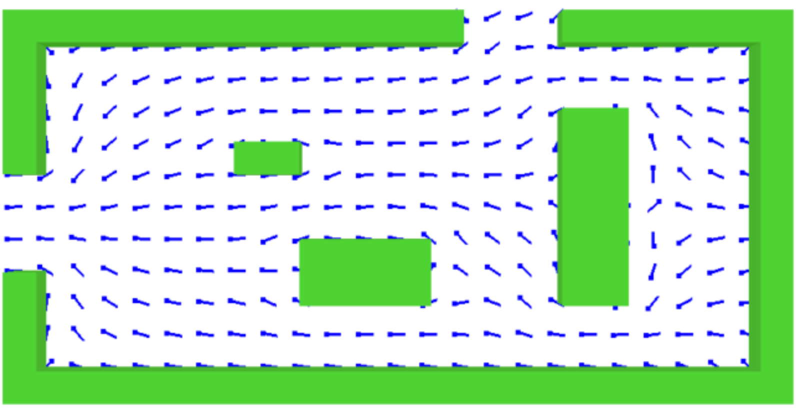

Figure III.25: An example of the 2-dimensional flow fields that are used to guide the agents towards the exit doors. Taken from [130].

The model considers different parts of human behaviour into account, of which the most important are counter flows [140], incapacitation [141], exit choice (blockage by smoke) [142], etc. The model has been validated against fire drills or other people movement experiments/trials, literature on past experiments, and other models [126]. FDS+EVAC has no user interface and is not further developed at the moment.

III.9.4.6 JuPedSim

JuPedSim is a continuous pedestrian model for simulating and analysing agents motion at a microscopic level [131]. It consists at the moment of three modules which are loosely coupled and which can be used independently. The first module simulates the movement of pedestrians given a geometry and an initial configuration. The second module visualises the geometry and the trajectories. The third module analyses the results from the simulation or any other source, for instance experiments, and generates different types of plots such as densities, velocities, and flows. The model incorporates specific parts of human behaviour into account. The most important are the effect of smoke on walking speed and the exit selection. The model has been validated against fire drills or other people movement experiments/trials, literature on past experiments, and other models [126]. JuPedSim has its own user interface and is still developed.

III.9.4.7 Discussion

A comparative analysis has been conducted to investigate the different possibilities, model components and accuracy of the evacuation models. BuildingEXODUS is considered the most advanced with respect to aspects of human behaviour. However, the model uses, just like STEPS, a grid-based structure and is not flexible regarding the I/O analysis. Pathfinder has the best user-interface and is user friendly. However, the model is considered to be the least advanced in terms of human behaviour features. FDS+EVAC and JuPedSim model specific parts of human behaviour, are flexible to modify and provide open source features. A disadvantage of FDS+EVAC is that it does not have a user interface. Additionally, some features of human behaviour need to be manually implemented in the model.

Based on this reasoning, two models are considered here for implementation in the deterministic framework: Pathfinder, for practicality, and JuPedSim, for flexibility. When fully developed, JuPedSim is expected to be a worthy competitor for more advanced models.

III.10 Consequence model

III.10.1 General

In order to determine how a fire hazard may cause loss or harm to occupants, some form of consequence analysis is required. Consequence analysis, a key component of risk characterization, determines the potential impact of a hazard event without considering the likelihood that the consequences will occur. Consequence analysis is more complicated than hazard assessment, in that it may not always be clear in what ways and to what extent something is valued and how the loss should be characterized. For life safety, the assessment may be binary (life or death), or may be continuous to cover quality of life, pain and suffering, and/or rehabilitation after a fire-induced injury. In this thesis, the model focuses on determining the consequences expressed in number of fatalities. The model obtains output from the evacuation model to assess the toxicity and heat doses of every occupant.

III.10.2 Life threatening factors

In order to find the possible fatalities for the consequence model, the factors which pose a hazard to people should be determined. The main toxic hazards associated with fire situations are [8,43,95]:

- Asphyxiants and irritant gases: asphyxiant gases can, upon inhalation, reduce decision making capacities, incapacitate and cause death. The most common toxic products are CO and HCN, of which CO has been proven to be the most frequent cause of death. Also, high levels of CO_2 and low levels of O_2 will provide negative consequences because they will increase the respiration rate, causing faster intake of toxic particles. Irritant gases such as halogen acids and organic irritants can cause immediate incapacitation due to the effects on the eyes and upper respiratory tract. Asphyxiant gases are taken into account by the consequence model in the toxicity assessment (see next section). The effect of irritant gases is reflected in reduced walking speed in the evacuation model.

- Smoke obscuration: low visibility due to smoke is not a direct threat but reduces people walking velocity and can disorientate them in case of emergency, which causes a longer exposure time to the products of the fire. This factor is discussed in the evacuation sub-model.

- Heat: there are three ways in which exposure to heat can lead to life threat: hyperthermia; body surface burns; and respiratory tract burns. When the sum of fractional doses of heat and radiant energy exceeds the safety threshold, this defines the possibility of a fatality. Radiation is of particular importance close to the fire because radiation decreases quadratically with the distance from the source. The other factor is hot smoke, which mainly affects the respiratory tract and is mostly dangerous close to the fire, where it does not have the chance to cool down. The effect of heat is taken into account by heat assessment.

III.10.3 The FID-concept

In order to calculate the number of fatalities in the building, the Fractional Incapacitation Dose (FID) factor is defined [143]. The FID is the ratio of the dose of a gaseous toxicant or temperature produced in a given test to that dose of the toxicant or heat that has been statistically determined from independent experimental data to produce incapacitation in 50 percent of test animals within a specified exposure and post-exposure time. One can see that the FID uses the IC_{50} (i.e., 50 % incapacitation dose) approach for determining the probability of incapacitation. FID originates from the FED or Fractional Effective Dose. When the FED ratio becomes unity, the chance of dying becomes 50%. The dose necessary for obtaining the same FID and FED values will always be lower for the FID because it is considered that a person becomes first incapacitated and will then perish. The FID is chosen because it is assumed that, during evacuation, once a person becomes incapacitated, this person will fall on the ground, will remain there and keep breathing toxic air and receiving heat until the person passes away. This approach is confirmed in [43], where it is states that incapacitation often leads to death. In the consequence model, the FID is calculated for both toxicity and hot temperature. The calculation methods are elaborated in the subsequent sections. Both FID values are analysed separately. The FID that reaches unity first will determine the main cause of fatality.

III.10.4 Toxicity assessment

Two methods have been studied to calculate the FID, namely the ISO 13571 [143] and the Purser method [43]. The ISO 13571 method uses the principle of Haber's rule (Blue line in Figure III.26) for CO, assuming that the deviations from linear uptake are small for exposure doses up to incapacitation for short periods [95]. The standard advises to use the Ct product correlation, where C is the concentration and t is the exposure time, for a maximum exposure dose of 35000 ppm min. The dose represents the critical value for humans engaged in moderate physical activity with a respiratory rate of 20 l/min. The standard takes into account other gases like HCN, CO_2, O_2. The general formula used reads:

$$FID = \sum_{i=1}^{n} \sum_{t_1}^{t_2} \frac{C_i}{(C * t)_i} \Delta t \qquad \text{(III.8)}$$

Where:

C_i	The average concentration of an asphyxiant gas "i" over the chosen time increment [ppm];
C	The exposure concentration causing occupants incapacitation at time t [ppm]
t	The chosen time increment, expressed in minutes [min]

The advantage of the ISO 13571 model is that it is very easy to use. The disadvantage is that in reality the intake of CO is not completely linear. When similar doses are applied, uptakes with high concentrations in short time periods can have different effects than uptakes with low concentrations over a longer period (Figure III.26). This causes under- or overestimation of the real situation.

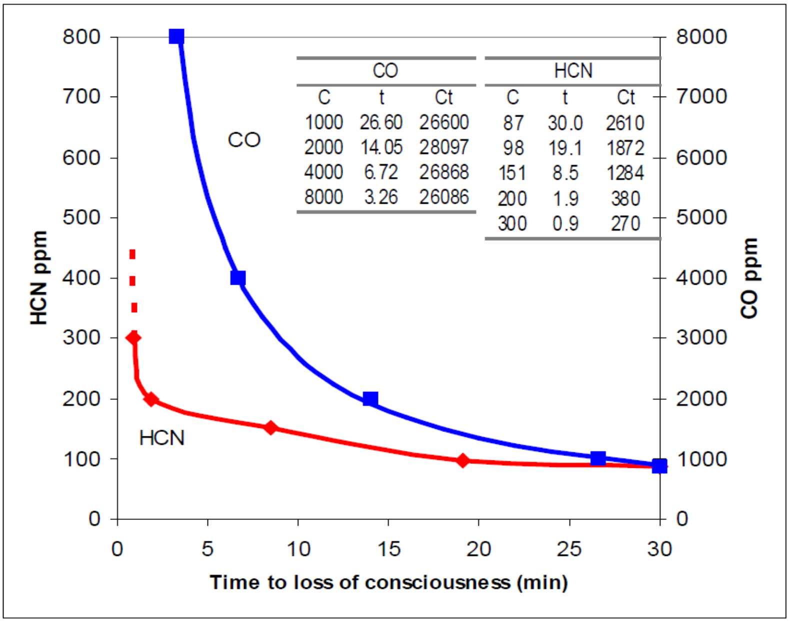

Figure III.26: Correlation between exposure concentration and time to incapacitation for CO and HCN for macaques. Taken from [144].

The second method is more realistic, in that it uses a non-linear correlation between the FID and the toxic concentrations of each gas, particularly for CO. The applied general model is taken from [43]:

$$FID = (F_{Ico} + F_{ICN}) * V_{CO2} + FID_{Io} \quad \text{(III.9)}$$

Where:

F_{Ico}	Fractional effective dose for incapacitation by CO [-].
F_{ICN}	Fractional effective dose for incapacitation by HCN [-].
V_{CO2}	Multiplicity effect of inhaled CO_2 [-].
FID_{Io}	Fractional effective dose for incapacitation by low oxygen hypoxia [-].

The F_{ICO} is calculated from the empirical Stewart-Peterson uptake model which takes into account %COHb rather than an exposure dose. The formula is taken from [43]:

$$F_{Ico} = 3.317 * 10^{-5} * [CO]^{1.036} * V_E * \frac{t}{D} \quad \text{(III.10)}$$

Where:

$[CO]$	CO concentration [ppm].
V_E	Volume of air breathed each minute [l/min].
t	Exposure time [min].
D	Exposure dose for incapacitation [%COHb].

The V_E depends on the body weight, smoke conditions and the occupant's activity. The D depends mainly on age, health and shape. The values of these parameters, for a person who is walking to escape, are typically taken as a fixed value (around 20-25 l/min for inhalation volume and of 30% COHb for susceptibility [43]). However, depending on the occupant type and physical challenges, these parameters may vary. Therefore, in the next subsection, a more in-depth study is performed to provide a better approximation for these parameters.

The F_{ICN} is calculated from the empirical correlation suggested by Purser [95]. The effect of HCN is exponential, which means that doses can't be added up and averaged because it would underestimate the effect of the gas. Important to mention is that HCN is 25 times more toxic than CO and that the FID for HCN and CO are additive. The formula reads [43]:

$$F_{ICN} = \frac{[CN]^{2.36} * V_E}{2.43 * 10^7} \; t \quad \text{(III.11)}$$

Where:

[CN]	HCN concentration [ppm].
t	Exposure time [min].

In order to incorporate the effect of CO_2 on the V_E rate, the following correlation is used [43]:

$$V_{CO2} = e^{\frac{[CO_2]}{5}} \qquad \text{(III.12)}$$

Where:

[CO_2] Carbon dioxide concentration [%].

t Exposure time [min].

The FED_{Io} is calculated by means of an empirical correlation [43]:

$$FED_{Io} = \frac{t}{e^{8.13-0.54(20.9-[\%O_2])}} \qquad \text{(III.13)}$$

Where:

[%O_2] Oxygen concentration [%].

t Exposure time [min].

III.10.4.1 The respiratory Minute Volume Rate V_E

The RMV (Respiratory Minute Volume) or V_E rate is the volume of air exhaled per minute. In smoke-free conditions, the V_E-rate depends on the occupant's activity and varies normally between 4.9 l/min (sleeping conditions) and 49 l/min (running conditions) [8]. For heavier labour or other activities, such as firefighting intervention, V_E rates up to 80 l/min can be achieved. In Table III.20 average V_E rates for several activity types are presented.

Table III.20: V_E rate for different activities (body weight 70 kg) [8].

Activity	v [km/h]	V_E [l/min]
Sleeping	0	4.9
Sitting	0	8.5
Standing	0	11.2
Walking	3	13.4
Walking	4	17
Walking	5	19.9
Walking	6	23
Walking	7	26
Running	8.9	49
Fire fighting	0-8	< 80

The data points discussed in Table III.20 are visualised in Figure III.27. A curve fit analysis is performed:

$$V_E = 33670760 + \frac{12.84212 - 33670760}{1 + \left(\frac{v}{559.9057}\right)^{3.323342}} \tag{III.14}$$

Where

v The walking speed [m/s]

The correlations are presented in Figure III.27 and implemented in the consequence model. This is done by linking the obtained dosages of every occupant to a walking speed. Different data would be needed for children or adults with bodyweights significantly different from 70 kg because V_E depends primarily on the body size of the subject and the level of physical activity.

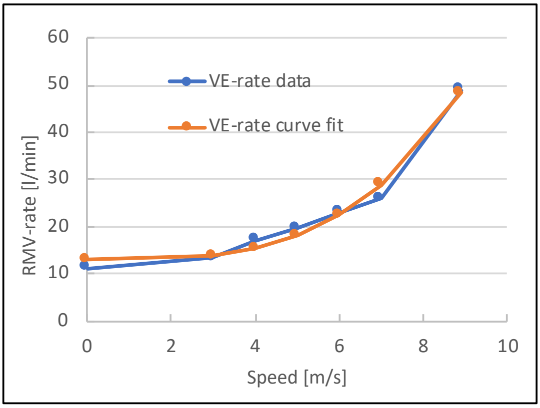

Figure III.27: V_E-rate in function of movement speed.

III.10.4.2 Susceptibility D

According to the definition of the FID and the IC_{50} approach, it is considered that a person who reaches an FID equal to unity or higher will perish unless they are rescued in time. However, the correlations used for the former formulas are obtained for healthy young men with a respiration rate of 20 l/min in normal conditions [145]. In reality a distribution of people with different ages and gender will be present, of which a considerable fraction is significantly more susceptible to the effects of the products of combustion, e.g., children, elderly, pregnant women. In order to consider these higher susceptibility range of occupants in fire safety designs, a safety margin is implemented by means of reducing the acceptable FID value to 0.3 [35]. However, for risk analysis this might not give a proper representation of reality. Therefore, instead of lowering the FID value, the %COHb can be approached more realistically [146]. Based on the data depicted in Figure III.28 and through personal communication with Purser, a normal and beta distribution are suggested in Table III.21. The distributions are presented in Figure III.29

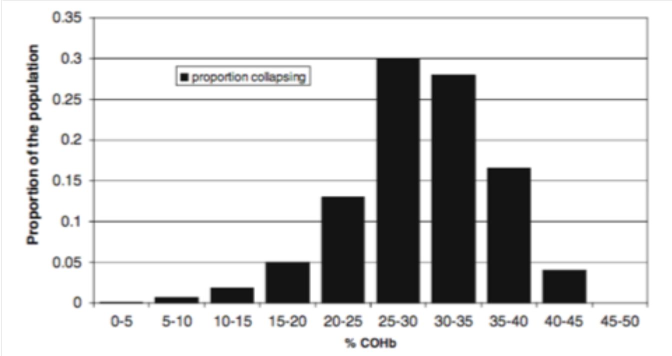

Figure III.28: Suggested population distribution of sensitivities to collapse from CO intoxication. Taken from [100].

Table III.21: Approximations of four normal and beta distribution [146].

Normal distribution [–]		Beta distribution [–]	
Mean or μ	30	Alpha or α	7.5186
STD or σ	8	Beta or β	4.1422
\	\	Lower limit a	-3.06E-16
\	\	Upper limit b	50

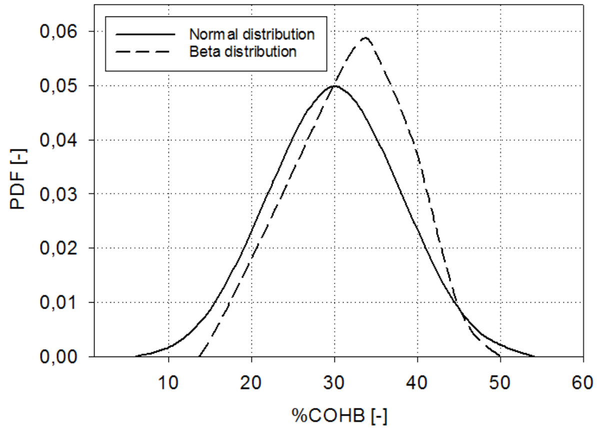

Figure III.29: Normal and Beta distribution suggested by Purser [147].

III.10.5 Heat assessment

As with toxic gases, the body of a fire victim may be regarded as acquiring a "dose" of heat over a period of time during exposure, with short exposure to a high radiant flux or temperature being more incapacitating than a longer exposure to a lower temperature or flux. A similar fractional incapacitating dose model as for the toxic gases can be applied and, providing that the temperature in the fire is stable or increasing, the fractional dose of heat acquired during exposure can be calculated by summing the radiant and convection fractions using [95], [43], [8]:

$$FID_{Heat} = \sum_{t_1}^{t_2} \left(\frac{1}{t_{Iconv}} + \frac{1}{t_{Irad}}\right)\Delta t \tag{III.15}$$

Where:

t_{Iconv} The time to incapacitation due to convective heat transfer [min]

t_{Irad} The time to incapacitation due to radiative heat transfer [min]

The radiant component is calculated by [8]:

$$t_{Irad} = \frac{r}{q^{1.33}} \tag{III.16}$$

Where:

r The radiant heat exposure dose [$(kW/m^2)^{4/3}$ min]

q The radiant flux from the fire or smoke layer [kW/m^2]

The threshold for pain occurs at an r value between approximately 1.33 and 1.67. Second-degree burns occur at 4.0–12.2 and third-degree (full-thickness) burns at approximately 16.7 $(kW/m^2)^{4/3}$ min (Table III.22).

Table III.22: Radiant heat exposure dose from different injuries

Radiant heat endpoint for exposed skin	R [$(kW/m^2)^{4/3}$min]
Severe skin pain	1.33-1.67
Second degree burns	4.0-12.2
Third degree (full-thickness) burns	16.7

The radiant heat flux can be calculated from the hot smoke layer temperature:

$$q = \varepsilon \, \sigma \, (T_i^4 - T_{skin}^4) \tag{III.17}$$

Where:

ε	Emissivity for smoke [-]
σ	Stefan Bolzmann constant $5.67*10^{-8}$ W/(m^{2}K^4)
T_i	Smoke layer temperature [K]
T_{skin}	Skin temperature of 306.6 K

For ε, typically a value of 0.5 is taken [8]. However, for dense black smoke it could be more conservative to take higher values closer to one into account. The expression for t_{Iconv} is related to exposure to heated air with less than 10% water content by volume [8]:

$$t_{Iconv} = 5 * 10^7 * T_{room}{}^{-3.4} \quad \text{(III.18)}$$

Where:

T_{room}	Room temperature [K].

III.11 Conclusions

In this part of the thesis, the deterministic framework has been described to quantify the consequences for life safety in case of fire. The objectives have been met:

1. The framework can take into account the effectiveness of different safety systems. The efficiency and reliability of passive and active fire protection systems can be implemented.
2. The procedure gives a step-by-step procedure to define representative design scenarios for fire and evacuation modelling in part 6 and 7.
3. The framework can take into account building, system, procedural, occupant, and environmental characteristics by using complex models (part 8 and 9).
4. The models are compatible with each other for efficient interaction and analysis.
5. A choice can be made between lower or higher computational affording models. In this way, a high number of scenarios can be analysed. The further elaboration of the simplified method is discussed in Chapter V.

Based on these conclusions, the methodology meets the predefined objectives. The framework will be validated in Part VI and tested by means of case studies in Part VII.

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CHAPTER IV

Probabilistic Framework

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B. Van Weyenberge, P. Criel, X. Deckers, R. Caspeele, B. Merci, Response surface modelling in quantitative risk analysis for life safety in case of fire, Fire Saf. J. 91 (2017).

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IV.1 Introduction of the developed framework

In this chapter, the probabilistic framework for quantifying the life safety risk to people in complex buildings in case of fire is developed. Currently, no universal risk assessment framework with practical interpretation exists that can objectify the safety level of buildings with complex layouts. Therefore, research is done to develop a full-probabilistic risk assessment model to quantify life safety in fire related conditions. The focus is put on different probabilistic methods that enable the integration of the proposed deterministic models from Chapter III into the framework. The method can be applied for designing new and existing buildings against a pre-defined safety level, for comparison of performance or prescriptive-based designs and for performing cost-benefit analysis of new and existing buildings.

In section 2, the problem objectives and challenges are formulated. In section 3, the global framework is proposed and explained by means of a flow chart. In section 4, the probabilistic part of the framework is developed. The method for conducting the probabilistic and reliability analysis is described in a step by step procedure by means of examples. In section 5, the conclusions are formulated.

IV.2 Objectives and challenges

The main goal is to objectively quantify fire safety designs by taking the uncertainty of design parameters and the reliability of safety systems into account. The purpose is to develop a framework that guides the fire safety engineer through the probabilistic analysis to determine the safety level of various types of fire safety designs for different types of buildings.

To design such a framework, several challenges are tackled. These challenges are considered fivefold. The first and main challenge is the need for a model that is able to objectively quantify the fire safety level of building designs. The framework should take the probability of the design scenarios and parameters into account. The final model should be a coherent application in combination with the deterministic evaluation of the sub-models developed Chapter III. The second objective is the applicability for engineering projects. The method should make it possible to design buildings with limited engineering cost and computational affordability. Computational demand increases with variability of the scenarios and input parameters, as well as with the complexity of the (sub)models (e.g. CFD, evacuation models, etc.) used for the risk analysis. The use of these computational affording models makes it not possible to analyse a large number of simulations. Therefore, efficient use of the sub-models and scenarios should be considered. The third challenge relates to the quantification of the safety level. The majority of risk methods give semi-quantitative output values which do not represent a proper physical meaning.

The results of these methods give no clear understanding for stakeholders not familiar with the applied method. Therefore, results should be quantified into output values which give physical meaning to the problem at hand. The fourth challenge is related to data storage and handling. These are key aspects in terms of processing a significant amount of data in case of the implementation of sophisticated sub-models. The use of the different sub-models and the communication between these models has a significant effect on the efficiency of the model.

The fifth challenge relates to the sensitivity of input parameters and the effect of specific safety system parameters. For simplified cases, only the most significant parameters and scenarios should be considered. Not every variable is equally sensitive and the sensitivity can vary for different configurations.

IV.3 Global framework

The proposed fire risk analysis model consists of a series of deterministic sub-models [1,2] combined with probabilistic techniques to define the overall fire safety risk to occupants. The main framework, presented in Figure IV.1, is inspired by international guidelines on performance based risk analysis [3–8]. The framework consists of seven steps where each step is elaborated in the following and, when necessary, simple examples are used to explain the approach.

Figure IV.1: Framework of the PRA-methodology. Adapted from [3].

In the first step, the building configuration and scope details are described [3]. The specific boundary conditions with respect to occupancy, building and environmental characteristics are defined. Important aspects that will have an impact on the definition of the fire safety design are analysed. After the definition of the scope, the goals and objectives are defined in step 2. Normally, the goals are identified by the stakeholders such as the owner, the commissioner, the contractor, the design team, the government (legislation and standards), occupants, community, etc. [3,9,10]. The building should be designed within the acceptable regulatory requirements in which specific physical, functional or procedural boundary conditions are set by the different stakeholders. The main objective is to achieve the pre-defined life safety level. Additional objectives can focus on a specific sub-category of occupant groups (e.g. elderly, disability, etc.) or when specific risks are expected (underground, nuclear, etc.).

In the third step, the performance criteria are developed based on the described goals, stakeholder and design objectives [3]. Depending on the problem description stated above, two types of performance evaluation can be defined. The first type of evaluation involves relative comparisons of different fire safety designs [11,12]. This is called the relative safety level for occupants (RSO). The safety levels of each of these fire safety designs are quantified through a safety factor. In traditional performance based designs, the quantification of these designs is conducted by calculating the safety factor by means of an ASET/RSET (available/required safe egress time) analysis. This method can be conducted to compare different fire safety systems and is typically used when applying performance based designs in a prescriptive based regulatory system when the building design deviates in certain aspects from the prescriptive legislation (e.g. maximum compartment surface, maximum walking distance to exit, etc.). By comparison, one can set a fully complying design as the reference level. This reference design will have a safety factor specific for its particular building configuration. The alternative design that deviates from prescriptive requirements will obtain a different safety factor which, in case of a lower safety factor, needs to be compensated by additional fire safety measures. The second type of evaluation can be defined as one in which the fire safety design is compared with absolute criteria derived from legislation, standards and guidelines [10,13]. The quantification of the absolute criteria is developed in Chapter VIII. In this thesis, the performance criteria are considered either reliability or risk based. For both relative and absolute evaluation, three types of criteria can be defined for the quantification of the acceptable risk level. The first criterion considers the probability of failure defined as the probability of a fatality over a period of time or given that a fire occurs [11]. In analogy to structural engineering, a target annual failure rate can be defined. The second criterion is defined in terms of the individual risk (IR) [1,13]. The third criterion is expressed as the societal risk that represents the risk to a group of people and is typically visualised by means of an FN curve. In Figure IV.2 an example is depicted of a quantitively comparison of different tunnel fire safety designs [1]. The objective of the study was to determine the most cost-effective design (orange FN curve) against the pre-defined acceptable criteria (straight lines).

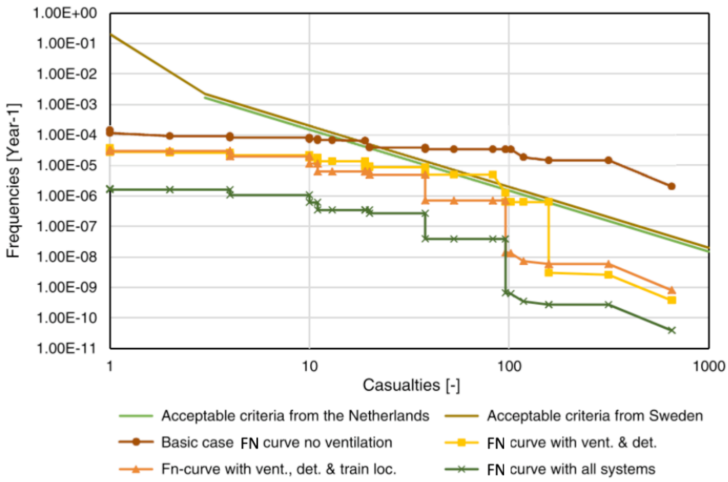

Figure IV.2: FN curve case study with different alternative solutions [1].

In the fourth step, the fire safety design is developed. The fire safety concept should be designed based on the main principles of fire safety design rules of good practice [3,14]. In most cases, these are initially defined based on prescriptive requirements. Once the fire safety design is developed, the deterministic and probabilistic analysis is conducted in step 5. The full elaboration of the proposed methodology is discussed in the following section by means of a step-by-step approach.

In the sixth step, the performance criteria are evaluated by means of comparison to the results with the individual and societal risk obtained in step 5. If the obtained results meet the risk criteria, the outcome is positive and the final design can be selected in step 7. If not, the fire safety design should be modified, by means of changing the configuration and/or taking additional safety measures, and the procedure should be repeated. When multiple designs are selected, the most cost-effective design that meets the minimum acceptable limit or reference design can be selected. This is done by taking the whole life-cycle into account so that commissioning, maintenance, control and inspection can be considered.

IV.4 Probabilistic framework

In the fifth step of the global framework, the deterministic and probabilistic analysis is performed. In Figure IV.3 an overview of the proposed framework for the probabilistic risk analysis is given. The method is divided in 11 sub-steps explained below and is implemented in the open source code Python [15] and Matlab [16].

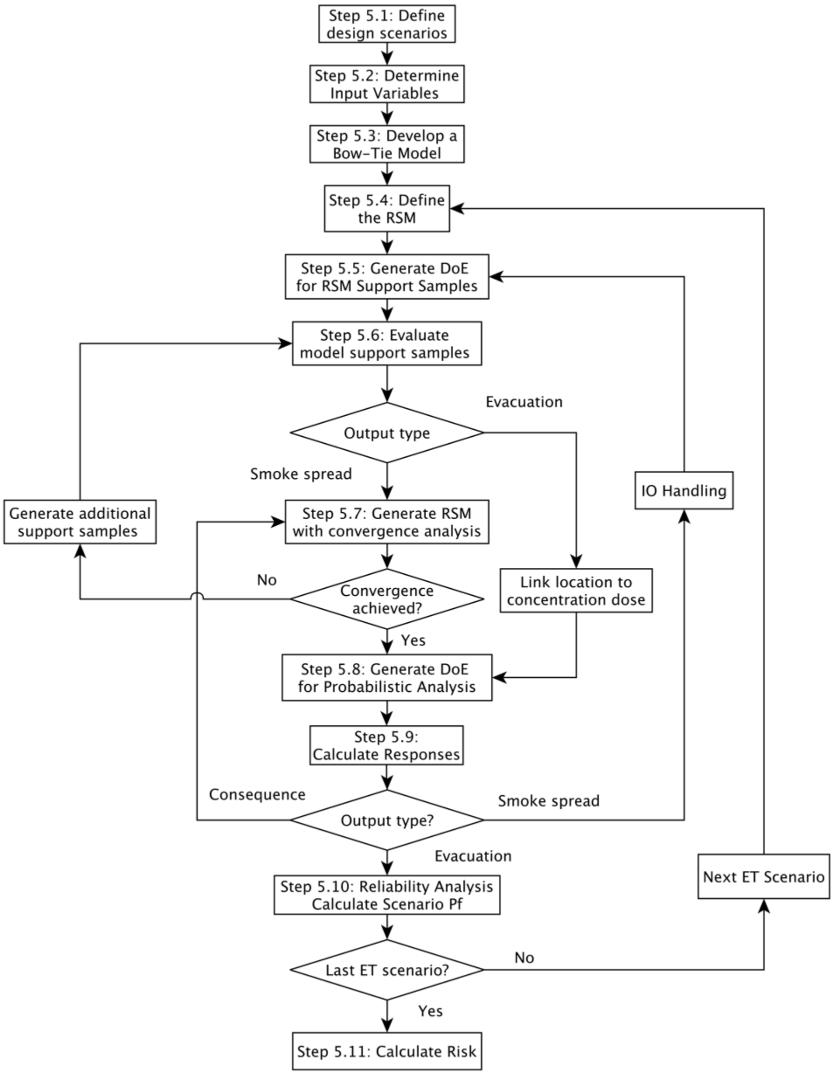

Figure IV.3: Probabilistic part of the framework (step 5 in Figure IV.1) [17].

IV.4.1 Step 5.1: Definition of design scenarios

In step 1 of the probabilistic framework, the main representative design fire scenarios are selected. These scenarios are chosen based on the building configuration (building type, height, adjacent buildings, structure type, etc.), environmental conditions (effect of wind, outside temperature, etc.), occupant characteristics (occupancy type, load, etc.) and fire safety design (safety systems, procedures, etc.). Design fires are chosen based on project specific parameters (atrium, open office plan, etc.) in combination with rules of good practice [18,19].

IV.4.2 Step 5.2: Definition of the input variables

In step 2, the most important input variables are determined based on a preceding sensitivity analysis [1]. For the considered variables, distributions are determined based on statistical data, fault tree analysis and engineering judgement [7]. In the Tables IV.1 and IV.2, a list of variables is given of the most sensitive parameters in the fire life safety analysis of a commercial building [20,21]. In theory, all these parameters should be implemented in the event tree analysis in step 3. However, in order to prevent an extensive event tree, the variables are divided into discrete and continuous parameters. The discrete variables are addressed in the bow-tie structure (Table IV.2). The continuous variables are addressed at the end of the event tree by means of the RSM (Table IV.1). The separation between the two types of variables is done for reasons of computational and operational efficiency (e.g. location of the fire). Secondly, some variables cannot be considered in continuous form due to their discrete nature (e.g. activation or failure of safety systems, the state of doors, etc).

For every variable in Table IV.1, an indication is given of the order of importance with respect to the results. The first order variables are considered the most significant based on preceding sensitivity analysis [22]. The preceding sensitivity analysis is based on research performed in the master thesis [14] and other sensitivity analyses performed [60-63]. Examples of additional type of sensitivity analysis is provided in Appendix D. This means that only parts of the domain close to the limit state need to be analysed. The second order variables are still significant but less sensitive than the first order. For these variables, a large part of the domain needs to be analysed. Third order variables, e.g. ambient temperature, material properties, etc., are the least significant and are considered deterministic in this study. For these variables mean values are taken as nominal values.

Table IV.1: Continuous input variables for response surface analysis.

nr	Type	Order of importance	Distr. type	Par 1[1] (μ,u,a)	Par 2[1] (σ,β,b)	Unit	Reference
1	Fire growth coefficient	1st	Lognormal	0.019	0.037	[kW/s²)	Nilsson [23]
2	Average HRRPUA	2nd	Lognormal	400	80	[KW/m²]	Yoshikazu [24]
3	Max area	1st	Lognormal	9.3	38.1	[m²)	Holborn [25]
4	Occupant density	1st	Lognormal	0.2	0.2	[p/m²]	NZ VM2 [26]
5	Affiliation	2nd	Beta	2.0	5.1	[%]	Case specific
6	Pre-evac time: close	1st	Lognormal	60	10	[s]	Modified VM2 [26]
	Pre-evac time: remote	1st	Lognormal	120	20	[s]	Modified VM2 [26]
7	Walking speed	2nd	Normal	1.12	0.25	[m/s]	SFPE [6]
8	Shoulder width	2nd	Normal	0.51	0.07	[m]	Albrecht [12]
9	Heat of Combustion	2nd	Normal	25	4	[kJ/g]	Yoshikazu [24]
10	Soot Yield	2nd	Normal	0.12	0.04	[g/g]	Albrecht [27]
11	CO-yield	2nd	Normal	0.09	0.03	[g/g]	Albrecht [27]
12	HCN-yield	2nd	Normal	0.006	0.002	[g/g]	Albrecht [27]
13	Susceptibility	2nd	Beta	7.5	4.1	[%COHb]	SFPE [6]
14	VE rate person	2nd	Normal	25	5	[m]	SFPE [6]

[1] The parameters μ and sigma σ are the mean and standard deviation of a normal or lognormal distribution, the parameters u and β are the location and scale parameters of the Gumbel distribution and a and b are the shape parameters of the beta distribution.

In Table IV.2, several variables are given which will be implemented in the event tree. The focus is put on reliability of the safety systems. For every safety system, the reliability is presented by a PERT distribution with their corresponding parameters. In the table, the most critical component is presented for each system that is the main cause of system failure. The presented reliability data is valid under the consideration of proper design, installation, testing and maintenance. In case of low testing and maintenance quality the reliability levels drop significantly. For sprinkler systems, the most frequent reason for system failure, ranging from 33% to 100% of the reported failures, is that the system was shut off after reparation or maintenance. One possibility to increase the reliability of sprinkler systems is to provide an electrical monitoring system that monitors the state of the main sprinkler valve. This way the reliability can be increased towards 95-99.9% [28]. Similarly, the reliability of SHC systems can be increased when the critical components are monitored.

Table IV.2: Safety system reliability data for event and fault tree analysis.

Safety system	Critical component	Low	Exp.	High	Ref.
Smoke detection	Poor maintenance	0.86	0.96	0.99	[28]
Alarm	Shut off after maintenance	0.85	0.95	0.99	[29]
Sprinkler	Main valve shut off	0.80	0.95	0.98	[28]
SHC	Damper failure	0.30	0.50	0.70	[30]
Smoke barrier	Door shutter failure	0.50	0.80	0.95	[29]

IV.4.3 Step 5.3: Construction of the Bow-Tie structure based on scenario analysis

In step 3, the bow-tie model is constructed. The bow-tie technique requires formation of fault trees at the left side and branch scenarios (event trees) at the right side of a particular event (start fire, detection, sprinkler activation, etc.). The ignition frequency data depends on the size of the building [31]. The probabilities in the fault tree are based on component analysis, historical data and engineering judgement. The event tree is structured based on pathway factors [7].

The factors are determined by dividing the variables in discrete and continuous parameters as illustrated in Table IV.3. The discrete variables are addressed in the bow-tie structure. The continuous variables are addressed in a later stadium by means of response surface modelling (RSM). The separation between the two types of variables is done for reasons of efficiency and because of the reason that some variables have to be treated as discrete variables (door open/closed, system activates/fails, etc.). On the other hand, depending on the properties of the considered variable, some variables are necessary to be analysed in continuous form (fire growth, max HRR, number of people, etc.). Therefore, not all variables will be included in the event tree. They are considered variable in the scenario itself. In Figure IV.4, the conceptual representation of the bow-tie structure is presented by means of a fault tree analysis (FTA) and event tree analysis (ETA).

Table IV.3: Describing discrete and continuous variables.

Discrete variables	Continuous variables
Location of the fire	Fire growth coefficient
Sprinkler activation	Heat Release Rate per Unit Area
SHC scenarios	Max fire Area
Fire doors state	Sprinkler location w.r.t. the fire
	Occupant density
	Pre-evacuation time
	Shoulder width (size)
	Movement speed
	Affiliation
	Soot yield
	γ_{CO} or CO-yield
	γ_{HCN} or HCN-Yield
	HoC or Heat of Combustion
	D or Susceptibility to fire
	V-rate or respiratory minute volume

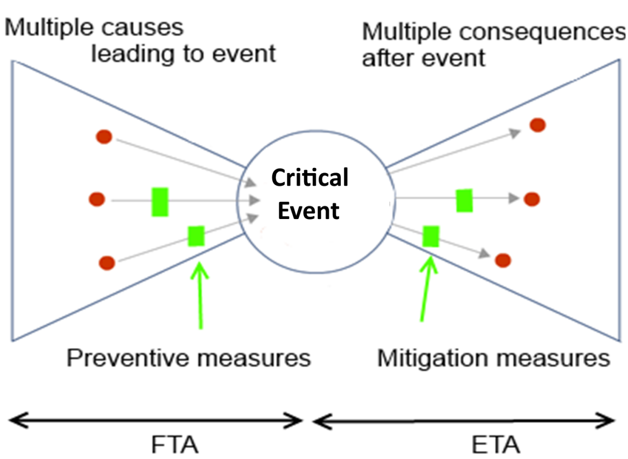

Figure IV.4: Concept of the bow-tie model. Adapted from [16].

In Figure IV.5, the conceptual representation of part of an event tree structure is presented.

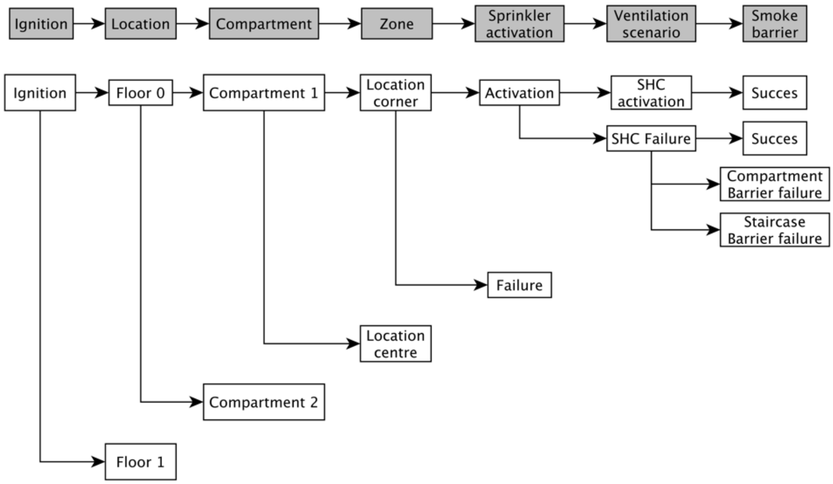

Figure IV.5: Conceptual representation of the dynamic bow-tie structure.

In the next steps, the failure probability of every branch scenarios is calculated.

IV.4.4 Step 5.4: Construction of the response surface model

IV.4.4.1 General concept

The basic concept of a response surface model is to approximate the response in the global domain for a specific model without relying upon the physics of the system. This can be the case when the modelling of the response becomes physically too complex. It is often used when the limit state function [32] is implicitly formulated [27] (e.g. structural engineering) which is the case for the numerical models considered in this framework [33]. In RSM, the results of a finite set of detailed model simulations are translated in a meta-model, which does not model the physics in any way. The formulation can be described as [22]:

$$y = f(\mathbf{X}) \tag{IV.3}$$

in which y is the response and **X** being the vector of input variables. A conceptual example is given in Figure IV.6.

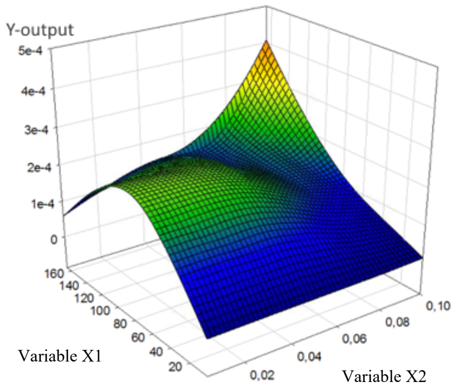

Figure IV.6: Example of a response surface model.

It is the goal of an RSM to replace the output information of the complex model $f(X)$ by an equivalent function $\bar{f}(X)$ by which the computational procedures can be simplified. An example of an RSM of a linear combination of second order polynomials can be depicted:

$$\bar{f}(\boldsymbol{X}) = a + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} c_i x_i^2 \qquad \text{(IV.2)}$$

in which $\boldsymbol{X} = (x_1, x_2, \ldots, x_n)$ are the variables and the parameters a, b_i, c_i, (i = 1,…, n) are to be determined.

It should be mentioned that in some cases the response surface may not be sufficiently accurate if it does not take interactions between variables properly into account, e.g. when interactions are expected between fire variables such as fire growth and fire area size. In the latter case, mixed terms may be included thus extending the approximate response surface $\bar{f}(X)$ as:

$$\bar{f}(\boldsymbol{X}) = a + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} c_i x_i^2 + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} d_{ij} x_i x_j \qquad \text{(IV.3)}$$

This response surface with interaction terms is more accurate. However, more evaluation simulations are needed to determine the coefficients.

IV.4.4.2 Multi-submodel response surface framework

The framework consists of multiple sub-models for determining the risk to failure. Depending on the scope, these sub-models will model fire ignition, fire spread, smoke spread, evacuation, toxicity effects, fire brigade intervention, etc. in which they have to interact with each other. Therefore, a link between these sub-models should be established. For example, output from the smoke spread model can be used for determining the visibility in evacuation models.

In Figure IV.7, a sequential method of three sub-models is shown: the smoke spread, the evacuation and the consequence model. The input for smoke spreads model is divided into primary and secondary parameters. The primary type are parameters that have a significant impact on the fluid dynamics in the smoke spread sub-model, e.g. fire growth, fire area, ventilation conditions, etc. The secondary type of variables are parameter inputs which are considered to have significantly less impact on the movement of smoke, e.g. toxicity yields, heat of combustion, etc. The variability of these parameters is considered outside the computational expensive model by an analytical model, this to reduce the dimensionality and the number of simulations. The output from the smoke spread sub-model is generated based on a limited learning set. The response model is then used to generate input data in terms of visibility, toxicity and temperature components for the evacuation model. In a similar way, the evacuation model is analysed. The output from the evacuation model is then used to perform the consequence analysis. This model will determine the consequences for each occupant in terms of injury or fatality. In the last step, the reliability analysis is performed by limit state design. The limit state design is coupled to the Fractional Effective Dose (FED) model in which the individual risk in terms of the probability of fatality is calculated. Next, the societal risk is visualised by means of an FN curve.

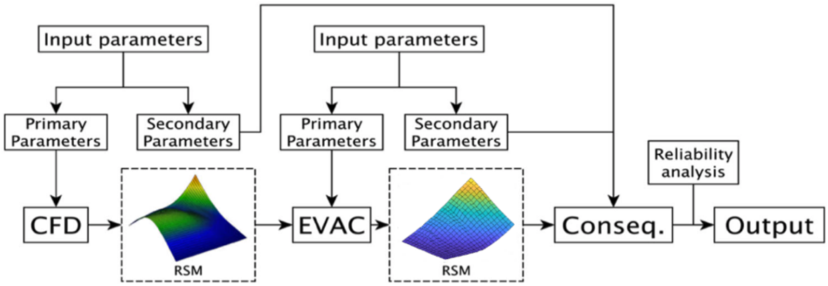

Figure IV.7: Simplified representation of the response surface model for multiple sub-models.

IV.4.4.3 RSM for bow-tie scenarios

Principally, the outcome of every event tree scenario in the bow-tie structure has multiple continuous variables. These variables need to be further analysed by means of the response surface model which is elaborated in the following steps. For bow-tie structures with limit sizes, the extent of the number of simulations is reasonable. However, in case of larger bow-tie models, an extensive number of simulations needs to be performed for the different sub-models. This will not be feasible when computational affording submodules are used. Therefore, the implementation of a comparative method for similar scenarios is suggested. The method is applied when similar sensitivities and behaviours are expected for branch scenarios. Multiple scenarios are grouped together in order to reduce the number of necessary model evaluations.

For one of the grouped scenarios, the reference scenario, the standard procedure is followed as discussed in step 5, 6, 10 and 11. Multiple support points are generated (steps 5 and 10) and deterministic evaluations are performed (steps 6 and 11). For the other scenarios, only one support point (the most conservative) $\kappa_{new\ scen}$ is chosen and evaluated with similar boundary conditions as one of the simulations $\kappa_{ref\ scen}$ in the scenario with multiple support points. The ratio between the results of these two identical scenarios is determined. Based on the ratio, additional support points for the other scenarios are generated. The results are obtained by means of the following formula:

$$\hat{y}_{scen} = y_{i_{other\ scen}} \frac{y_{\kappa_{other\ scen}}}{y_{\kappa_{ref\ scen}}} \quad \text{(IV.4)}$$

Where:

$\hat{y}_{scen}$	Component value (CO, CO_2, O_2, HCN, T) of support point for other scenarios.
$y_{i_{other\ scen}}$	Component value of other scenario i.
$y_{\kappa_{other\ scen}}$	Component value of other scenario κ.
$y_{\kappa_{ref\ scen}}$	Component value of reference scenario κ.

IV.4.5 Step 5.5: Generation of the support points for smoke spread to be used in the response surface modelling

In the first phase, the variables for deterministic analyses are chosen. The total computational time is reduced by only implementing the fundamental input variables that affect the main physics of smoke movement (Figure IV.7). The chosen variables, based on a preceding sensitivity analysis, are the fire growth coefficient α, the heat release rate per unit area (HRRPUA) and the maximum fire area (A_{max}). Other primary variables can be the sprinkler activation time, the wind effect, etc. In Table IV.1, the distributions for these variables have been listed.

Next, the support samples are defined for the deterministic analysis. Sample combinations need to be chosen that give sufficient information to generate an accurate response surface model. In [2] it is discussed that fractional factorial design is a suitable Design of Experiment (DoE). Other suitable designs are Central Composite and Box-Behnken designs [34]. The samples should be chosen to cover the domain of the expected limit state that covers the highest failure domain, i.e. the closest part of the limit state design from the origin in standard normal space (Figure IV.8).

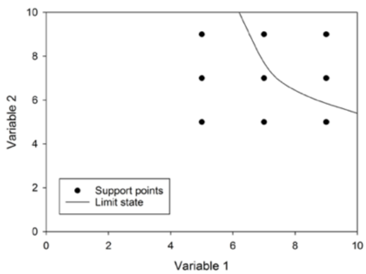

Figure IV.8: Selection of supports considering a limit state.

In order to determine the optimal support points to generate the RSM, several aspects have to be considered. The first step is to choose a representative domain for every variable. Not the entire domain should always be chosen because it is expected that only a specific part of the domain will significantly contribute to the value of P_f, as e.g. the fire grows too slowly, the fire area is too small, the sprinkler extinguishes the fire, etc. In Table IV.4, the suggested ranges are shown for the analysed variables. The choice of the ranges for every variable is based on a preliminary iteration in which first a broad parameter range is chosen, which is subsequently narrowed down. For example, the support points for the fire growth coefficient in a specific scenario can initially vary from slow to ultra-fast. After narrowing down, the risk analysis can be conducted for values from fast to ultrafast.

Table IV.4: Input values for the support points for the RSM of the smoke spread sub-model (LL = Lower Limit, MV = Mean Value, UL = Upper Limit, CDF(LL) = Cumulative Density Function Lower Limit, CDF(UL) = Cumulative Density Function Upper Limit).

Variable input	LL	MV	UL	Units	CDF(LL)[1]	CDF(UL)[1]
Fire growth	0.012	0.12	0.188	kW/s^2	0.88	0.992
HRRPUA	300	450	600	kW/m^2	0.0816	0.99
Max fire area	4	10	100	m^2	0.6	0.98

[1]CDF evaluated in the lower limit (LL) and upper limit (UL).

In the second part of step 5, the DoE is chosen based on full fractional factorial design [35,36]. For every variable, a minimum of three values are chosen [35]. This gives a total of 3^n or 27 simulations. The lower limit (LL) values are adopted based on the method described above. The upper limit (UL) is taken based on physical boundaries (max fire area and maximum fire growth). The mean values (MV) are based on the linear or logarithmic average between the lower and higher limit. In order to test the convergence of the model, additional samples are evaluated to analyse the convergence rate of the developed RSM (see step 7).

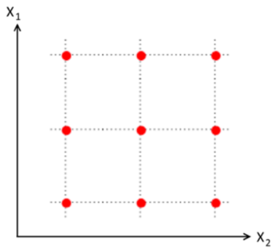

Figure IV.9: DoE fractional factorial design.

In case correlation between variables is expected, correlation effects need to be implemented in the methodology. An extension of LHS or Sobol technique can be performed with correlated variables [37–39]. The method is extended by implementing a correlation matrix (see Table IV.5). The correlation matrix is a $n \ x \ n$ matrix, with n the number of variables, which defines the correlation between variables. Correlation between variables is possible because of the physical boundary effects (e.g. a slowly growing fire is less likely to reach a significant fire surface area). The values in the table are arbitrary values. Secondly, some combinations are not relevant for the analysis as they are not located in the vicinity of the limit state and hence are of minor importance when looking for the most likely failure point and the associated exceedance probability. The values in the table have been chosen as possible values here, in order to illustrate the proof of concept of the technique.

Table IV.5: Correlation coefficients for a problem formulation with 3 variables [2].

Variables	α	$HRRPUA$	A_{max}
α	1	0.85	0.35
$HRRPUA$	-	1	0.2
A_{max}	-	-	1

IV.4.6 Step 5.6: Evaluation of the training set with deterministic analysis

In step 6, the training set is evaluated by means of the deterministic smoke spread sub-model [2]. The corresponding input parameters are implemented and the scenarios are evaluated. Two models are considered: a zone model (e.g. Branzfire or CFAST) for simple compartment configurations and a field model FDS [40] for complex layouts. The output of the smoke spread sub-model is obtained in 3D values for every time step and translated into compatible input for subsequent sub-models.

IV.4.7 Step 5.7: Generation of the response surface smoke spread model

The RSM is generated in step 7. Two methods are analysed for response surface modelling in the framework of life safety analysis [2,22]. These are the Interpolating Moving Least Squares (IMLS) method and the Polynomial Chaos Expansion (PCE) method. Both methods have a different approach for estimating the response surfaces and will prove to be sufficiently accurate for the intended purpose (see Chapter 6) [2].

The PCE estimates one response surface for the entire domain independent of the chosen support points. The model provides a more accurate method when fewer irregular patterns are observed (e.g. field far from the fire, low turbulence, etc.). In this thesis, the PCE methods is chosen for the analysis because of its higher accuracy for this type of configurations [2]. In general, the PCE method consists of two steps. First, it estimates a response surface based on the support samples for the chosen domain. In the second step, for every new combination of input variables, the RSM estimates the outcome by addressing the response surface. PCE is based on the homogeneous chaos theory proposed by Wiener [41]. PCE is a powerful surrogate modelling technique that aims at providing a functional approximation of a computational model through its spectral representation on a suitably built basis of orthogonal polynomial functions. The proposed methodology is explained in more detail in [42].

The IMLS method has only one step. For every new sample combination of input variables the method estimates a response surface which fits the best for that specific sample point. This means that the response surface and output value is generated at once for every new combination of input parameters. In Figure IV.10, the conceptual representation of the IMLS is depicted for two new samples (blue samples). Each new sample gives a different response surface because a weight function is used to give more importance to the support samples (red samples) close to the new samples (red arrows). All support points have an influence on new samples. However, only the closest ones will have a significant impact based on the weighting function. The method is a more accurate method when strongly irregular patterns are observed (e.g. close to the fire, high turbulence or irregular sampling techniques). The advantage is that the method fits the best surface for the chosen support point. The mathematical explanation is discussed in 4.7.2.

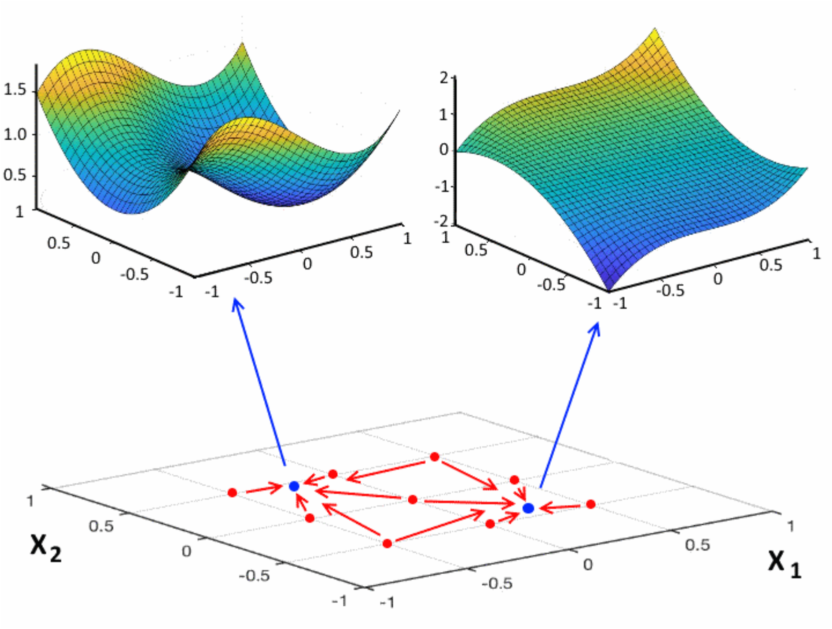

Figure IV.10: Conceptual representation IMLS method.

IV.4.7.1 Response surface modelling with polynomial chaos expansion

PCE in mathematical terms is based on the homogeneous chaos theory proposed by Wiener [41]. PCE is a powerful surrogate modelling technique that aims at providing a functional approximation of a computational model through its spectral representation on a suitably built basis of orthogonal polynomial functions.

Consider a random vector with independent components $X = (x_1 \ x_2 \ x_3) = (\alpha, \text{HRRPUA and } A_{max}) \in R^M$ described by the joint probability density function (PDF) *f(**X**)* . Consider also a complex model as a map $Y = M(\boldsymbol{X})$. The PCE of $M(\boldsymbol{X})$ is defined as:

$$Y = M(\boldsymbol{X}) = \sum_{\alpha \in N^M} \beta_\alpha \Psi_\alpha(\boldsymbol{X}) \tag{IV.5}$$

where $\Psi_\alpha(\mathbf{X})$ are multivariate polynomials, orthonormal with respect to $f(\boldsymbol{X})$. $\alpha \in N^M$ is a multi-index that identifies the components of the multivariate polynomials Ψ_α and $\beta_\alpha \in R$ are the corresponding coefficients. In realistic applications, the sum given in Eq. (IV.5) needs to be truncated to a finite sum, by introducing the truncated polynomial chaos expansion:

$$M(\boldsymbol{X}) \approx M^{PC}(\boldsymbol{X}) = \sum_{\alpha \in \mathcal{A}} \beta_\alpha \Psi_\alpha(\mathbf{X}) \tag{IV.6}$$

In Eq. (IV.6) $\mathcal{A} \subset N^M$ is the set of selected multi-indices of multivariate polynomials.

IV.4.7.1.1 Define the basis of the multivariate polynomials Ψ_α

Conventionally, for normally distributed input variables, PCE constructs an RSM for the output using Hermite polynomials, which are orthogonal with respect to the standard normal distribution. The weight function and Hilbertian basis of the Hermite polynomials are presented in Table IV.6.

Table IV.6: Implemented orthogonal polynomial for Gaussian variable associated with classical probability density function.

Orthogonal polynomials	Weight function
Hermite $H_{e_k}(x)$	$\frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}}$

For input variables following some specific non-normal distributions, Wiener-Askey polynomials can be chosen as the orthogonal basis. However, if these non-normal distributions can be transformed to normal distributions, the Hermite polynomials can be used.

The subset $\mathcal{A}$ in equation IV.6 is determined in such a manner that the number of polynomials used in the analysis do not exceed the number of samples, in order to avoid over-fitting (which is a common problem in response surface methods). A standard truncation scheme is used, corresponding to all polynomials in the M input variables of total degree less than or equal to p:

$$\mathcal{A}^{M,p} = \{\alpha \epsilon \mathbb{N}^M : |\alpha| \leq p\} \quad \text{(IV.7)}$$

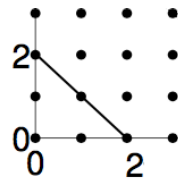

Figure IV.11: Truncation set for p = 2.

A second truncation scheme used is the hyperbolic truncation scheme (or q-norm). The scheme makes use of the parametric q-norm to define the truncation [42]:

$$\mathcal{A}^{M,p,q} = \left\{\alpha \epsilon \mathbb{N}^{M,p} : \|\alpha\|_q \leq p\right\} \quad \text{(IV.8)}$$

where:

$$\|\alpha\|_q = \left(\sum_{i=1}^{M} \alpha_i^q\right)^{1/q} \quad \text{(IV.9)}$$

The associated multivariate polynomial reads:

$$\Psi_\alpha(\boldsymbol{x}) \stackrel{\text{def}}{=} \prod_{\boldsymbol{i=1}}^{M} \Psi_{\alpha_i}^{(i)}(x_i) \quad \text{(IV.10)}$$

where $\Psi_{\alpha_i}^{(i)}(x_i)$ is the univariate polynomial of degree α from the orthonormal family associated to variable x_i.

Classical orthogonal polynomials are defined for reduced variables (e.g. standard normal variables). In practical problems the physical variables are modelled by random variables that are not necessarily reduced and not necessarily from a classical family, e.g. lognormal variable. Therefore, an isoprobabilistic transformation is necessary:

$$X_i = \mu_i + \sigma_i \, \xi_i \quad \text{(IV.11)}$$

This gives for response model:

$$M^{PC}(\mathbf{X}) = \sum_{\alpha \in \mathcal{A}} \beta_\alpha \Psi_\alpha(\boldsymbol{\xi}) \quad \text{(IV.12)}$$

Next, the Hermite polynomials are defined by means of recurrence generation:

$$\begin{cases} H_{-1}(x) = H_0(x) = 1 \\ H_{n+1}(x) = x * H_n(x) - n * H_{n-1}(x) \end{cases} \rightarrow \begin{cases} H_0(x) = 1 \\ H_1(x) = x(1) - 1 * 0 = x \\ H_2(x) = x(x) - 1 * 1 = x^2 - 1 \end{cases} \quad \text{(IV.13)}$$

The polynomials are normalized by dividing through $\sqrt{\|H_n\|^2}$:

$$\|H_0\|^2 = 1, \|H_1\|^2 = 1, \|H_2\|^2 = 2 \quad \text{(IV.14)}$$

The normalized Hermite polynomials are:

$$\begin{aligned} He_0(x) &= 1 \\ He_1(x) &= x \\ He_2(x) &= (x^2 - 1)/\sqrt{2} \end{aligned} \quad \text{(IV.15)}$$

All the polynomials of $(\xi_1 \xi_2 \xi_3)$ that are products of univariate Hermite polynomials and whose total degree is less than 2 are considered as provided in Table IV.7:

Table IV.7: Polynomials considered in the PCE model.

j	α	$\Psi_\alpha = \Psi_j$
0	[0,0,0]	1
1	[1,0,0]	ξ_1
2	[0,1,0]	ξ_2
3	[0,0,1]	ξ_3
4	[1,1,0]	$\xi_1 \xi_2$
5	[1,0,1]	$\xi_1 \xi_3$
6	[0,1,1]	$\xi_2 \xi_3$
7	[2,0,0]	$(\xi_1^2 - 1)/\sqrt{2}$
8	[0,2,0]	$(\xi_2^2 - 1)/\sqrt{2}$
9	[0,0,2]	$(\xi_3^2 - 1)/\sqrt{2}$

Based on Table IV.7, the following formula can be written:

$$\begin{aligned} \mathrm{Y} = \mathrm{M}^{\mathrm{PC}}(\xi_1, \xi_2, \xi_3) = {} & a_0 + a_1 \xi_1 + a_2 \xi_2 + a_3 \xi_3 + a_4\, \xi_1 \xi_2 \\ & + a_5\, \xi_1 \xi_3 + a_6 \xi_2 \xi_3 + a_7 ({\xi_1}^2 - 1)/\sqrt{2} \\ & + a_8 ({\xi_2}^2 - 1)/\sqrt{2} + a_9 ({\xi_3}^2 - 1)/\sqrt{2} \end{aligned} \quad \text{(IV.16)}$$

Were a_0, a_1, ... a_9 are the coefficients.

IV.4.7.1.2 Calculate the coefficients by means of Least Squares Minimization $\boldsymbol{\beta}$

Next, the coefficients have to be calculated. These are determined by means of a least squares minimization. The exact (infinite) series expansion is considered as the sum of a truncated series and a residual:

$$Y = M(\boldsymbol{X}) = \sum_{\alpha \in \mathcal{A}} \beta_\alpha \Psi_\alpha(\mathbf{X}) + \varepsilon_p \equiv \boldsymbol{\beta}^{\mathbf{T}} \Psi(\mathbf{X}) + \varepsilon_p(\mathbf{X}) \tag{IV.17}$$

The unknown coefficients are estimated by minimizing the mean square residual error:

$$\hat{\boldsymbol{\beta}} = \arg\min \mathrm{E}[\varepsilon_p^2(\mathbf{X})] = \arg\min \mathrm{E}[(\boldsymbol{\beta}^{\mathbf{T}} \Psi(\mathbf{X}) - \mathcal{M}(\mathbf{X}))^2] \tag{IV.18}$$

The coefficients can be calculated as:

$$\hat{\boldsymbol{\beta}} = \left(\mathbf{H}^{\mathrm{T}}\, \mathbf{H}\right)^{-1} \mathbf{H}^{\mathrm{T}}\, \mathbf{y} \tag{IV.19}$$

The vectors **H** and $\boldsymbol{y}$ are discussed and explained below.

IV.4.7.1.3 Construction of the matrix H

H is a 2D-matrix with size m x n containing m support points and n-nonlinear functions $h_i(x_i)$. In a general form the matrix can be described as the following:

$$\mathbf{H} = \begin{array}{c} \\ 1 \\ 2 \\ \vdots \\ 27 \end{array} \begin{array}{c} \begin{array}{cccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \end{array} \\ \left[\begin{array}{cccccccccc} 1.0 & \xi_{1,1} & \xi_{2,1} & \xi_{3,1} & \xi_{1,1}\xi_{2,1} & \xi_{1,1}\xi_{3,1} & \xi_{2,1}\xi_{3,1} & \frac{\xi_{1,1}^2 - 1}{\sqrt{2}} & \frac{\xi_{2,1}^2 - 1}{\sqrt{2}} & \frac{\xi_{3,1}^2 - 1}{\sqrt{2}} \\ 1.0 & \xi_{1,2} & \xi_{2,2} & \xi_{3,2} & \xi_{1,2}\xi_{2,2} & \xi_{1,2}\xi_{3,2} & \xi_{2,2}\xi_{3,2} & \frac{\xi_{1,2}^2 - 1}{\sqrt{2}} & \frac{\xi_{2,2}^2 - 1}{\sqrt{2}} & \frac{\xi_{3,3}^2 - 1}{\sqrt{2}} \\ & & & & & \vdots & & & & \\ 1.0 & \xi_{1,27} & \xi_{2,27} & \xi_{3,27} & \xi_{1,27}\xi_{2,27} & \xi_{1,27}\xi_{3,27} & \xi_{2,27}\xi_{3,27} & \frac{\xi_{1,27}^2 - 1}{\sqrt{2}} & \frac{\xi_{2,27}^2 - 1}{\sqrt{2}} & \frac{\xi_{3,27}^2 - 1}{\sqrt{2}} \end{array} \right] \end{array} \tag{IV.20}$$

IV.4.7.1.4 Construction of the vector $\boldsymbol{y}$

The $\boldsymbol{y}$ matrix is a 1-dimensional vector containing the responses for the support samples at a considered location, timestep and component.

$$\boldsymbol{y} = [y_1 \;\; y_2 \cdots\; y_{27}] \tag{IV.21}$$

IV.4.7.2 Response surface modelling with interpolating moving least squares

For every combination of input samples output data is generated by means of the IMLS method. For every sample data is generated by means of the following formula:

$$\hat{y}(\mathbf{x}) = \mathbf{h}(\mathbf{x})\, \widehat{\boldsymbol{\beta}}(\boldsymbol{x}) \tag{IV.22}$$

$$\widehat{\boldsymbol{\beta}}(\boldsymbol{x}) = (\mathbf{H}^{\mathbf{T}}\mathbf{W}(\mathbf{x})\ \ \mathbf{H})^{-1}\, \mathbf{H}^{\mathbf{T}}\mathbf{W}(\mathbf{x})\, \boldsymbol{y} \tag{IV.23}$$

In which,

$\hat{y}(\mathbf{x})$	The output response value.
$\mathbf{h}(\mathbf{x})$	1D vector with containing the polynomials for the input variables x
H	2D matrix with size m x n containing n linear functions hi(xi)
$\mathbf{W}(\mathbf{x})$	2D diagonal weighting matrix with size m x m
y	1D vector with size m containing response data

The construction of the different vectors and matrices is explained below.

IV.4.7.2.1 Construct the matrix **H**

H is a 2D-matrix with size m x n containing m support points and functions $h_i(x_i)$. In a general form the matrix can be described as follows:

$$\mathbf{H} = \begin{array}{c} \\ 1 \\ 2 \\ \vdots \\ 27 \end{array}\begin{array}{c} \begin{array}{cccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \end{array} \\ \begin{bmatrix} 1.0 & x_{1,1} & x_{2,1} & x_{3,1} & x_{1,1}x_{2,1} & x_{1,1}x_{3,1} & x_{2,1}x_{3,1} & x_{1,1}^2 & x_{2,1}^2 & x_{3,1}^2 \\ 1.0 & x_{1,2} & x_{2,2} & x_{3,2} & x_{1,2}x_{2,2} & x_{1,2}x_{3,2} & x_{2,2}x_{3,2} & x_{1,2}^2 & x_{2,2}^2 & x_{3,2}^2 \\ & & & & & \vdots & & & & \\ 1.0 & x_{1,27} & x_{2,27} & x_{3,27} & x_{1,27}x_{2,27} & x_{1,27}x_{3,27} & x_{2,27}x_{3,27} & x_{1,27}^2 & x_{2,27}^2 & x_{3,27}^2 \end{bmatrix} \end{array} \tag{IV.24}$$

In a more specific form for the case studies described in Chapter VII:

$$\mathbf{H} = \begin{array}{c} \\ 1 \\ 2 \\ \vdots \\ 27 \end{array}\begin{array}{c} \begin{array}{cccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \end{array} \\ \begin{bmatrix} 1.0 & \alpha_1 & \mathrm{HRRPUA}_1 & \mathrm{A}_{\mathrm{max}_1} & \alpha_1\, \mathrm{HRRPUA}_1 & \alpha_1 \mathrm{A}_{\mathrm{max}_1} & \mathrm{HRRPUA}_1\, \mathrm{A}_{\mathrm{max}_1} & \alpha_1^2 & \mathrm{HRRPUA}_1^2 & A_1^2 \\ 1.0 & \alpha_2 & \mathrm{HRRPUA}_2 & \mathrm{A}_{\mathrm{max}_2} & \alpha_2\, \mathrm{HRRPUA}_2 & \alpha_2 \mathrm{A}_{\mathrm{max}_2} & \mathrm{HRRPUA}_2\, \mathrm{A}_{\mathrm{max}_2} & \alpha_2^2 & \mathrm{HRRPUA}_2^2 & A_2^2 \\ & & & & & \vdots & & & & \\ 1.0 & \alpha_{27} & \mathrm{HRRPUA}_{27} & \mathrm{A}_{\mathrm{max}_{27}} & \alpha_{27}\, \mathrm{HRRPUA}_{27} & \alpha_{27} \mathrm{A}_{\mathrm{max}_{27}} & \mathrm{HRRPUA}_{27}\, \mathrm{A}_{\mathrm{max}_{27}} & \alpha_{27}^2 & \mathrm{HRRPUA}_{27}^2 & A_{27}^2 \end{bmatrix} \end{array} \tag{IV.25}$$

The values for α, HRRPUA and A_{max} are obtained from the input given in Table IV.4.

IV.4.7.2.2 Construction of the matrix $\mathbf{W}(\mathbf{x})$

For every combination of input variables and thus every smoke spread simulation, the weighting matrix $\mathbf{W}(\mathbf{x})$ needs to be determined. $\mathbf{W}(\mathbf{x})$ is a 2D diagonal matrix with size m x m.

$$\mathbf{W}(\mathbf{u}) = \begin{matrix} & \begin{matrix} 1 & \dots & 27 \end{matrix} \\ \begin{matrix} 1 \\ \vdots \\ 27 \end{matrix} & \left[\begin{pmatrix} w_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & w_i \end{pmatrix}\right] \end{matrix} \tag{IV.26}$$

Every w_i is calculated by means of the following formula.

$$w_i(\|\boldsymbol{u} - \boldsymbol{u}_{\boldsymbol{m}_i}\|) = \frac{\widetilde{w}_i(\|\boldsymbol{u} - \boldsymbol{u}_{\boldsymbol{m}_i}\|)}{\sum_{j=1}^{m} \widetilde{w}_i\,(\|\boldsymbol{u} - \boldsymbol{u}_{\boldsymbol{m}_i}\|)} \tag{IV.27}$$

with

$$\widetilde{w}_i(\|\boldsymbol{u} - \boldsymbol{u}_{\boldsymbol{m}_i}\|) = \left(\|\boldsymbol{u} - \boldsymbol{u}_{\boldsymbol{m}_i}\|^2 + \varepsilon_{reg}\right)^{-2}, \varepsilon_{reg} \ll 1 \tag{IV.28}$$

where $\boldsymbol{u}_{m_i}$ and $\boldsymbol{u}$ are the values chosen in Table IV.4 and transformed to the standard normal space. This is done in order to work with relative distances and not absolute ones so that the scale of the variables does not have an impact on the weighting factor. A regularization parameter ε_{reg} is implemented in the method so that sample points at the support point location can be evaluated. In general a regularization parameter of $\varepsilon_{reg} = 10^{-5}$ is recommended [27].

IV.4.7.2.3 Construction of the vector $\mathbf{h}(\mathbf{x})$

For every combination of input variables and thus every smoke spread simulation $\mathbf{h}(\mathbf{x})$ needs to be determined. A quadratic scheme is chosen for $\mathbf{h}(\mathbf{x})$ in which the variables are fitted with respect to a second order degree and a first order interaction. The values for x_1, x_2 & x_3 are generated from data obtained in Table IV.1

$$\mathrm{h(x)} = [1\ \ x_1\ \ x_2\ \ x_3\ \ x_1x_2\ \ x_1x_3\ \ x_2x_3\ \ x_1^2\ \ x_2^2\ x_3^2] \tag{IV.29}$$

IV.4.7.2.4 Construction of the vector $\boldsymbol{y}$

The y matrix is a 1-dimensional vector containing the responses for the support samples at a considered location, timestep and component.

$$y = [y_1 \ y_2 \ .... \ y_{27}] \tag{IV.30}$$

IV.4.7.3 Regularization of the model

The purpose of the implementation of a regularization factor is to prevent overfitting of the response surface model. In regression analysis, the larger the number of parameters in the surrogate model, the better the fit to the original model. However, the higher the number of parameters, the higher the complexity and the higher the possibility of overfitting. In general, overfitting occurs when the number of unknown parameters in the regression model are equal or more as the size of the training set. A visual example of overfitting for a one-dimensional model is given in Figure IV.12.

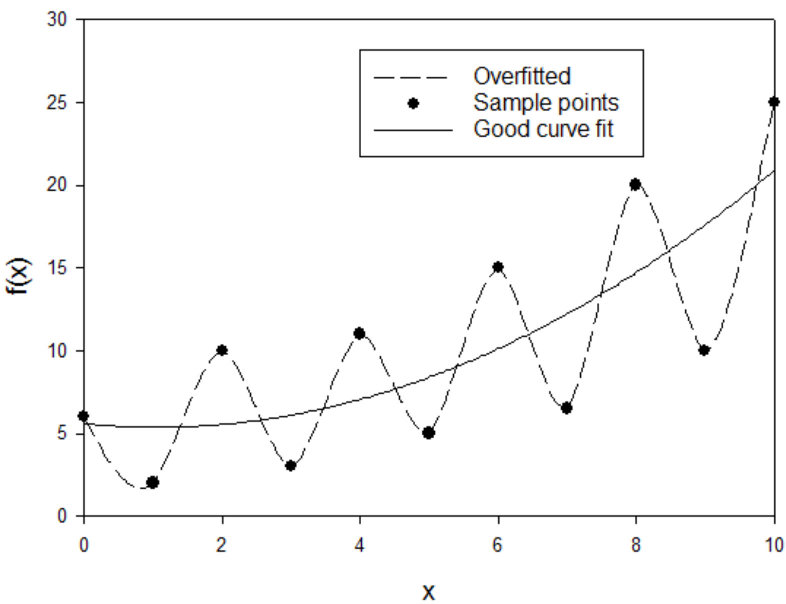

Figure IV.12: Example of overfitting in linear regression.

In order to overcome this problem of overfitting, the L_2 regularization or ridge regression [43] is applied. For every chosen set of combinations of parameters in the surrogate model, the method determines a cost function $J(\boldsymbol{\beta})$ in which an additional term is added to penalize higher degree fitting surrogates. The cost function is defined as follows:

$$J(\boldsymbol{\beta}) = \frac{1}{2m}\left(\sum_{i=1}^{m}\left(y^{(i)} - \hat{y}(\mathbf{x})^{(i)}\right)^2 + \lambda \sum_{i=1}^{n} \boldsymbol{\beta}^{\,2}\right) \tag{IV.31}$$

with m the size of the training set, n the number of parameters and λ the regularization or shrinkage parameter. The latter parameter causes the coefficients to shrink as much as possible and is calculated in practice by using nested cross validation. From several case studies is found that a λ between 0.01 and 0.3 is appropriate.

The purpose of the cost function is to find a balance between the size of the error and the complexity of the model. In other words, a trade-off is found between bias and variance in the model prediction. The concept is illustrated in Figure IV.13. The method is applied for both IMLS and PCE methods.

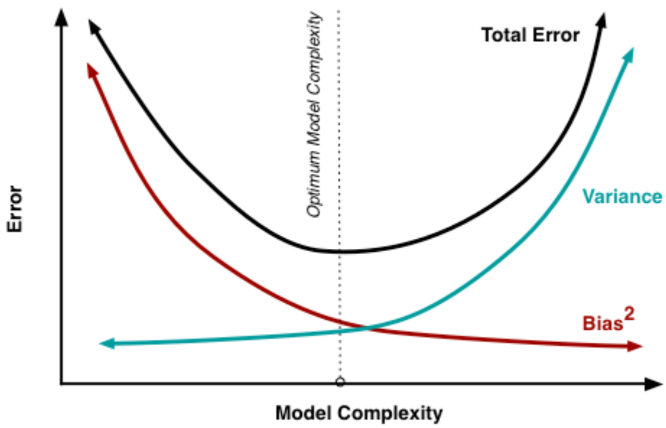

Figure IV.13: Bias and variance contributing to total error.

IV.4.7.3.1 Implementation of regularization in IMLS

In order to implement the method of regularization in the IMLS method the expression for eq. 23 is extended as follows:

$$\widehat{\boldsymbol{\beta}}(\boldsymbol{x}) = (\mathbf{H}^{\mathbf{T}}\mathbf{W}(\mathbf{x})\,\mathbf{H} + \lambda\,\mathbf{I}\,)^{-1}\,\mathbf{H}^{\mathbf{T}}\mathbf{W}(\mathbf{x})\,\boldsymbol{y} \tag{IV.32}$$

Important to mention is that the variables should be rescaled to the standard normal space in order to prevent bias for larger scale variables. Otherwise λ is not a fair predictor for smaller scale variables.

IV.4.7.3.1.1 Implementation of regularization in PCE

In order to implement the method of regularization in the PCE method the expression for eq. 19 is extended is as follows:

$$\hat{\boldsymbol{\beta}}=\left(\mathbf{H}^{\mathrm{T}}\,\mathbf{H}+\ \lambda\,\mathbf{I}\right)^{-1}\mathbf{H}^{\mathrm{T}}\,\mathbf{y} \tag{IV.33}$$

IV.4.7.4 Convergence analysis

The aim of the convergence analysis is to obtain an independent result with respect to the number of samples considered. Therefore, in step 5 and 10, n additional samples are generated and a response surface is determined for each additional sample. Next, for each additional sample, the convergence rate of the response surfaces is determined by calculating the absolute value of the relative error [44]:

$$\overline{e}_{conv,n} = \left|\frac{y_n - y_{n-1}}{y_n}\right| \leq 5\ \% \tag{IV.34}$$

with $\boldsymbol{y}_n$ the result when including the additional sample and $\boldsymbol{y}_{n-1}$ is the result without the additional convergence sample. The result is considered converged when the error of the last sample is smaller than 5 % [45], [44]. If the results are not converged, additional samples are generated until the criteria are met. Both LHS and Sobol sampling can be applied to increase the sampling pool while maintaining the original samples. An example is given in Figure IV.14 where additional samples are evaluated and added, with Sobol sampling, until the performance criteria are met for n = 3 runs in a row.

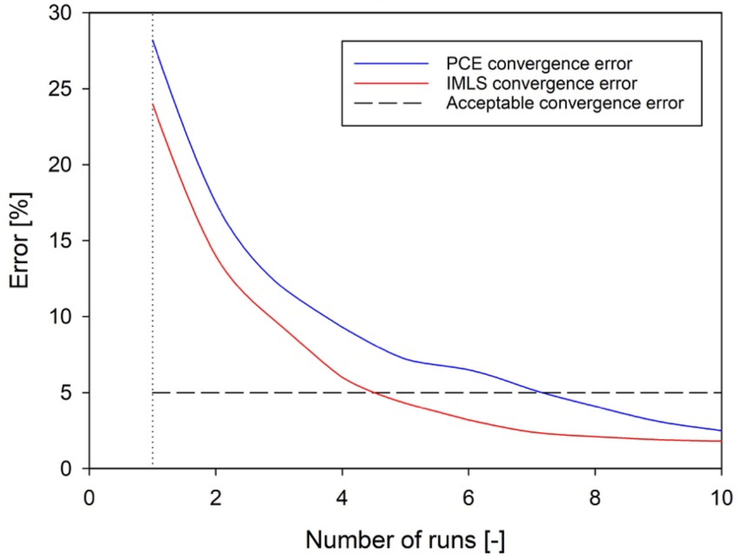

Figure IV.14: Example of a convergence analysis for the PCE and IMLS method.

IV.4.8 Step 5.8: Generation of the DoE for probabilistic analysis of smoke spread RSM

In step 8, the DoE is generated for the probabilistic analysis of the smoke spread RSM. In order to give a proper representation of the entire domain, a probabilistic sampling method is defined which covers the chosen domain. Therefore, two aspects have to be clarified: the preferred sampling technique and the domain to be analysed.

IV.4.8.1 Sampling techniques

Two sampling methods are discussed. The Latin Hypercube Sampling (LHS) and the Sobol Sampling technique.

IV.4.8.1.1 Latin Hypercube Sampling

The LHS method [46], [47], [48] is a statistical method for generating a near-random sample of parameter values from a multidimensional distribution. A Latin square is a nxn $s$quare filled with n different samples in such a way that each sample appears once in each row and column. The LHS method for two variables and 10 samples method is illustrated in Figure IV.15. LHS is based on the Latin square design, which has a single sample in each row and column.

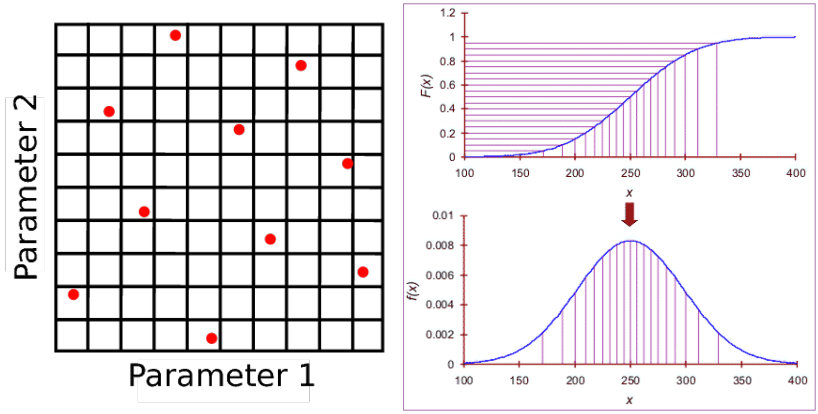

Figure IV.15: Multidimensional Latin Hypercube Sampling [47].

Additional techniques are implemented to optimize the sampling pattern of LHS. By means of maximizing the minimum distance between sample points, an improved representative sampling distributions can be obtained [49]. Secondly, in [38] and [50], research is conducted to enrich existing LHS sets with new samples while maintaining an overall LHS sampling set. The advantage of the method is that the original sampling pool can be reused and no support samples are lost.

IV.4.8.1.2 Sobol Sampling

The Sobol Sampling technique is based on the Sobol sequences which are quasi-random low-discrepancy sequences. The main difference between random sampling techniques (e.g. random sampling, LHS, etc.) is that the sample values are chosen under consideration of the previously sampled points thus avoiding the occurrence of clusters and gaps. In Figure IV.16, the difference is shown between classical random sampling, LHS and a Sobol sampling technique. The figure demonstrates that the Sobol sampling method represents a better distribution pattern [48], [51]. Further, the method shows the advantage of generating additional samples within the existing sample pool. In case of convergence analysis, it is of importance to perform a larger sampling sequence without the need to execute a new sampling scheme.

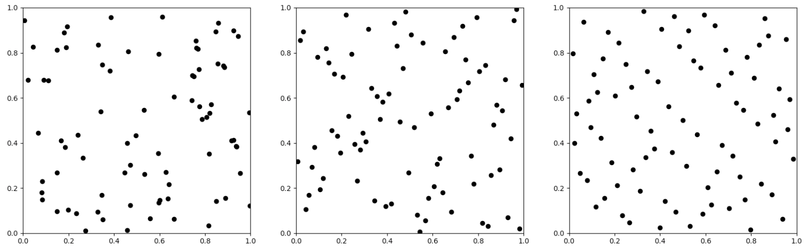

Figure IV.16: Sampling patters with n = 80 for a) random sampling, b) Latin Hypercube sampling and c) Sobol sampling.

IV.4.8.2 Investigated domain

The purpose of this section is to determine the domain to be investigated. In previous case studies [52] it is observed that, for an important part of building types, analysis of a large part of the input domain does not have a significant impact on the results. This can be due to the physical restrictions of the variables such as small fire size or a low fire growth. These parameters result in negligible consequences and have no added value to the output. Consequently, the analysis of such parts is not efficient and considered irrelevant. Therefore, it is suggested to reduce the domain to the part of the domain which has a significant impact on the final results.

For more complex cases a conservative approach can be followed that stepwise narrows the domain. Initially, broad ranges should be applied in order to prevent underestimation of the failure domain. Next, the domain can systematically be narrowed until a significant impact is observed on the output.

For common buildings types and their boundary conditions, a reduction of the domain can be done based on past experience. The boundaries are set and the domain is narrowed (red part Figure IV.17). In order to represent reality, the occurrence probability of samples in the neglected domain should be considered. This is accomplished by incorporating a weight factor to the probability of occurrence. The following weight factor for smoke spread or WF_{SS} is applied:

$$WF_{SS} = (1 - F_X(x)_\alpha) * (1 - F_X(x)_{HRRPUA}) * (1 - F_X(x)_A) \tag{IV.35}$$

$$WF_{SS} = (1 - 0.88) * (1 - 0.0816) * (1 - 0.6) = 0.044 \tag{IV.36}$$

where $F_X(x)_\alpha$, $F_X(x)_{HRRPUA}$ and $F_X(x)_A$ are the cumulative distribution values for the fire growth coefficient, HRRPUA and the maximum fire area. The values are taken from Table IV.4. The weight factor will be multiplied by the final failure probabilities to take the entire domain of the distributions into account.

The LHS (Figure IV.17) or Sobol method is applied between the suggested limits in Table IV.4. An output $n \; x \; m$ matrix is generated for n samples and m variables. An example is given in the figure below for $n \; = \; 10 \; and \; m = 1$ between the given limits. It is suggested to sample a sufficient number of samples to reach convergence of the failure probability.

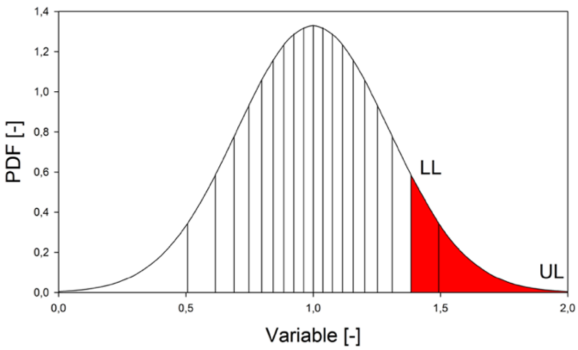

Figure IV.17: LHS between upper and lower limit.

IV.4.9 Step 5.9: Calculation of the fire and smoke spread responses based on RSM

In step 9, the output results are obtained by addressing the RSM for the chosen input combinations. For every sample defined in step 8, the outcome is predicted by the RSM generated in step 7. Extrapolation is suggested not to be applied to avoid large errors in the model.

Once the smoke spread results are obtained, the procedure continues to the analysis of the evacuation part of the method. In order to do this, the procedure loops back to step 5 and the output from the smoke spread is provided as input for the evacuation analysis.

IV.4.10 Step 5.5: Generation of the support points for EVAC RSM

The main input parameter from the smoke spread model that has a significant impact on the evacuation modelling is visibility. For every fire scenario, each evacuation model will have a different outcome. However, the combination of the sampled smoke spread scenarios in step 8 and the chosen evacuation scenarios gives a large number of evacuation scenarios to be analysed. Therefore, the smoke spread and evacuation modelling is partially decoupled. The effect of visibility is considered by analysing three representative smoke spread scenarios for each evacuation scenarios instead. The first scenario is considered the best-case scenario when only one person is affected by a low smoke density and has a reduced walking speed. All the other occupants are not affected and therefore the impact of smoke on walking speed is negligible. This scenario is considered an evacuation scenario in smoke free conditions. All the evacuation scenario providing less severe smoke conditions give the same results in terms of movement dynamics. The second scenario is the worst-case scenario when the visibility conditions are the most negative. This is considered for the smoke spread scenarios with the highest smoke generation. The third scenario is chosen between the two former scenarios based on the average between the input values.

Next, the support points for deterministic evacuation analysis are chosen. In order to reduce the total computational time, only the primary input variables that affect the main physics in terms of evacuation dynamics are implemented (Figure IV.7). The variables occupant density (OD), affiliation (exit familiarity), pre-evacuation time, shoulder width and movement speed are considered significant parameters affecting the output. An additional important parameter can be detection sensitivity or the activation of the alarm in case manual intervention is necessary. In Table IV.1, the distributions for these variables are listed. The secondary parameters considered are the respiratory minute volume (VE-rate) and susceptibility of people to smoke. These parameters are analysed in the consequence model.

The support samples are generated for evaluating the deterministic analysis. To determine these support points, several aspects have to be considered. The first aspect is to choose a representative domain for every variable. In analogy to step 5 in the smoke spread sub-model, only a specific part of the domain is chosen in which fatalities are expected. No fatalities are expected to occur in particular domains because the population density is too small or the response is too fast. In the table below, the suggested ranges are shown. The choice of the ranges for every variable is based on a preliminary iteration in which first a broad parameter range was chosen and subsequently narrowed down. The ranges are chosen for higher occupant densities and are broader for the variable affiliation because fatalities can be expected even for optimal exit choice.

Table IV.8: Upper and lower variable limit. (LL = Lower Limit, IV1/2 = Intermediate Value 1/2, UL = Upper Limit, CDF(LL) = Cumulative Density Function Lower Limit, CDF(UL) = CDF Upper Limit).

Variable	LL	IV1	IV2	UL	unit	CDF(LL)[1]	CDF(UL)[1]
Occupant density	380	550	750	945	[pp]	0.02	0.97
Affiliation	0.2	0.5	0.65	0.8	[-]	0.09	0.8

[1]CDF evaluated in the lower limit (LL) and upper limit (UL).

Secondly, the DoE is chosen based on full factorial design. For every variable, four values are chosen. This gives a total of 4^n or 32 simulations. The chosen data for 4^n input combinations are presented in the table above. The lower values are taken based on the limits discussed in Table IV.8 because interpolation will be performed. The upper limit is adopted based on physical boundaries (maximum fire area and maximum fire growth). The middle values are based on the linear or logarithmic average between the lower and higher limit.

IV.4.11 Step 5.6: Evaluation of the support samples with deterministic analysis

In step 6, the training set is evaluated by means of the deterministic evacuation sub-model in analogy with the theory explained in [2]. Several evacuation models are investigated of which Pathfinder [53] and JuPedSim [54] are implemented in the framework. Pathfinder is suggested for practical applications because of the high efficiency in practical use. JuPedSim is implemented for flexibility and research purpose. This model can be adapted because it is open source. However, it needs more engineering time for the set-up of the building geometry. The two evacuation sub-models consist of a combination of different models in which occupant movement, human behaviour and interaction with the environment is considered. The output provides time-depend 3D locations data for every occupant.

In the next steps the RSM should be applied. However, when a similar procedure would be applied for the response surface modelling like in the smoke spread analysis, the model will be interpolated between occupant locations. This would not give the desired result because, depending on the scenario, the occupant will evacuate to different exits. This means that the interpolated result will give a location in between the exits which is not realistic and will couple toxic concentrations data with occupant locations which do not match with the real location of the occupant for either scenario. Therefore, the focus of the interpolation is shifted from occupant locations to the dosage obtained for each occupant at a specific exit. Each exit will give way for evacuation of a group of occupants. When analysing the toxic and temperature dosages for all the occupants at a specific exit it can be observed that the dosages and corresponding calculated FID values increase in a continuous form. An example is given in Figure IV.18 where 235 occupants evacuate to a specific exit where the FID increases from almost 0 to 1.5. Therefore, it is decided to first analyse the dosages and corresponding FID values and then continue to the response surface modelling of the evacuation parameters. In order to perform this strategy, once the results from the evacuation RSM are obtained, the procedure loops to step 8 (Figure IV.3). The output obtained from step 5 is used as input for the consequence analysis sub-model after linking the locations of the occupants to their corresponding dosages.

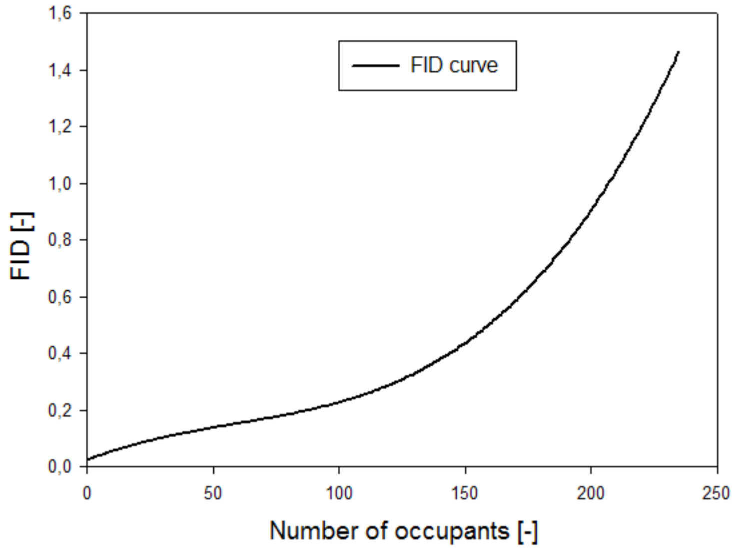

Figure IV.18: Example of continuous increase in FID values for a group of people at an exit door.

IV.4.12 Intermediate step: linking location-based concentration data with agents tracking

After the analysis of the responses, the geometrical concentration data is coupled with the location data of the occupants. For every occupant the doses are calculated for every time step of 60 s. In case insufficient data is obtained from the smoke spread model (evacuation time longer than smoke spread simulation), the data is linearly extrapolated over time.

IV.4.13 Step 5.8: Generation of the DoE for probabilistic consequence analysis

A DoE is generated for the probabilistic consequence analysis. The secondary variables not considered in the previous sub-models are implemented in the consequence sub-model. This is done to reduce the variability of the more computational affording models by only taking parameters into account that have an important impact on the smoke spread (smoke spread model) and evacuation dynamics (evacuation model). The secondary parameters are implemented in the consequence model because the model is an analytical model that efficiently evaluates the deterministic scenarios. The effect of the variables CO-yield (γ_{CO}), HCN-Yield (γ_{HCN}), Heat of Combustion (HoC), Susceptibility (D), Respiratory minute volume (V-rate) is simulated. The same sampling technique is chosen for this part as discussed in step 8 of the smoke spread model.

IV.4.14 Step 5.9: Calculation of the consequences for life safety

Next, the consequences for life safety are determined in step 9. The input from the previous two steps is combined into analytical formulations. The effect is quantified through combining toxicity and heat (convective and radiation) effects into the Fraction Incapacitation Dose (FID) [1,55]. This value determines whether a person will manage to escape or get incapacitated. According to the definition of the FID, it is considered that a person who reaches an FID equal to unity or higher will not be able to survive the fire. The FID is calculated by means of the consequence model in analogy with [1] and as discussed in Chapter III.

For every sample combination obtained from step 8, a set of FID values is obtained equal to the number of occupants in the building for the corresponding scenario. Each set is subdivided into a number of subsets equal to the number of exits in the analysed building. The FID values of every person is then appointed to the corresponding used exit door for the corresponding occupant. An example of an ascending order of FID values is given in Figure IV.19 (black line).

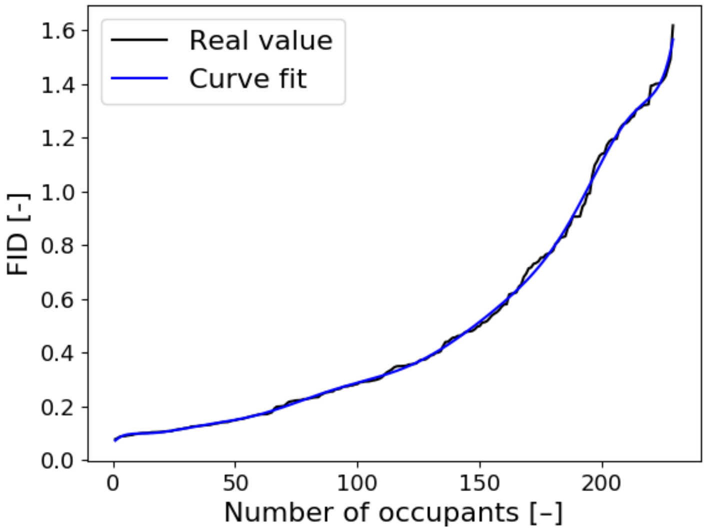

Figure IV.19: FID values for a set of occupants evacuating through an exit.

Next, a polynomial curve with max degree of 10 is fitted to the FID values for each exit and sample scenario. In this way, all the values do not have to be kept in storage and interpolation can be done between multiple scenarios. The purpose of the polynomial curve fit is to facilitate a proper interpolation between different scenarios.

IV.4.15 Step 5.7: Generation of the response surface evacuation model

Once the curve fitting is performed, the procedure loops back to step 5.7 and the RSM for evacuation is developed. The RSM is applied in two phases for the evacuation data. Firstly, the RSM is conducted for determining the number of people evacuating towards each exit. Secondly, the RSM is applied for implementation of the other variables. The reason for the distinction is that first the number of people need to be fixed in order to interpolated between the FID curves.

For the first RSM evacuation application, a different approach is applied than the method applied for the smoke spread interpolation. This is due to the fact that the variables occupant density and affiliation are translated to the variables occupant density and occupant exit load. In order to determine the latter, several steps are taken. First the two variables occupant density and affiliation are translated to normal distributed values. Then, the estimated mean and variance are determined for the joint density function [56]:

$$E = \mu_x \mu_y \tag{IV.37}$$

$$Va = \mu_x^2 \sigma_y^2 + \mu_y^2 \sigma_x^2 \tag{IV.38}$$

This is done for both type of exits (main and back) so that for every original sample set two new sample sets exist. Depending on the chosen exit, the main or back exit density should be applied. More practically, one sample set with a fixed value for occupant density and affiliation will be translated into two sets. Sample set one will be the combination of the parameter occupant density together with exit load for the front exit. Sample set two will be the combination of the parameter occupant density together with exit load for the back exit.

Next, for every exit in every support sample scenario, the FID curves are rescaled to the number of occupants estimated before. An example for a set of six support points is given in Figure IV.20. Originally, these curves were fitted for different occupant sizes. However, interpolation between them would not be possible. Therefore, a scaling algorithm is implemented to rescale every curve to the desired number of occupants.

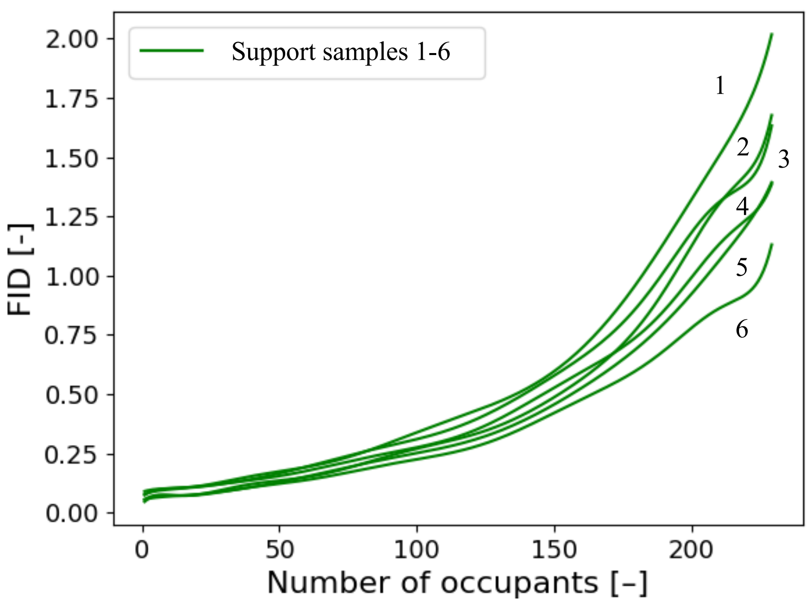

Figure IV.20: Rescaled FID curves for a support sample of a particular exit and scenario.

After rescaling the FID curves, the second RSM evacuation application interpolates between the rescaled FID curves for variables such as pre-movement time, detection time, etc.

IV.4.16 Step 5.8: Generation of the DoE for probabilistic evacuation analysis

In step 8, the DoE is generated for probabilistic evacuation analysis. Only a part of the domain is analysed for the same reason as discussed earlier. Samples with low occupant densities will not give a significant added valued to the results. Therefore, it is chosen to narrow the domain and give a weight to the results.

In order to take into account the probability of occurrence, the following weight factor for evacuation or WF_{Evac} is applied from Table IV.8:

$$WF_{Evac} = \left(1 - EVAC_{LL\_OD}\right) * \left(1 - EVAC_{LL\_Aff}\right) \tag{IV.39}$$

$$WF_{Evac} = (1 - 0.02) * (1 - 0.09) = 0.941192 \tag{IV.40}$$

where $F_X(x)_{OD}$ and $F_X(x)_{Aff}$ are the cumulative distribution values for the occupant density and affiliation towards the main exit. The weight factor will be multiplied with the final failure probabilities to take the entire domain of the distributions into account. The weight factor is multiplied with the failure probability after applying the reliability analysis.

IV.4.17 Step 5.9: Calculation of the evacuation data based on RSM

Once the input combinations are chosen, the samples are evaluated by means of the response surface model for evacuation discussed in section 4.15. In Figure IV.21 an example is given of the estimation of an FID curve by RSM. The red line is the estimated curve and the blue line is the real value. Two support samples are presented in green to illustrated that the new samples are interpolated between the support samples.

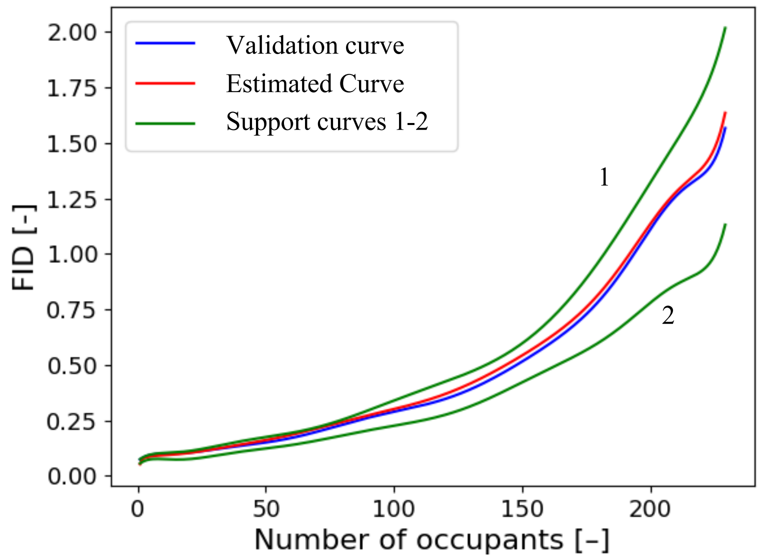

Figure IV.21: Estimated FID curves for a new sample for a particular exit and scenario.

IV.4.18 Step 5.10: The reliability analysis

In step 10, the failure probability in relation to the specific scenario is calculated. The combined result of the analysis will be expressed in an FID value. Therefore, the following limit state is applied:

$$\mathrm{g}(\mathbf{X}) = \mathbf{FID} - \mathbf{1} = 0 \qquad \text{(IV.41)}$$

In case a sufficient number of occupants obtain an FID ≥ 1, a direct failure can be calculated in which the number of subscenarios (determined by Sobol Sampling) containing one or more occupants with an FID ≥ 1 or $Subscenario_{FID\geq 1}$ is divided by the total number of subscenarios or $Subscenario$ considered in the specific event tree scenario:

$$P_{f,scenario} = \frac{\#Subscenario_{FID\geq 1}}{\#\,Subscenario}\ WF_{SS}\, WF_{Evac} \qquad \text{(IV.42)}$$

In case an insufficient number of occupants obtain an FID ≥ 1, an indirect failure probability needs to be calculated because the failure probability or risk level cannot be zero. An approximate calculation is performed in which the most suitable distribution is fitted to the FID results. Next, the probability of FID ≥ 1 for the fitted distribution is calculated. In Figure IV.22, a conceptual fitted normal distribution is presented with red marked the zone in which FID > 1.

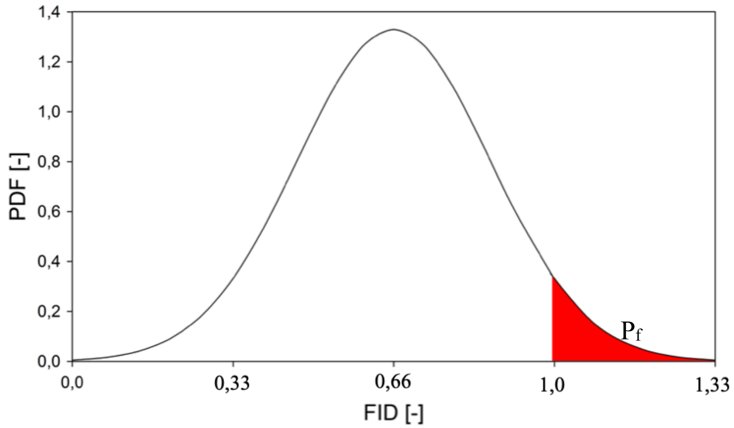

Figure IV.22: Failure probability of the FID distribution.

The model fits multiple possible distribution types with the corresponding data by means of the Maximum Likelihood Estimation [57]. For each of the considered distributions the residual sum of squared errors (SSE) is calculated. The SSE is a measure of the discrepancy between the obtained data and the fitted distribution. The following formula is suggested:

$$SSE = \sum_{i=1}^{n} (y_i - f(x_i))^2 \tag{IV.43}$$

The fitted distribution with the lowest SSE value is considered the best fit. The SSE method is considered a good method for estimating the goodness of fit for the entire distribution. However, the focus of the curve fitting should be put on the tail of the distribution. Because the failure probability will be determined based on the area in that tail with FED > 1. Therefore, the Anderson-Darling (AD) test is suggested. The AD test [58] is used to test if a sample of data came from a population with a specific distribution. It is a modification of the Kolmogorov-Smirnov (K-S) test [59] with more focus on the tails of the distribution.

$$A^2 = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)[\ln\,(F(X_i) + \ln\big(1 - F(X_{n-i+1})\big)] \tag{IV.44}$$

where n is the number of samples and $F(X_i)$ is the considered distribution type. The lowest value for A^2 gives an indication of the applicability the corresponding fit. When the most optimal distribution is fitted, the probability for obtaining an FID > 1 for the specific scenario is determined as:

$$P_{f,scenario} = WF_{SS}\, WF_{Evac} \int_{FID=1}^{FID=\infty} f(FID)d(FID) \qquad \text{(IV.45)}$$

In analogy to previous steps, a convergence analysis is performed to determine the accuracy of the results. The calculation procedure from step 4-10 is repeated for every event tree scenario.

IV.4.19 Step 5.11: Calculation of the general, individual and societal risk

Finally, in step 11, the general risk, individual risk and societal is calculated. The risk is calculated by taking the sum of the conditional frequencies obtained from the event tree analysis combined with the failure probabilities for every event tree scenario:

$$R = \sum_{i=1}^{n} P_{scen,i} * \#fatalities_{scen,i} \qquad \text{(IV.46)}$$

where n_{scen} are the number of scenarios. The branch probabilities are determined by multiplying the corresponding frequencies of the pathway factors (e.g. ventilation conditions, safety system state, etc.) which are determined by the fault tree analysis. The societal risk is calculated for all the different scenarios and represented by means of a FN curve. The resulting values of fatalities (N) obtained for every scenario are plotted against the cumulative frequency (F) the log/log diagram. In order to give a clearer explanation regarding the PRA model. A worked out example for one event tree scenario is provided in Appendix E.

IV.5 Conclusions

In this part of the thesis, the probabilistic framework is developed for quantifying the life safety risk in case of fire. The proposed method can objectively quantify fire safety designs by taking the uncertainty of design parameters and the effectiveness of safety systems into account. The parameters and representative design fire scenarios can be analysed by the proposed deterministic framework. The model can take the effect of efficacy and reliability of different safety systems into account.

The implementation of the response surface model in combination with design of experiments techniques allows for a significant reduction of the computational time. The challenge of data allocation and communication when dealing with large data files is tackled. Several techniques such as compression and averaging are used to reduce the data files for storage and communication for input/output handling.

The results can be quantified reliability-based in terms of a failure probability or risk-based in terms of an individual and a societal risk.

Overall, the framework provides a guideline for the fire safety engineer to perform a probabilistic analysis to determine the safety level of various types of fire safety designs for different types of buildings.

Based on these conclusions, the methodology meets the predefined objectives. The framework will be validated in Chapter V and illustrated and discussed by means of case studies in Chapter VI.

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CHAPTER V

Simplified model

V.1 Introduction to the simplified method

In this chapter, a simplified version of the probabilistic methodology is developed. The objective of the simplified method is to provide a first indication of the fire safety level by implementing less accurate but relative fast models. The simplified model will provide a rough estimate of the safety level to highlight the main strengths and weaknesses of the building and occupant configuration. The simplified method is presented in this chapter, it is validated in chapter VI and tested on case studies in chapter VII.

V.2 Problem description and objectives

One of the main challenges of the developed probabilistic model in chapter IV is to find a trade-off between the number of representative scenarios and the available time for the analysis. In this way, the necessary computational power to perform the simulations is reduced. However, even in optimized form, the computational affordance required to analyse complex building designs is still significant. Additionally, it might not always be necessary to perform an in-depth analysis. Therefore, a simplified method that performs a pre-analysis of fire safety building designs needs be developed to give a rough estimation of the safety level and distinguish whether a design is sufficiently safe or needs further analysis.

The objective is to develop a simplified method that gives a first estimate of the fire safety level of the considered building in a relatively short time span, in the order of one day of work. The goal is to reduce the computational time of the framework by implementing simplified smoke spread and evacuation submodels. The general framework is identical to the one discussed in chapter IV; only the smoke spread and evacuation model are substituted by simplified models. This is done because these models require the most engineering and computational time. Both models are discussed in the subsequent chapters.

V.3 Smoke spread zone model

There are two options to simplify the implemented field model for smoke spread, namely analytical mass loss models or numerical zone models. Typically, the analytical models are faster and used to give a first estimation of the smoke generation. The numerical models take more time to apply and are typically used for time dependent analysis or to obtain more accurate results. For this application, numerical zone modelling is chosen because it takes the basic principles of thermodynamics into account, and it requires computational time in the order of minutes. The compartment is subdivided into only two volumes, the upper hot gas layer and the lower ambient air layer.

Both layers are assumed to have homogeneous temperatures and mass concentrations, which limits the model applicability to simple compartment geometries [1].

Based on the assumption of two volumes, the change in the zone temperatures and the layer height (hL) can be computed numerically by time-stepwise solutions of the equations for conservation of mass (m) and conservation of energy (E) for each zone, as schematically depicted in Figure V.1. State-of-the art zone models, such as CFast, B-RISK, or MRFC, are capable of computing multiple compartments and contain simple combustion models.

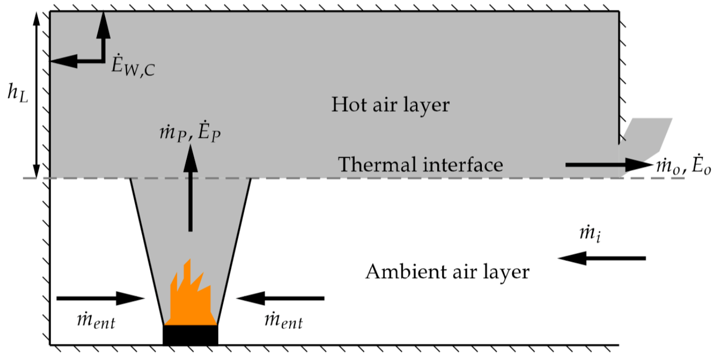

Figure V.1: Schematic representation of the assumptions used in zone models. Taken from [2].

For the simplified model, the zone model B-RISK is chosen. The model incorporates the same basic correlations as C-FAST, but has additional submodels for glass failure and fire growth over linings. The model is under continuous development and has a probabilistic feature. In Figure V.2, an application to B-RISK for an atrium building is provided.

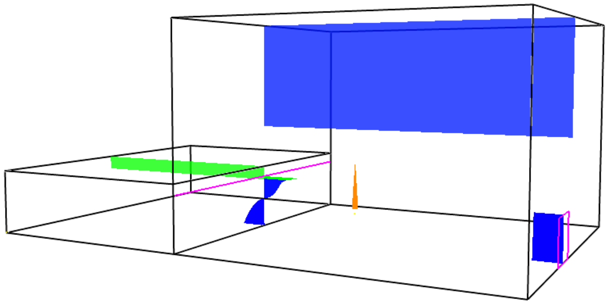

Figure V.2: Application of B-RISK for atriums.

Similarly to the main framework, the input parameters are provided to the model and the results are obtained in the form of concentrations. Contrary to the CFD output, the location dependent toxicity and temperature data are limited to one data value per room for every output type. These output data values are then linked to the other models (evacuation and consequence model). For further technical elaboration, reference is made to the technical manual [3].

V.4 Evacuation network model

There are two possibilities to simplifying the continuous evacuation model, namely analytical and numerical network models. Although both are hydraulic models, the latter provides more accurate results for complicated building configurations. Therefore, the focus is put on numerical modelling. More in particular, the focus is put on coarse network models. When using a coarse network, the network does not explicitly represent all the occupiable space. A coarse network divides the floor plan into rooms, corridors, stair sections, and so on, and the occupants move from one structural component to another (e.g., room to corridor). The best way to segregate and hence to represent the structure within a coarse network model is not always clear. The segmentations will have a direct impact on the obtained results, since they directly influence the movement of the occupants and the routes that may be adopted. In a coarse network, the occupants will move from one segmented area to another through links. It is up to the user to provide segmented areas that are representative of how occupants might move throughout the space.

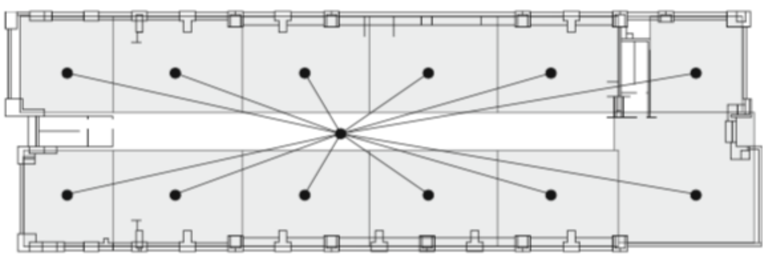

Figure V.3: Example of a segmented office floor plan. Taken from [4].

Several network models have been analysed, of which EvacuatioNZ, WAYOUT, EVACNET4 and EXIT89 are the most known and available for analysis. From these tools, EvacuatioNZ is considered the most sophisticated one [5,6]. The model allows for incorporation of probabilistic Monte Carlo approaches and can take reduced walking speed into account. However, this method (and others) has several disadvantages with respect to implementation in the framework. First, the I/O treatment is very rigid for serial analysis.

Second, the effect of smoke on walking speed cannot be directly taken into account. Third, it is not possible to obtain agent-based locations. This is a major disadvantage of EvacuatioNZ and other network models. Therefore, an in-house model is developed, inspired on EvacuatioNZ, that is able to easily track occupants and take the effect of smoke on walking speed into account [7,8,9]. The occupants in the model can be appointed to familiar exits. The model is developed in python and described in the subsequent sections.

V.4.1 Input parameters

The model can take several variables into account. The mean input parameters are occupant density, unimpeded walking speed, response time, familiarity, smoke density, occupant size, exit behaviour, boundary layer, etc. These parameters can be identified by the user through GUI. The default values are presented in the table below.

Table V.1: Default values and calculation procedure for the network model.

Parameter	Default	Units	Ref.
Maximum walking speed	1.20	m/s	[10]
Pre-evacuation time	30	s	[11]
Specific flow rate	1.33	pers/s/m	[10]
Exit behaviour	Min distance	-	[6]
Starting distance	Random distance	-	[6]
Body size	0.45/5	[m]	[10]

Furthermore, building properties and calculation parameters such as stair dimensions, door width, path width and length, time step can be determined by the user.

V.4.2 Submodel framework

The network model contains several submodels that assist in the global dynamics of the evacuation process. The main submodels are the building network, the travel, the door and stair flow, the routing, random start, pre-evacuation and agent submodel.

V.4.2.1 Building geometry

V.4.2.1.1 Nodes

The model consists of five different types of nodes: the source, travel, door, stair and safe node. The source node provides the start point for occupants throughout the building. The node can only exist in a room type. A specific occupant density can be assigned to each of these node types. The node is red in the model. The second node is the travel node. The node can only be used to travel from one node to the other and can exist in a room type. This node is black in the model. The door node provides passage through doors and simulates door flows. They can only exist at door locations. The stair node provides passage through stairs and forms the link between levels. The safe node is a node in which the occupants are considered safe from the effects of fire. One or more safe nodes can exist in and outside the building. The goal of the occupant is to reach a safe node before untenable conditions occur. In a scenario with more than one safe node, the occupants can choose the safe nodes that they will travel to, according to the exit behaviour specified by the user. An example of a network structure of a floor level is given in Figure V.4.

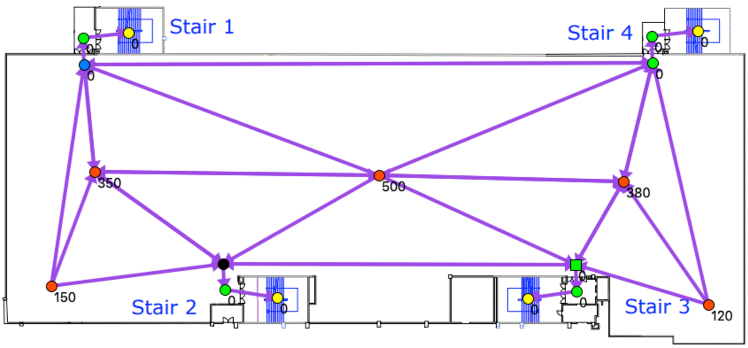

Figure V.4: Example of network structure with nodes and links.

V.4.2.1.2 Links

The links provide travel opportunities between different nodes (Figure V.4). The links are physical tubes that can hold people. The links represent paths between nodes in rooms and evacuation routes in hallways between doors.

V.4.2.2 Agent

The objective of the occupant pre-evacuation sub-model is to determine the occupant behaviour during evacuation. The main purpose is to translate this occupant behaviour into (in)actions taken during egress which have influence on the evacuation dynamics and the consequence for the occupants.

The general model structure is based on the Evacuation Decision Model developed bij Reneke [12]. The model considers the fact that occupants can have three different states: the Normal State (NS), the Investigating State (IS) and the Evacuating State (ES). The agent can shift between states depending on the perceived risk. The allowed passages are those from NS to IS, from NS to ES and from IS to ES (Figure V.5). The occupant can perform actions depending on its corresponding state.

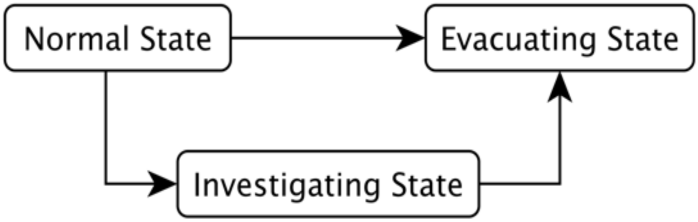

Figure V.5: Proposed behavioural states [12].

For the purpose of the simplified model, human behaviour is implicitly modelled through implementing pre-movement response times by means of a pre-defined distribution.

V.4.2.3 Movement

The walking speed of occupants has been extensively studied in the past. Gwynne et al. provided a review of walking speeds in different models [10]. For the development of the submodel, a literature study has been performed in the Appendix F. Apart from the nominal walking speed, three factors that impact traveling speed are implemented. The first factor takes into account the characteristics of the person. The second factor is the effect of occupant density. This factor takes into account the type of path (evacuation route, connection, stair, ramp, etc.) and its conditions (rough, obstacles, etc.). The third factor incorporates the effect of smoke on occupant movement.

V.4.2.3.1 Effect of occupant characteristics

The effect of occupant age and body weight is implemented in the submodel. The first factor (age) is directly related to a deterioration in physical, mental and neurological functions, which has a negative impact on individual movement, e.g., speed and stride length [13]. Recent studies [14] have quantified the impact of population age on crowd speed (Figure V.6). Three population types were included in the study: adults, children and elderly. The figure shows reduced speeds for elderly and children.

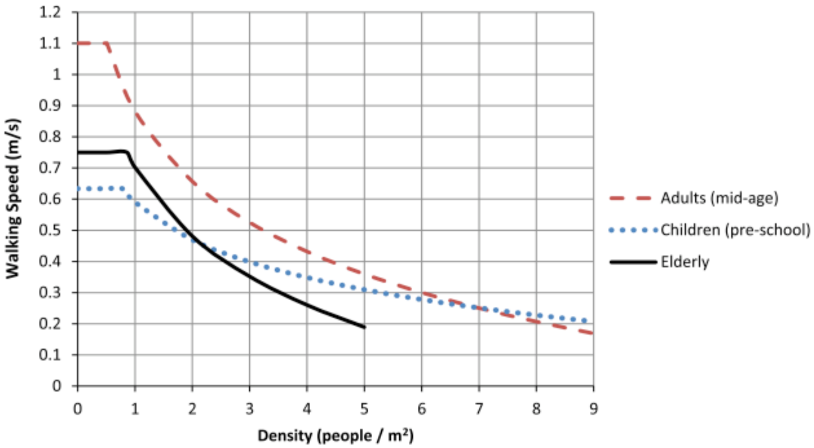

Figure V.6: Walking speed vs density for different age demographics. Taken from [14].

The effect of body weight on walking speed has been proven to have significant impact on walking speed dynamics [14]. The actual impact of the increasing proportion of obese people has yet to be properly considered with respect to crowd movement. However, from initial research [10,15], it is estimated that increased body size can reduce the movement speed and flow rate up to 25%.

V.4.2.3.2 Effect of occupant density on horizontal and vertical walking speed

Extensive research has been conducted regarding the effect of occupant density on walking speed [10]. Experiments show an inverse relationship between the two parameters. The waking speed decreases as the occupant density increases (Figure V.7). An important limitation of this relationship is the exclusion of body size. The real density might vary depending on the body size (small children vs. obese adults). A possible adaption could be to represent the correlation in terms of occupant coverage per square meter.

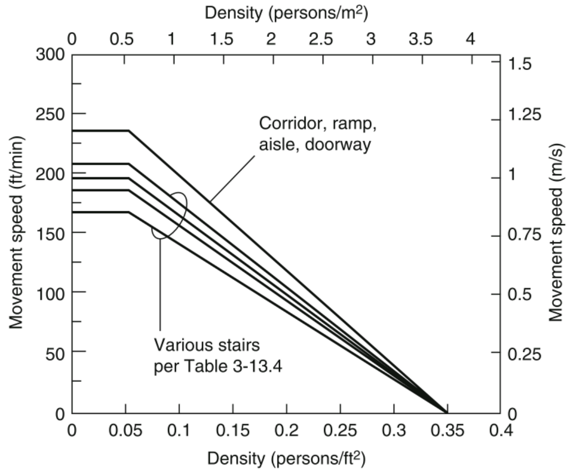

Figure V.7: Relation between walking speed and density through doors, on stairs and slopes. Taken from [10].

Movement on slopes, stairs and escalators presents a different challenge than horizontal movement, given the extra degree of freedom available in the movement, the constraints imposed by the stair design, and the additional effort required to traverse the stair component. Extensive research was done [16,17], giving a wide range of results depending on density and floor levels. A mean movement speed of 0.48 m/s ± 0.16 m/s was obtained [17]. In Figure V.7, several correlations for walking speeds on stairs are suggested.

V.4.2.3.3 Effect of smoke on walking speed

It is considered to have occupants which walk through low-irritant smoke conditions. These occupants are either sufficiently familiar with the environment, or they are guided towards the exits. Based on multiple research studies [7,8,9], it is suggested to implement a correlation interpretation of the data set in which the variable unobstructed and minimum walking speed are applied (Figure V.8). The general formulation of the calculation of the walking speed v_i^s reads:

$$v_i^s = max\left\{v_{i,min}(i), v_i^0 c(K_S)\right\} \tag{V.1}$$

The walking speed in smoke v_i^s of occupant i is a fraction $v_i^0(k_s)$ $(i.e. 0 < c \leq 1)$ of the walking speed in clear condition is v_i^0 and depends on the extinction coefficient Ks. In dense smoke there is a considerable scattering of speeds, i.e., $v_{i,min}$ depends on the characteristics of the occupant, i.e., $v_{i,min} = v_{i,min}(i)$. n smoke/speed curves are produced in accordance with the characteristics of n individuals. The minimum speed depends on the characteristics of the individuals. Occupants, even in dense smoke, keep walking with n different minimum speeds, depending on their individual skills. A minimum threshold is applied for each individual. A fictive example is given below.

Figure V.8: Schematic representation of the fractional/variable minimum speed interpretation.

In order to take the above discussed probabilistic method into account, the method is divided into three different states for non-irritant smoke conditions [18].

Visibility ≥ 3 m: The walking speed in a smoke free environment v_{Sf} is represented by a randomized value from a normal distribution curve with an average value of 1.35 m/s and a standard deviation of 0.25 m/s [19], with minimum and maximum limits of 0.85 and 1.85 m/s respectively.

0.5 m < visibility < 3 m: In case of lower visibilities, the walking speed is calculated according to the following formula:

$$v = min(v_{Sf}; max(v_{min}; \frac{v_{Sf} - v_S}{3 - 0.5}(V - 0.5) + v_S)) \qquad \text{(V.2)}$$

were V is the visibility in meter. A minimum for v_{min} of 0.2 m/s is applied. The above equation also represents the randomness of the individual occupant characteristics.

Visibility ≤ 0.5 m: In case of very dense smoke, the walking speed in smoke v_S is represented by a randomized value from a uniform distribution with minimum and maximum limits based on the 95% confidence level of the forecast range [9]. The minimum value is at least 0.2 m/s and, at most, it is the individual's velocity in smoke free environment. In Figure V.9, a visual representation of the probabilistic approach for multiple occupants is depicted.

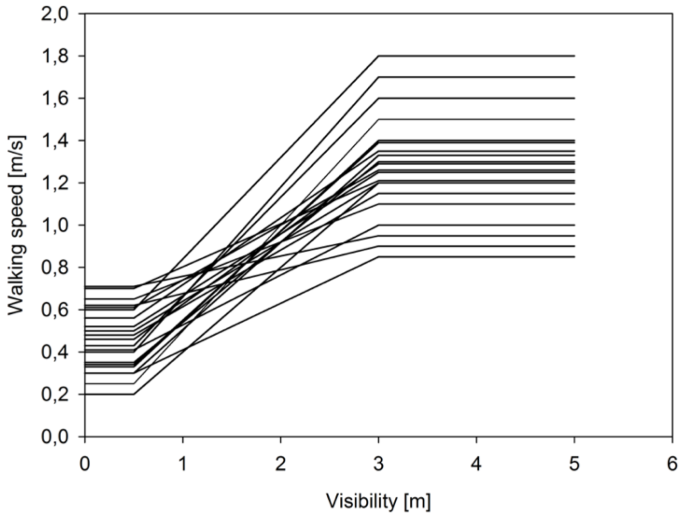

Figure V.9: Probabilistic approach of the relation between walking speed and visibility.

V.4.2.4 Flow

The flow of occupants through geometrical constraints has been extensively studied in the past [10]. The main influence factors affecting flow performance can be distinguished into internal and external factors. Internal factors are due to the occupant's individual characteristics (age, fitness, focus, etc.). External factors are mainly due to occupant density, merging and building configuration (Slope, stair, etc.). The effect of these parameters show a wide range of possible average flows (between 0.0 and 2.0 pp/m/s) applied in evacuation models [10].

V.4.2.4.1 Effect of occupant characteristics

The effect of occupant age and body size is implemented in the submodel. The first factor age has been experimentally studied [14]. Three population types were included in the study: adults, children, and elderly. Figure V.10 shows reduced flow rates for elderly. For children, an increased flow rate is observed for high densities due to the smaller body sizes.

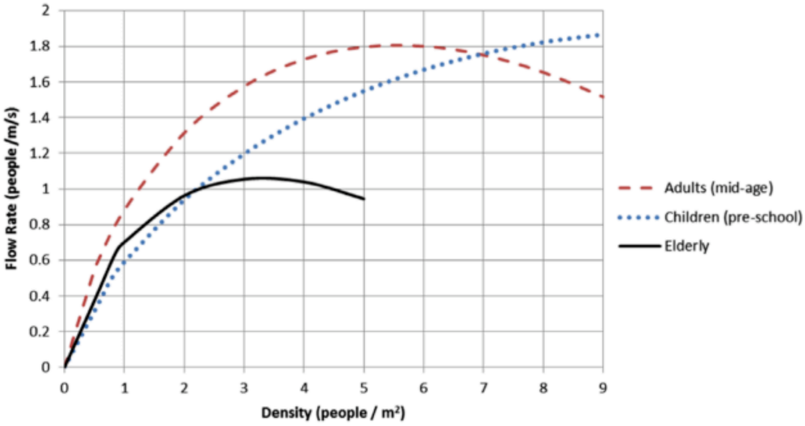

Figure V.10: Crowd flow rate vs. density for different age demographics. Taken from [14].

The second factor is body size. From research it is observed that a change in body size has a significant impact on modelling evacuation time. Purser and Gwynne performed a sensitivity analysis with a mean body size of 0.46 m diameter and a variation between 0.3 - 0.7 m [20]. For smaller body sizes, the effect was small. For larger body sizes, a variation up to 50% is observed because the flow rate is heavily reduced.

The impact of significantly higher proportions of obese people has yet to be properly considered with respect to crowd movement. However, from initial research [10,15], it is estimated that increased body size can reduce the movement speed and flow rate by up to 25%.

V.4.2.4.2 Effect of occupant density on horizontal and vertical flow

Experiments show a parabolic relationship between occupant density and flow. The flow first increases from low to medium densities up to 2 p/m^2. Subsequently, the flow decreases from a maximum value to almost zero for higher densities around 4 p/m^2.

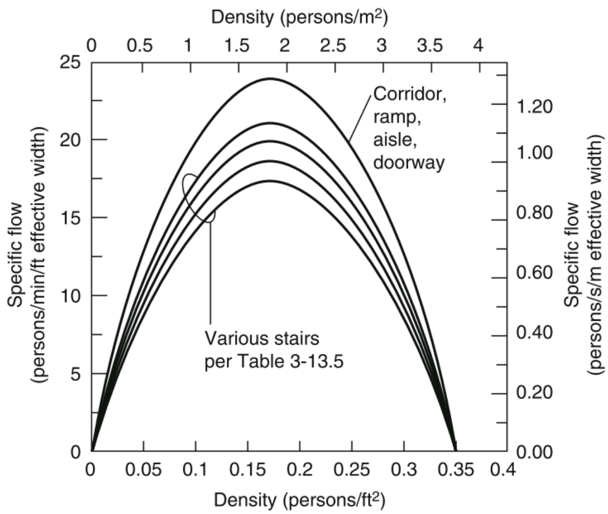

Figure V.11: Specific flow as a function of population density. Taken from [10].

V.4.2.4.3 Effect of merging in staircases on flow

The effect of different merging dynamics in staircases can have a significant impact on the exposure time of occupants in the incident compartment to the effluents of a fire. Purser described that most experiments show merging flows in the order of a 50:50 ratio [21]. In these circumstances the top floor empties first and then from bottom up. Ronchi et al. found that in the case of low occupant load and low densities, stair mergers seem too often have priority over floor mergers (in the order of 60-70:40-30) [22]. It was also discussed that the majority of the evacuation models approximate a 50:50 percentage ratio for most stair configurations [23].

V.4.2.5 Pre-evacuation model

In Appendix C, a literature study is performed to study the different pre-evacuation modelling techniques. The chosen approach for the simplified model specifies pre-movement response times as a distribution or a random number. This approach is used in models such as EvacuatioNZ [24]. A Sobol sampling scheme is used for assigning pre-evacuation times. The approach is an improvement with respect to methods with a fixed value. However, it is still not a general model, since the effects of fire severity and fire detection and alarm systems on occupant response are not reflected.

V.4.2.6 Exit choice

The purpose of the occupant exit choice model is to determine the exit choice for every occupant in the building during emergency evacuation. In the past, exit choice was mainly an optimization problem. Models were designed to assign agents to a certain exit depending on the shortest travel time. These algorithms give the shortest evacuation times. However, research has shown that people do not always know all exit possibilities, or do not always have a clear overview of the fastest route [25,26]. In Appendix C, a literature study is performed to study the different exit choice modelling techniques.

Three submodels are implemented in the model: the ‘shortest path’, the ‘fastest path’, and the ‘affiliation’. The shortest path calculates the fastest exit route and appoints this exit to the occupant. Shortest path is determined using the “Dijkstra” algorithm [27]. The fastest path chooses the fastest route to the outside taking into account queuing. The affiliation model takes into account a distribution of occupants assigned to each exit. A fourth submodel is considered, in which a combination of the former two is implemented. In this submodel, the occupants travel to the fastest known exit based on the affiliation parameter. During the evacuation simulation, for every timestep, the occupant re-evaluates their exit choice based on the influence of dynamic factors such as population size and environmental factors (smoke, signage, etc). The occupant may redirect due to higher expected queuing times or unavailability due to smoke.

V.4.2.7 Random start

The random start possibility randomises the start positions of the occupants. The occupants are randomly spread in the room in which represented by the corresponding node. This feature helps to make the model more realistic because in real situations, occupants are distributed within the space, and they do not usually have the same travel distance to the room exit. The result of this is that the occupants arrive at the door at different times. Therefore, by using the random start feature, we allow the occupants closer to the door to leave the room before the majority of the other occupants arrive to queue.

Figure V.12: Randomised vs standard occupant distribution.

V.4.3 User framework

The user framework contains different steps to perform the evacuation analysis. In Figure V.13, the interaction between the different parts of the software is presented.

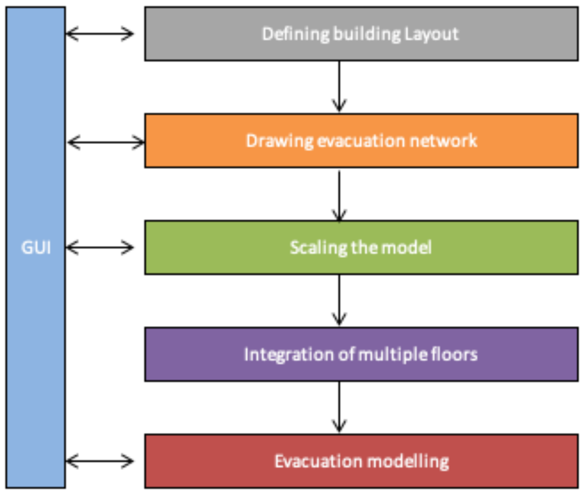

Figure V.13: User framework.

Step 1 – Defining building layout: The building layout provides a user interface to draw a network. Therefore, a map or building plan is required and imported into the building layout model. Different type of files can be imported (e.g., PGM, PPM, GIF or PNG format).

Step 2 – Drawing evacuation network: To create a network, the 'network creator' module is used. This module provides a platform for the user to draw the network and add network properties utilizing key and click handlers. In this part, doors, travel links, start points, stair cases, floor connections are designed. The network is then saved.

Step 3 – Scaling the model: Next, the design is scaled. The problem with utilizing an image as building plan is the scale of the image. Different images could have different scales, which will change the result of simulations. The 'PhotoImage' widget used in Python translates pixel to meter by a conversion factor equal to one. Therefore, 'pixel_to_meter' module was developed to facilitate the conversion with a real scale specified by the user. The module receives two nodes identified by the user and the distance in between; dividing the distance by the distance already measured in pixel, the meter to a pixel ratio is obtained, which will be used for converting pixel to meter during evacuation calculations. Moreover, for modelling a multi-storey building, different floors may have different map scales. This will also be taken into account by the software. To do so, the software will implement the corresponding meter to pixel ratio of each floor during evacuation calculations of that floor.

Step 4 – Integration of multiple floors: Since the software environment for creating a network is two dimensional, for simulations of a multi-storey building, evacuation networks of all the floors must be connected at connection points such as stairs. Therefore, 'multi_floor' and 'multi_floor_support' modules have been developed to facilitate the task. These modules combine separate networks of all the floors into one network, by automatically creating links between connection nodes, and save it to a 'graph.data' file. In order for the code to connect two floors, their connection points must be identified by the user on both floors by selecting connection type nodes. Each connection type node will then be linked to the connection node with the same group number on the adjacent floor.

Step 5 – Evacuation modelling: The 'evacuation_plan' is the module for identifying the next path during evacuation. The evacuation submodel decides what link the agent will turn to from a given intersection. Currently, this module provides multiple ways to define the exit strategy. This can be based on the exit choice, the random path or the shortest path model. The evacuation simulator, included in the 'evacuation' module, is the main algorithm for the simulation of the evacuation network. Several functions are defined in order to calculate the location of agents per time, their arrival at different node types, and calculate cumulative waiting times for people during their evacuations. The calculations take into account the number of people queuing at specific locations such as door inlets, narrow hall ways, and stairways.

The GUI provides an interface for the user to access different features of the software. GUI is prompted by 'GUI', 'GUI_support', 'GUI_Options' and 'GUI_Options_Support' modules. To develop the interface, tkinter widget has been employed [28].

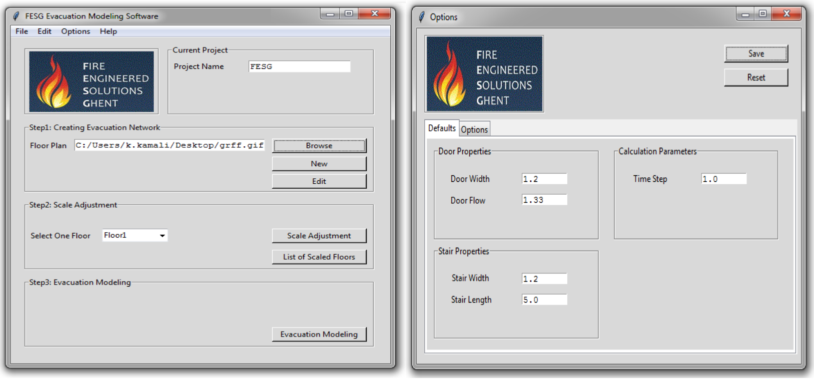

Figure V.14: Graphical user interface.

V.4.4 Limitations and future optimizations

In this part, limitations and possible future optimizations are discussed. The main limitations are:

- In terms of geometry, the software provides a convenient platform for modelling complicated multi-storey buildings, where the user does not need a complicated three-dimensional model of the building and the modelling can be performed with only two-dimensional plans of floors; however, the model is sensitive to network drawing. For example, when the obstructions are unknown, it is not convenient to draw the proper network structure.
- The modelling accuracy is less than with fine networks or continuous models, due to a coarser representation of the building; but, similar to those models, agents can have attributes and their exact locations during evacuation can be modelled by the software.
- Specific geometry configurations (lifts, turnstiles, etc.) cannot be taken into account.

Several possible suggestions are made for future developments:

- The user interface can be made more user-friendly. The option ‘delete’ for omitting ‘link’ objects should be incorporated.
- Additional correlations can be implemented into the model, for example the effect of fatigue on walking speed.
- Several programming functions can be added to the model to make simulations even faster in densely populated case studies. (e.g., parallel computing, NumPy arrays and error handling).

- A new module for importing FDS results and modelling interactions between fire and people during evacuation can be added to the software.

V.5 Conclusions

In this part of the thesis, the simplified version of the probabilistic framework has been developed for quantifying the life safety risk in case of fire. In order to accomplish this challenge, the objective was to develop a simplified method that gives a first estimate of the fire safety level of the considered building in a relatively short time span, in the order of one day of work. Two submodels are replaced to reduce the engineering and computational time. The simplified method is validated in chapter VI and tested on two case studies in chapter VII.

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CHAPTER VI
VERIFICATION & VALIDATION

Redrafted after publication of:

B. Van Weyenberge, P. Criel, X. Deckers, R. Caspeele, B. Merci, Response surface modelling in quantitative risk analysis for life safety in case of fire, Fire Saf. J. 1 (2017). doi:https://doi.org/10.1016/j.firesaf.2017.03.020.

VI.1 Introduction

One of the most important parts in simulation modelling is to ensure that the model represents the developer's conceptual description and that the model is correctly translated to software applications. Therefore, several validation and verification cases are analysed in order to determine the accuracy of the different submodels. Initially, the verification and validation objectives are defined. Next, the case configurations and boundary conditions used for the analysis are defined. After the definition of the case configurations, three verification procedures are defined and results are discussed. The first case analyses the performance of the Pyhton code during the modelling. The second case describes several algorithm tests. The focus is put on convergence analysis. The third study verifies the simplified model with respect to the full probabilistic model. Next, three validation studies are performed. The first validation study analyses the accuracy of the smoke spread RSM, the second analyses the evacuation RSM, and the third analyses the probabilistic representation of fire locations. After the analysis of the validation cases, the results are discussed and conclusions are drawn.

VI.2 Validation and verification objectives

For the model to be implemented in future projects, the most sensitive and critical parts have to be subjected to validation and verification.

VI.2.1 Verification

By its definition, verification is a process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model [1]. Furthermore, verification means checking that the source code contains no errors in terms of the calculation process.

Verification mainly deals with the mathematical and numerical solution of the underlying physical problems. The "verification suite" is a collection of simple calculations that typically test some specific feature of the model [2]. Hence, in practice, executing the verification process is to determine whether the source code used for the modelling t contains errors or not.

The objective of verifying a calculation method or procedure by error estimation is determining the accuracy of a calculation. The strategy is to identify and quantify the errors in the model implementation and the solution.

There are two aspects of verification (Figure VI.1): software quality testing and algorithm testing. The former deals with code errors and performance, the latter puts focus on algorithm performance and accuracy.

For software quality testing, two basic approaches are used for verifying the simulation software; these are static and dynamic testing. In static testing the computer program is analysed, without executing the code, to determine if it is correct by using such techniques as structured walkthroughs, correctness proofs, and examining the structure properties of the program. The objective of static testing in this research is to find preliminary errors and optimize the code structure. This is done for the different scripts. Since the focus of the research is not on programming, this part is not further elaborated in the thesis. The second approach for verifying the code is dynamic testing, in which the software is compiled, executed, and compared for the expected output. Additionally, parameters such as memory usage, CPU usage, response time, and overall performance of the software are analysed. In the research study, both functional (unit, integration and system testing) and non-functional (performance testing) testing is performed. Functional testing is not further elaborated in this thesis. Performance testing is discussed in the next chapter.

In the algorithm testing, the focus is put on error estimation by means of convergence analysis of the implemented probabilistic DoE. The objective is to define an algorithm that dynamically defines the optimum DoE for every case study.

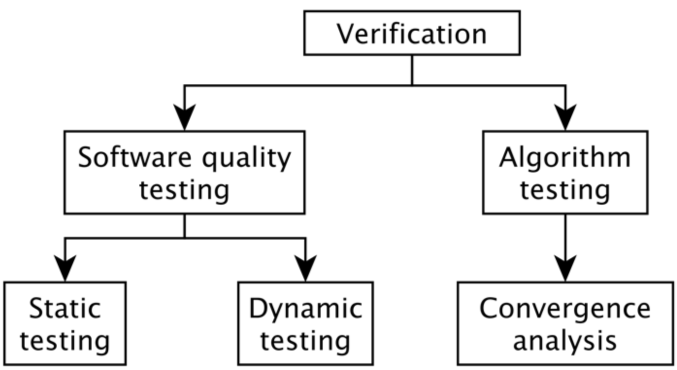


Figure VI.1: Verification process for the developed methodology. Adapted from [1].

In analogy to the full-probabilistic model, the simplified model is verified by doing both software quality and algorithm testing. The focus in this thesis is on the verification by means of dynamic testing.

VI.2.2 Validation

In order to prove that the model represents real conditions as accurately as possible, validation is needed. Validation is defined as "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" [3,4]. Therefore, the validation process is defined as a process of decisive level for a model simulation in order to represent its intended use in the real-world case. By that definition, it can be determined that the purpose of the validation process is to know the accuracy level of the simulation model in describing the actual condition.

The results of the validation process are used for two purposes. First, they are applied to direct the future improvement of the model by revealing the parts of the model having highest errors and uncertainties. The second and more important use of the validation simulations is the estimation of model uncertainty, explained in the next part, in a way that is useful for the end users [5].

The fundamental approach of validation is to identify and quantify the main error and uncertainties in the conceptual and computational models. In validation the numerical errors are quantified and the experimental uncertainty is estimated by comparison between the computational results and the experimental data [6].

The objective of validation in this research is twofold. First, the RSM for smoke spread and evacuation modelling is validated. The validation is performed for simple and more challenging case studies and the results are presented in terms of relative error estimations. Second, the probabilistic representation of fire location is analysed. The necessary number of fire locations to obtain a global representation of fire in a building is defined for specific cases. The methodology for validation of the two objectives is presented in Figure VI.2.

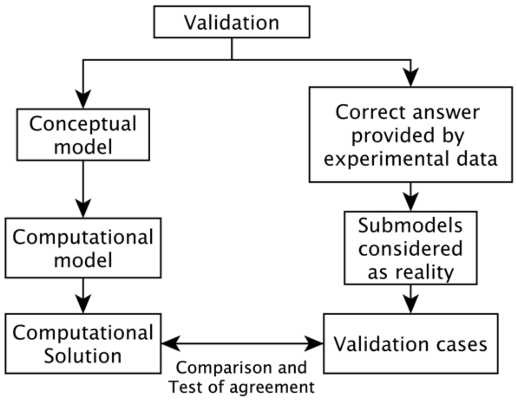


Figure VI.2: Validation process for the developed methodology. Adapted from [6].

VI.2.3 Model uncertainty

Because the analysis of model uncertainty is an important part in the validation of models, it is briefly discussed in this section and applied in parts of the validation case studies.

Models having different complexity are designed to describe, for a certain degree of approximation, systems and processes in different aspects of the real world (e.g. industrial, social, or economic). The use of these models involves the presence and treatment of uncertainties [7]. The input for a model is subject to many sources of uncertainty including errors of measurement, the absence of information, scaling errors, design of experiments, out of-date information, and poor or partial understanding of the main driving forces and mechanisms [7].

This imposes a limitation on the certainty in the response of the model. Sensitivity and uncertainty analysis are able to increase this confidence in the model and its predictions. This by providing an global understanding of how the model response variables respond to changes of the input variables [7]. Therefore, the difference between the response result and the simulation result generates an error. However, this error rate should be examined further in order to conclude whether it is acceptable or not.

Moreover, errors can be determined as an unavoidable element in the measurement process. Error in measurement is usually defined as the difference between the true value and the measured value. When used in the context of measurement, uncertainty has a variable associated with it. More specifically, the measurement uncertainty has the same units as the measurement results. A careful uncertainty calculation does not only provide an accurate estimate of the research data obtained, but also can be used to determine the measurement that requires higher precision in order to obtain accurate results. Uncertainty analysis is a very useful tool for determining the reliability level of a measurement and for the validation of theoretical and simulation models.

In general, the uncertainty can be expressed as a relative error calculated as follows:

$$relative\ error = \frac{absolute\ error}{Theoretical\ value} \quad \text{(VI.1)}$$

In this research, model uncertainty analysis is performed considering two approaches. The first one calculates the mean and standard deviation (STD) of the error considering a normal distribution. The second one is based on the European standard document EN 1990 Annex D [8]. This method calculates the mean and STD of the relative error considering a lognormal distribution. The formulas for the second approach are discussed below.

The approach from the European standard EN 1990 Annex D is applied by first calculating the error term δ_i. For each experimental value r_{ei} and theoretical value r_{ti} the error term should be calculated from the following equation:

$$\delta_i = \frac{r_{ei}}{br_{ti}} \quad \text{(VI.2)}$$

where b is the “Least Squares” best fit to the slope and should be determined by the following formula:

$$b = \frac{\sum r_e r_t}{\sum r_t^2} \quad \text{(VI.3)}$$

From the value of δ_i an estimated value of error variance V_δ is determined by the following equation:

$$\Delta_i = \ln(\delta_i) \quad \text{(VI.5)}$$

$$s_\Delta^2 = \frac{1}{n-1}\sum_{i=1}^{n}(\Delta_i - \bar{\Delta})^2 \quad \text{(VI.5)}$$

$$\bar{\Delta} = \frac{1}{n}\sum_{i=1}^{n}\Delta_i \quad \text{(VI.6)}$$

From Equation 4, 5 and 6 a value of error variance V_δ is calculated by the following equation:

$$V_\delta = \sqrt{\exp(s_\Delta^2) - 1} \tag{VI.6}$$

Based on the model uncertainty analysis it can be determined whether the error is acceptable or not. This application is applied in several of the following sections.

VI.3 Verification and validation test cases

For the verification and validation of several parts of the methodology, two test configurations are investigated. A simple and a more challenging case are chosen for the validation of the methodology.

VI.3.1 Configuration of the simple case

The building configuration used for the several verification and validation tests embodies the configuration of a multi-purpose community assembly compartment [9]. The building can be used for festivities, receptions, etc. The compartment consists of a large main room with a dancing floor and bar, and smaller rooms which consist of a storage, a dressing room, a cloak room and a VIP room (Figure VI.3). The compartment has dimensions of 25.0 m x 18.0 m x 3.0 m. Three emergency exits are shown in three different outer walls. The main emergency exit is 1.8 m x 2.2 m, the back and staff exits are 1.2 m x 2.2 m. The exit next to the bar is only used by staff. The exits are considered as open boundaries. No additional fire safety systems are considered.

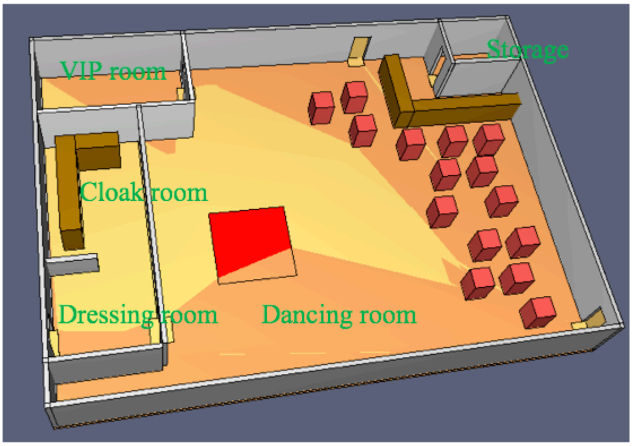


Figure VI.3: Case study multiple purpose assembly building.

VI.3.2 Configuration of the challenging case

The case study embodies the configuration of a multi-purpose commercial building (step 1 in Chapter IV). The shopping mall offers different types of merchandise (e.g. clothes, multimedia, healthcare, beauty, etc.) over a total surface area of 25000 m^2 (Figure VI.4). The building consists of one main compartment of 5 floors from level -1 to level 3, with a surface area of about 5000 m^2 per floor and ceiling heights between 3 and 4 m. Figure VI.5 shows a schematic floor plan of the ground floor. The floors are interconnected by four escalators (orange marking) distributed over two central openings. Emergency exits are positioned on each floor by means of four compartmentalized staircases (blue marking). Four exits are foreseen for evacuation of people on the ground floor. Level -1, 0, 1 and 2 are only used for commercial purposes. On level 3, a restaurant of 2000 m^2 is located in the same compartment. In this case study no external influences (e.g. wind, seasons, fire brigade, etc.) or bottlenecks (e.g. merging flows, direct access to street, etc.) are taken into account.

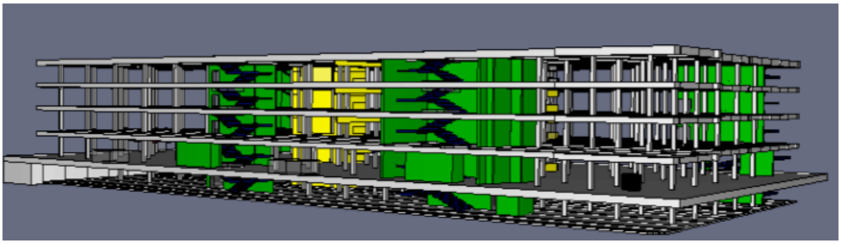


Figure VI.4: Model of the shopping mall.

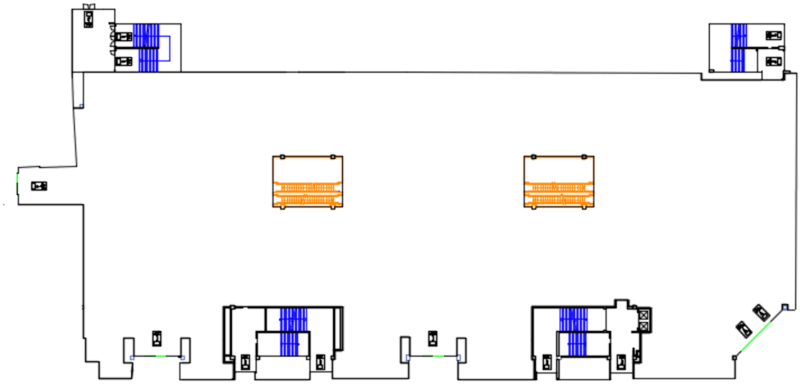


Figure VI.5: Ground plan of floor level 0.

VI.4 Verification of the methodology

Several verification studies are performed in order to present the correctness of the implemented models. Three verification tests are presented. The first test analyses the code performance during the development of the model. The second test analyses the convergence rates of the critical submodels. The third study deals with the verification of the essential submodels of the simplified version of the methodology.

VI.4.1 Dynamic testing: algorithm performance

The purpose of the dynamic testing process during the development of the code is to increase the performance of each module/script individually as well as for the entire model. From the first version of the algorithm to the final version, optimizations have been performed to decrease the calculation time. In Figure VI.6, the code performance increase is depicted for the challenging case with a sample DoE set of 100 samples.

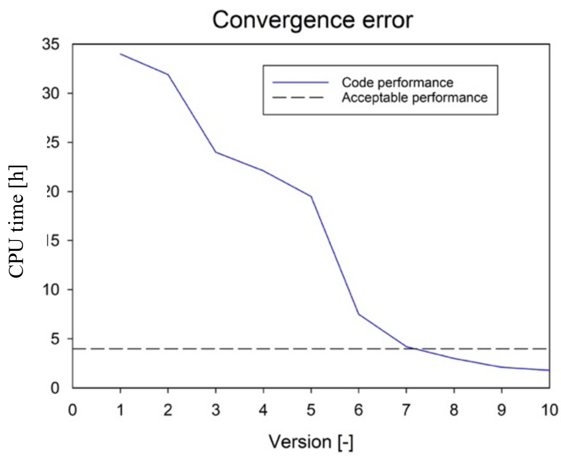


Figure VI.6: Performance evaluation over time.

The major optimization performed in the coding process is the shift from functional to object-oriented programming in version 3. The second major performance increase is due to the shift from serial to parallel calculation procedures in version 6. The performance optimizations in other versions are mainly due to improved memory allocation, cleaning the code, the implementation of vectorized functions, etc. In order to obtain an efficient algorithm, the performance criteria for the considered number of DoE is set to a maximum of 4 hours for each fire safety design. From the results presented in Figure VI.7 can be concluded that the objective was achieved from version 7 onwards.

VI.4.2 Algorithm testing: convergence analysis

The convergence analysis has already been discussed in Chapter IV. The purpose is to analyse the accuracy of the DoE and RSM modelling and update the sampling scheme with additional samples until the desired accuracy is achieved. In Figure VI.7, the most negative scenario in the challenging case study is presented. Here seven additional samples needed to be added to obtain the desired accuracy defined in Chapter IV [10]. For 95-99% of the scenarios no additional samples were necessary due to immediate convergence.

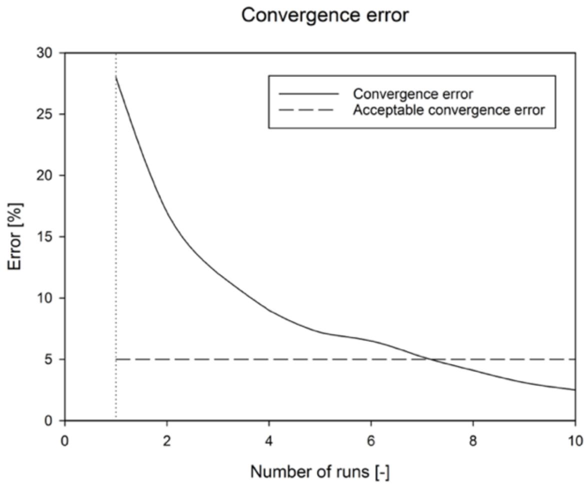


Figure VI.7: Convergence analysis method by means of analysing additional samples.

VI.4.3 Verification of the simplified model

For the verification of the simplified model, only the part consisting of the evacuation submodel is verified because the implemented smoke spread model has already been verified and validated in past research [11]. The other models are similar to the comprehensive QRA model.

According to [12], five main elements should be verified for an evacuation model, i.e. pre-evacuation time, movement, exit choice, route availability and selection, and flow condition/constraints. To assess the model capabilities, the behaviour in these five aspects of the model should be compared with ideal cases, which are understood as "scenario tests". For this thesis, the model components pre-evacuation time, (smoke) movement, door and stair queuing, exit choice and route selection will be tested to ensure that they are working and producing representative results.

The verification is performed by means of component testing because this is a fundamental approach to validating and verifying a model. The global comparison between the results of the case studies is made in Chapter VII.

VI.4.3.1 Pre-evacuation time

The verification test is performed to verify the model's ability to assign distributions of pre-evacuation times to agents. The proposed test is a modified version of IMO Test 5 [13]. The test is performed in the simple case study including 100 occupants. The pre-evacuation time is normal distributed with parameters $\mu = 180\ s$ and $\sigma = 20\ s$. The simulation is performed five times to verify the repeatability of the model. For every simulation a Kolmogorov-Sminorf test was performed comparing the test data with the pre-defined normal distribution. For every simulation the test showed that the theoretical data and the experimental data were not significantly different ($p > 0.05$).

For each occupant, an initial pre-evacuation time t_i is assigned by sampling from the distribution. Both the initial pre-evacuation time t_i and the observed pre-evacuation time t_o are recorded when the evacuee began moving towards the exit. The results are presented in Figure VI.8 by means of a smoothed histogram and compared with the PDF of the distribution. The comparison predicts relative errors of less than 5%. The variability in the different test runs was negligible.

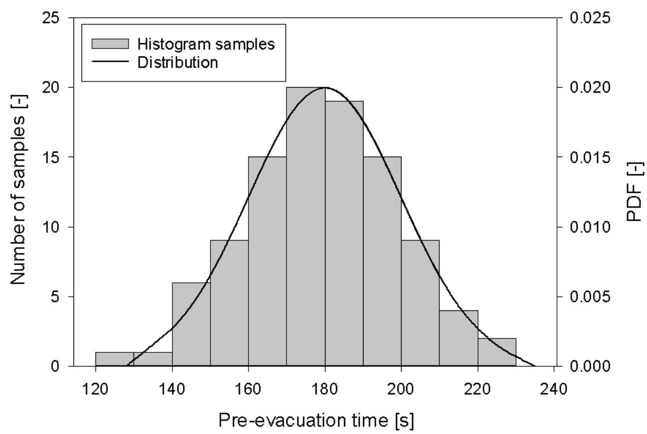


Figure VI.8: Comparison of implemented t_i and observed t_o evacuation time.

VI.4.3.2 Movement and navigation

This test is basically related to the speed in a corridor as proposed in [14]. It is good practice to verify the travel time of an evacuee maintaining an assigned walking speed over time. The test is based on IMO Test 1 from the IMO Guidelines [13]. The test is performed in the simple case between a source node and an exit node. The link between the nodes is 12 m long and 1 m wide. The scenario considers one evacuee with an assigned walking speed of 1.2 m/s. Two different scenarios are studied: one without smoke and one with smoke. The test is performed 10 times, the average travel time in clear conditions is observed to be 10 s, which corresponds to the theoretical walking speed. The same test is performed in smoke with a velocity reduction factor of 2. The average travel time obtained is 20.1 s which is very close to the theoretical walking speed. The main difference is related to conversion errors from soot extinction to walking speed.

VI.4.3.3 Door and stair queuing

The applied door queuing and stair flow rate algorithm was verified by considering a simple two-node map with a door linking the two nodes (Figure VI.9). The door width was varied and the flow rate for the evacuation of 100 people was calculated. For the verification procedure, it was assumed that the maximum occupant density was 2 persons/m^2 [15] and the maximum potential travel speed was 1.2 m/s when the occupant density was below 0.5 persons/m^2. To set the occupant density in the starting node, the area of the starting node was modified for the two scenarios.

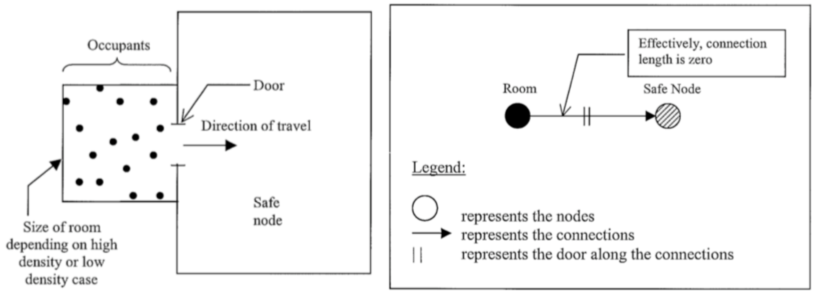


Figure VI.9: (Left) Layout of the building for the testing of the door queuing component. (Right) Nodal representation of the building in the door queuing example.

The results of the simulated versus theoretical evacuation time is presented by means of the model uncertainty in Figure VI.10. The calculated mean relative error is less than 0.01 and a standard normal deviation of 0.012 is obtained.

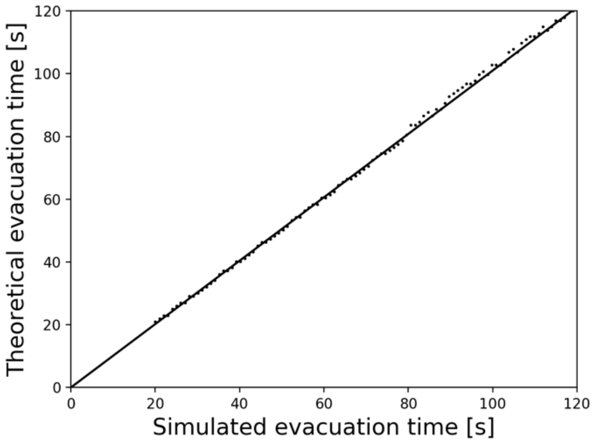


Figure VI.10: Model uncertainty for the verification of the door flow model.

A similar validation procedure is applied for a stair with inclination of 30°. The obtained results are in the same order of magnitude as for the door verification test.

VI.4.3.4 Exit choice and route selection

The purpose of this section is to verify the ability of the model to choose the proper exit given certain parameters. The exit choice in evacuation may rely on simple criteria (shortest distance, user-defined), allowing for a deterministic rather than predictive result. An exit route allocation test based on IMO Test 10 [13] is suggested. Additionally, the possibility of simulating affiliation/familiarity with the exit is tested. The case is presented in Figure VI.11. The building is populated with 2 people per room having a fixed walking speed of 1.2 m/s. The corridor towards the main exit is filled with smoke causing a speed reduction of a factor 3. The exit doors are 0.8 m wide.

Three scenarios are considered. In the first scenario, the shortest path is applied. In the second scenario, the fastest path is evaluated. In the third scenario, a 60/40 affiliation is applied to the main/secondary exit.

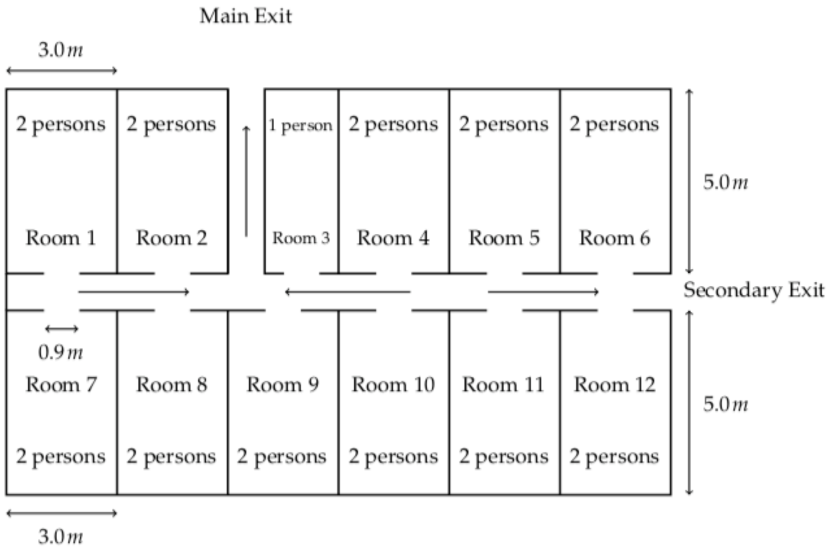


Figure VI.11: Case geometry for exit choice validation.

The simulation of the scenario including the shortest path shows that 12 occupants evacuate towards the main exit and 12 occupants towards the secondary exit. This is in line with the expectation that the shortest path is determined for each occupant individually. The simulation with the fastest path shows that 3 occupants evacuate to the main exit and 21 occupants evacuate towards the secondary exit. When the queuing time is not taken into account, all occupants should evacuate towards the secondary exit. This is because of the significant walking speed reduction of the smoke. However, due to limited flow capacity the flow of occupants is restricted causing three occupants to evacuate towards the main exit. This is also observed analysing the model with Pathfinder [16].

VI.4.3.5 Discussion

Four important aspects of the network model have been verified. The model verification tests show good agreement with the theoretical calculations. This means that the verification tests can be considered successful.

Although there are still more component tests to be done [13], the testing of basic components such as the door queuing model and stair movement model is essential as a first step in validating the program.

VI.5 Validation of the methodology

In this part, several validation studies are performed to present the validity of the implemented models. Three verification tests are presented. The first two tests analyse the accuracy and model uncertainty of the RSM for the smoke spread and evacuation modelling. The third test analyses the probabilistic representation of fire locations throughout the building.

VI.5.1 Validation of the smoke spread RSM

As discussed in section 2, validation in the context of this research is performed with respect to prediction of the simulations of the field models. Validation with respect to real experiments is not considered in this thesis. In the first validation case, the performance of the IMLS and PCE RSM are analysed for the simple case study. The objective is to determine the most optimal method with respect to its estimated error for the smoke spread submodel in terms of toxicity yields and radiation. The analysis is performed by applying the proposed framework in Chapter IV.

VI.5.1.1 Method and analysis

In this case study, the influence of the variability of the fire parameters is analysed considering only one sub-model, namely smoke spread. A 20 cm mesh is used in combination with a 10 cm mesh in the vicinity of the fire. A sensitivity study has been performed to obtain these mesh sizes. The detailed results are not included in the thesis. Note that no special emphasis is put on obtaining high-resolution CFD results. Rather, the aim is to illustrate/validate the proof-of-concept of the RSM approach: starting from a set of CFD simulations (taken as reference here), a response surface is defined and subsequently other CFD results are predicted through the RSM approach. From preceding sensitivity analyses, it is decided to take three important input parameters into account: the fire growth rate, the Heat Release Rate per Unit Area (HRRPUA) and the maximal area of the fire. In Table VI.1, the distributions for these parameters are described. A constant CO-yield of 0.15 g/g is considered. A radiative fraction of 0.35 is applied.

Table VI.1: Input variables.

Type	Distr type	μ_{ln}	σ_{ln}	Analysed range	Ref.
Fire growth [kW/s^2]	LN	-6.6	2.2	0.01-0.07	[17]
HRRPUA [KW/m^2]	LN	5.97	0.191	320-500	[18]
Max area [m^2]	LN	0.78	1.7	2.0-28.0	[17]

The support samples are chosen based on LHS and the input range is chosen based on the expected failure domain [9]. Failure in this case relates to fatalities obtained by intoxication. 64 simulations (blue points in Figure VI.12) have been performed over a wide spectrum of the input range (see Table IV.1)

In step 2, the most important input variables are determined based on a preceding sensitivity analysis [1]. For the considered variables, distributions are determined based on statistical data, fault tree analysis and engineering judgement [7]. In the Tables IV.1 and IV.2, a list of variables is given of the most sensitive parameters in the fire life safety analysis of a commercial building [20,21]. In theory, all these parameters should be implemented in the event tree analysis in step 3. However, in order to prevent an extensive event tree, the variables are divided into discrete and continuous parameters. The discrete variables are addressed in the bow-tie structure (Table IV.2). The continuous variables are addressed at the end of the event tree by means of the RSM (Table IV.1). The separation between the two types of variables is done for reasons of computational and operational efficiency (e.g. location of the fire). Secondly, some variables cannot be considered in continuous form due to their discrete nature (e.g. activation or failure of safety systems, the state of doors, etc).

For every variable in Table IV.1, an indication is given of the order of importance with respect to the results. The first order variables are considered the most significant based on preceding sensitivity analysis [22]. This means that only parts of the domain close to the limit state need to be analysed. The second order variables are still significant but less sensitive than the first order. For these variables, a large part of the domain needs to be analysed. Third order variables, e.g. ambient temperature, material properties, etc., are the least significant and are considered deterministic in this study. For these variables mean values are taken as nominal values.

Apart from the 64 support points, an additional 20 validation samples are simulated (orange points in Figure VI.12), also spread over a wide range. These samples are not used for estimating the response surface. The purpose is to evaluate the quality of the RSM by comparing the response of the validation set with a full CFD simulation, which is computationally expensive. The validation samples are chosen between the ranges shown in Figure VI.12.

The sampling technique LHS is combined with a correlation matrix (see Table VI.2) [19]. The correlation matrix is a n x n matrix, with n the number of variables, which defines the correlation between variables. Correlation between variables is possible because of the physical boundary effects (e.g. a slowly growing fire is less likely to reach a significant fire surface area). Some combinations are not relevant for the analysis as they are not located in the vicinity of the limit state and hence are of minor importance when looking for the most likely failure point and the associated exceedance probability. The values in the table have been chosen purely on the basis of expert judgement, in order to illustrate the proof of concept of the technique.

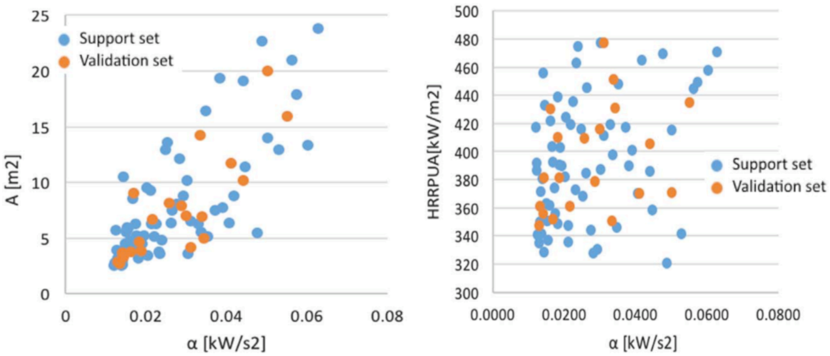


Figure VI.12: DoE input samples for the considered variables.

Table VI.2: Correlation coefficients.

Parameters	α	HRRPUA	Area
α	1	0.85	0.35
HRRPUA	-	1	0.2
Area	-	-	1

The support samples are evaluated by means of the smoke spread sub-model FDS version 6.1.1 [20]. After evaluation of the support samples, the smoke spread RSM is generated using the PCE and IMLS method. In order to make a fair comparison with respect to the two response surface techniques, the same number of coefficients should be chosen for both models. For the PCE model a degree p of 2 and q-norm of 0.5 is chosen, leading to 7 coefficients. For the IMLS model, the 3 parameters, the interaction components, and the constant coefficient are considered, also giving a total of 7 coefficients to be estimated. Next, the support samples are calculated.

VI.5.1.2 Performance criteria

To consider the RSM model as sufficiently accurate, performance criteria are defined for the mean and standard deviation of the relative error for the concentration and FID-values. The RSM model is considered acceptable if the absolute value of the mean and spread (σ) of the error is lower than 5% [21].

VI.5.1.3 Results

In this part, the results of the validation study are presented. The focus is put mainly on the comparison of the toxicity yields. Since the results for the radiation comparison are similar, the output is shown in summarized form.

The validation of the toxicity estimation is performed by means of CO-concentrations. In Figure VI.13, the predictive capability of the model is visualised for one of the 20 validation cases as slice file results from FDS 6. Comparison is made between the validation set and the two RSM models for two-time steps during the progress of the smoke development. The CO-concentrations are presented for the validation case with the following parameters: α = 0.0142, HRRPUA = 356 kW/m^2 and A_{max}=3.68 m^2. No colour bars are shown. Instead, for every time step, one CO-equipotential line (same concentrations) is shown to illustrate the comparison between the validation set and the results of the two methods. Figure VI.13 shows good qualitative agreement between the estimated values based on the developed response surface and the validation set. For both methods, the results show good agreement with the validation set at every position of the compartment.

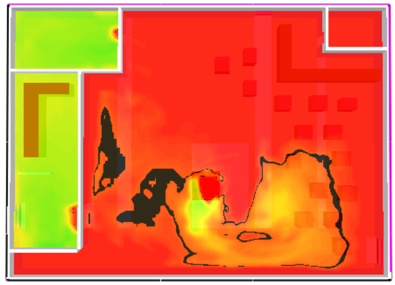
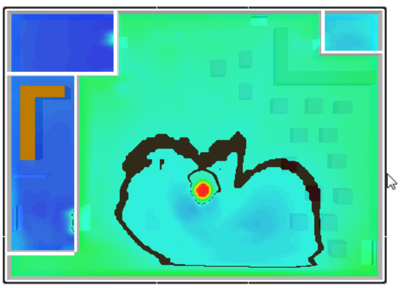
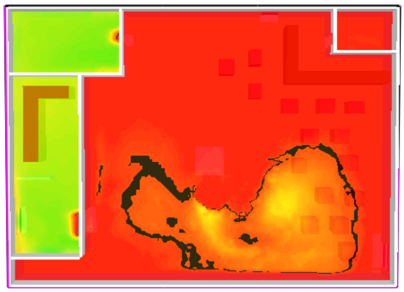
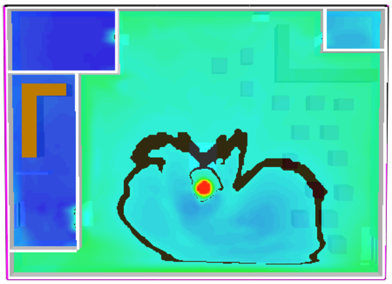
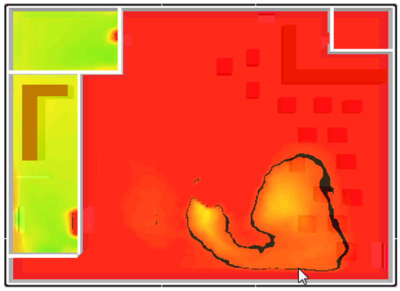
CO-concentration at t = 240 s	**CO-concentration at t = 480 s**
Equipotential [CO] = 600 ppm	Equipotential [CO] = 1900 ppm
 Validation set	 Validation set
 Estimated based on PCE	 Estimated based on PCE
 Estimated based on IMLS	 Estimated based on IMLS

Figure VI.13: Case study results for CO-concentrations at 2.0 m.

In the second step, the mean error in % is calculated between the estimated set and the validation set for the 20 validation cases, for every cell in the horizontal plane and for every time step separately:

$$\Delta error_{av\_xy} = \frac{1}{n}\sum_{sim=1}^{n}\frac{[CO]_{estimated} - [CO]_{validation}}{[CO]_{validation}} \quad \text{(VI.8)}$$

Where n is the number of validation cases. In Figure VI.14 and Figure VI.15, the mean error, expressed in %, is shown for the 20 validation cases with the IMLS and PCE models at time 480 s (which is time step 96). After 480 s, steady-state conditions were obtained. The last time step is chosen because the heat release rate is at its maximum and the strongest turbulent flows are expected. The results show that for both methods the mean error is very low, with the error between −2.5% and 1% at most locations. The results for the PCE method show slightly smaller mean errors (in absolute value) compared to the IMLS method (which shows more negative mean errors). This means that the IMLS model underestimates the CO-concentrations more than the PCE model.

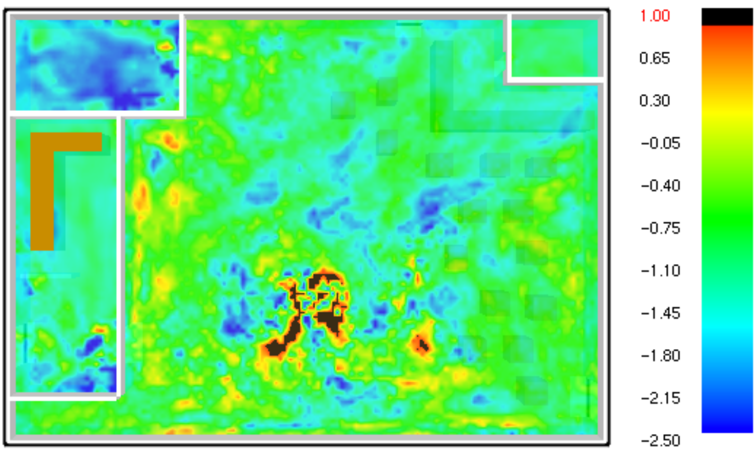


Figure VI.14: IMLS - mean error [%] of the 20 validation cases for all locations at t = 480 s.

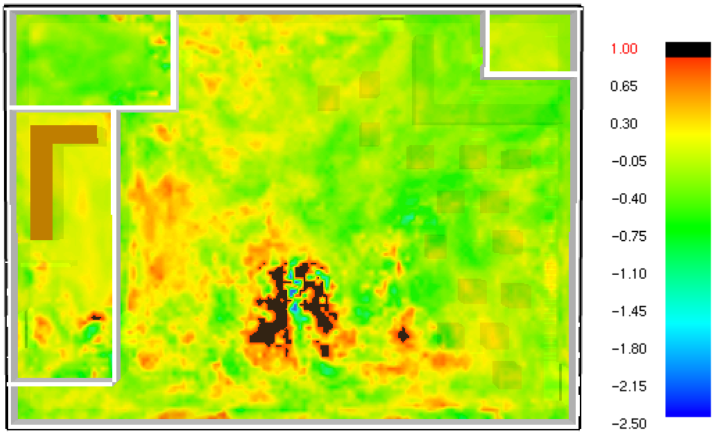


Figure VI.15: PCE - mean error [%] of the validation cases at t = 480 s.

In Figure VI.16 and Figure VI.17 the corresponding standard normal deviation (STD) of the error is presented, expressed in %. The results show that for both methods the STD is very low, with values below 10% at most locations. The results for the PCE method show significantly lower STD values (close to zero) compared to the IMLS method. This means that the IMLS model has a higher spread of errors. For both the mean and the STD, the results show larger errors in the region close to the fire. This is expected, as the largest turbulent fluctuations occur there. This also means that the model is particularly reliable for analyses remote from the fire.

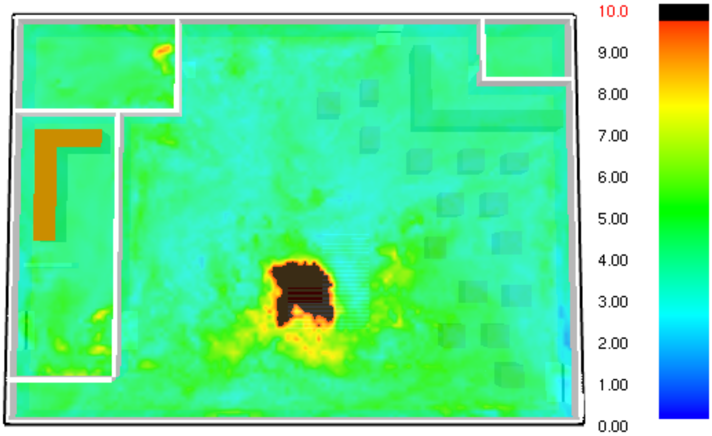


Figure VI.16: IMLS – standard deviation of the error [%] of the validation cases at t = 480 s.

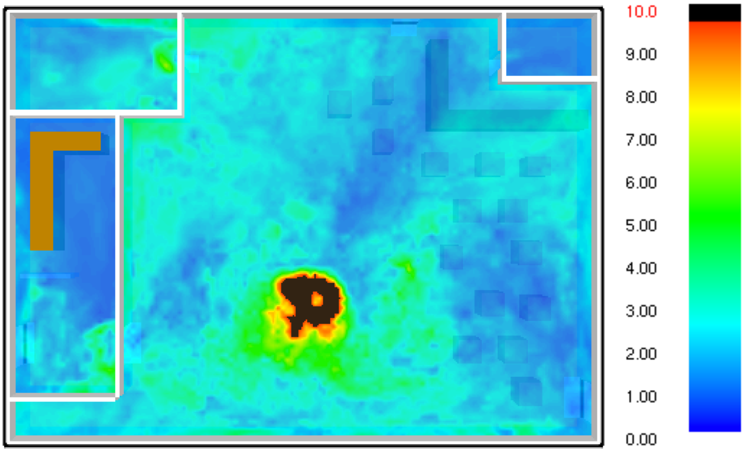


Figure VI.17: PCE - standard deviation of the error [%] of the 20 validation cases for all locations at t = 480 s.

In the third step, the mean error (expressed in %) is calculated between the estimated and validation set and over the entire horizontal plane, for every time step separately:

$$\Delta error_{av\_all} = \frac{1}{n_{sim} n_x \, n_y} \sum_{sim=1}^{n} \sum_{i=1}^{x} \sum_{j=1}^{y} \frac{[CO]_{estimated} - [CO]_{validation}}{[CO]_{validation}} \qquad (VI.9)$$

Figure VI.18 presents the results for the 96 time steps. The mean error for the PCE model varies between -0.6 % and 0.7 %, while with the IMLS method a value between -1.5 % and 0.5 % is observed. Hence, both approaches yield very good agreement, considering the turbulent conditions in the compartment. The PCE model shows better agreement than the IMLS model. Considering the 20 validation cases, only 76 local points out of 21600000 points (combination of the number of validation cases and cells in the x and y direction times the number of time steps: 20 x 125 x 90 x 96) in the PCE model reached an error larger than 20%, while with the IMLS model 5151 local points had an error exceeding 20%.

The zero values for the initial time are due to two reasons: zero concentrations are measured at the beginning (absence of smoke), and errors on concentrations below 100 ppm are not taken into account because of insignificance for life safety (short exposure periods).

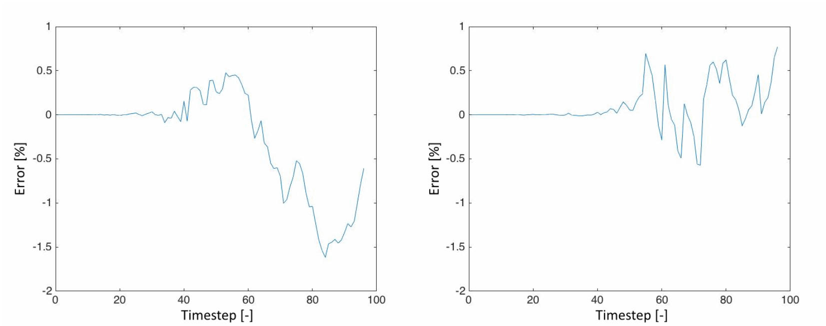


Figure VI.18: Mean error of the CO-results for the validation simulation set.
Left: PCE; right: IMLS.

For the comparison of the radiation calculations, an analogous approach is conducted. The only difference is that no slice file data are compared but 10 individual device locations chosen at strategic locations Figure VI.19. The radiative heat flux is measured.

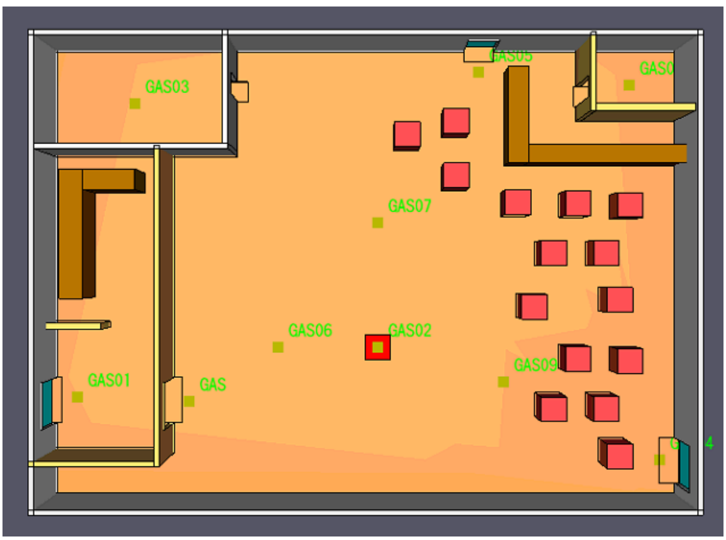


Figure VI.19: Location of radiation devices.

The results are depicted in Figure VI.20. Similar results are obtained as for the toxicity yields. This means that the behaviour is similar for both patterns.

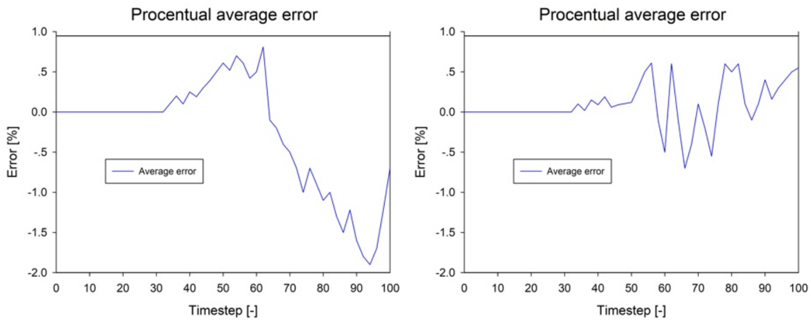


Figure VI.20: Mean error of the radiation results for the validation simulation set. Left: PCE; right: IMLS.

VI.5.1.4 Discussion

The analysis in this validation case was restricted to the possibility of using PCE and IMLS for response surface modelling for smoke spread and evacuation in the context of probabilistic fire safety analyses.

For the RSM in the smoke spread sub-model, the mean and standard deviation for the relative error of the IMLS and PCE models are below the pre-defined performance criteria. Therefore, both models are considered suitable for the analysis. The results are in favour of the PCE model. However, for more irregular patterns (close to the fire), the IMLS shows better results. Therefore, for evacuation analysis it is suggested to implement the IMLS.

From this analysis was observed that care should be taken in the choice of the output. If the output is discrete, rather than continuous, in nature, the development of the RSM is difficult to achieve. One example is the number of fatalities, which would yield a value of zero in most training sets, and then jump to non-zero integer numbers in other sets. Therefore, for the evacuation RSM, the output in terms of Fractional Incapacitation Dose (FID) values is calculated. This output presents a gradual (continuous) increase over time and population density [22].

VI.5.2 Validation of the evacuation RSM

In the second validation case, the performance of the RSM method is validated for the evacuation submodel. The objective is to determine the accuracy of the evacuation RSM for the simple and challenging building configurations. The challenging case is split up into two analysis in which one case examines the evacuation of one floor and in the second case, the entire building is evacuated.

The results are compared in terms of FID values. This chapter is supported by the work performed by one of the master theses during the phd program [23].

VI.5.2.1 Method and analysis

Similar to the first validation case, the influence of the variability of the evacuation parameters is analysed, considering the variability of only one sub-model, namely evacuation. No variability of the smoke spread model is considered.

Therefore, only one sample set of fire parameters is applied: $\alpha = 0.046$ kW/s^2, HRRPUA = 400 kW/m^2 and Amax = 16 m^2 and evaluated by means of FDS 6.1.1. For the evacuation variables, it is decided to take three important input parameters into account: the mean pre-movement time, affiliation and occupant density. The affiliation represents the percentage of people evacuating towards the main exit. The variables are chosen based on a preceding sensitivity analysis [24]. In Table VI.3 and Table VI.4, the distributions for these parameters are described for the simple and challenging case. A constant CO-yield of 0.15 g/g is considered.

Table VI.3: Input variables simple case.

Type	Distr	μ	σ	Analysed range
Pre-evacuation time [s]	Normal	160	13.3	120-200
Affiliation [-]	Normal	0.6	0.033	0.5-0.7
Occupant density [m²/pp]	LN	0.7	0.5	0.2-2

Table VI.4: Input variables challenging case.

Type	Distr	μ	σ	Analysed range
Pre-evacuation time [s]	Normal	220	15	180-260
Affiliation [-]	Normal	0.6	0.015	0.55-0.65
Occupant density [m²/pp]	LN	4	1	2-6

The support samples are chosen based on fractional factorial design. The chosen input domain ranges are depicted in the tables above and chosen based on three times the standard deviation. A total of n^3 or 27 support samples are analysed. Apart from the 27 support points, an additional 20 validation samples are simulated. These samples are not used for estimating the response surface. The support and validation points for the simple configuration are presented in Figure VI.21. A similar pattern is used for the challenging case and therefore not repeated in the thesis.

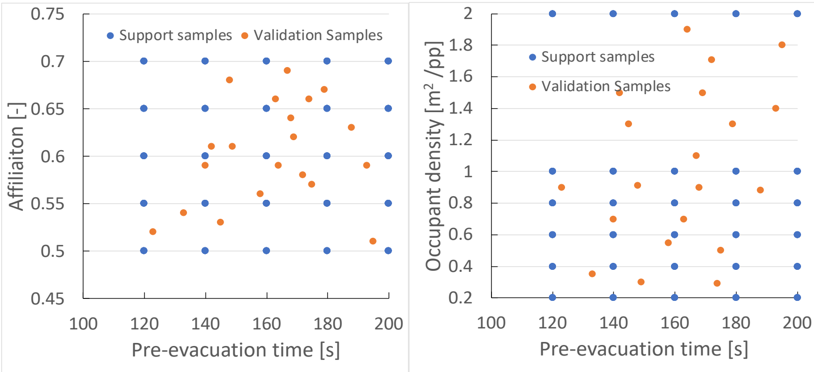


Figure VI.21: DoE input samples for the considered variables.

The support samples are evaluated by means of the evacuation tool Pathfinder [16]. After evaluation of the support samples, the RSM is generated and the set of validation samples are estimated. In Figure VI.22, an example of an evacuation simulation is presented.

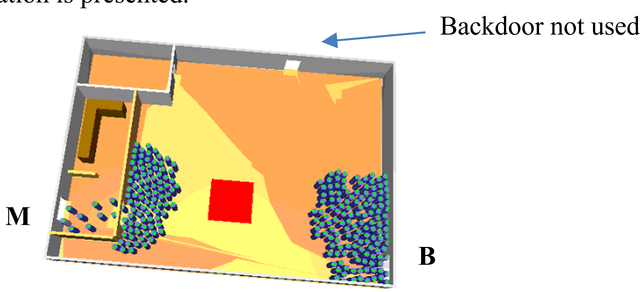


Figure VI.22: Pathfinder simulation example.

For the simple case, only two exits are chosen: the main (M) and back (B) exit. For the challenging case, four exits are chosen: A, B, C and D (Figure VI.23).

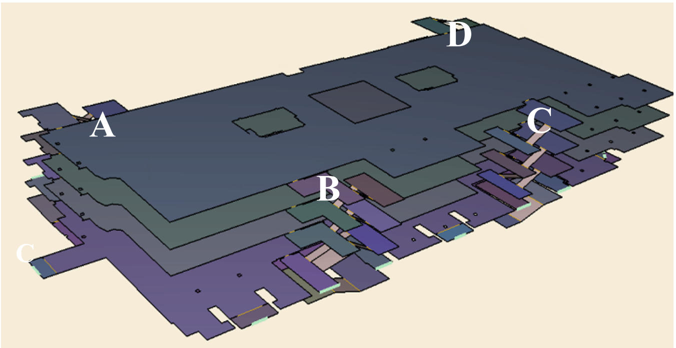


Figure VI.23: Evacuation model challenging case.

VI.5.2.2 Performance criteria

Similar to the RSM for smoke spread, a response surface evacuation model is considered acceptable if the absolute value of the mean error and the spread of the error is lower than 5% [21].

VI.5.2.3 Results

The results are presented in terms of FID values. In Figure VI.24, an example of the simple configuration is given. The predictive capability of the model is visualised for one of the 20 validation cases by means of the FID values for every person. The FID approximations are analysed and presented in ascending order for every exit separately. This means two curves for the simple case and four for the challenging case are considered. The presented sample in the figure is for the combination: pre-movement time 140 s, affiliation = 0.59 and an occupant density of 0.87 m2/pp. The blue line is the real value obtained from the validation set and the red line is the estimated value obtained by the RSM. The figures show good agreement between the estimated values based on the developed response surface and the validation set.

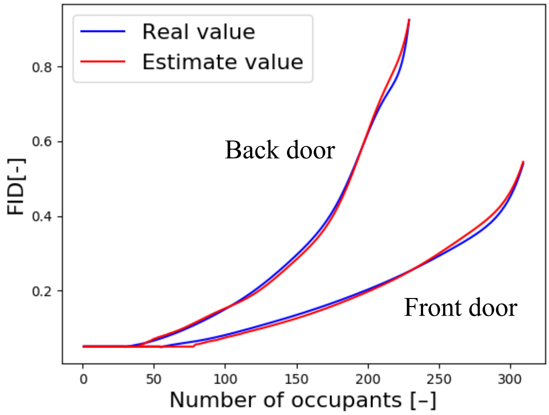


Figure VI.24: FID estimation for the main exit and back exit.

To analyse the performance of the prediction, the model uncertainty is calculated. Both the simplified and the Eurocode approach are applied, as discussed in part 2.3, for the mean error calculation between the estimated set and the validation set for all the 40 validation cases and every occupant.

Considering the errors as normally distributed variables, the mean and standard deviation of the relative error are calculated as 0.59 % for the mean and 3.64 % for the standard deviation. The errors are only calculated for FID values > 0.3.

The uncertainty model error is also calculated according to the Eurocode. For b, the best fit of the slope of the regression of FID_e in function of FID_t, the following is obtained:

$$b = \frac{\sum FID_e FID_t}{\sum FID_t^2} = 1.00217 \tag{VI10}$$

The estimated value of σ_Δ:

$$s_\Delta^2 = \frac{1}{n-1}\sum_{i=1}^{n}(\Delta_i - \bar{\Delta})^2 = 1.74 * 10^{-6} \tag{VI.11}$$

The coefficient of variation is calculated by the following equation:

$$V_\delta = \sqrt{\exp(s_\Delta^2) - 1} = 0.00132 \tag{VI.12}$$

The mean value is calculated:

$$\mu_X = \frac{1}{n}\sum_{i=1}^{n}\Delta_i = 1.0039 \tag{VI.13}$$

Moreover, the mean and STD lognormal of error are calculated by the following equation:

$$\sigma_{\ln X} = \sqrt{\ln\left({V_x}^2 + 1\right)} = 0.00132 \tag{VI.14}$$

$$\mu_{\ln X} = E(\ln X) = \ln \mu_X - \frac{1}{2}\sigma_{\ln X}^2 = \ 0.0039 \tag{VI.15}$$

From the obtained error value, a lognormal mean error of 0.0039 and lognormal STD of 0.00132 for all validation cases are observed. The mean error is 1.0039 and the STD is 0.0364. The results for all occupants and validation scenarios are presented in Figure VI.25. The black line presented the average error slope. The red line represents the 99.7% confidence interval of the average error. The closer the value is to unity, the better the agreement between the RSM model estimation and the simulation result.

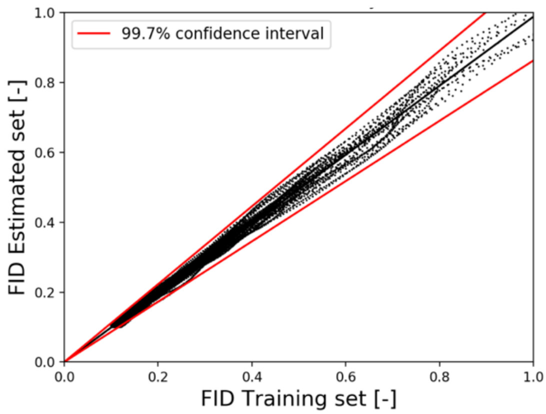


Figure VI.25: Representation of the model uncertainty by the $r_i - r_e$ diagram for the simple case validation set.

The results for the challenging case with one floor (upper floor) are in the same trend with respect to the simple case. An example case is presented in Figure VI.26.

Figure VI.26: Evacuation simulation for the challenging case of one floor.

The results for one validation case is presented in Figure VI.27. Four curves are depicted because four exits are implemented. Two exits show higher values due to the difference in affiliation and therefore more occupants are appointed to the main exits. For this case 65% of the occupants are assigned towards the main staircases A and B.

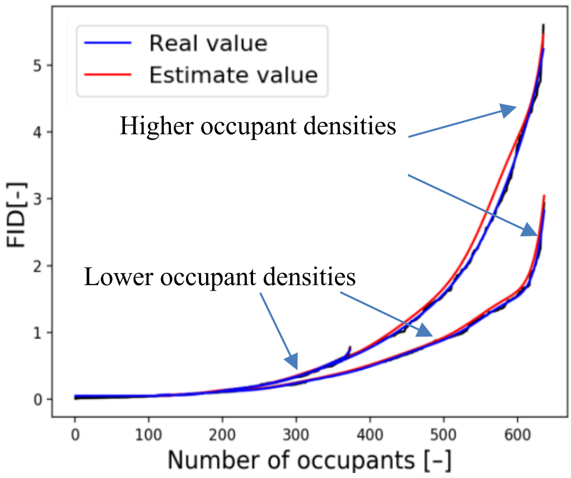


Figure VI.27: FID values of one validation set for the challenging configuration with one floor.

Considering the errors as normally distributed variables, the mean and standard deviation of the relative error are calculated: 1.57 % for the mean and 4.98 % for the standard deviation are obtained for FID values larger than 0.3. Values lower than 0.3 are not considered relevant for the analysis.

From the obtained error calculation according to the European standard, a lognormal mean error of 0.00972 and lognormal STD of 0.00246 is calculated. Based on these results, the mean is 1.011 and the STD is 0.052. The results for the support and validation scenarios are presented in Figure VI.28.

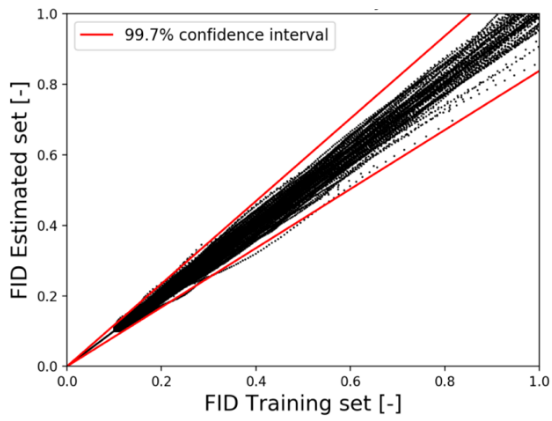


Figure VI.28: Representation of the model uncertainty by the $r_i - r_e$ diagram for the challenging case validation set (one floor).

The results for the challenging case with multiple floors are in the same trend with respect to the other cases. Considering the errors as normally distributed variables, the mean and standard deviation of the relative error are calculated as 0.82 % for the mean and 2.50 % for the standard deviation are obtained for FID values larger than 0.3.

From the obtained error value calculation according to the European standard, a lognormal mean error of 0.004 and lognormal STD of 0.0249 is determined. Based on these results, the normal mean is 1.0043 and the normal STD is 0.024. The result for all occupants and validation scenarios are presented in Figure VI.29.

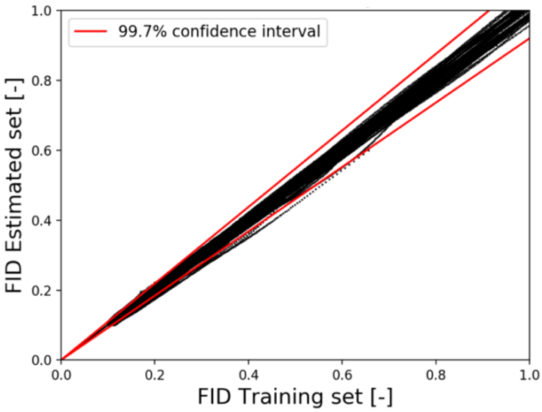


Figure VI.29: Representation of the model uncertainty by the $r_i - r_e$ diagram for the challenging case validation set (multiple floors).

VI.5.2.4 Limitations of the model

An additional analysis is performed to study possible limitations of the RSM. Three specific circumstances are analysed: scenarios with low occupant densities, exits close to each other and a reduced number of support samples.

In the scenario with low occupant densities, the same conditions are applied as in Table VI.3. Only the occupant density is reduced with occupancies between 5 and 20 pp /m^2. 40 validation cases are performed of which the best and worst results are selected and presented in Figure VI.30. The validation case 11 shows better agreement than case 16. It gives a good confirmation of the model limitations, since the validation case 16 has a lower occupant density than case 11.

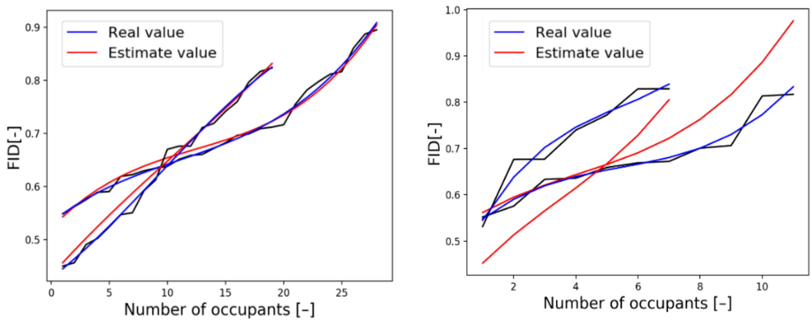


Figure VI.30: The FID results of validation cases 11 and 16.

Similar to the other validation cases, the model uncertainty is calculated. Considering the errors as normally distributed variables, the mean and standard deviation of the relative error are calculated as -2.66 % % for the mean and 8.27 % for the standard deviation are obtained for FID values larger than 0.3. From the obtained error value calculation according to the European standard, a lognormal mean error of -0.0045 and lognormal STD of 0.0889 is determined. Based on these results, the normal mean is 0.999 and the normal STD is 0.089. The result for all occupants and validation scenarios are presented in Figure VI.31. the results show a higher spread than for the original cases. This means that the RSM is less suitable for low densities.

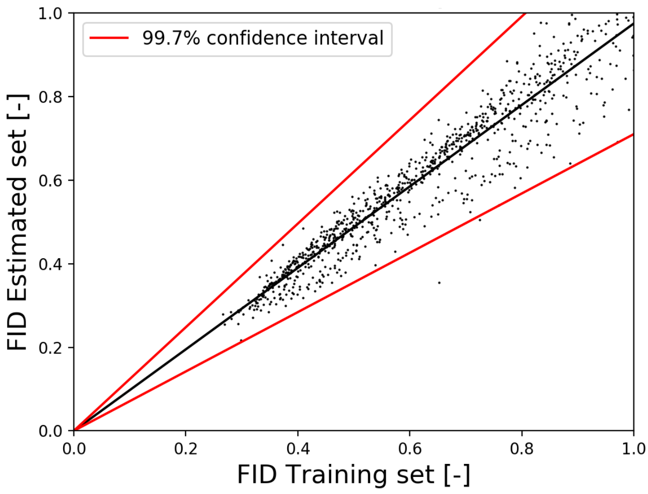


Figure VI.31: Representation of the model uncertainty by the $r_i - r_e$ diagram for the simple case validation set (first limitation analysis).

In the scenario with adjacent exits, the same conditions are applied as in Table VI.3. Only in this case, two exits are placed next to each other (Figure VI.32).

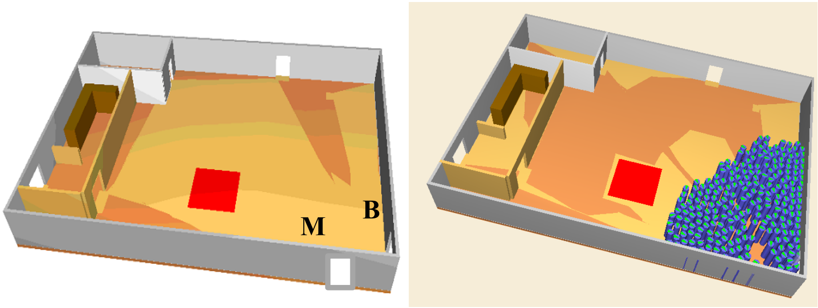


Figure VI.32: (Left) The simulation geometry of adjacent case study and (Right) an example of a simulation.

An example of one of the simulations is shown in Figure VI.32. 40 validation cases are performed of which the best and worst results are selected and presented in Figure VI.33. Both results show good agreement with the validation cases.

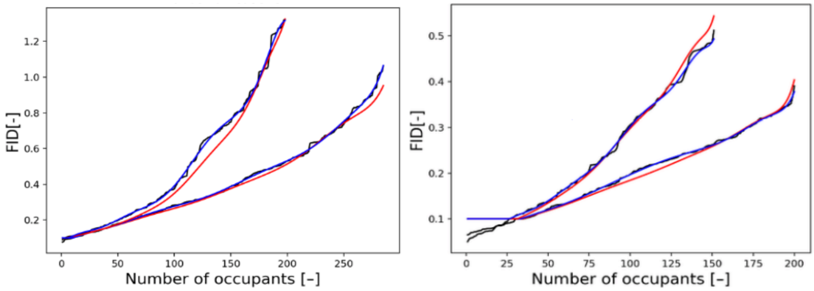


Figure VI.33: FID results validation case 5 and 14 for the adjacent door case.

Similar to the other validation cases, the model uncertainty is calculated. Considering the errors as normally distributed variables, the mean and standard deviation of the relative error are calculated as 1.3% for the mean and 7.93 % for the standard deviation are obtained for FID values larger than 0.3.

From the obtained error value calculation according to the European standard, a lognormal mean error of -0.0024 and lognormal STD of 0.189 is determined. The result for all occupants and validation scenarios are presented in Figure VI.34. The results show a higher spread than for the original cases.

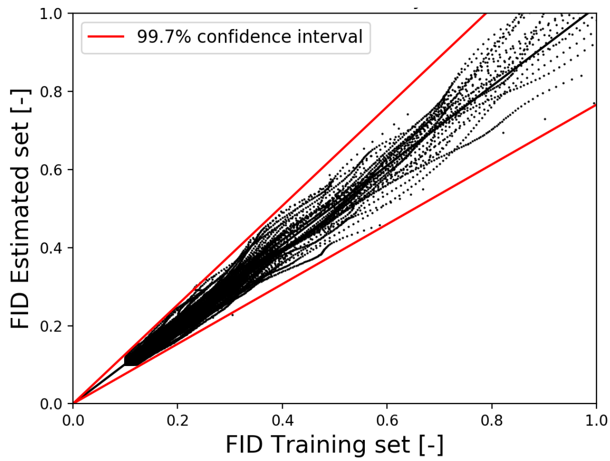


Figure VI.34: Representation of the model uncertainty by the $r_i - r_e$ diagram for the simple case validation set (second limitation analysis).

In the scenario with less support points, the same conditions are applied as in Table VI.3. The only difference is that less support points are assigned to the case. Instead of 5^3 only 3^3 support samples applied (Figure VI.35).

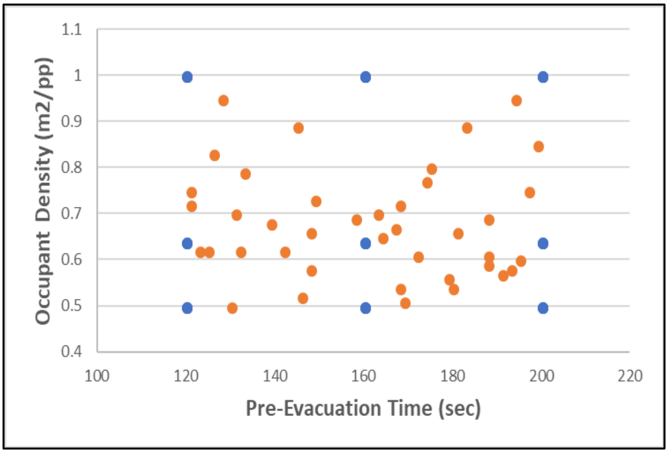


Figure VI.35: DoE for the combination of pre-evacuation time and OD for the sample case with less support points.

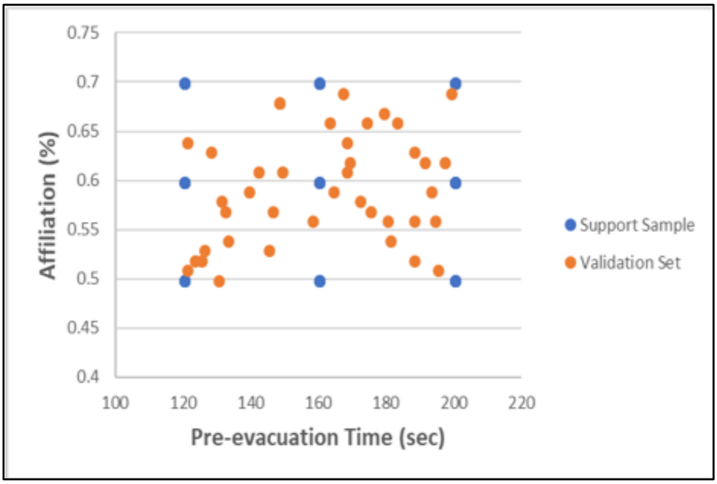


Figure VI.36: DoE for the combination of pre-evacuation time and OD for the sample case with less support points.

40 validation cases are performed of which the best and worst results are selected and presented in Figure VI.37. Both results show good agreement with the validation cases.

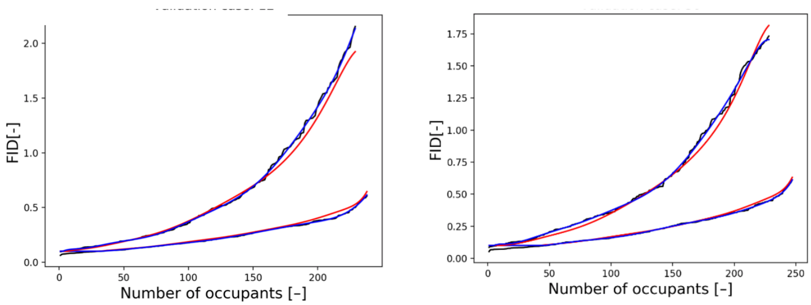


Figure VI.37: FID-results for case 12 and 30 for the sample case with less support points.

Similar to the other validation cases, the model uncertainty is calculated. The normal parameters are calculated: a mean relative model error of 0.74 % and a STD of 4.95 % are obtained for FID values > 0.3. Next, the lognormal parameters are calculated, a mean error of 0.0104 and an STD of 0.0588 is obtained. The result for all occupants and validation scenarios are presented in Figure VI.38. The results show a higher spread than for the original cases.

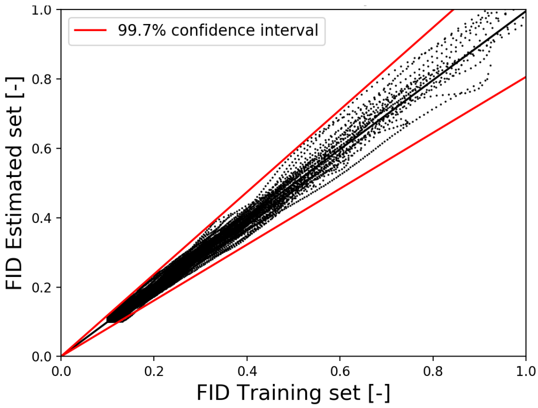


Figure VI.38: Representation of the model uncertainty by the $r_i - r_e$ diagram for the simple case validation set (third limitation analysis).

VI.5.2.5 Discussion

The analysis of this part was limited to the possibility of using RSM algorithm for evacuation parameters to predict the FID value of the simulation results in the context of life safety analysis. The validation analysis is done to find out the accuracy of RSM algorithm model in predicting the simulation result. Therefore, relative errors are analysed and represent the level of accuracy of the RSM model. The mean and STD of error for all cases are presented in Table VI.5.

Table VI.5: The mean and STD of the relative error of simple and challenging cases.

Simple case		Challenging case one floor		Challenging case multiple floors	
μ	σ	μ	σ	μ	σ
0.59%	3.64 %	1.57%	4.98%	0.82%	2.5%

The results obtained in the three cases gives similar errors with respect to their complexity. The simple case gives lower relative errors than the challenging cases. From these results it can be concluded that more complex designs give higher errors. However, the same trend is not observed between the challenging cases of one and multiple floors. The error for one floor is higher than that for multiple floors. It is expected that this outcome can be allocated to the difference in occupant load. The higher occupant load gives better results because the results are smoothened by a larger number of occupants for each exit.

With respect to the performance criteria, all three validation cases pass the 5% criterion. This means that the proposed approach is suited for the analysed cases.

Further analyses were performed to explore the possible limitations of the model. Three limitation cases are analysed for the simple geometry. The results are summarized in Table VI.6.

Table VI.6: The mean and STD of the relative error for the sample case with less support points.

Low Density of Occupant		Adjacent Exit		Less Support Point	
μ	σ	μ	σ	μ	σ
-2.66%	8.27%	1.30%	7.93%	0.74%	4.95%

The results show that the methodology is less suitable from lower occupancy loads and when exits are close to each other. The results when less support points are applied are within the pre-defined error criterion. This means that for the simple case, even less support points could be used.

VI.5.3 Validation of probabilistic representation of fire location in a building

Further, a validation of the probabilistic modelling for smoke spread is performed for the challenging case. More in particular, the focus is put on the necessary number of fire locations for obtaining a probabilistic representation of possible fire locations in the building. The objective is to find the minimum number of fire locations to obtain a sufficient accurate representation of the possible fire locations. The results are compared in terms of FID values.

VI.5.3.1 Method and analysis

The influence of the variability of the fire location is analysed by choosing different fire locations on multiple floors. Nine fire locations for each floor are analysed (Figure VI.39). No variability of other parameters in the smoke spread and evacuation model is considered. Therefore, only one sample set of fire parameters is applied: α = 0.046, HRRPUA = 400 kW/m2 and Amax = 16 m2 and evaluated by means of FDS 6.1.1. For the evacuation variables, also one sample set is applied: pre-movement time = 220 s, affiliation = 0.5, and 0.3 m^2/pp and evaluated by Pathfinder 2018. A constant CO-yield of 0.09 g/g is considered.

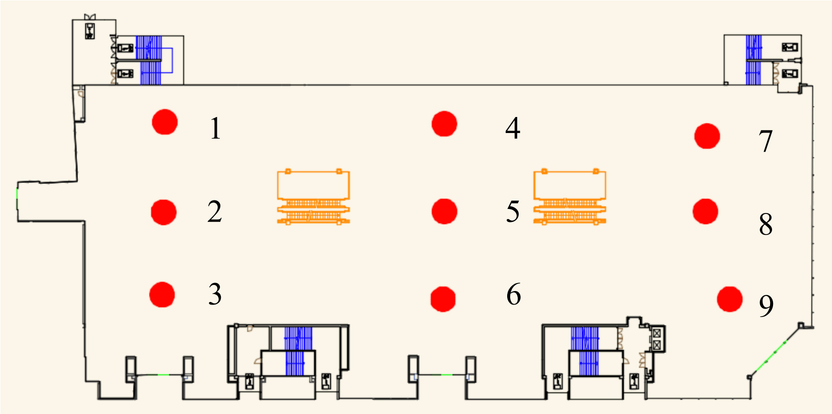


Figure VI.39: Schematic representation of fire locations in the challenging case study.

The analysis consists of nine scenarios in which the first scenario is considered as the reference scenario. In the following scenarios multiple fire locations are omitted from the analysis until only one location is left. The configurations are described in Table VI.7. The choice of omitting particular scenarios is because it is expected that interpolation will be more accurate forward than extrapolation [25].

Table VI.7: Fire location configurations.

Scenario	# Sim	Floors	Location
1	45	1-5	1-9
2	30	1-5	1-6
3	15	1-5	2,5,8
4	10	1-5	2,5
5	9	1,3,5	2,5,8
6	6	1,3,5	2,5
7	5	1-5	5
8	2	1,5	5
9	1	3	5

VI.5.3.2 Performance criteria

Similar to the other validation cases, The representation is considered acceptable if the absolute value of the mean error and the spread of the error is lower than 5% [21] with respect to the reference scenario.

VI.5.3.3 Results

The simulations are analysed in terms of FID values. In Figure VI.40, the obtained results present the number of occupants with the corresponding FID value or higher.

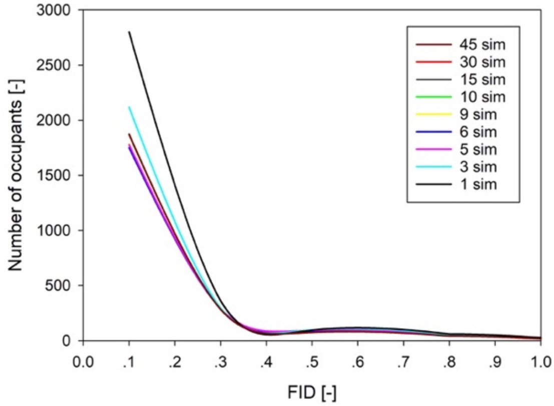


Figure VI.40: FID results for the nine scenario configurations.

The results of the scenario cases are compared with the reference case of 45 simulations. The relative error with respect to the number of occupants with FID values equal or higher than the corresponding value is determined and presented in Figure VI.41.

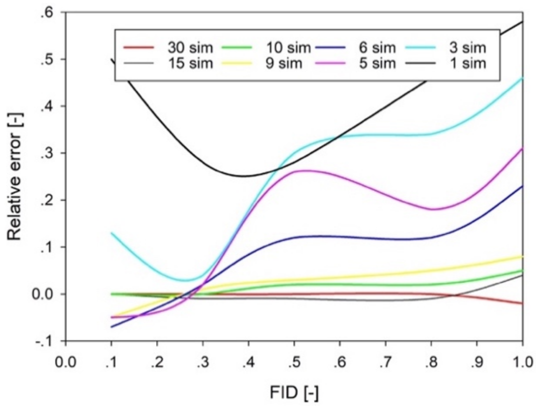


Figure VI.41: FID estimation error relative to the reference scenario.

VI.5.3.4 Discussion

The results of the analysis show the applicability of reducing the necessary number of fire locations for the probabilistic fire representation in shopping mall building. The results show that the reduction from 45 to minimum 10 simulations provides accuracy errors of less than 5%. What can be established from these results is the necessity of the analysis of fire simulations on each floor for proper representation of fire through the building.

VI.6 Conclusions

In this chapter, extensive verification and validation of the full-probabilistic and simplified model has been performed. Through a set of verification tests, the model proves able to give a good representation of the modelling accuracy of the RSM and evacuation submodel of the simplified risk model. Overall, the verification and validation tests show good agreement between the theoretical and the simulation cases.

There are still more components that should be tested before this model can be used for design purposes. More specifically, additional validation should be performed for the evacuation network model.

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CHAPTER VII

Case studies

VII.1 Introduction

In this chapter, the probabilistic risk assessment methodology is tested against the two case studies discussed in chapter V. The purpose is to test the validity and feasibility of the full and the simplified QRA method for practical projects. The first case study is the simple case that embodies the configuration of an assembly hall and serves as a night club. This case is used as a first step to analyse the shortcomings of the method before continuing towards larger and more complicated projects. The second case study, the more challenging case study of a multi-storey shopping mall, is used to analyse how the method deals with more complicated configurations. For both case studies, the extensive and simplified QRA method are applied, the results are compared and discussed. Since the QRA method is developed for these types of projects, it is important to analyse shortcomings and make suggestions for further improvements.

A remarque should be made with respect to the comparison of the comprehensive and simplified method. The models used in the comprehensive method are seen as most advanced models in FSE. Although that these models have their uncertainty and error, the results obtained from these models are typically considered as true values (at least in Belgium) for fire safety design. Therefore, when comparing these advanced models with other models, the term error is used rather than uncertainty.

VII.2 Case study 1: Assembly hall

In this section, the extensive and simplified QRA-method is applied to a simple building configuration. Since both methods apply the same procedure with different sub-models, the case study details are explained once, for the full QRA method. Only the results and modifications are discussed for the simplified method.

VII.2.1 Comprehensive QRA analysis

The probabilistic QRA method is applied to the assembly hall validation case discussed in Chapter VI (step 1). The main purpose is to investigate the feasibility and efficiency of the framework for a simple case study. The goal (step 2) of the QRA analysis is to determine the life safety level of the building in case of fire. The defined risk criteria (step 3) are threefold and will be explained in Chapter VIII. The first objective is defined in terms of a failure probability of 10^{-4} fatalities per year for the entire building [1]. The second objective is expressed as an acceptable individual risk of 10^{-6} fatalities per individual per year [1]. The third objective is defined in terms of the societal risk. The acceptable societal risk level is presented by an FN-curve and obtained from Chapter VIII with starting point 10^{-5} for N = 1, with a slope of -1. No ALARP criterion is defined.

In step 4, the fire safety design is developed. The building is considered as one compartment and the main passive fire safety components have a fire rating of R60 and two exits doors of 80 cm width (left and right). The upper door is only used by staff. The main active fire components are smoke detection, fire alarm and sprinkler system. The safety systems are designed according to the Belgian and European standards [2,3]. The procedure with respect to detection provides a 60 s delay before activation of the alarm. One fire safety design is analysed with three reliability levels for the implemented sprinkler system. For the first design, a high maintenance and inspection level is considered. For the second, a low maintenance level is implemented. The third fire safety design does not have a sprinkler system.

In step 5, the probabilistic and deterministic analysis are performed. In step 5.1 of the probabilistic analysis, the main design fire scenarios are defined. Four fire scenarios are considered (Figure VII.1): in the main room (1), the VIP room (2), a hidden fire in the storage room (3) and the cloakroom (4).

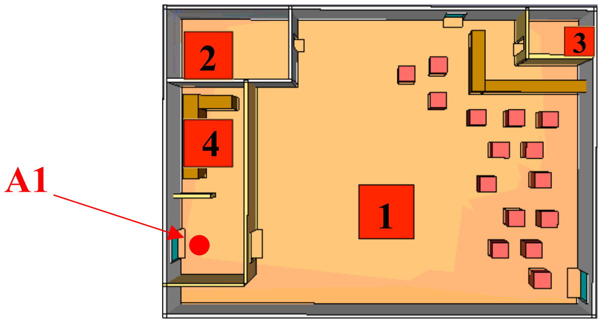

Figure VII.1: Plan view of the assembly hall.

In step 5.2, the most important input variables are defined. The variables reported in Table IV.1 are adopted for the case study. In step 5.3, the event tree is constructed based on the location of the fire and on the performance of the active fire protection systems. A simplified version of the location, alarm, detection and sprinkler performance is presented in Figure VII.2.

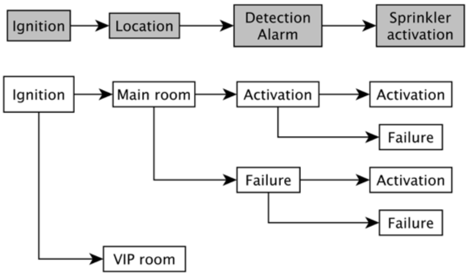

Figure VII.2: Part of the event tree of the simple case study.

An initial ignition frequency of 0.00194 fires per year is assumed [4]. The reliability data used for the sprinkler system with high maintenance is 0.95 and for low maintenance quality 0.6 [5]. The probability of fire occurrence in the four rooms is assigned according to the surface of each room in comparison to the total building area.

In step 5.4, the RSM is defined and in step 5.5, the support points are generated. The sample set suggested in Table IV.4 is analysed by means of the smoke spread model FDS version 6 [6] in step 5.6. In case of the simplified method, the analysis is performed by means of a zone model [7]. After evaluation of the support samples, the smoke spread RSM is generated (step 5.7). In Figure VII.3, an example of the RSM for the smoke spread is presented. The results are depicted for CO concentrations in front of exit 1 (point A1 in Figure VII.1) at 450 s after ignition (t_0). At this point, the fire and evacuation are at full development. For visualisation, the variables fire growth area and maximum fire area, which are considered the most sensitive [8], are shown, while the HRRPUA is kept constant at 450 kW/m^2 (average value) because the former two variables are considered the most sensitive [9]. A convergence analysis is performed and showed that no additional sample points were necessary because the calculated convergence error was below the pre-defined criterion of 10%.

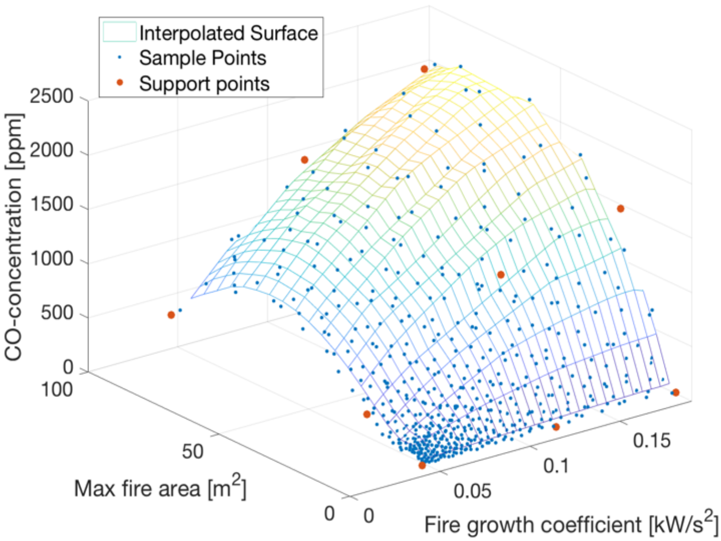

Figure VII.3: Smoke spread RSM of CO concentrations at 450 s at location A1 at 2.0 m height.

Next, the Design of Experiments (DoE) is conducted to obtain a uniform representation of the analysed input domain (step 5.8). For each scenario 100 samples are generated and simulated in step 5.9 (blue points in Figure VII.3). The results are provided as input for the evacuation analysis (loop to step 5). The support points for the evacuation RSM are generated based on Table IV.4 (step 5.5). The samples are analysed by means of the evacuation model Pathfinder (step 5.6). Next, the concentrations are linked to the occupant locations and doses are calculated for every occupant and scenario sample. At the same moment, the DoE is generated for the consequence analysis in step 5.8 and together with the toxicity dosages, evaluated in step 5.9. Hereafter, the system loops back to step 5.7, in which the RSM, generated for the evacuation input parameters, is implemented. In Figure VII.4, the application of the RSM for the evacuation sub-model is visualised. The results are depicted for CO concentrations in front of the main exit at 450 s. The variables 'affiliation to the main exit' and 'occupant density' are analysed, while the fire parameters are kept constant for each fire scenario.

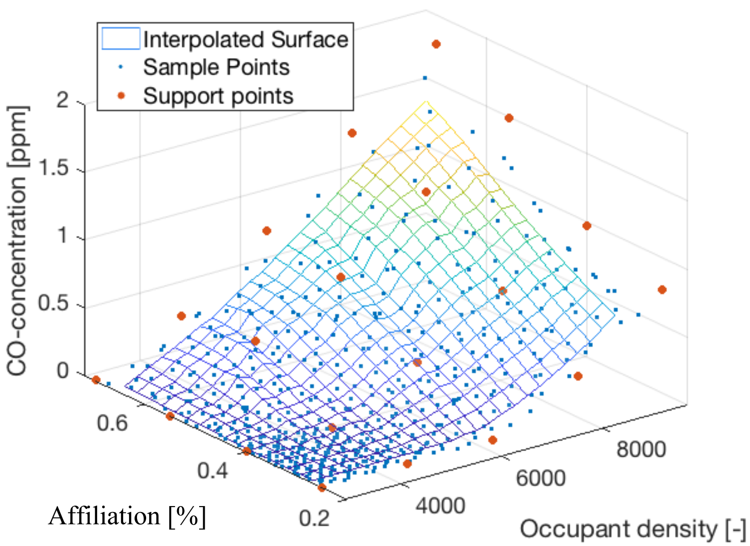

Figure VII.4: Representation of the evacuation RSM of CO concentrations at 450 s in front of the main door.

In step 5.8 the DoE of 100 samples is generated for the evacuation analysis and the responses are obtained in step 5.9. In Figure VII.5, the range of results of the support points is given for a particular scenario with a fixed number of occupants.

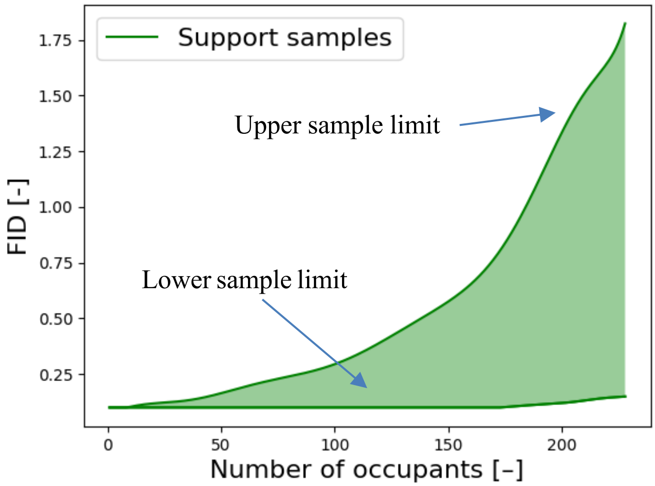

Figure VII.5: Range of results of the support points.

In step 5.10, the probability of fatality is calculated for every scenario and in step 5.11 the final probability of fatality and risk are calculated. The results obtained for the probability of fatality and the individual risk are presented in Table VII.1. The results show that the three safety levels are within the pre-defined acceptable safety limits. The probability of fatality is in increasing order due to the decreasing reliability of the sprinkler system. The individual risk is lower than the probability of fatality because the probability of having a fatality in a group is higher than having a fatality as an individual.

Table VII.1: Results simplified method for the probability of fatality (P_f) and the individual risk (IR).

Option	Fire safety design	P_f [1/yr]	IR [1/yr]
1	High maintenance level	$5.3 * 10^{-8}$	$2.5 * 10^{-8}$
2	Low maintenance level	$3.9 * 10^{-7}$	$2.3 * 10^{-7}$
3	No sprinkler	$8.8 * 10^{-7}$	$4.8 * 10^{-7}$
-	Acceptable limit	10^{-4}	10^{-6}

In Figure VII.6, the societal risk is presented in terms of an FN curve. The results show the difference between the two safety levels, which indicate the importance of reliability assessment with respect to maintenance and inspection in the overall risk assessment. The FN curves shift vertically because only the frequencies change for this case. Further, an additional reduction of the safety level can be observed when no sprinkler system is implemented.

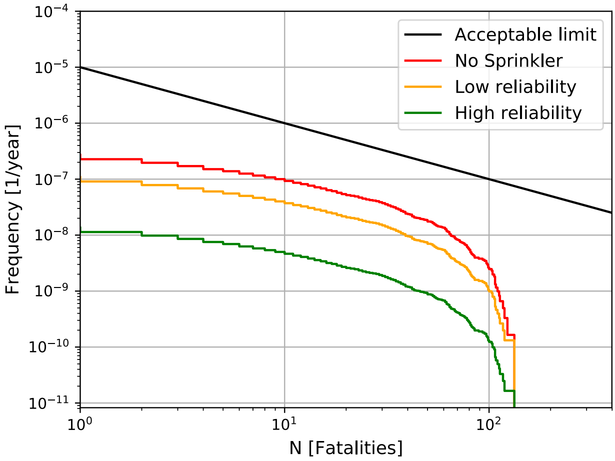

Figure VII.6: FN curves for the different fire safety designs.

VII.2.2 Simplified QRA method

The simplified QRA method is applied on the assembly hall building through the same framework. Only different sub-models for smoke spread and evacuation are implemented (see Chapter V). In Figure VII.7, the smoke spread and evacuation models are depicted.

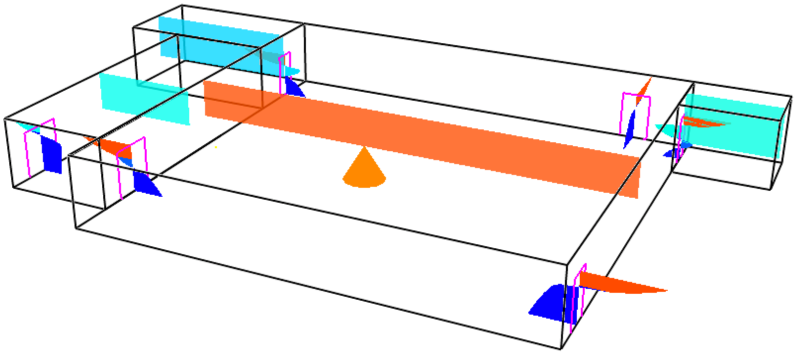

Figure VII.7: Representation of the simplified geometry in B-RISK.

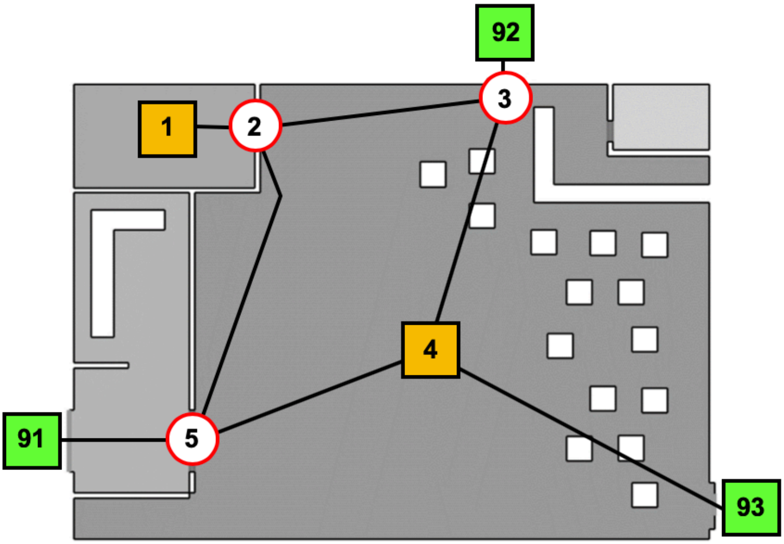

Figure VII.8: Representation of the simplified geometry in the evacuation network model.

The results for the individual risk and probability of fatality are presented in Table VII.2. The results illustrate that, similarly to the comprehensive method, the obtained safety levels are within the pre-defined acceptable safety limits.

Table VII.2: Case study results for the probability of fatality (P_f) and the individual risk (IR).

Option	Fire safety design	P_f [1/yr]	IR [1/yr]
1	High maintenance level	$5.6 * 10^{-7}$	$3.0 * 10^{-10}$
2	Low maintenance level	$4.1 * 10^{-6}$	$1.4 * 10^{-9}$
3	No sprinkler	$9.0 * 10^{-6}$	$1.0 * 10^{-8}$
-	Acceptable limit	10^{-4}	10^{-6}

In Figure VII.9, the societal risk is presented in terms of an FN curve. Similarly to the comprehensive analysis, the results depict expected differences and are below the acceptable criterium.

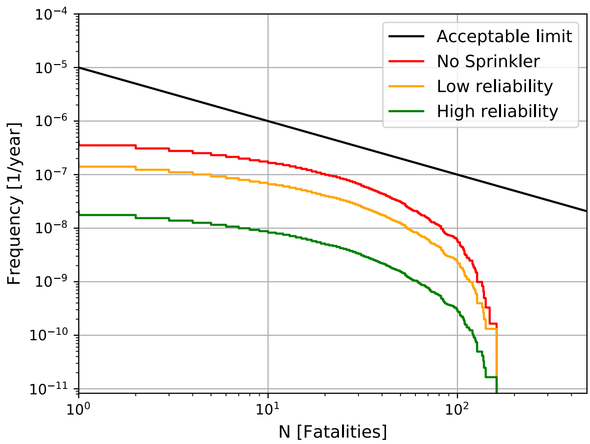

Figure VII.9: FN curves for the different designs.

VII.2.3 Comparison and discussion

The analysis of both methods on the simple case show results that are very similar. Additionally, a systematic difference can be observed between the results of the simple and the comprehensive method. The fatality rates of the simplified method show higher values than the partially more accurate solution. It is observed that the differences are mainly due to the two-zone model overestimating the toxicity concentrations at the occupant inhalation height. A second reason is the more conservative approach if the evacuation network model is used. The evacuation times are slightly higher. In Figure VII.10, the six FN-curves are presented.

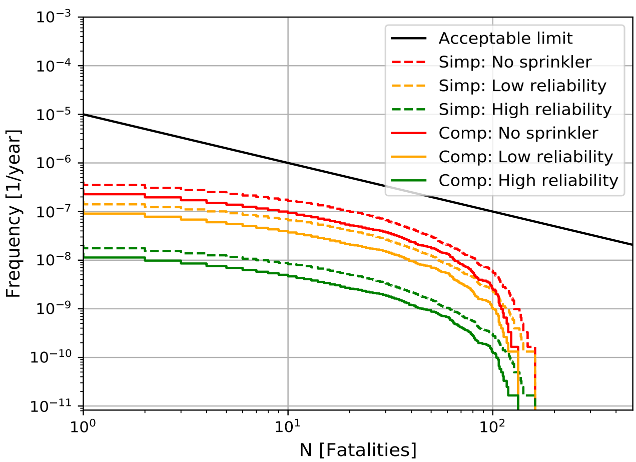

Figure VII.10: Results of the comprehensive and simplified method.

The probability of fatality for the two methods are repeated in Table VII.3 and the relative error for the two methods are calculated by means of eq. VI.1. The error varies between 7% and 15% and is higher for lower probabilities of fatality because these scenarios are more sensitive to variation. The differences between the values obtained with the two methods are small, so it can be concluded that the simplified method can be applied to simple cases. Moreover, the results provided by the simplified method are more conservative. This is consistently observed in other simple case studies. Therefore, it can be concluded that the simple method provides a good first estimate of the safety level.

Table VII.3: Probability of fatality for the simplified ($P_{f_{Full}}$) and comprehensive method ($P_{f_{Simpl}}$) for case study 1.

Option	Fire safety design	$P_{f_{Full}}$ [1/yr]	$P_{f_{Simpl}}$ [1/yr]	Error
1	High maintenance level	$5.3 * 10^{-8}$	$5.6 * 10^{-7}$	5%
2	Low maintenance level	$3.9 * 10^{-7}$	$4.1 * 10^{-6}$	4.5%
3	No sprinkler	$8.8 * 10^{-7}$	$9.0 * 10^{-6}$	2.9%

The results reveal that the fire risks of all the scenarios are below the acceptable limit, so that no sprinkler system would be necessary for the case at hand. This aligns with the Belgian regulatory framework, which requires no sprinkler system for the considered building configuration.

VII.3 Case study 2: Shopping mall

In this section, the QRA methods are applied to a more challenging building configuration. Similarly to the first case study, this case is explained completely for the detailed method and only the results are shown for the simplified analysis.

VII.3.1 Comprehensive QRA method

The QRA method is applied to the multi-purpose commercial building case study discussed in Chapter VI (step 1). The objective of this case study is to analyse the applicability of the model for this type of projects. No external influences (e.g., wind, fire brigade, etc.) or bottlenecks (e.g., merging flows, direct access to street, etc.) are taken into account. The building is considered to be occupied by customers (90%), who are not familiar with the building, and staff (10%), who are familiar with the building. The occupant density is presented in Table IV.1 and based on an average of 1 occupant per 5 m^2 [10]. The occupants are considered to have mean pre-evacuation times between 60 s and 120 s [10].

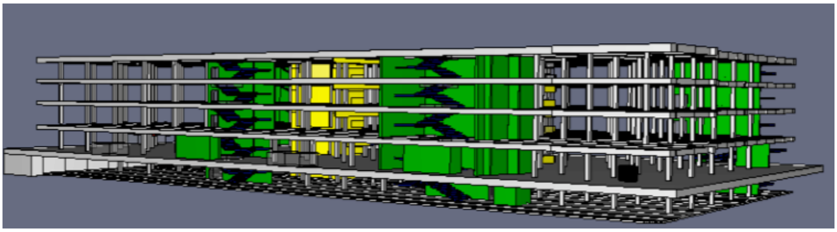

Figure VII.11: Model of the shopping mall.

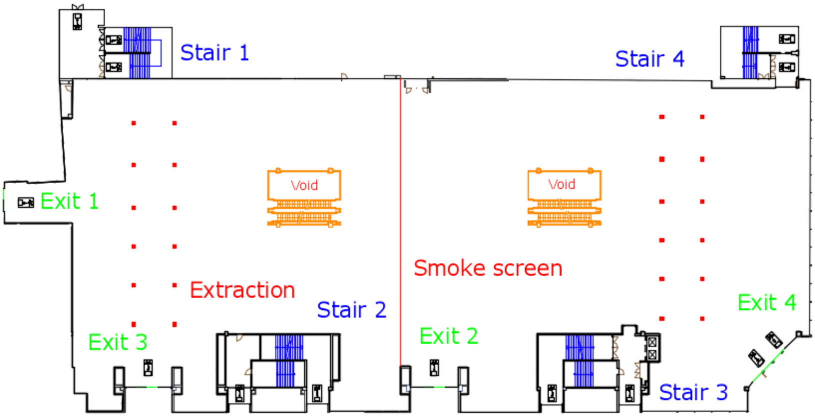

Figure VII.12: Ground plan of floor level 0 for option 1 (with sprinkler and SHC system). For more information see Chapter VI.

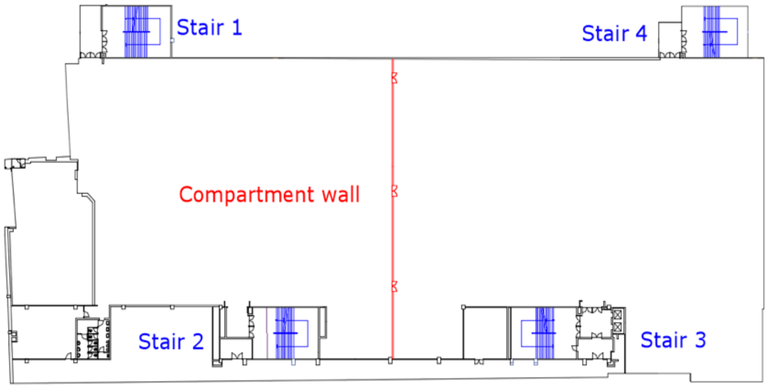

Figure VII.13: Ground plan of floor level 1 for option 2 with additional compartmentation.

The goal (step 2) of the QRA analysis is to determine life safety in case of fire. The same risk criteria for the probability of fatality, individual and societal risk are defined as in case study 1 (step 3).

In this case study, three developed fire safety designs (step 4) are analysed (step 5) and eventually evaluated against the pre-defined risk criteria (step 6). The first and the second option both follow the main considerations of the Belgian prescriptive requirements regarding passive and active fire safety systems for safe evacuation, fire rated elements and fire brigade assistance. The requirements are in analogy to other countries with a prescriptive framework (e.g., France, Netherlands, etc.). The three options have several common and different features. The common features are structural stability (R 60), compartmentation of staircases (EI 60), number and width of emergency exits, automatic smoke detection and standard alarm system. The alarm system is delayed by 120 s after initial detection. This method is typically applied in larger commercial buildings in Belgium and allows the security to confirm the fire and reduce the risk of false alarm.

The distinctive features of the different options relate to vertical compartmentation and active safety systems. More in detail, in the first option, all the floors are considered as a single compartment. The fire safety design consists of a smoke and heat control system (SHC) and a sprinkler system. The fire safety concept is designed according to the rules of good practice. The SHC system is designed in accordance with the EN12101-5 (Figure VII.12) and is composed of natural (1/3) and mechanical (2/3) air supply (mechanical front doors) and mechanical extraction of 60000 m^3/h of smoke, divided over multiple extraction points on the incident floor. Every floor is divided into two

SHC zones, separated by a fixed smokescreen. The sprinkler system is an ordinary hazard (OH) 3 installation in accordance with the NBN EN 12845 [3]. The reliability of the sprinkler system is considered 0.95. An ASET/RSET analysis is performed to evaluate the performance. In the second option, a complete prescriptive solution is designed: a sprinkler system is implemented, the floor levels are compartmented and every floor is divided in two compartments smaller than 2500 m^2 (Figure VII.13). The compartments are connected by three self-closing doors in case of fire. In the third option, the same fire safety design is applied as in option 1. However, no SHC system is implemented in this case. The purpose of this option is to determine the effect of the SHC-system on the safety level.

Next, the probabilistic and deterministic analysis are performed. In step 5.1 of the probabilistic analysis, the main design fire scenarios are defined. Three representative design scenarios are considered: a fire in the open commercial area (1); a fire in a small storage room (2); and a fire in the restaurant (3). In step 5.2, the most important input variables are defined. The variables discussed in Table IV.1 are adopted for the case study. For every first order parameter, the CDFs are presented for smoke spread in Figure 14-15, and for evacuation in Figure VII.16-17. On these figures, the adopted parameter values for traditional performance-based analysis tools (e.g. BS PD7974, C/VM2, CIBSE, etc.) are depicted to show the conservatism of these parameter values. The range of the arrow is the analysed domain in the probabilistic analysis. The figures show that most standards and guidelines use fixed parameters. These parameters are mostly situated towards the conservative side (right part of the figures) of the distribution with respect to the available literature. In this way, some kind of safety factor is taken into account in the parameters.

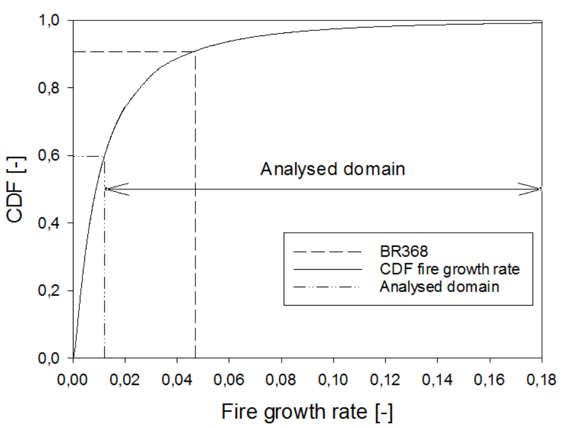

Figure VII.14: CDF of the fire growth rate.

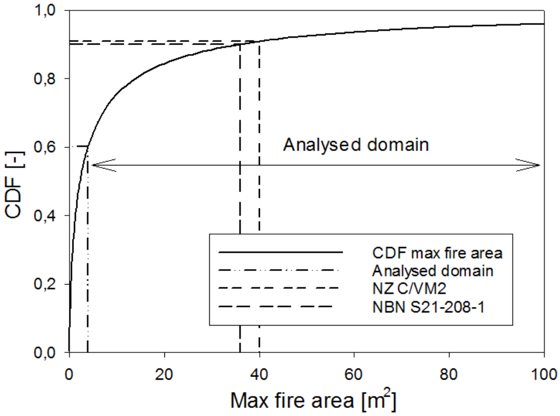

Figure VII.15: CDF of the maximum fire size.

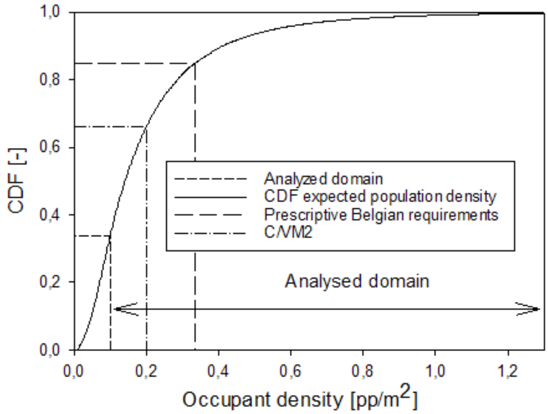

Figure VII.16: CDF of the occupant density.

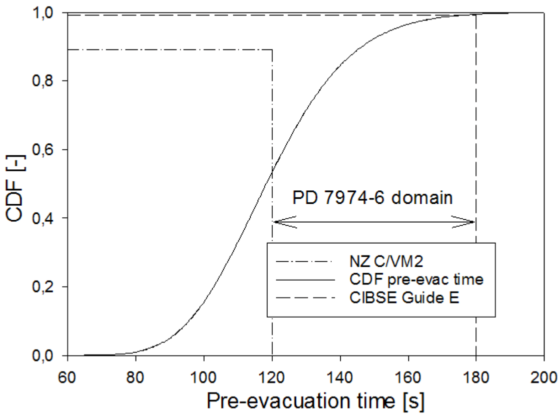

Figure VII.17: CDF of the pre-evacuation time.

The bow-tie model is generated for every design scenario (step 5.3). To construct the event tree, multiple pathway factors are considered: the location of the fire (5 floors, 3 zone and 2 room types room); sprinkler activation (activation and failure); SHC performance (activation, 50% activation, and total failure); detection (normal, sprinkler, and delayed); alarm performance (normal and delayed), and failure of passive systems (e.g., door shutter failure of self-closing door). The event tree is constructed similar to Figure VII.2. In total, 64 event tree scenarios are considered important to be analysed for the smoke spread RSM analysis. The other scenarios are only analysed for one combination of parameters. They are not analysed by means of RSM sensitivity because they are considered similar to one of the 64 scenarios (e.g., symmetrical configuration), not significant because of negligible consequences (e.g., sprinkler extinguishment, ect.) or can be interpolated (intermediate floors, etc.). An important boundary condition of the case study is that the staircases are considered smoke free during the evacuation for all scenarios. This is a limitation of the model because failure of a fire door causes smoke leakage into the staircase, which will have a major impact on the safety level.

An initial ignition frequency of 0.062 fires per year is taken into account [4]. The probability frequencies of the branch scenarios are determined by the combination of the probabilities of the pathway factors. These probabilities are obtained through fault tree analysis and analysis of historic data [5,11,12]. The probability data used in the case study is presented in Table IV.2. For the considered case study, the analysis is done with the provided PERT distributions.

In step 5.4, the PCE RSM is chosen for the case study because of its efficiency and high accuracy for the region of interest, namely the far field of fire. In step 5.5, the support points are generated. The sample set suggested in Table IV.4 is analysed by means of the smoke spread sub-model FDS version 6 [6] in step 5.6. In Figure VII.18, a cross-section of the smoke spread for a conservative fire scenario (α = 0.012 kw/s^2, HRRPUA = 450 kw/m^2, A_{max} = 100 m^2) is shown on the ground floor in the left part of the compartment at 250 s after ignition. At this moment, the smoke has already spread to all floors. In this scenario, an SHC-system is implemented and considered to have a reliability of 0.6 based on statistical data [5]. The smoke has spread to the other floors through the central openings relatively quickly.

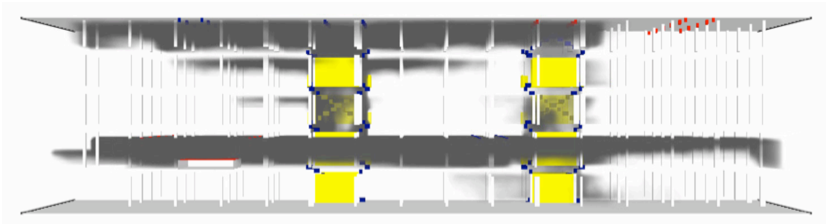

Figure VII.18: Smoke spread for a fire scenario on the ground floor.

After evaluation of the support samples, the smoke spread RSM is generated (step 5.7). The toxicity, temperature and radiation concentrations are calculated at multiple locations. In Figure VII.19, the resulting temperatures at 450 s (evacuation at full development) are depicted on the ground floor for the sample combination S1: $\alpha = 0.101$ kW/s^2, HRRPUA = 575 kW/m^{2,} and A_{max} = 88 m^2. The results show a clear separation of the floor into two SHC zones due to the fixed smoke curtain in the middle.

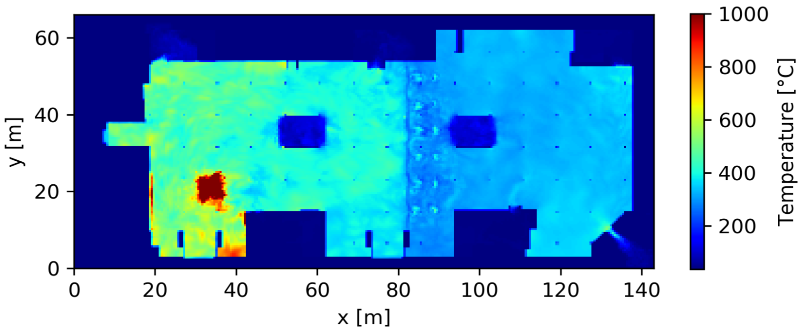

Figure VII.19: Estimated temperatures at 2.0 m above the ground floor for the sample combination S1 at 450 s.

A convergence analysis is performed to determine the accuracy of the RSM. In 90% of the cases when the RSM is applied, convergence (less than 10% error) was immediately achieved. In 9.5% of the cases only 1 or 2 additional samples were necessary and in other cases multiple extra samples were necessary. For one case close to the fire, 8 additional support points were necessary in order to achieve convergence. The analysis is shown in Figure VII.20 (blue line). The main reasons for the deferred convergence is due to the difficult flow patterns occurring in the scenario with a fire on the top floor in combination with the implementation of an SHC system. Additionally, a sensitivity analysis is performed to analyse the convergence rates of the PCE and the IMLS method. For the more turbulent regimes, the IMLS method has a significantly better convergence rate.

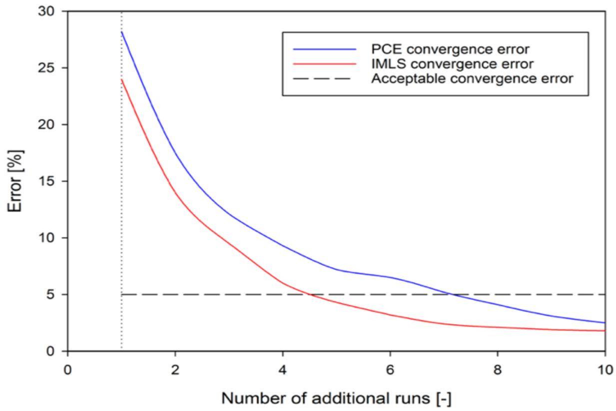

Figure VII.20: Convergence analysis of the PCE and IMLS smoke spread RSM for case design scenario 1.

Next, the DoE experiments are determined to obtain a uniform representation of the analysed domain (step 5.8). For each scenario 100 samples are generated and simulated in step 5.9. The results are provided as input for the evacuation analysis (loop to step 5.5). The support points for the evacuation RSM are generated (step 5.5). The sample is analysed by means of the evacuation model Pathfinder (step 5.6). In Figure VII.21, an evacuation simulation is depicted for a scenario with normal affiliation and high occupant density at 450 s after ignition. The scenario takes into account a fire on the ground floor.

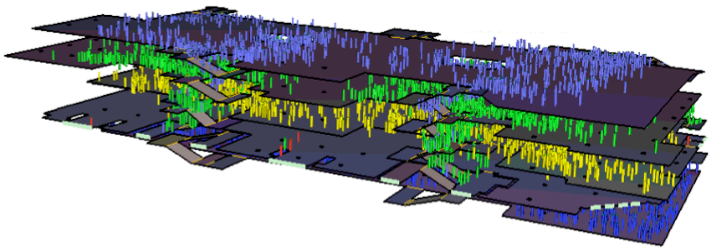

Figure VII.21: Location of the occupants for a fire on the ground floor at 450 s after ignition.

In order to increase the efficiency of the method, data is retained only at locations where occupants move. In Figure VII.22, an example is depicted of the agent occupation (yellow) on the ground floor for all evacuation scenarios and all time steps. The four stairs and four exits are visible. The figure reveals that many locations are not relevant for further analysis. This is an important aspect in terms of data allocation to reduce memory usage and to increase computational efficiency. During the probabilistic simulations it is observed that the computational time is reduced by a factor 2-5.

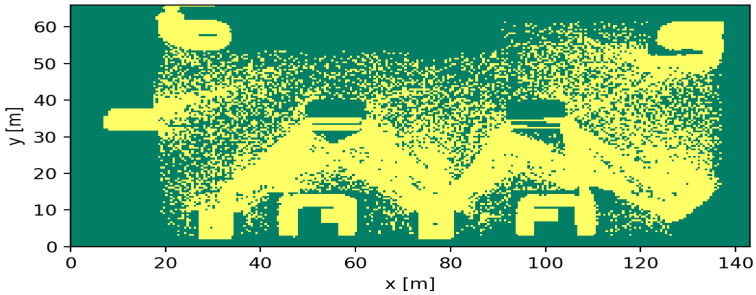

Figure VII.22: Indication of used locations (yellow) for evacuation on the ground floor.

After evaluation of the support samples of the evacuation analysis, the dosages are linked to the locations and the consequence output is calculated. The five remaining variables provided in Table IV.1 are implemented and the DOE experiments are generated to obtain a uniform representation of the analysed domain (step 5.8). It is only now that the DoE for probabilistic representation of the evacuation variables is generated and the evacuation RSM is applied to determine the output for the generated DoE. For each event tree scenario, a total of 100^3 (smoke spread, evacuation and consequence sub-model) samples are generated and analysed in step 5.9 by means of the analytical sub-model [13,14]. Similarly to the smoke spread sub-model, a convergence analysis is performed to determine the accuracy of the RSM.

In Figure VII.23, the results for two event tree scenarios are presented in terms of FID values. The results show that, within the analysed domain, most of the occupants are able to escape in smoke-free circumstances, which means that sample points are chosen at the safe side of the limit state. Secondly, some of the occupants obtain a FID value higher than 1, which means that multiple sample points are at the unsafe side of the limit state. The two event tree scenarios shown below depict different results because the limit state shifts, from left to right, due to the implementation of different safety systems, causing safer conditions. In the left figure more people are affected by smoke conditions. In the right figure, an SHC system is implemented increasing tenability conditions. A curve fitting analysis is performed (orange line Figure VII.23), for each event tree scenario, based on the Sum of Square Error (SSE) to determine the probability density function and the probability of fatality. For the left and right figure, a lognormal distribution is derived. The results are calculated for each event tree scenario and for the three fire safety designs.

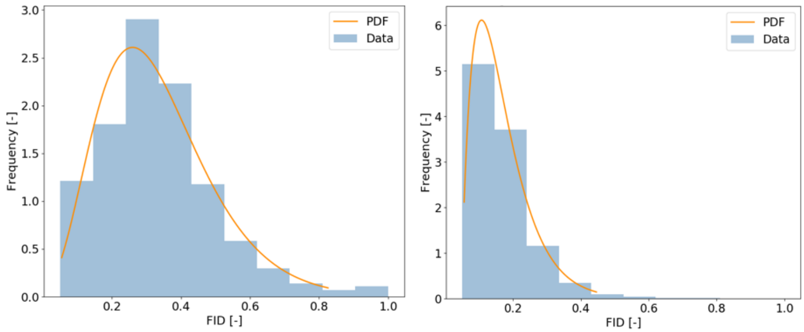

Figure VII.23: FID data and fitted PDF for two event tree scenarios.

In step 5.10, the probability of fatality is calculated for every scenario and in step 5.11 the final probability of fatality and risk are calculated. The results obtained for the probability of fatality and the individual risk are presented in Table VII.4. The results show that the three options are well within the pre-defined acceptable safety limits. The second option obtains the highest safety margin. The third option results in the lowest safety margin.

Table VII.4: Case study results for the probability of fatality (Pf) and the individual risk (IR).

Option	Fire safety design	Pf [1/yr]	IR [1/yr]
1	Sprinkler + SHC	$3.8 * 10^{-6}$	$2,1 * 10^{-7}$
2	Sprinkler + comp.	$9.9 * 10^{-7}$	$8.5 * 10^{-8}$
3	Sprinkler	$9.8 * 10^{-6}$	$7.8 * 10^{-7}$
-	Acceptable limit	10^{-4}	10^{-6}

In Figure VII.24, the societal risk is presented in terms of an FN curve. The three fire safety designs and acceptable limit are depicted. The three options are below the acceptable limit, which means that any of these designs can be selected. Option 2, with sprinklers and compartmentation, obtains the highest safety level, signifying that, for this case study, compartmentation with sprinklers provides a higher safety margin than a sprinkler system in combination with a SHC system. Two reasons can be formulated. The first reason for the higher impact of compartmentation is because fewer people are exposed to the smoke due to the physical separation of smoke from other sub-compartments and from the staircases in the model. This is also the reason why more fatalities can occur without compartmentation. Smoke spread in staircases due to door barrier failure is not taken into account. It is expected that the risk level will increase when failure of the smoke barriers that protect the staircase, is taken into account. Most likely, the effect of taking this additional fire scenario into account will not be equivalent for the three fire safety designs because the SHC will have an important role in avoiding of smoke spread in the staircases due to the creation of under pressure in the incident compartment. The second reason for the higher impact of the compartmentation is the low reliability of the SHC with respect to other safety systems. Increasing the reliability by reducing complexity or improving redundancy will increase the safety margin.

The final selection of the fire safety design can be further determined using a cost benefit analysis (life cycle cost) or in terms of functionality (open plan) and flexibility (changing walls). Other systems can be implemented to increase the safety level or omitted to increase functionality (alarm delay).

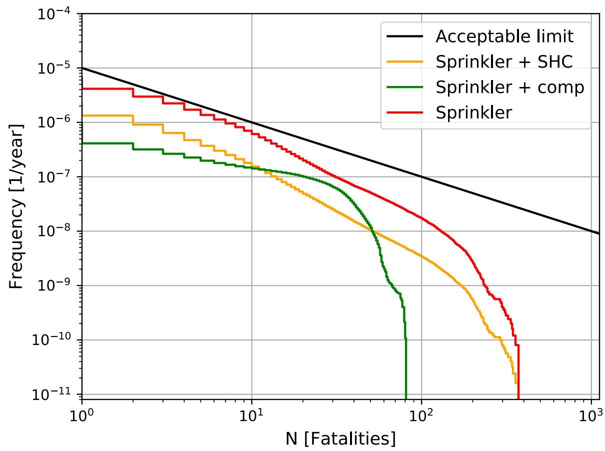

Figure VII.24: FN curves of the three fire safety designs for the comprehensive method.

An additional analysis is performed to analyse the equivalence of options 1 and 2. Both designs comply with the Belgian legislative framework. However, the designs show different safety levels. In order to obtain an equal safety level for both designs, option 1 can be reverse engineered to determine which reliability the SHC system leads to equivalence. In order to determine this safety level, the reliability of the SHC system is increased until the risk is equal for both fire safety designs. Basically, the probability of the event tree branch "Successful SHC" is increased and "SHC failure" is lowered until the risk level became equal. The visualisation of the equal safety level is shown in Figure VII.25. The orange FN curve shifted downwards. The red areas represent lower risk for option 1 and the green areas represent lower risk for option 2. A reliability of 0.88 was calculated, which is significantly higher than the originally assumed average reliability of 0.6. The higher reliability level can be achieved when important failure characteristics of the system are reduced (Table IV.2). Another possibility is to improve and optimize the SHC design with respect to the proposed standard to reduce the presence of toxic species and heat in the incident compartment. In this way, the consequences, instead of the frequencies, are reduced.

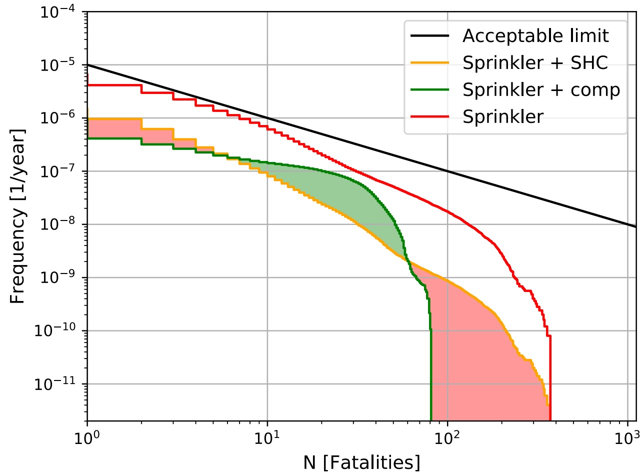

Figure VII.25: FN curves of the three fire safety designs with increased reliability of the SHC-system.

VII.3.2 Simplified QRA method

The simplified QRA method is applied through the same procedure with different sub-models for smoke spread and evacuation (see above). The representation of smoke spread in the zone model is presented in Figure VII.26.

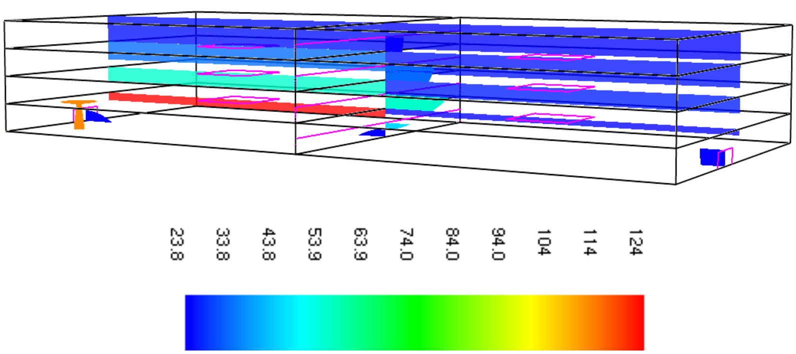

Figure VII.26: Representation of smoke spread by temperature distribution in the zone-model at 250 s.

The results for the individual risk and probability of fatality are presented in Table VII.5. These results illustrate that, for individual risk, the safety levels are within the pre-defined acceptable safety limits.

Table VII.5: Case study results for the probability of fatality (Pf) and the individual risk (IR).

Option	Fire safety design	Pf [-]	IR [-]
1	Sprinkler + SHC	$4.8 * 10^{-6}$	$5.1 * 10^{-7}$
2	Sprinkler + comp.	$1.5 * 10^{-6}$	$1.8 * 10^{-7}$
3	Sprinkler	$1.2 * 10^{-5}$	$2.8 * 10^{-6}$
-	Acceptable limit	10^{-4}	10^{-6}

In Figure VII.27, the societal risk is presented in terms of a FN curve. Similarly to the detailed analysis, the results depict important differences between the three safety levels. The option with only the sprinkler system is not within the acceptable limits. This is mainly due to the errors obtained by the simplified method with respect to the comprehensive model.

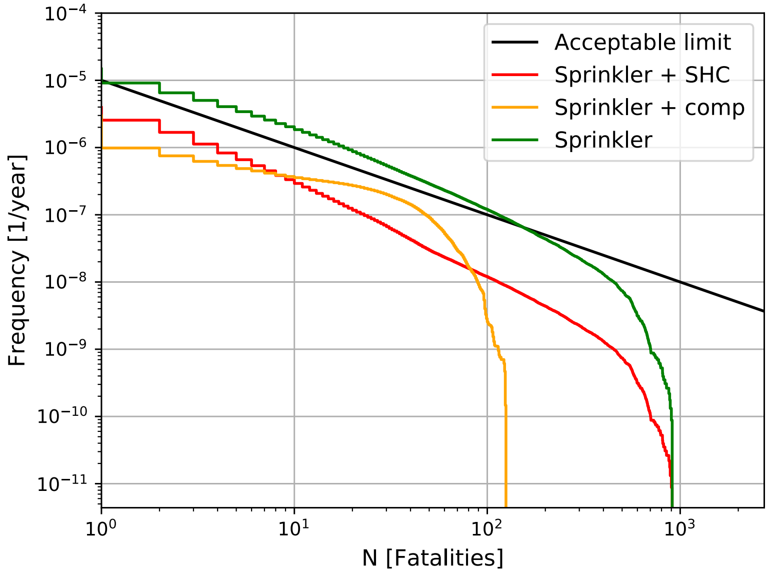

Figure VII.27: FN curves of the three fire safety designs for the simplified method.

VII.3.3 Comparison and discussion

The comparison of the results between the simple and comprehensive method show systematic differences. The fatality rates of the simplified method show higher rates compared to the more accurate solution. In Figure VII.28, the six FN curves are presented.

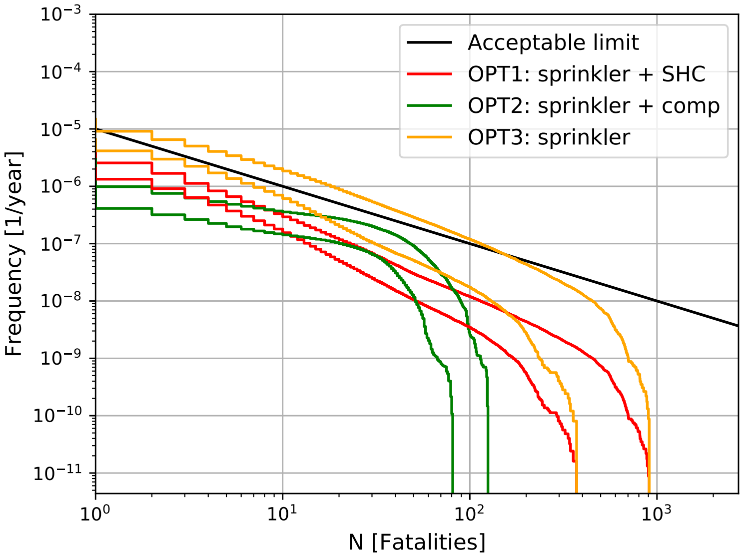

Figure VII.28: Results of the comprehensive and simplified method. The results for the comprehensive method are each time the lower FN curve.

The probabilities of fatality for the two methods are repeated in Table VII.6 the relative error for the two methods is calculated based on eq VI.1. The error varies between 21% and 53%. The error is higher for lower probabilities because these scenarios are more sensitive to variation. Based on the size of the error, it could be concluded that the simplified method is less applicable to more complex cases. However, because results of the simplified method are consistently more conservative, it can give a good estimate of the safety level.

Table VII.6: Probability of fatality for the simplified and comprehensive method for case study 2.

Option	Fire safety design	Pf_{Full} [-]	Pf_{Simpl} [-]	Error
1	Sprinkler + SHC	$3.8 * 10^{-6}$	$4.8 * 10^{-6}$	26%
2	Sprinkler + comp.	$9.9 * 10^{-7}$	$1.5 * 10^{-6}$	51%
3	Sprinkler	$9.8 * 10^{-6}$	$1.2 * 10^{-5}$	22%

From the results of the comprehensive analysis it can be observed that all the scenarios are below the acceptable limit. This implies that only a sprinkler system would be necessary for the case at hand. This is not in line with the Belgian regulatory framework that requires option 1 or 2 for the considered building configuration. However, the design with only a sprinkler system is in line with the New-Zealand C/VM2 regulations [10].

VII.4 Conclusion

The objective of this chapter was to analyse the applicability of the method for different case studies, concerning a simple and a more challenging building configuration. The simplified and comprehensive QRA methods were tested and a comparison was made between the results.

For the simple case, the results are very similar. A systematic difference was observed between the simple and comprehensive method, the simple method providing more conservative results. It can be concluded that the simplified method can be applied to simple cases, that do not deviate too far from the analysed cases, because the results are slightly more conservative.

For the complex case, the results differ more strongly. A systematic difference was observed again, the simple method again providing for more conservative results in the order of 20% to 50% higher risk levels. This seems to be a high error. However, because of the logarithmic scale, the analysis can still provide useful results to give a coarse estimate of the location of the FN-curve with respect to the acceptable risk level. Therefore, it can be concluded that the simplified method can be applied to challenging cases to provide a good first estimate of the safety level. It should be noted that in principle, this conclusion is only valid for similar cases. When the scope would be significantly different, a new validation case should be performed.

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CHAPTER VIII

Assessment of risk acceptability

VIII.1 Introduction

In the previous chapters, the full and simplified QRA methods were developed, validated, and tested on the basis of multiple case studies. The final objective of the QRA method is to quantify the fire safety level of a building design and evaluate the calculated safety level against a predefined acceptable risk criterion. In Chapter II, three methods to quantify the risk level were defined: the failure probability in terms of the probability of fatality, the individual risk and the societal risk. In Belgium and most other countries, no specific fire risk criteria are defined. Therefore, the objective of this chapter is to investigate possible acceptable safety levels which can be used to evaluate the fire safety level of challenging building designs by means of a full probabilistic fire safety analysis. Firstly, the risk criteria tolerable and acceptable risk are discussed. Secondly, important factors for quantifying life safety are analysed. Thirdly, acceptance criteria based on different methods are investigated. Finally, the quantification of fire safety designs in different countries for the same case study is analysed.

VIII.2 Tolerable and acceptable risk criteria

When making a fire safety design compliant with the pre-defined performance criteria, it is assumed that the design is at is minimum tolerable within the considered context. The tolerability limit of a design is the combination of the possible consequences and their associated occurrence probabilities. For individual risk and the probability of having a fatality, this means the multiplication of both terms and summating up to one term. For societal risk, the tolerability of a design is a function of the severity, and ensures that societal differentiation between high consequence and low consequence events is taken into account [1]. This is presented by a FN curve (Chapter II).

In addition to the tolerability limit for societal risk, defined by means of an FN curve, a second threshold can be defined to make a distinction between the region on the FN diagram that can be considered as negligible and the region that can be considered as the ALARP zone [2]. Between these limits the design is only tolerable if the fire safety engineer proves that the risks are reduced as low as reasonably practical. An example is given in Figure VIII.1.

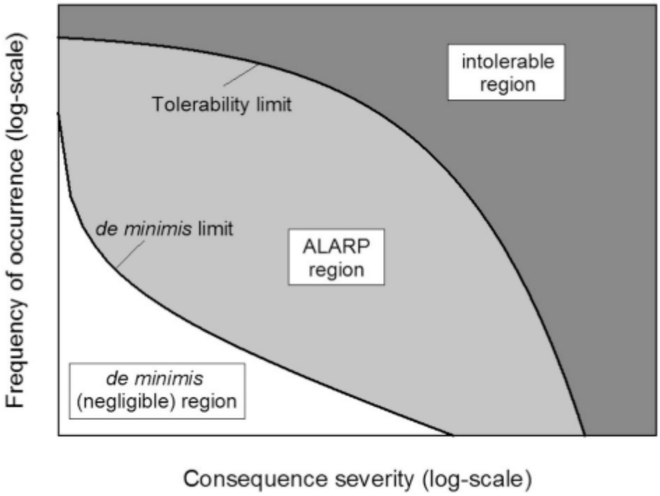

Figure VIII.1: Generalised representation of the ALARP principle. Taken from [1].

VIII.3 Important factors for quantifying risk acceptance criteria

When determining the acceptable risk, different aspects must be considered. In this part, several factors that can have an important impact on the quantification of the acceptability limits are discussed. Four factors are analysed: assumptions in regulatory frameworks, voluntariness, age, and geographic impact.

VIII.3.1 Assumptions in regulatory frameworks

An important aspect in prescriptive fire safety legislation is that the acceptable safety level, which is represented by the regulation and code requirements, takes into account the degradation of the safety level over the lifespan of the building. This degradation can be caused by multiple factors:

- Design of the scope is not compliant with the pre-defined safety level.
- Construction and installation errors made on site.
- Administration errors and change of function during the life cycle of the building.
- Lack of proper maintenance and inspection of the systems.

A visualisation of these factors is given in Figure VIII.2. In case one or more of these factors are taken into account in the risk model, the acceptable level needs to be reviewed. This means that the acceptable level can be adjusted towards a higher or lower acceptable risk, depending on what is taken into account.

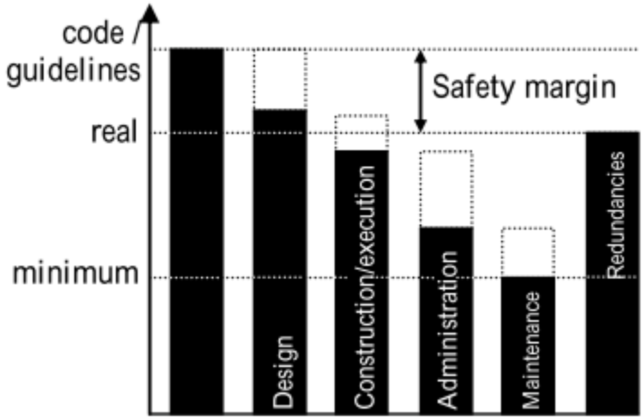

Figure VIII.2: Levels of fire safety and the reduction due to the different processes. Taken from [9].

VIII.3.2 Voluntary and involuntary risk.

One important aspect is the willingness of taking the risk. Bohnenblust and Slovic [14] suggest that when the risk is voluntary, e.g. sports or driving, the upper limit of probability of fatality per year is defined as 10^{-2}. When the risk is not voluntary (e.g. using public transport or flying) then a probability higher than 10^{-4} is not tolerable while risk below 10^{-6} are considered negligible [11]. Other research confirms this reasoning that the public accepts voluntary risks in the order of 100 to 1000 times greater than involuntary risks [12].

The reason for the difference is originated in the public's perception of risk. When a person is able to take charge over an activity such as driving a car then this person will be more inclined to accept more risk than he would drive along with somebody else or ride with public transport. When the person is able to make their own risk vs. benefit analysis they are more likely to take that extra risk to obtain extra benefit. On the other hand, in case a person needs give control away to another person then this individual will be less inclined to give control away because there is no possible choice involved. Another aspect is uncertainty. When a person can take charge of a situation, this person will be more aware of what is going on and knows its own capabilities and limitations. However, when losing control, the person will be more uncertain about the person who is taking control (e.g. public transport).The same is true for public buildings. People feel less in control when a fire occurs in a non-familiar building. Therefore, the acceptable risk will be different between criteria in domestic housing and public buildings (UK regulations).

VIII.3.3 Age difference

Another important factor is age difference. Some countries put emphasis on different acceptability rates for building types with specific age groups (e.g. day-care and elderly homes). For example, the Netherlands set a fixed tolerable criterion based on the age group with the highest life expectancy [13].

Meacham discusses that from a regulatory point of view, the suggested method is relatively easy to implement because only one fixed criterion should be taken into account. However, he discusses that a fixed value will be much easier to reach when the background risk of a specific age group (e.g. children) is low while it will be much more difficult when the background risk of a specific age group (e.g. elderly) is high. This means that significantly more safety measures need to be taken in an elderly home than for a day case. Therefore, Meacham suggested to take a dynamic acceptable limit into account by using 1% of the background risk depending on the age of the focus group [13].

In figure VIII.3, an example is given of the background risk for males in Australia based on statistical data. It can be observed that the background risk for an 85 year old is about 1000 times higher than for a 10 year old.

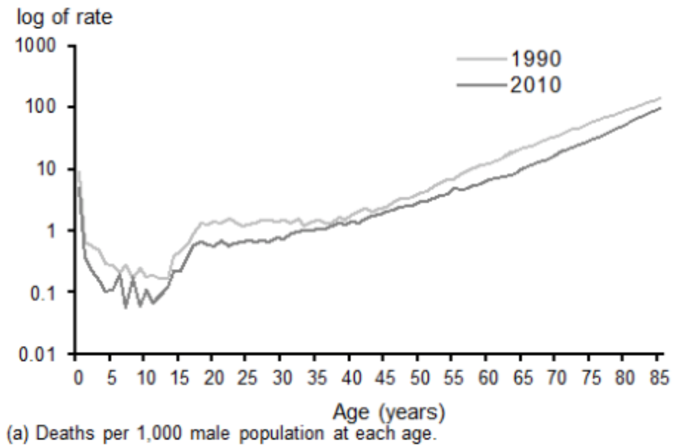

Figure VIII.3: Background risk for males living in Australia. Taken from [12].

Meacham discusses that by adopting a target safety level of 1% (0.01) of the background risk, the risk contributed by the building would not be expected to be more than around 10^{-3} for people in their eighties, for people between 15-45, the acceptable risk would be around 10^{-5}, for infants the criterion would be 10^{-4} and for young children 10^{-6}.

VIII.3.4 Geographical

Similarly to the age factor, the geographical factor can be applied as a uniform value or as a varying parameter depending on the geographical location. When a fixed value would be considered based on the average background risks then regions with higher risks like earthquake or cyclone sensitive regions would demand less safety measures to be implemented. While regions with a lower environmental impact would ask more implementation of safety measures than if only the risk of that specific region would be taken into account [13].

VIII.4 Quantification of risk criteria

In the next sections, several methods to determine the acceptable risk are discussed. The purpose is to analyse the different methods and make suggestion for further implementation in the developed QRA-method.

VIII.4.1 Acceptable criteria based on recent mortality rate data

The most simple approach to assess the overall consequences and the acceptable risk is a frequentistic approach [15]. According to De Smet [16], the basic acceptable level of risk is usually defined in a situation of permanent exposure, where the danger and the risk are always together. The community is prepared to accept the risk when the probability of fatality is less than 1 per million persons per year. In case the exposure is not permanent, the risk will be more easily accepted. This is more suitable for fire related risks. In European countries, the average number of deaths in buildings caused by fire is somewhere between 4 and 15 per million habitants per year [16].

Data from the UK proves that mortality rates decrease steadily from the first observations in the 1980 [17]. In buildings other than dwellings, mortality rates decreased to 20 fatalities in 2017. Given that the population of the UK is about 66.02 million and that at least 99% of the population visits buildings other than dwellings, the calculated mortality rate is $0.3 * 10^{-6}$. Fire related injuries were estimated about $1.5 * 10^{-5}$. These results are in line with older data from the PD 7974-7 for probabilistic risk assessment [19]. The USA obtained similar rates of about 90 fatalities per year. Given a population of 328 million and that 98% of the population visits buildings other than dwellings, the calculated mortality rate is $0.27 * 10^{-6}$.

In Belgium, only data between 2016-2018 of domestic fires was found, the average rate of fatalities was 62 [19]. Based on a population of 11.35 million inhabitants, a mortality rate of $5.5 * 10^{-6}$ is calculated.

VIII.4.2 Acceptable criteria implemented in regulatory frameworks and standards

Another method to obtain acceptable risk criteria is to choose criteria from other countries and sectors. The first acceptable risk criteria were developed for nuclear industries to map the risk levels for these special facilities [3]. Later on, countries like UK, Netherlands, Sweden, NSW, Switzerland, China, Hong Kong, and Australia developed specific risk criteria in their standards and codes. Most of these criteria are for more general purposes and industrial facilities.

The regulatory body for major hazard industries in the UK is the Health and Safety Executive (HSE). They have both a statutory role for enforcement with major hazard industries and an advisory role in respect of land use planning (LUP). For the individual risk, the HSE makes a distinction between risk at home and other sleeping accommodations with $1.5 * 10^{-5}$ and other buildings with $1.5 * 10^{-6}$ [18,19] (Table VIII.1).

Table VIII.1: Proposed BSI risk criteria. Taken from [19].

Category	Probability
Max tolerable risk to indiv.	10^{-4} fat/year
General accepted risk to indiv.	10^{-6} fat/year
Individual risk from fires only:	
At home or sleeping	$1.5*10^{-5}$ per indiv./year
Elsewhere	$1.5*10^{-6}$ per indiv./year
Risk of multiple death from fires only	
> 10 Fatalities	$5*10^{-7}$ per indiv./year
> 100 Fatalities	$5*10^{-8}$ per indiv./year

For the societal risk, the HSE suggested that the risk of an incident causing more than 50 fatalities or more people in a unique event should be regarded as intolerable if the frequency is estimated to be more than one in five thousand per annum for dangerous facilities. This criterion fixed one point and the HSE adopted a risk neutral concept by applying a slope of -1 (Figure VIII.4). An ALARP region is suggested in which the curve is shifted downwards by a factor of 10^{-2}. For fires specifically, the BSI proposed two societal risk criteria, for 10 and 100 fatalities based on fire statistics.

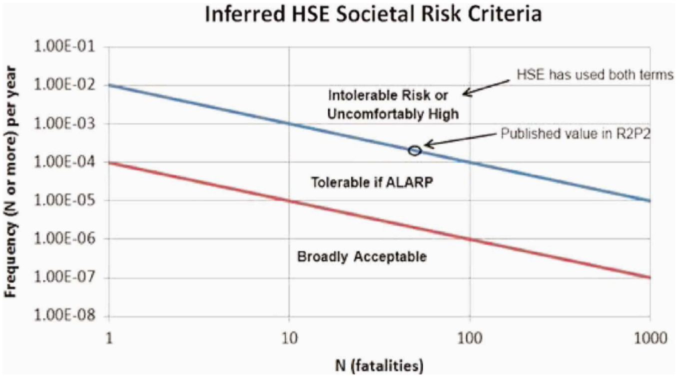

Figure VIII.4: Representation of the acceptable risk criterion by HSE. Taken from [3].

The Dutch government incorporates historical risk data in its tolerable risk level [22]. The criteria based on the population with the highest life expectancy, which are 14-year-old children, are used. This life expectancy was reflected by a minimum death rate of 10^{-4} per year. The Dutch government imposed that the tolerable safety level for a dangerous situation should be reduced to only 1% of the existing probability to die that year, or 10^{-6} per year [23,24]. This was set for risk associated with new facilities. For existing facilities, the risk of dying was set at 10^{-5} per year. For the societal risk, the Dutch define the tolerable risk for hazardous installations by means of an FN curve presented in Figure VIII.5.

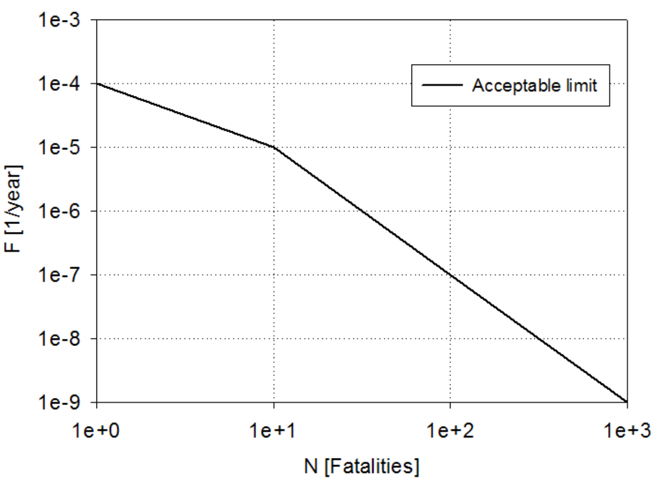

Figure VIII.5: Representation of the acceptable risk criterion. Adapted from [22].

In 2004, Belgium experienced a major gas pipeline explosion in Ghislenghien, near Brussels, that led to about 24 fatalities and injured 122 people. Because of this major incident issued guidance for QRA in Seveso studies in 2009 [3]. The department of Environment, nature and energy demands an independent QRA analysis for higher risk Seveso Directive companies. The considered risks are evaluated for individual and societal risk. For the individual risk, the maximum location-specific risk on plants boundary line is 10^{-5} per year, at residential areas it is 10^{-6} per year, and at vulnerable areas it is 10^{-7} per year. For the societal risk, the tolerable risk for dangerous zones is presented by means of an FN curve in Figure VIII.6.

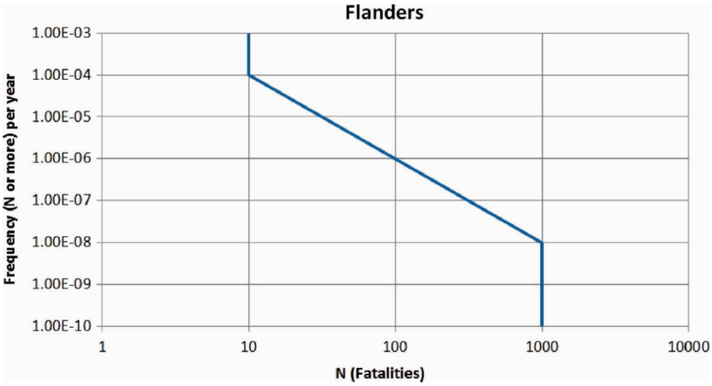

Figure VIII.6: Representation of the acceptable risk criterion. Taken from [3].

The Australian government does not provide any risk data. However, efforts are done to implement risk criteria in their future building code. Based on statistical data, the government chose that the risk of death from disease is chosen as a psychological yardstick for establishing a level of risk acceptability in terms of fire and disasters. Meacham proposed to implement a regulatory benchmark such that the maximum contribution to risk to life, as related to all building features regulated by the National Construction Code (NCC), is no more than 1% of the background risk for new construction and no more than 10% of the background risk for existing buildings [13].

New South Wales (NSW), a state in Australia, issued specific guidelines for individual and societal risk [25]. In Table VIII.2, the individual risk criteria suggested by the guidelines are presented. The criteria are based on the principle set out above by the Australian government.

Table VIII.2: Individual risk for NSW. Taken from [25].

Category	Probability of fatality
Hospitals, schools, child-care facilities, elderly	$0.5 * 10^{-6}$
Residential, hotels, motels, tourist resorts	$1 * 10^{-6}$
Commercial developments including retail centres, offices and entertainment centres	$5 * 10^{-6}$
Sporting complexes and active open space	$10 * 10^{-6}$
Industrial	$50 *10^{-6}$

For the societal risk, the suggested criteria take into account the fact that society is particularly intolerant of accidents which have a potential to create multiple fatalities. Therefore, the guidelines propose a slope of -1.5 (Figure VIII.7). The guidelines suggest that the criteria are broadly consistent with those adopted in a number of other jurisdictions and have been refined by consideration of the results from land use safety studies conducted by the department in and around the industrial installations in industrial areas [25].

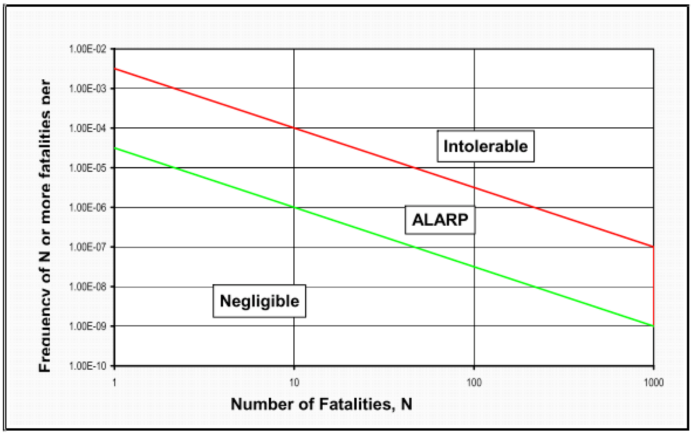

Figure VIII.7: Societal risk criteria. Taken from [25].

The Hong Kong land use planning proposes an individual risk limit of 10^{-5}. For the societal risk, a risk neutral principle is applied with starting point N = 1 with a probability of 10^{-5} and a cut off at n = 1000. The ALARP region is shifted with a factor of 100 [26]. The FN curve is presented in Figure VIII.8.

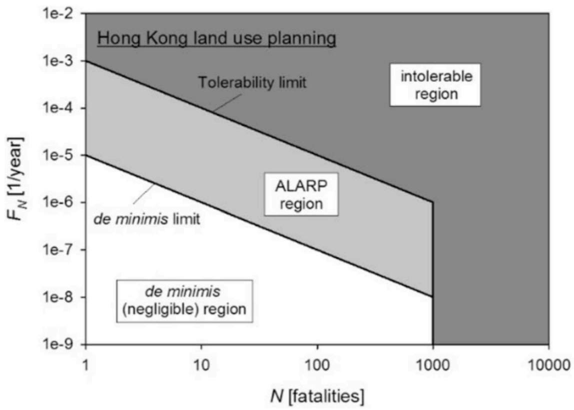

Figure VIII.8: Societal risk criteria Hong Kong. Taken from [1].

In Sweden, there is no formal approved criteria for risk criteria in generic building types. Some international criteria that may be used if ”approved” by the stakeholders, which are, principally the project owner and any relevant authority. Research was done suggesting risk criteria for rail tunnels and for bus stations. An individual risk of 10^{-6} was suggested [30]. For rail tunnels, the societal risk was defined on the risk per train kilometres driven and is presented in Figure VIII.9.

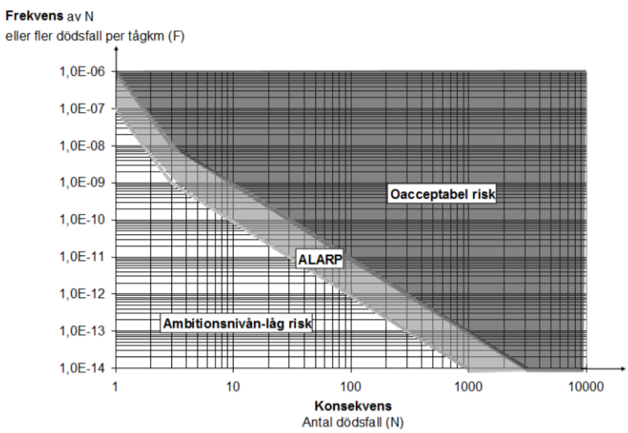

Figure VIII.9: Societal risk for rail tunnels in Sweden. Taken from [27].

The Swiss government proposes an individual risk limit of 10^{-5} [28]. For the societal risk, a risk adverse principle is applied (slope = -2) with starting point N = 1 with a probability of 10^{-5} and a cut off at n = 1000 [28]. The FN curve is presented in Figure VIII.10.

For Denmark, only a societal risk was found. The risk adverse principle is applied (slope = -2) with starting point N = 1 with a probability of 10^{-2} [28].

The State California in the USA proposes an individual risk of 10^{-6} [28]. For the societal risk, the state differentiates between on-site and off-site risk. For both types, the risk adversity principle is applied in which the slope of the FN curve equals -2. The on-site risk has a starting point N = 1 with a probability of 10^{-1} . The acceptability of the off-site risk is 100 times less.

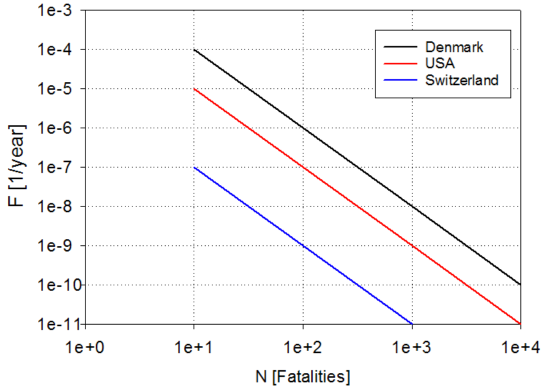

Figure VIII.10: Societal risk limits for California, Denmark and Switzerland.

VIII.4.3 Acceptable criteria based on prescriptive and PBD regulatory frameworks

From a general point of view it is believed that risk is considered only acceptable when society accepts it [14]. Therefore, it is considered that regulative and international organisation bodies are responsible for providing engineers with regulations, recommendations and guidelines. Included in their responsibilities is the task to determine what levels of risk should be considered acceptable. For regulatory purposes, prescriptive and performance-based legislation can be considered as accepted frameworks.

In Belgium, a prescriptive legislation is applied that defines the prescriptive safety level depending on the type of building. The acceptable safety level will be variable and case dependent. If the developed comprehensive QRA method is applied on buildings that fulfil these regulations, the obtained risk profiles could be applied to quantify the acceptable risk criteria. For every building type, a risk profile can be determined based on the average profile of multiple case studies. Similarly, for PBD codes, the reference level can be determined for different buildings codes. In the next part, the case study of the shopping mall is designed according to the fire safety codes in three different countries, both prescriptive and PBD. Each fire safety design is analysed by the QRA method to show the acceptability limits for that specific building.

VIII.5 Assessment of case study acceptability

A case study is performed and designed against multiple regulatory frameworks. The case study of the shopping mall is used and designed to be in conformity with the regulatory frameworks of three different countries, both prescriptive and PBD. For the prescriptive, the building is designed according to the Belgian legislation. For the performance-based principle, the building is designed according to the New-Zealand and Swedish regulatory framework. For the performance-based countries, the designs were checked against the predefined fire scenarios and performance criteria. The fire safety design of each country is analysed by means of the QRA method to show the societal risk corresponding for that specific building type and inherently accepted as an acceptable risk limit though the regulatory framework in place. It is important to mention that for this case study the four staircases are considered as protected compartments and free of smoke.

The main design differences in the study was the difference in the assignment of occupant densities, exit and stair widths and implementation of safety systems. These are presented in Table VIII.3. The table shows that the Belgian legislation requires to take more occupants and more exit and stair width per occupant into account. Therefore, the Belgium case can be considered the most conservative, which should be reflected in the results (e.g. lower FN curve).

Table VIII.3: Major design differences for the three countries.

Characteristic	NZ	Sweden	Belgium
Area for occupant density	gross	net	gross
Occupant density	1 p/3.5 m^2	1 p/2 m^2	1 p/3 m^2
Occupant density	0.29 m^2/p	0.50 m^2/p	0.33 m^2/p
Total occupants	7622	8003	8883
Hor. width of escape routes	7 mm/p	6.7 mm/p	10 mm/p
Vert. width of escape routes	9 mm/p	6.7 mm/p	down: 12.5 mm/p up: 20 mm/p
Main safety systems	Sprinkler, detection, alarm	Sprinkler, detection, alarm	Sprinkler, SHC, detection, alarm

The results of the analysis for the failure of fatality and the individual risk are presented in Table VIII.4. The results show that the Belgium case is the most conservative and the New Zealand case is the least conservative.

Table VIII.4: Case study results for the probability of fatality (P_f) and the individual risk (IR).

Option	Fire safety design	P_f [-]	IR [-]
1	Belgium	$3.8 * 10^{-6}$	$2.1 * 10^{-7}$
2	New Zealand	$3.5 * 10^{-5}$	$2.9 * 10^{-6}$
3	Sweden	$2.9 * 10^{-5}$	$1.2 * 10^{-6}$

In Figure VIII.11, the societal risk is presented in terms of FN curves. Similarly to the individual risk, the Belgium case is significantly more conservative comparing to the other two cases. The results of the safety level of the Swedish and New-Zealand case are close to each other. The Swedish case is slightly more conservative than the New Zealand case due to the wider exits. With respect to the definition of acceptability limits, it appears that acceptability limits which would correspond to the cases study for the Swedish and New Zealand can be considered more or less on the same level. The level of acceptability in Belgium is much more conservative compared to the other two countries. With respect to the safety level of other countries, the three case studies would be tolerable in Hong Kong, Denmark, UK and NSW. In the USA, Switzerland and the Netherlands the three designs would not be acceptable. This is mainly related to the risk averse slope of the curve. The data from the other countries were not applicable for this case study.

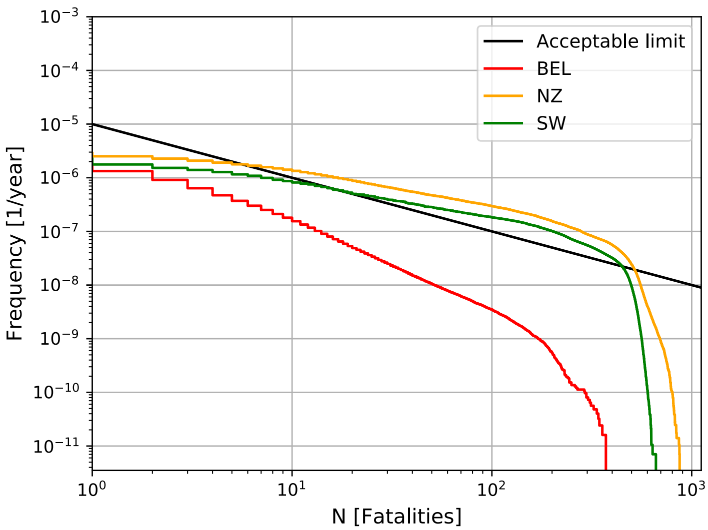

Figure VIII.11: Representation of the societal risk for the three countries by means of FN curves corresponding to the shopping mall case study.

IV.6 Discussion and conclusions

The objective of this chapter was to asses acceptability limits for analysing fire safety designs. The literature study of risk criteria showed that statistical data is most often used for defining acceptability limits. Based on this reasoning, the latest available mortality rates (2016) in Belgium can be analysed to determine the background risk [29]. In Figure VIII.12, the mortality rates for men and women are presented. The risk to women is significantly lower. Between 5- and 80-years old people, the risk to life for men is almost a factor 2 higher.

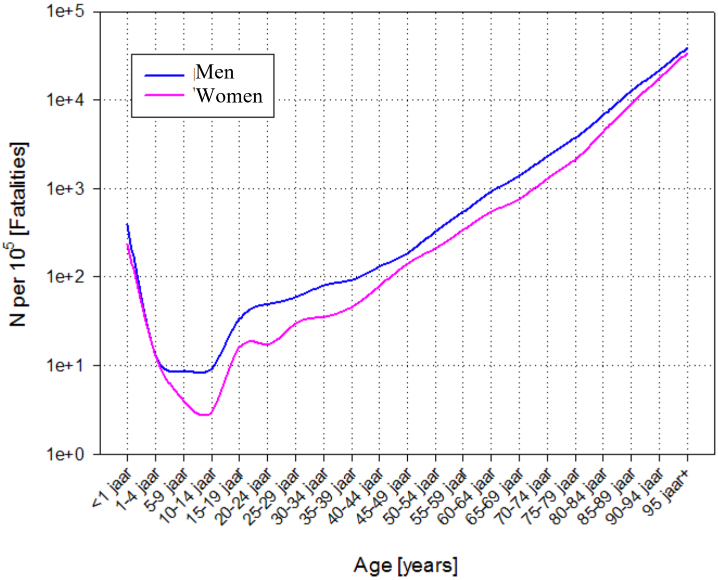

Figure VIII.12: Risk to life in Belgium in 2016. Taken from [29].

For determining the tolerable/acceptable risk, the average mortality rate for people between 20 and 50-60 years old is determined. The background risk varies between $7.9 * 10^{-4}$ and $1.5 * 10^{-3}$. Therefore, it is suggested to define an average rate of 10^{-3}. Similarly to the reasoning discussed by Meacham [9], an acceptable risk of 1% of the background risk for people in new buildings is suggested. Therefore, a starting point for the FN-curve of 10^{-5} is chosen. Although, most countries use a risk averse slope, for the visualisation of the FN curve, to take into account the indirect costs and reduce the impact on public opinion, here, a risk neutral slope of -1 is suggested. The reason for this is suggested by Maes et al. [26], who suggested that the true societal preferences correspond with a risk-neutral evaluation (where events with the same risk indicator are similarly valued). In principle only a risk-neutral position can be justified for a societal decision-maker to objectify the fire safety designs [5]. Van Coile suggested that, because societal resources are limited, safety investments are necessarily limited as well, and a balance between different safety investments is required [1]. Sunstein suggested that real risk aversion does not exist, since some of the money spent on the over-valued low-probability vs. high-consequence events could be put to better use elsewhere and therefore saving more lives [27].

In Figure VIII.13, the proposed acceptable risk is presented together with the upper and lower limits found in the discussed literature. The proposed curve lies between the two limits and is close to the upper limit for lower number of fatalities and tends to go to the lower limit for a higher number of casualties. People younger than 20 years and older than 60 years should have different acceptable risk criteria because of the significantly different background risk.

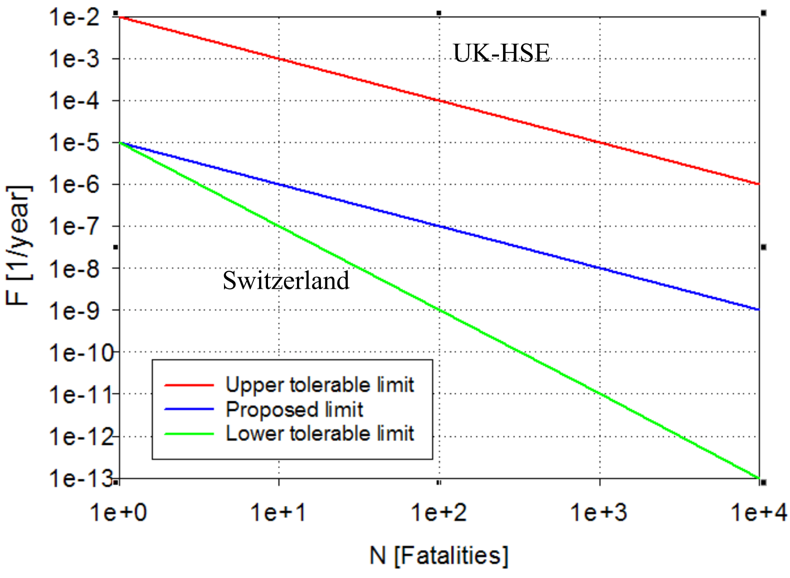

Figure VIII.13: Summary of FN-curves.

In case the proposed tolerable societal risk limit is compared with the shopping mall case study for the three countries in Figure VIII.14, the Swedish and New Zealand case would not be tolerable. The FN curves of the two designs are close to the tolerable limit. Therefore, relatively small additional efforts can be done to fall below the tolerable limit. An example would be to increase the redundancy of the sprinkler system (Chapter III). If the reliability of the sprinkler system would be increased from 0.95 to 0.98 for the Swedish case and to 0.99 for the NZ case, the FN-curves of the two countries would be within the proposed acceptability limit presented in Figure VIII.14. Another possibility to reduce the societal risk can be to improve the reliability and efficiency of the SHC system. Both parts of the effectiveness can have a major impact on the risk level.

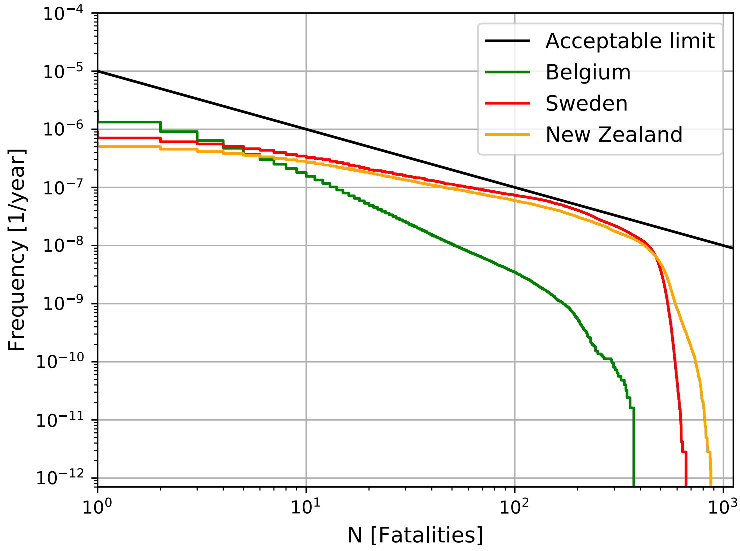

Figure VIII.14: Representation of the societal risk for the three countries by means of FN curves with improved sprinkler reliability for the SW and NZ case.

From the applied methodology it can be concluded that the choice of the acceptable limit has an important impact on the acceptability of the fire safety design. In order to make the chosen acceptable limit and historical accepted designs compatible, more acceptable designs should be analysed and a calibration should be made in future steps.

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CHAPTER IX
GENERAL CONCLUSIONS
&
FUTURE RESEARCH

IX.1 General conclusions and recommendations

Life safety design in case of fire is one of the main tasks in Fire Protection Engineering. A lot of consideration and effort is usually required to find sufficient and cost-effective solutions to reduce the risk of life loss to a pre-defined acceptable level. In order to find a suitable methodology for this process, this thesis proposed a new framework for quantifying the fire safety level of new and existing buildings.

First, in Chapter II, a closer look was taken at the term risk, which can be interpreted in many different ways. In order to constitute a basis for further considerations, risk concepts and possible quantification methods were discussed. Several existing risk multi-models were analysed. Strengths and weaknesses were investigated to incorporate the better parts of these models into the methodology.

Based on the literature study, a deterministic and probabilistic framework was developed. In Chapter III, the deterministic models were developed and discussed. The focus was on a holistic approach of multiple submodels to combine the different influence factors from safety systems, design scenarios, evacuation, smoke spread, and consequence modelling in one framework. In Chapter IV, the probabilistic framework was developed. The method consists of multiple probabilistic techniques to quantify the safety level on a reliability and risk-based level. Three criteria were defined: a probability of fatality, an individual and a societal risk for quantifying the risk level. The core of the method consists of a response surface model in combination with sampling techniques and convergence methods. The outcome was a computationally efficient model to accurately quantify fire safety designs. In order to further optimize the computational model, in Chapter V, a 'simplified' model was proposed, with simplified submodels for smoke spread and evacuation analysis. For smoke spread, a zone model was proposed instead of a field model. For evacuation, an in-house network model was developed, instead of a continuous model.

In Chapter VI, an extensive verification and validation analysis of the full probabilistic and simplified model has been performed. Through a set of verification tests, the model proved to give a good representation of the modelling accuracy of the RSM and evacuation submodel of the simplified risk model. The validation tests show good agreement with the theoretical and experimental cases.

The objective of Chapter VII was to analyse the applicability of the method for different case studies. Two case studies were chosen: a simple configuration and a more challenging building configuration. The simplified and comprehensive QRA method was compared for both case studies. The results revealed that for simple configurations both the simplified and comprehensive method provide accurate results. For more challenging case studies, only the comprehensive method obtained accurate results. The simple method showed errors up to 50%. However, because of the logarithmic scale, the analysis can still provide useful results to give a coarse estimate of the location of the FN-curve with respect to the acceptable risk level. Therefore, it can be concluded that the simplified method can be applied to challenging cases to provide a good first estimate of the safety level.

The final objective of the thesis was to quantify the fire safety level of a building design and evaluate the calculated safety level against a predefined acceptable risk criterion. Therefore, in Chapter VIII, a proposal was made for an acceptable risk level, as presented in Figure IX.1, together with acceptable designs for the shopping mall case study designed for three different countries.

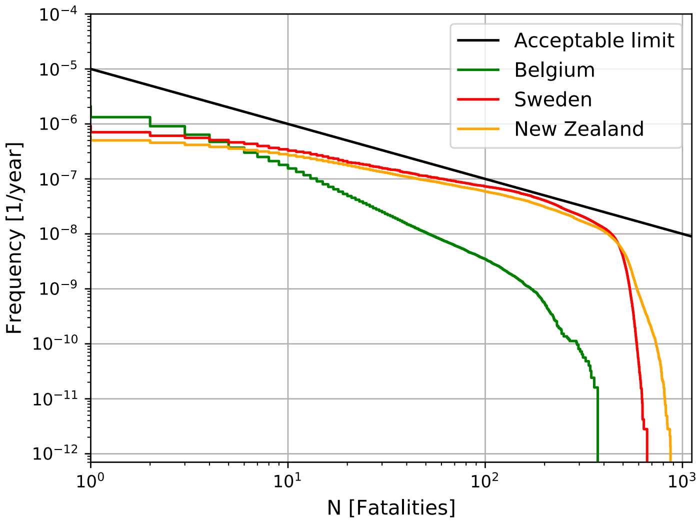

Figure IX.1: Representation of the Societal risk for the three countries by means of FN-curves with improved sprinkler reliability the SW and NZ case.

IX.2 Limitations

The conclusions resulting from the application of the QRA framework developed in this thesis should always be analysed alongside the underlying assumptions and simplifications, as discussed in the related chapters. Note that the models have been developed for Belgian conditions and may not represent a realistic fire situation in other countries. Despite the developed risk models being intended to represent the fire situation as realistically as possible, the main focus of this thesis was to demonstrate the application of the introduced framework for risk-based decision-making.

IX.3 Suggestions for future research

Future work directly in the line of this dissertation concerns improving the different submodels, performing additional validation for specific submodels and testing the method for different building types by means of multiple case studies.

More specifically, the in-house developed evacuation network model should be further validated for its different parts (e.g. effect of smoke on walking speed vs occupant density). Also, the implementation of human behaviour during evacuation should be analysed more in depth to provide for more realistic and accurate results.

The efficiency and reliability of several fire safety systems should be further investigated. An example is the effectiveness of pressurization systems, which is proven to depend significantly on the applied code or standard.

Another important gap is the lack of data in the fire safety community. While there are large advances in the physical representation of fire scenarios by engineering models (e.g. combustion models, computational fluid dynamic models or evacuation models), there is a considerable amount of missing basic data to accurately represent the uncertainties associated with the fire situation when aiming at a full probabilistic representation. Finding this data will be an important challenge for future researchers.

The QRA methodology should be tested for more case studies and different building types in order to analyse the applicability and to obtain a global idea of the overall safety level of new and existing buildings. More specifically, the simplified QRA method should be analysed for more challenging case studies to confirm that it always provides for an overestimation of the risk level and thus provides for conservative results.

A IGNITION FREQUENCY

A.1 Objective

The objective of this study is to give an overview of the existing literature regarding the determination of the ignition frequency for different building types.

A.2 General

For quantitative estimation of fire risks, it is crucial to obtain reliable information on ignition frequency derived from relevant building stock and fire statistics. The probability of a building catching fire has been known to depend not only on the building use types under study but also on the size of the building itself. The larger the building, the smaller the likelihood of a fire to take place per unit floor area per year. This tendency is based on statistics from nations as the UK [1,2], Finland [3,4], Japan [5] etc. In order to confirm these findings, a comparative research study is performed in this chapter. In total, seven fire frequency data studies are analysed and discussed.

A.3 Fire frequency data studies

A.3.1 Historical development

The first findings of the interaction between fire frequency and surface originated in 1907 when Professor Sergius von Sawitsh expressed that fire insurance claims frequency had a linear relationship with volume or value at risk [6]. Then, in 1937, Berge demonstrated, on the basis of Swedish dwellings, how the claims frequency and the fire loss ratio increase with the size of the house [6]. Professor D'Addario [7] followed in 1940 by expressing claims frequency, $f(s)$, of the Swedish statistics explained by Berge, as a function of the size (s, sum insured) as:

$$f(s) = A\, s^{\alpha} \tag{A.1}$$

where A and α are empirically fitted coefficients. This power law model is currently in use in PD [8] .

In 1968 Ramachandran combined national fire statistics, developed by local authority fire brigades, with financial loss data from British Insurance Association. Ramachandran estimated, for different occupancy types, the total number of fires and the total cost in thousands of pounds [9] for large fires. In the following years, he developed a brief analysis of large fires from 1965 to 1968 where the total number of fires and the total cost in thousands of pounds for different occupancy types was expressed. In the 1969 research, fire frequency, place of origin, source of ignition, material first ignited, age of the building, number of storeys, spread of fire, attendance time and fire protection devices [10] were also assessed. In 1970, Ramachandran produced fire loss indexes defined as loss per square foot of floor area or loss per hundred pounds of value at risk [11].

A.3.2 Rutstein (UK 1979)

In 1979, Rutstein [12] affirmed that the risk of fire (probability of fire and its consequence) can only be expressed in probabilistic terms and can be estimated by examining past fire incidence data. Furthermore, Rutstein determined the probability of fire by comparing the number of fires reported by the fire brigades divided by the total amount of property at risk, determined from survey data of manufacturing industry undertaken by the Home Office Scientific Advisory Branch in 1977. The fire probability, F, is described with a power law according to the total area of the building A:

$$F = a\,A^{b} \tag{A.2}$$

where A is the total floor area (m^2) of the building and a and b are constants for buildings of different occupancies. The constants a and b were estimated using statistical regression analysis. The constants determined for different occupancies are given in the table below. The above equation reveals that the probability of fire in a building does not increase proportionately with the building size. In other words, a building twice the size of another building does not have a probability twice as high as the other.

Table A.1: Fire frequency data parameters Rutstein. Taken from [12].

Occupancy	a	b
Industrial buildings		
Food, drink and tobacco	0.0011	0.60
Chemicals and allied	0.0069	0.46
Mechanical engineering and other metal goods	0.00086	0.56
Electrical engineering	0.0061	0.59
Vehicles	0.00012	0.86
Textiles	0.0075	0.35
Timber, furniture	0.00037	0.77
Paper, printing and publishing	0.000069	0.91
Other manufacturing	0.0084	0.41
All manufacturing industry	0.0017	0.53
Other occupancies		
Storage	0.00067	0.5
Shops	0.000066	1.0
Offices	0.000059	0.9
Hotels, etc	0.00008	1.0
Hospitals, etc	0.0007	0.75
Pubs, restaurants, etc*	0.00007	1.0
Schools	0.0002	0.75

*Table 3.1. Values of the constants a and b in different occupancies. *No information was available for the estimation of the probability of a fire in pubs and restaurants. The probability shown is assumed to be intermediate between the estimated probabilities for Shops and Hotels.*

A.3.3 Centre de Recherches (France 1999)

In 1995, with help of the French fire brigades data of fires in the country was collected [13]. The statistics were used to give the number of fires per building class. The total floor area of different occupancies at risk were estimated. Since the number of fires in different occupancies for one year and the combined area of each occupancy are known, the average ignition frequency [$1/ym^2$] can be estimated (Table A.2).

Table A.2: Average ignition frequency in different occupancies. Taken from [13].

Occupancy	Number of fires	Total surface at risk ($10^6 m^2$)	Average ignition frequency ($1/ym^2$)
Public	7 337	821	$8.9 \cdot 10^{-6}$
Offices and dwellings	60 313	2 851	$2.1 \cdot 10^{-5}$
Industrial buildings	6 210	1 469	$4.2 \cdot 10^{-6}$
Warehouses	8 319	374	$2.2 \cdot 10^{-5}$

A.3.4 Tillander (Finland 2003)

Tillander et al. generalized the theory of Ramachandran and analysed data from the national accident database Pronto [3]. They used mathematical functions from fitting models to the statistical data by means of the Barrois model. In this model, two power law functions are summed up and fitted to the statistical data. The frequency of ignition, f_m'', is then:

$$f_m'' = c_1 \, A^r + c_2 \, A^s \tag{A.3}$$

where A is the floor area and c1, c2, r and s are coefficients. The coefficients were determined experimentally from observations for different building categories. Tillander et al. explained why the ignition frequency is higher in small buildings than in larger. Since the larger buildings have more planned fire safety measures and precautions against fire, they have more stringent rules than smaller buildings. This definitely affects the ignition frequency.

Table A.3: Fire frequency data parameters Tillander. Taken from [4].

Key	Occupancy	c_1	c_2	r	s
A	All buildings	1.24	$6 \cdot 10^{-6}$	-2.75	-0.05
B	Residential buildings	0.01	$5 \cdot 10^{-6}$	-1.83	-0.05
C	Industrial buildings and warehouses	0.07	$6 \cdot 10^{-6}$	-1.48	-0.05
D	All other	0.01	$3 \cdot 10^{-6}$	-1.25	-0.05

Building category	c_1	c_2	r	s	R^2 [%]
Residential buildings	0.010	5E-6	-1.83	-0.05	84
Commercial buildings	7E-5	6E-6	-0.65	-0.05	26
Office buildings	0.056	3E-6	-2.00	-0.05	74
Transport and fire fighting and rescue-service buildings	7E-5	1E-6	-0.65	-0.05	75
Buildings for institutional care	2E-4	5E-6	-0.61	-0.05	68
Assembly buildings	0.003	2E-6	-1.14	-0.05	85
Educational buildings	0.003	3E-6	-1.26	-0.05	46
Industrial buildings	3E-4	5E-6	-0.61	-0.05	90
Warehouses	3.82	2E-6	-2.08	-0.05	98
Other buildings	1.18	1E-4	-1.87	-0.20	95

A.3.5 Sandberg (Sweden 2004)

Sandberg did a full review on ignition frequencies in his thesis [14]. He developed ignition frequencies per unit area for specific building types.

Table A.4: Fire frequency data parameters Sandberg. Taken from [14].

Key	Major group	Number of premises	No of fires	Floor area [10^6 m^2]	Average ignition frequency [1/y m^2]
A	Hotels and restaurants	5 463 ± 253	200	6.5 ± 0.3	$3.1 \cdot 10^{-5}$
B	Offices	16 200 ± 454	123	30.7 ± 0.9	$4.0 \cdot 10^{-6}$
C	Stores and warehouses	11 065 ± 578	227	14.0 ± 0.6	$1.6 \cdot 10^{-5}$
D	Buildings for institutional care	5 884 ± 332	575	18.4 ± 1.0	$3.1 \cdot 10^{-5}$
E	Educational buildings	13 053 ± 247	422	36.2 ± 1.2	$1.2 \cdot 10^{-5}$
F	Churches/correspondin g	5 505 ± 324	20	3.6 ± 0.5	$5.6 \cdot 10^{-6}$
G	Theatres, cinemas and other assembly buildings	11 715 ± 637	52	6.0 ± 0.7	$8.7 \cdot 10^{-6}$
H	Buildings for sport activity	3 806 ± 207	59	7.0 ± 0.8	$8.4 \cdot 10^{-6}$
I	Industrial buildings	41 335*	1274	112.0**	$1.1 \cdot 10^{-5}$

A.3.6 Lin (Taiwan 2005)

Lin studied fire frequency data from the Taiwanees Centra Police University was studied [15]. The data shows high frequency data between 0.0015-0.0279 fires per year depending on the building type. The data is presented in the figure and table below. In comparison to other frequency data, the frequencies are orders of magnitude higher. Therefore, this data is not considered to be valid.

Table A.5: Fire frequency data parameters. Taken from [15].

Building type	Fire frequency [-/year m^2]
Residential	0.0096
Shop	0.0024
Industry	0.0134
Public	0.0073
Other	0.0027

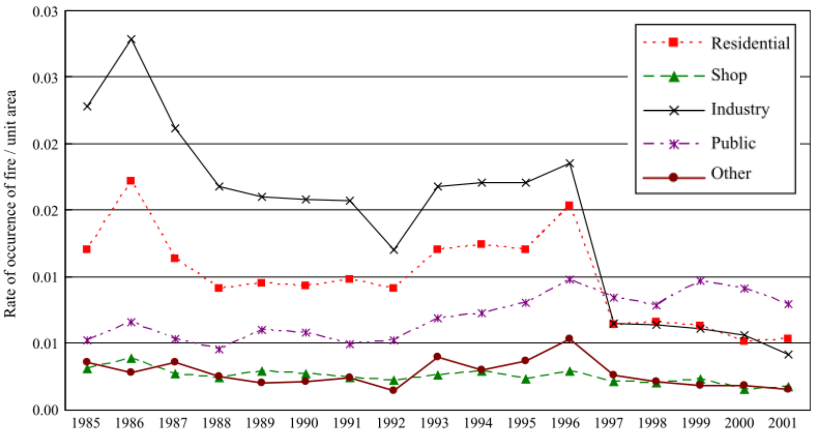

Figure A.1: Fire frequency data in Taiwan between 1985-2001. Taken from [15].

A.3.7 Ghosh (New Zealand 2008)

Gosh presented the results of an NZ study from NZFIRS [16]. The data is presented in the table below. Similar to [15], the fire frequencies are orders of magnitude higher than the other studies. Therefore, this data is not considered to be valid.

Table A.6: Ignition frequencies from 2003-2004 in New Zealand. Taken from [16].

Property type	No. of fires [-]	Total building area [fire/y m^2]	Fire freq. [fire/y m^2]
Singe house	1657	248720	0.00666211
Apartment	260	78666	0.003305113
Hotels/motels	26	123918	0.000209816
Restaurants, Pub, Taverns	61	42816	0.001424701
Shops, malls, supermarkets	92	114141	0.000806021
Services, repair, drycleaners, etc.	27	8666	0.003115624
Office, bank, etc.	36	94309	0.000381724
Industrial	126	419510	0.00030035
Storage warehousing	53	34147	0.001552113
Educational	104	86362	0.001204233
Hospital, rest homes	26	25764	0.00100916
Prisons	3	12250	0.000244898
Stadion, theatres, etc.	42	20853	0.002014099
Sports clubs, churches, halls	62	34853	0.0017789

A.3.8 Fischer (Switzerland 2012)

Fischer et al. analysed data from insurance companies. From the research a correlation based on volume is proposed [17]:

$$\lambda = e^{\alpha} * Vol^{\beta} \tag{A.7}$$

Were α en β are the correlation parameters. The parameters implemented in the formula are presented in the table below.

Table A.7: Fire frequency data parameters Fischer. Taken from [17].

Code	Zweckbestimmung	$E[\alpha]$	$E[\beta]$	$Var[\alpha]$	$Var[\beta]$	$Cov[\alpha,\beta]$
1	Verwaltung, öffentl. Geb.	-9.5994	0.5277	0.1270	0.0017	-0.0144
2	Wohngebäude	-11.7628	0.8700	0.0136	0.0002	-0.0018
3	Landwirtschaft	-10.0219	0.5536	0.1457	0.0024	-0.0184
5	Handel	-8.9791	0.4447	0.2232	0.0026	-0.0236
6/7	Industrie und Gewerbe	-10.2969	0.5720	0.0749	0.0009	-0.0080
8	Gastgewerbe	-8.8318	0.5505	0.7024	0.0098	-0.0825

A residential building with a volume of 1000 m^3 (typical single-family dwelling) results in an annual fire probability of $3*10^{-3}$ per building or of $3*10^{-6}/m^3$, so it burns about every 300 years. For a volume of 2000 m^3 there is a probability of 5.8 10^{-3} per building or 2.9 10^{-6} / m^3. The fire probability per m^3 is approximately constant for large volumes when the model parameter β is close to unity.

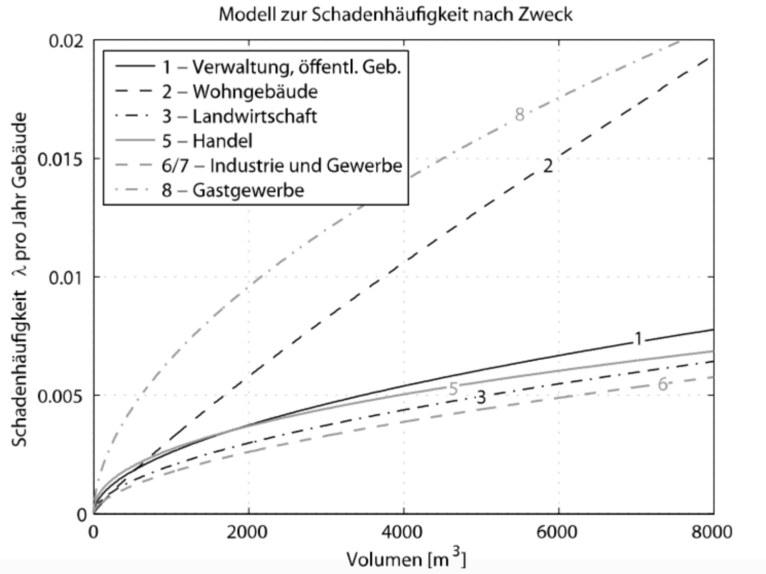

Figure A.2: Fire frequency per unit volume. Taken from [17].

A.3.9 Kobayashi (Japan 2017)

Kobayashi did a review of Japanese structure fires from data obtained from local fire brigades assembled in a national database [5]. He developed a formulation based on the following equation:

$$P = (1-\alpha)\left(1-\Phi\left(\frac{x-\mu_1}{\sigma_1}\right)\right)+\alpha\left(1-\Phi\left(\frac{x-\mu_2}{\sigma_2}\right)\right) \tag{A.5}$$

Where

Φ: the standard normal CDF

x: base-10 logarithm of severity measure

μ_1, σ_1: mean and standard deviation corresponding to the primary floor area model

μ_2, σ_2: mean and standard deviation corresponding to the secondary distribution

α ratio of the secondary model to the overall distribution

The values for the different parameters are shown in the table below.

Table A.8: Fire frequency data parameters Kobayashi part 1. Taken from [5].

Property	Floor Area N (m^2)	α	Mode 1		Mode 2	
			μ1	σ1	μ2	σ2
Outside of Factory	1,028,205,000	0.1047	3.4732	0.6729	4.7812	0.5771
Office	293,344,000	0.4342	3.0757	0.5075	4.1834	0.6336
Shop	217,846,000	0.7266	2.8601	0.3199	3.9789	0.7591
Warehouse	170,050,000	0.0629	3.5239	0.7128	7.1932	3.8838
Hotel	55,994,000	0.3866	3.5401	0.4631	4.6087	0.5588
Educational	83,221,000	0.0283	3.6132	0.4886	2.0252	2.8552
Religious	46,428,000	0.0913	2.8468	0.5857	4.7068	0.4607
Other	161,325,000	0.1005	3.5432	0.5689	4.2132	1.0205
Inside Factory	622,412,000	0.2229	3.9235	0.7676	5.2528	0.5704

Table A.9: Fire frequency data parameters Kobayashi part 2. Taken from [5].

Property	n	α	Mode 1		Mode 2	
			μ_1	σ_1	μ_2	σ_2
02:Office	5065	0.2275	2.1885	0.7778	2.9098	1.1167
03:Shop	15399	0.0954	2.4337	0.6126	4.3210	0.4265
04:Warehouse	11828	0.0376	1.9161	0.6054	3.5347	0.5702
05:Garage	1167	0.5600	1.9873	0.2810	2.6536	0.9785
06:Hotel	1202	0.4084	3.0524	0.5416	3.2559	0.9235
07:Educational	3332	0.4035	3.6441	0.2460	2.8139	0.7528
08:Relighious	1230	0.1650	1.7106	0.6668	2.4939	0.4006
09:Medical	1195	0.4660	3.0578	0.6011	4.0256	0.3704
10:Factory	25036	0.5909	2.4738	0.4389	2.8335	0.7722
11:Mixed	3310	0.2328	2.7183	0.5665	4.3958	0.5824
12:Other	5567	0.0083	2.6576	0.9606	3.0292	1.4925

Fire frequencies are provided in function of structure size for different building types are provided in the figure below. The results show, initially, an inverse correlation between surface area and frequency per unit area. For larger areas, the correlation becomes more constant.

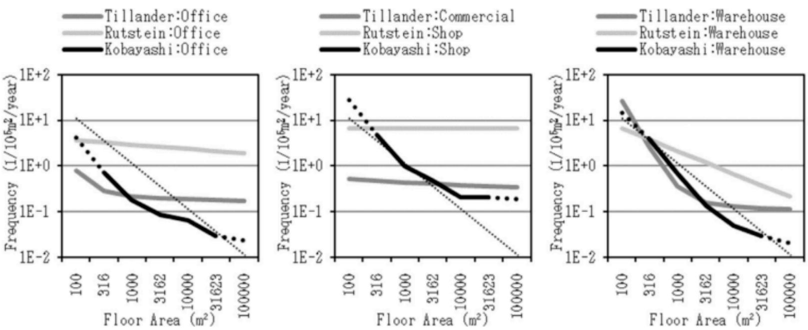

Figure A.3: Examples of fire frequencies per unit area for increasing building surface. Taken from [5].

A.3.10 FIRS (USA 2018)

An in-depth investigations performed to evaluate the current frequency data of the PD 7974-7 [8] and determine new frequencies based on more recent frequency data [18]. The study showed that for non-residential buildings, fires are more frequent in Food and drinks premises, hotels and communal living (4.61%) in in the UK; and in the US fires are more frequent in educational premises (5.51%) and Entertainment, culture and sport spaces (5.45%). Analysing the NFIRS in the USA fire statistics, it is possible to attribute the high fire frequency in educational premises to open flames (potentially due to arson) with related high financial losses. The lowest percentages in the figure below are in offices and call centres; retail premises (0.37%) in UK and other public buildings and services (0.06%) in USA.

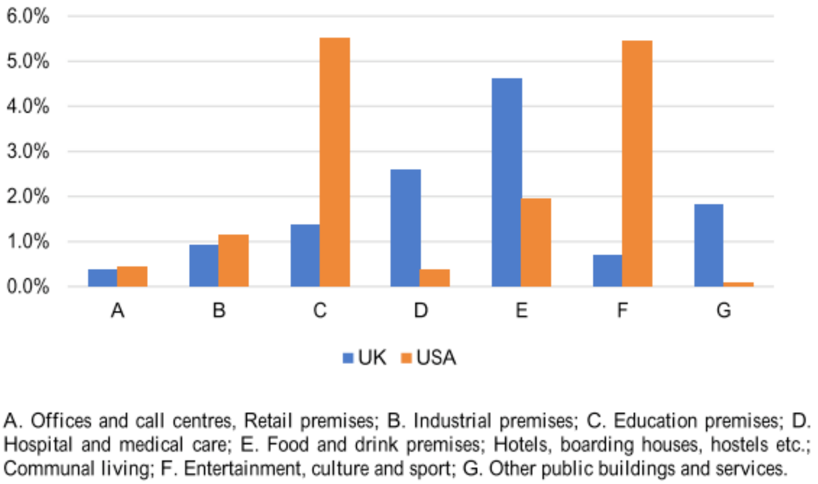

Figure A.4: Fire statistics USA. Taken from [18].

Table A.10: Overall probability of fire starting in various types of occupancy. Taken from [18].

Occupancy	PD 7974-7	UK	USA
Industrial	4.4	0.903	1.121
Storage	1.3	N/A	N/A
Offices	0.62	0.369	0.423
Assembly entertainment	12	0.687	5.446
Assembly non-residential	2.0	N/A	N/A
Hospitals	30	2.571	0.363
Schools	4.0	1.362	5.512
Dwellings	0.3	0.133	0.151

Table A.11: Probability of fire starting in different occupancy types. Taken from [18].

Other Occupancies	PD 7974-7		US Fire Statistics						
	Power law		Power law (+ve b)		According to dots graph probability of fire – tot floor space				
					Power law			Improved form	
Trend in figures x-x below	[Power (PD)]		[Power (USA - Rutstein)]		[Power (USA - Improved)]			[Poly (USA - Improved)]	
	a	b	a	b	a	b	R^2	Law	R^2
Storage	0000067	0.5	0.0023	0.0392	0.0001	0.349	0.405	$-3.75*10^{-17}A^3+7.26*10^{-12}A^2-9.90*10^{-8}A+0.0019$	0.993
Shops	0.000066	1	0.0010	0.0589	0.00005	0.4514	0.927	$4.88*10^{-17}A^3-4.61*10^{-12}A^2+2.25*10^{-7}A+0.0008$	0.997
Offices	0.000059	0.9							
Hotels	0.00008	1	0.0037	0.0125	0.0003	0.366	0.673	$-1.10*10^{-16}A^3+1.13*10^{-11}A^2+9.35*10^{-8}A+0.0031$	0.991
Hospitals	0.0007	0.75	0.0029	0.0115	0.0001	0.4867	0.839	$-2.37*10^{-12}A^2+4.71*10^{-7}A+0.004$	0.742
Schools	0.0002	0.75	0.0012	0.0101	0.0002	0.2179	0.768	$2.92*10^{-16}A^3-7.76*10^{-12}A^2+1.04*10^{-7}A+0.0010$	0.983

A.4 General

In the figure below, a comparative example is given of the ignition frequency per unit area for a retail building. The results show that two correlations have no dependence on building area while three correlations have a negative correlation between ignition frequency per unit area and the building surface area. The results show to differ up to an order of 200 for higher building areas. This might be due to the lower fires in large retail buildings which can give non reliable data. It is suggested to apply the average of the four curves (yellow curve) and the outer boundaries as uncertainty. The older data provided in [12] is not taken into account. It is important to emphasize that the frequency should be calculated per building and not per compartment.

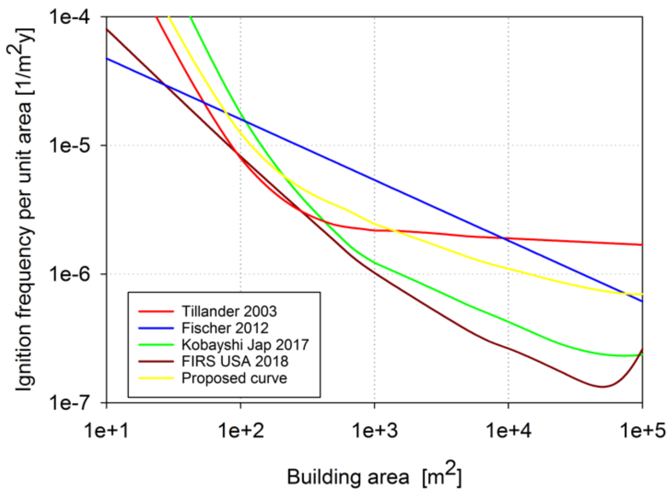

Figure A.5: Ignition frequency per unit area for a retail building.

A.5 Case study - Shopping mal

The shopping mall has a floor area of 5*5000 m^2, a total height of 5*4m and is a considered a commercial building. The ignition frequency for the different methods is depicted below.

Table A.12: Fire frequencies for the shopping mall case study.

	Methods	Frequency [y^{-1}]
1	Rutstein	$P(A) = 0.000066\ A^1 = 1.65$
2	CdR	$P(A) = 0.000022\ A = 0.55$
3	Tillander	$f''_m = c_1\ A^r + c_2\ A^s = 0.00007\ A^{-0.65} + 0.000006\ A^{-0.05} = 0.093$
4	Sandberg	$P(A) = 0.000016\ A = 0.4$
5	Lin	$P(A) = 0.0024\ A = 60$
6	Ghosh	$P(A) = 0.00074\ A = 18.5$
7	Fischer	$\lambda = e^{\alpha} * Vol^{\beta} = e^{-8.98}\ (5000 * 20)^{0.445} = 0.021$
8	Kobayashi	$Pr = 0.054$
9	USA 2018	$P(A) = 4.18 * 10^{-17} * A^3 - 4.61 * 10^{-12} * A^2 + 2.25 * 10^{-7} * A + 0.0008 = 0.0043$

The case studies show significant differences in fire ignition frequency. The difference between the lowest and highest value is a factor of 15349. The reason for the difference can be related to different issues:

- The data from Lin and Ghosh shows unrealistic high fire frequencies and are omitted from further analysis. Omitting this result gives a maximum ratio of 79 times difference between the highest and lowest frequency.
- The data from Rutstein does not allow for high commercial area spaces. The power law 1 is probably an overestimation for larger building sizes. Therefore, this value is considered an overestimation.
- The data from Sandberg and Centre de Recherches are in the same order. However, the frequency per unit area is independent from building size. Therefore, this might data be an overestimation for larger buildings sizes.
- The results from Tillander, Fischer and Kobayashi follow the same trend.

- The data from the USA are recent data pointing towards the trend of less fires because of increased investment in fire prevention.

A.6 Conclusion

In general, it can be concluded that the larger the building the higher the probability of ignition. However, from the analysed research, it is possible to conclude that the effect is nonlinear and that the non-linearity could be attributed to two main reasons:

- There may be a scale effect: if a building is enlarged to double its original size, not all the services would double in size or in fire risk so that the risk of fire in a larger building would be less than two times than the original building.
- Composition of the sample: it is expected that larger buildings (non-industrial) increase their effort in terms of fire prevention management (e.g. prevention officer) or first aid firefighting capability. The awareness is increased and therefore the expected frequency is does not increase linearly.

B GLASS BREAKAGE DYNAMICS

The objective of this study is to give an overview of the existing literature regarding the determination of glass breakage in compartment fires.

B.1 Background

In case of under-ventilated burning is the size (more technically, the heat release rate) of fires is limited by the flow of oxygen available to it. In all except very rare circumstances, the flow of oxygen into a room comes largely from open doors and open windows, and to a slight extent from any mechanical ventilation systems and from building leakage. Once a fire gets going, however, windows previously closed may crack and break out. The results will often be drastically different, depending on whether the windows break or not. Thus, it becomes of significant interest to be able to predict if, and when, glass may break out.

When a window pane of ordinary float glass is first heated, it tends to crack when the glass reaches a temperature of about 150 – 200°C. The first crack initiates from one of the side edges. At that point, there is a crack running through the pane of glass, but there is no effect on the ventilation available to the fire. For the air flows to be affected, the glass must not only crack, but a large piece or pieces must fall out.

B.2 Types of glass

Glass in a window or curtain wall system can present a route for flames to spread should the glass break and fall from its containment or framing system. Today’s windows and curtain wall systems use a wide variety of glass types and framing methods (vinyl, wood, aluminium). Glass can be of a variety of colours, opacity, area, varying sheet thickness and with or without multilayer construction (e.g. single, double, or triple glazed). Glass panels may be annealed or float glass, heat strengthened, tempered/toughened, reflective, laminated, or wired. The complexity of glass installations from building to building can vary significantly and the current state-of-the art available to predict glass breakage is limited with high degrees of uncertainty given the possible configurations and variations in window and curtain wall construction.

In Belgium, most public buildings such as offices, commercial, assembly spaces, etc., contain mostly double or triple layered glass for energy purposes. Additionally, for safety purposes, the standard NBN S23-002 [19] is considered a rule of good practise for determining the glass type of outer and inner windows. In the building envelop, mostly layered glass with special interlayer protection is applied. Inside the buildings, depending on the location, size, etc. also tempered glass can be found and under specific conditions (outside human activity zones) regular glass can be used.

B.3 Types of thermal exposure

It must be realized that there are at least two distinct types of thermal exposure to glass that is involved in fires:

1. A window is inside a room in which a fire is taking place. The window is being subjected to immersion heating from one side. The local gas temperature and the radiating temperature are rather similar. There may be a gradient of temperature and heat flux from the top down to the bottom.
2. A window is exposed to an outside fire, typically a wildland or bush fire. In that case, there may be relatively little difference in exposure between the top and the bottom of the window. The heating is primarily by radiation. Local gas temperatures may be near-ambient, since flames are not directly washing against the window and there is a convective cooling flow along the surface.

The focus of the current research is on the first type of exposure.

B.4 Types of breaking mechanisms

The thermal breaking mechanism of glass can be categorized in the following categories [20]:

- Intensive heat flux: if an intense heat flux is suddenly applied on one side of a glass pane, a steep thermal gradient will be created across the thickness of the layer. This phenomenon is called ‘’thermal shock’’ and causes thermal stresses which could break the pane;
- Thermal gradient: a thermal gradient over the thickness of the pane will cause the planar plane to deform. The boundary conditions (edge conditions, glass type etc.) will cause stresses which are larger in the corners of the plane. These stresses could become particularly high in very small panes, controversially for the larger panes which are more flexible;
- Non-uniform heating: thermal stresses and tension will occur when the glass pane is not uniformly heated. This situation occurs when parts of the glass are shaded from radiation, which is the case for the shielded edge of the window by the shading of the frame. As a result, the maximum stress will always occur at the rim of the pane. The non-

uniform heating between the central glass pane and the shaded area will be addressed in this study as the temperature difference (ΔT).

Besides the higher stresses along the edges of the pane, the area can also contain micro cracks due to the cutting process. These manufacturing imperfections can also contribute to cracks and eventual early fallout of the entire window. The non-uniform heating is in practice the most normative parameter during a fire. Additionally, pressure variations could also potentially affect the failure of glass planes. However, the influence of pressure lies beyond the scope of the present study.

B.5 Literature

Most research has been done regarding glass breakage of single glazed windows. These types of windows are applicable for inner windows between rooms and hallways. Double and triple glass are used in the building envelop and for inner windows for safety purposes.

B.5.1 Single float glass

The earliest guidance to be found in the literature on the question of when glass breaks out in fires comes from the Russian researcher Roytman [21] who notes that a room gas temperature of around 300°C is needed to lead to glass breakage.

In [22], a series of experiments in a half-scale fire test room using 0.9 x 1.6 m single-glazed windows where they created a natural top-to-bottom temperature gradient in the room and in the glass. At the time the first crack occurred in 4 or 6 mm thick glass panes, gas temperatures in the upper layer of 323-467°C were recorded. By the end of their 20 min tests, gas temperatures were at ca. 500°C. Yet in only 1 of 6 tests there was there any fall-out of glass. Temperature differences between the glass exposed surface and the shielded portion ranged between 125°C to 146°C at the time of crack initiation. These temperatures were about twice that predicted from the no-vertical-gradient theories. The authors do not give the exact room fire temperature at which the glass fall-out began in the one test where this occurred, but this had to be higher than 431°C (crack initiation) and lower than ca. 450°C (end of test). One can put these data together, then, to conclude that at a room gas temperature of around 450°C the probability is 1/6 for glass to break out. In [23], further tests were conducted using a room with three windows glazed with 6 mm thick panes. Glass fell out when the exposed surface temperature reached 415 – 486°C on the average. But there was quite a lot of variability and individual values ranged from 278 to 615°C at failure. It required a heat flux of around 35 kW m^{-2} for fall-out to occur. In a follow-on test series [24] it was noted that the lowest temperature of the glass at fall-out was 447°C.

B.5.2 Single tempered glass

Small scale tests have shown that heat strengthened and tempered glass survived 43 kW/m^2 for 20 min without breaking while reaching temperatures of 350°C [25]. In large scale tests with panes up to 0.91 x 1.5 m^2 no cracking occurred up to 29.2 kW/m^2 [26].

Unlike common float glass, tempered glass falls out upon cracking and does not exhibit a cracked-but-still-in-place condition. This is due to the large stresses induced in the glass [27].

On the basis of experiments [28] of the breakage behaviours of toughened glass with thicknesses of 6 and 10 mm, it is suggested that a critical temperature difference, between the inner and outer pane, is required for the crack and fallout of toughened glass with a certain thickness. The results from the experiments show critical temperature difference for the 6mm-thick toughened glass of about 330-380°C. For 10-mm-thick toughened glass, a critical breakage temperature difference of approximately 470-590°C is measured. It was observed that flashover conditions need to occur in order for the tempered glass to break. The 6 mm glass required around a 330-380°C temperature difference to fail, while for the 10 mm thick glass it was 470-590°C [28].

From research it was concluded that tempered glass is not likely to break out until after room flashover has been reached [27].

In case of large glass panes, caution should be taken when using the discussed data. Safety margins should be taken into account or special measures should be implemented to reduce the thermal stresses in the window pane.

B.5.3 Double layered glass

Double-glazed (or triple-glazed) windows can be expected to survive much longer in a fire without breaking out [29]. The spectral radiant absorption characteristics of window glass are such that there is a very high transmission within a certain wavelength region that encompasses the visible and the near infrared parts of the spectrum. Outside of this region, glass is essentially opaque. Thus, in a double-glazed window, the radiation transmitted through the first pane is transmitted only in the spectral regions where the second pane also shows nearly no absorptivity. The consequence is that the second pane is not appreciably heated as the first pane is warming up. This behaviour means that the second pane will probably never break out in a fire of short duration or will break out much later in a long fire. Experimental results confirm this reasoning. Shields, Silcock and Hassani [30] exposed two sizes of double-glazed windows to room fires. The glass thickness was 6 mm. The room fire reached a peak of 750°C and no glazing fell out up to the peak. However, during the decay part of the fire, in one of 3 tests with the larger-size window (0.8 x 1.0 m) fall-out of the inner pane occurred at 21 min, when the temperature had dropped to 500°C. Glass did not ever fall out from the outer pane, nor did any fall-out occur in the smaller (0.8 x 0.5 m) window, nor did any fall-out occur in the other two tests. In another test [31] involving double-glazed windows with 6 mm-thick panes, the authors found that a heat flux of around 70 - 110 kW m^{-2} was needed to cause a substantial amount of both panes to fall out and a through-opening to thereby be created in a 0.85 x 1.9 m high window. A smaller, 0.85 x 0.85 m window, however, broke out its second pane a long time after the heat flux peak had been reached and the fire had substantially decayed.

The Loss Prevention Council of the UK [32] studied room fires which were providing fire exposure to a multi-story facade test rig. Double-glazed windows were examined, with each pane being 6 mm thick. Using 3 MW wood crib fires, it was found that temperatures of at least 600°C had to be sustained for 8 - 10 min before glass started falling out sufficiently so that fire venting would occur. When tests were repeated using a fully-furnished office room arrangement, however, glass broke out at 5 min after the start of fire. In that test, the temperature was also about 600°C at the time of failure, but occurred immediately as the temperature was reached. Thus, the findings lead to the conclusion that double-glazed windows using 6 mm thick glass will fail at ca. 600°C and that, if the fuel load is significant, the failure may be expected to occur essentially at the instant that 600°C is first reached.

In other large scale tests [26], double-glazed windows (panes up to 0.91 x 1.5 m^2), they found that fluxes between 20 and 30 kW m^{-2} were required to cause fall-out in both panes.

From experiments [33] with double and triple (4 mm) glazing was observed that the double glazing assembly did not experience major glass fallout before a gas temperature of 350°C. These results are in the same trend as discussed above. The composition with triple glazing did not experience major glass fallout before a gas temperature of 450°C (Figure B.1). For both type of experiments an average of no more than 50% of the glass fell out. However, in some windows up to 80% fell out.

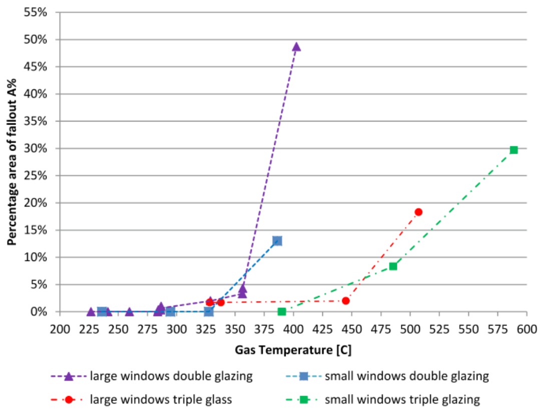

Figure B.1: Average glass fallout as a function of gas temperature. Taken from [33].

B.5.4 Double glazed curtain wall systems

In the past decade, several high-rise buildings were constructed with curtain wall systems because glass curtain wall systems have low costs and give a good visual effect. In these cases, breakage mechanisms can be divided into two different thermal stress. The first mechanism is due to thermal stress of the glass by temperature differences in glass. The second is due to thermal deformation of the frame.

B.6 Suggested parameters

Based on the literature study, critical gas temperature with associated glass fall out is suggested in Table B.1.

Table B.1: Suggested critical gas temperatures and fall out for different window types and thicknesses.

Glass type	Thickness [mm]	% fall out [-]	Gas temp. [°C]	Radiative heat flux [kW/m^2]	Ref.
Single float	4	50%	360	-	[34]
Single float	6	50%	450	35	[24]
Single tempered	6	100%	Flashover	43	[27]
Double layered	4	50%	375	25	[33]
Double layered	6	50%	600	35	[32]
Triple layered	4	20%	475	30	[33]

C HUMAN BEHAVIOUR

The objective of this section is to investigate the main aspects of human behaviour during emergency evacuation. The primary focus of human behaviour in fire research and its application in evacuation modelling is to minimize the risk to people from fire. It is a much investigated and discussed matter that is still in an early stage of development [35–39]. The purpose of implementation of human behaviour in risk and evacuation models is to give a more accurate representation of evacuation behaviour during fire and model the delays that go with it.

Research has shown that human behaviour aspects can cause for significant delays and increase exposure during evacuation [37,40]. Current state of the art models try to take into account the main behavioural factors such as response to fire cues, affiliation, interaction with fire, route mapping, etc. In all these cases, simplified models are developed due to limited research, lack of computational power and to make the models practical for projects.

In the next sections, several important aspects with respect to human behaviour in emergencies are discussed. First, the main human behaviour influence factors are discussed. Secondly, behavioural uncertainty is discussed. Next, the focus is put on two important parts of human behaviour modelling. These are occupant response (pre-movement time) and exit choice modelling.

C.1 Human behaviour influence factors

In order to properly address the impact of human behaviour in fire. The most important influence factors are analysed. A brief review is given below:

- Environmental influence factors: Building layout and situational conditions (e.g. smoke, lighting, etc.) impact both behaviour and movement [41,42].
- Social influence: The influence of others and social norms have proven to cause delays in evacuation behaviour [43,44].
- Activity: focus and awareness are key factors to observe and interpret cues [35].
- Individual characteristics: The perception and assessment of cues are individual characteristics of occupants. Perception also depends on physical and cognitive abilities [38,41].
- Affiliation: Both social (group) and place affiliation are important factors to determine pre-movement time and exit choice [45–47] [48].

- Role and function: The influence of role and leadership have important impact on the occupant himself and others to start evacuation and exit choice [45], [46].

C.2 Behavioural uncertainty

Two sources of behavioural uncertainties have been defined: intrinsic behavioural uncertainty, and perceptions and preferences behavioural uncertainty [49]. Intrinsic behavioural uncertainty captures the fact that (a) the choices taken by different decision-makers perceiving a situation in the same way may be different (i.e. evacuees having the same risk perception of evacuation scenarios can act differently depending on their risk aptitude); and (b) the same decision-makers could choose different actions when they face the same situation at different times. Perceptions and preferences behavioural uncertainty is related to different decision-makers' perceptions (i.e. different decision-makers can have different quantitative estimates of the same factor) and preferences (i.e. a certain factor may have different importance to different evacuees) concerning the variables that influence the choice. Therefore, the source of behavioural uncertainty explains why evacuees/pedestrians do not always make the same decisions under the same circumstances.

C.3 Human behaviour and affiliation

Only little data is available on affiliation towards familiar exits during emergencies in case of fire. The most important experimental results regarding exit choice is discussed below. Experiments preceded by a number are already elaborated in the section on pre-movement times. Only the relevant information regarding exit choice is repeated.

1. Retail area (2000) [50]: From experiments in large retail areas in England it was observed that between 61% and 72% of the occupants chose a familiar exit when no additional safety measures were implemented. When additional safety measures were taken, in this case guidance of staff (50% alerted by staff) and automatically opening of emergency exit doors, the majority of the people tended to evacuate towards the closest exit.

2. Furniture warehouse area (2001) [51]: Unannounced evacuation experiments were performed in three different Swedish IKEA warehouses with low occupant densities. People tend to use known exits in a very high degree. Many customers, therefore, walked very long distances before they came to an open exit. There were cases where people moved more than 75 meters even if they initially stood next to an emergency exit. In the evacuation from the Älmhult store some particular emergency exits were used by a high number of customers. What distinguish these exits from other emergency exits is that they

are located so they face the customers as they walk along the path in the warehouse. The exits are in the line of sight and clearly visible as the customers arrive to the area.

6. Industry with office (2007) [52]: During experiments in an industry hall with offices was observed that the majority of the people chose the nearest exit. Only a very small part of the occupants chose the further familiar main exit. The reason for the observed exit was that the low population density and the occupants were properly trained and familiar with the exits.

7. Office and cinema (2008) [43]: From experiments in an office building and a cinema theatre it was observed that the majority of the occupants chose a familiar (main) exit (>80% for office and 100% for cinema) when no additional safety measures were implemented. When green flashing lights were implemented near the exits, more people were attracted to the emergency exits with flashing lights. The effect in the office building with high familiarity was limited. Only a small increase of 11% to 19% was observes. The effect in the cinema with low familiarity was significant. An increase from 0% to 100% was observed. This could indicate that the safety measure flashing lights is more affective for non-familiar occupant types. For familiar occupant types other measures such as training could be more affective.

8. Hotel (2010) [42]: From experiments in a hotel it was observed that during evacuation trails without smoke people tend to take familiar exits (55%). While in similar trials with smoke people tend to go to the nearest exit (64%). In a third scenario with smoke and improved exit signage, it was observed that the majority of the people took the closets exit (75%). This could indicate that the perception of risk, related to smoke present, has an important impact on exit choice. Secondly, the effect of properly designed signage has an important impact on exit choice.

University (2013) [53]: During evacuation experiments in a university it was observed that people tend to evacuate towards the familiar route (>90%) when they are unaware of other available routes. When they are more familiar with the other exits they tend to evacuate towards the closest exit.

University (2016) [54]: Evacuation experiments were performed in a university building. Results showed that people tend to evacuate towards the familiar staircase (62-87%). However, the impact of changing the configuration of alarm was significant.

C.4 Occupant pre-evacuation modelling

C.4.1 General

The purpose of most building occupant response sub-models is to take into account the pre-movement time of these occupants by providing a proper representation of the occupants' responses and actions during a fire evacuation emergency. The response of these occupants to a fire represents a complex interaction between the occupant behaviour, the physical environment and the development of the fire. In the past, it was assumed that people evacuate a building immediately upon hearing an alarm bell or seeing smoke [55]. These explanations of occupant evacuation motivation were based on stimulus and response theory. Psychological studies from past decades have illustrated that motivation is not produced by discrete factors but is derived from information processing and decision making [56–59]. Occupants are alerted by different cues such as auditory, visual, olfactory and tactual cues. They then become involved in the process of information search, interpretation and appraisal, and decision making from which evacuation may emerge as the coping strategy [60,61].

C.4.2 Importance of pre-evacuation time

The pre-movement time is an important parameter in the deterministic model because it will may have a significant impact on the total evacuation time [42,60,62–65]. From experiments and incidents it was found that the pre-movement response times following central alarm sounding accounted up to 2/3 of the total evacuation times [47,66]. Therefore, in the next sections, a literature review is conducted regarding sub-models and calculation methods to determine the pre-movement time based on occupant response behaviour.

C.4.3 Main factors influencing pre-evacuation time

The pre-evacuation time is generally dependent on the nature of the occupancy, the state of the occupants, the quality of the management system, the type of alarm system in place, even the time of day and the presence of additional supporting cues such as the presence of smoke or instructions from a member of staff.

C.4.4 Statistical data

Various studies and experiments have been conducted to assess pre-movement times in different buildings types. A brief review of several relevant experiments and research studies concerning public buildings is given below.

1. Multifunctional retail area (2000) [50]: Experiments were performed in four English retail stores of M&S with an average occupancy of 518 customers. During the experiments on average 81% of the occupants were females, 61% was between 15-65 years, 64% was accompanied and 98% visited the shop more than once. It was observed that the most people needed multiple cues to evacuate. About 33% of the occupants only needed one cue, i.e. the alarm bell (Type W3 [67]), to understand the seriousness of the situation. Others needed prompting by staff or needed to see others evacuating. Average pre-movement times between 25 s and 37 s were observed.

2. Furniture retail area (2001) [51]: Unannounced evacuation experiments were performed in three different Swedish IKEA warehouses with low occupant densities of less than 1 occ. per 20 m^2. The evacuations were initiated by a normal escape alarm in each warehouse. All escape alarms were assisted by pre-recorded messages with information about what the customers should do. The pre-movement time was considered low, less than one minute as an average value. Most customers responded within a 30 second period. People staying in the cash desk queue showed a longer pre-movement time, as they were more reluctant to leave the place in the queue.

3. University lecture building (2001) [68]: Three unannounced evacuation trials were performed in New-Zealand University buildings. Occupant loads varied from 278 for the single-story building to 716 occupants for the eight-story building. The buildings were equipped with an alarm and voice communication system. Average pre-movement times were recorded between 19 s and 38 s.

4. University library (2003) [69]: An unannounced trial evacuation of an English university facility was performed. 361 occupants (90% students) were present with an average density of 1 occ./10 m^2. The university employed a procedure whereby once the alarm sounded nominated members of staff swept each of the rooms. It was found that pre-movement times ranged from around 10 to 200 seconds. The greatest proportion (54%) of individuals undertook two actions prior to commencing to evacuate. Of the remainder, 28% completed one or no actions, and 18 % completed three or more. The range of prior actions analysed comprised of: evacuate immediately, perform a computer shutdown, disengage socially, collect items, including bags, coats, paperwork etc. and investigate the incident. Additional findings:

- The Pre-evacuation time is strongly linked to the role of the occupant. Staff warning students have longer pre-movement times (μ = 85 s σ = 65 s) than staff considered to evacuate immediately (μ = 32 s σ =

60 s). The most important aspect of this analysis is that the staff pre-evacuation distribution can be further refined, according to their role.

- Several students needed to be encouraged in order to evacuate. 52% of the students did not need prompting (μ=65 s), 10% needed prompting from other students (μ=92 s), 38% needed prompting from staff members (μ=82 s). The pre-movement time for these students was then dependent on the time taken for staff to reach the students in the course of completing their sweep of the building. The figure below, the pre-movement times are depicted in the figure below.

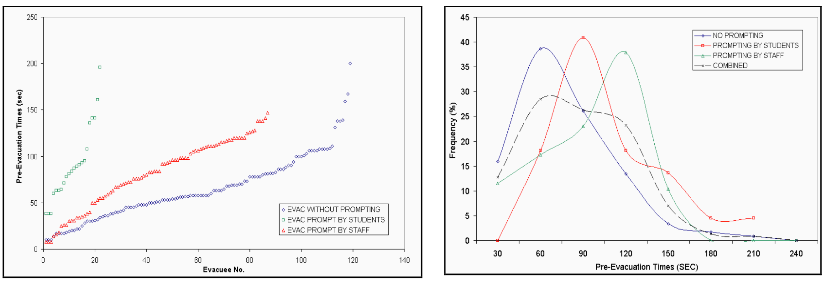

Figure C.1: (a)Pre-evac. times and (b) Frequency distribution according to prompting. Taken from [69].

5. Hospital (2003) [69]: An announced evacuation experiment was performed in an English hospital department. The compartment contained 14 staff members and 19 non-ambulant patients (outpatients). The results showed that patients only started to evacuate after being prompted by the staff. The average patient pre-evacuation time was 59.1 seconds, while the staff members were seen to act after 45.0 seconds.

6. Industry with office (2007) [52]*:* Experiments were performed in an industry hall with offices (NZ) containing 256 occupants (low density) with high familiarity and even proportion between male and female. Pre-evacuation times between 20 s and 180 s were estimated. The main indication for longer pre-evacuation times were due to focus and shutting down equipment.

7. Database USTC (2009): A database was developed in China based on western data sets. The Database includes data on pre-movement times, exit choice, walking speeds, actions and delay, etc.

8. Hotel (2010) [42]: Three experiments were conducted in a hotel in the Netherlands during night time with occupant groups between 24-39 people. The alarm was given by an individual telephone call in order to not awake any other participants. For the three experiments a mean pre-movement time of

103 s was observed. The main delay time was due to changing clothes and gathering of belongings.

9. Database NRCC (2010) [70]: A database was developed to give an overview of pre-movement times in different occupancy types (office, hotel, stores, apartment, etc.) for different heights. For each data set, additional factors concerning cues prior knowledge, etc. was given.

10. Database SFPE Handbook (2016) [71]: An extensive summary of pre-movement times is presented in the SFPE handbook for fire engineering. For each event the most important results are discussed.

C.4.5 Methods

A great number of evacuation models have been developed to predict evacuation time [38]. In these models, movement dynamics have been fairly well modelled. However, pre-evacuation response behaviour is rarely explicitly modelled. Often the modeller needs to model pre-evacuation behaviour implicitly by implementing a pre-movement time. In general, five approaches are adopted to take model pre-evacuation behaviour.

The first approach sets the pre-movement response time as a fixed value specified by the user, as used in Fluid Model [72] and Magnetic Model [73]. While this approach is fairly simple to perform, it completely ignores the probabilistic characteristics of the perceptions and actions of occupants and the effects of fire detection and alarm systems on perception time.

The second approach specifies pre-movement response times as a distribution or a random number. This approach is used in models such as EvacuatioNZ [74]. The approach is an improvement with respect to the first approach. However, it is still not a general model since the effects of fire severity and fire detection and alarm systems on occupant response are not reflected.

In the third method, the pre-evacuation behaviour is partially implicitly modelled. The model assumes that occupant response is probabilistically related to the perceived level of fire severity. This approach is used in risk models such as CRISP [75] and Evacsim [76]. While this approach is more advanced compared with the first and second method, aspects such as perception time, perception probability, random actions, and the effects of fire detection and alarm systems are not considered.

The fourth approach involves the user assignment of sequences of pre-evacuation actions. The simulated evacuees move to different parts of the simulated building to perform their activities. Each action has a pre-defined specific duration for each evacuee.

The fifth approach considers occupant response and evacuation as a result of a PIA process, i.e. Perception, Interpretation, and Action, which may interact with each other. It was proposed to be incorporated in a risk-cost assessment model [77]. This approach relates the variation of response probability with time to fire severity. According to the relationship between the occupant's location and the compartment of fire origin, occupants in a building are classified into three groups, i.e. occupants in the compartment of fire origin, occupants in the same level as the compartment of fire origin, and occupants in other levels. Occupants perceptions consist of occupants' direct perception, warnings from fire detection and alarm systems, and warnings from other occupants and the fire department. Following their perceptions, occupants will interpret their perceptions and take various actions including commencing evacuation. The calculation of the perceptions of occupants in all compartments is related to fire states in the compartment of fire origin. This may not be appropriate, as occupants generally perceive a fire from in their own environment. Additionally, the classification of occupants into three groups makes the approach not appropriate to be applied to buildings with more than two storeys.

C.4.6 Decision models

C.4.6.1 Traditional models

Almost all modern numerical evacuation models require the implementation of a user pre-defined pre-evacuation time. This in the form of a constant value or distribution. From research it is observed that most evacuations models, despite the use of different distribution laws of probability, predict similar evacuation times [78].

C.4.6.2 Choice action model

In [79] research was done identify the sequence of actions taken in different types of fires. Based on a study in the UK, decomposition diagrams were generated for various types of fire events that identify the sequence of actions. The study included results for domestic fires, multiple-occupancy fires and hospital fires. In the figure, the dashed circles indicate the acts which occurred with a lower frequency. The relationships between acts are indicated by arrows. The numbers next to an arrow refer to the strength of the association. The higher the association number, the greater the association is, i.e. the more likely it is that given the performance of one act, the next action will follow. The challenge of the model is to couple time delays to every event. Secondly, the probability of every event will depend on the occupant in relation to the location of the fire. Occupants closer to the fire will have different response than occupants on another floor.

C.4.6.3 CUrisk occupant response model

The developers of the CUrisk developed an occupant response model to determine the pre-movement time for evacuation of apartment and office buildings. The model simulates the basic processes of human responses by implementing the concept of the PIA process, i.e. Perception, Interpretation and Action [77]. The processes of perception, interpretation and action interact with each other resulting eventually in the response of evacuating the building. The model calculates during each timestep the probability of evacuation for each occupant during each time step.

An update of the occupant response model was done and discussed in [40]. Several improvements were implemented to give a better representation of reality. More specifically, detection data was replaced by heat detection calculations and probability data was updated based on statistical data. Additionally, delay times based on experiments were included.

C.4.6.4 The PADM concept

The Protection Action Decision Model (PADM) is a social psychological conceptual model [80]. The model provides an explanation of the meaning-making process in crises to disaster situations. The model (Figure C.2), which is based on over 50 years of empirical studies of hazards, disasters and theories provides a framework that describes the information flow and decision-making that influences individual protective actions taken in response to natural and technological disasters. This framework shows that cues from the physical environment as well as information from the social environment (i.e. emergency messages or warnings), if perceived as indicating the existence of a threat, can interrupt normal activities of the recipient. Depending upon the perceived characteristics of the threat (e.g. assessments of risk to themselves or others), certain types of actions will be performed. The PADM is the precursor of the EDK model which is explained in the next section.

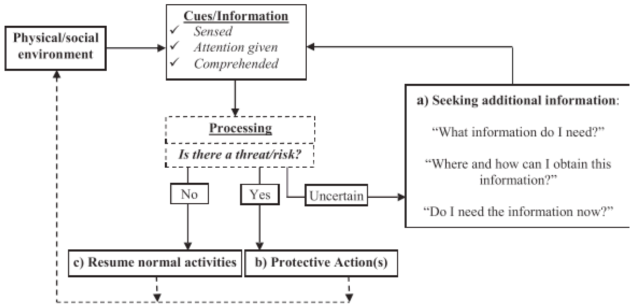

Figure C.2: The Protective Action Decision Model. Taken from [80].

C.4.6.5 The EDK concept

The Erica Dawn Kuligowski (EDK) concept is a pre-movement behaviour concept for developing egress behaviour [39,81–84]. The main focus of the EDK model was to understand the actions performed during the pre-evacuation period of the WTC disaster and the process by which evacuees decided upon these actions. The EDK concept gives guidelines for the model developer to which behaviours and models should be implemented for accounting the different occupant behavioural aspects.

The EDK model was further developed in [39], to develop a general structure for the modelling of both the pre-evacuation and evacuation phase in case of fire. The translated EDK model is depicted in Figure C.3. The concept consists of three phases. The Cue Processing (CP), Situation Assessment (SA) and the Response Selection (RS) phase. External cues are provided to the Cue Processing phases in which the cues are assessed. If these cues are deemed credible the situation is interrogated. Depending on the experience of the agent, the threat is assessed or a direct response is generated. Next, the agent selects a response in the RS phase. During each timestep of the (pre-)evacuation, the model is constantly looped so that the output of the RS provides input for the external world and the CP phase.

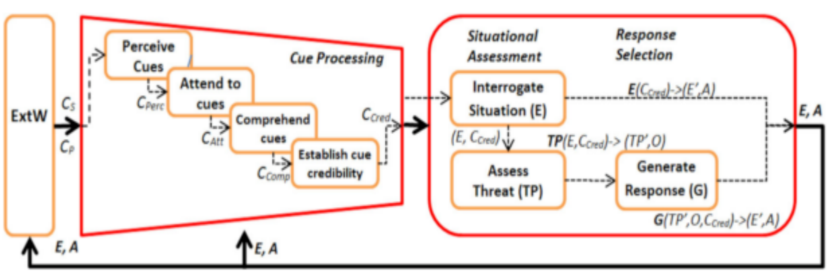

Figure C.3: Translated EDK model. Taken from [39].

C.4.6.6 Evacuation Decision Model

The Evacuation Decision model (EDM) is a pre-evacuation human behaviour that introduces a differential equation model calculating the level of perceived risk, which allows estimating the behavioural state of evacuees among three possible states, namely: normal, investigating and evacuating [85]. The differential equation defining the relation between perceived risk level $R_i(t)$ and the cues is:

$$\dot{R}_i(t) = f(\mathbf{X})R_i(t) \qquad (C.1)$$

where $\dot{R}_i(t)$ is the rate of increase/decrease of perceived risk over time and f is a linear function of all the n environmental and social influence affecting the risk variation, which can vary over time.

C.4.6.7 RUT evacuation decision-making model

Random Utility Theory or RUT is the most common theoretical framework/paradigm, which has been used over the last 50 years to develop discrete choice models. In [86–88], a RUT model is developed for the simulation of (pre-)evacuation behaviour. The proposed model represents the evacuation behaviour of simulated occupants considering three behavioural states: normal, investigating and evacuating.

The model is developed to take both deterministic and behavioural uncertainty into account. Therefore, it is assumed that the utility of each alternative for the decision-maker consists of two terms: a deterministic V_{iq} and a random component ε_{iq}. The random utility is calculated:

$$U_{iq} = V_{iq} + \varepsilon_{iq} \qquad (C.2)$$

The calculation of the two components is given in [49]. For each time step, each occupant revaluates the utility of every alternative exit and adapts his choice depending on the circumstances.

The model simulates the probability of choosing to start investigating and evacuating in relation to physical and social environmental factors as well as personal occupant characteristics. The main difference between the developed model and existing predictive-based models is that it is data-driven. The model is calibrated for a theatre compartment environment and shows good result. The disadvantage of the model is the lack of data and the fact that calibration is only valid for very specific circumstances.

C.5 Occupant exit choice modelling

C.5.1 General

The purpose of the occupant exit choice model is to determine the exit choice for every occupant in the building during emergency evacuation. In the past, exit choice was mainly an optimization problem. Models were designed to assign agents to a certain exit depending on the shortest travel time. These algorithms give the shortest evacuation times. However, research has shown that people do not always know all exits, or have a clear overview of the fastest route [49,89].

C.5.2 Importance of exit choice

The selection of an emergency exit is an important parameter in evacuation modelling because it will may have a significant impact on the total evacuation time. From modelling research it was found that uneven distribution of exit selection can significantly increase [90,91].

C.5.3 Main factors influencing exit choice

In order to develop an exit choice simulator, a model should be developed that takes the most significant parameters into account. Past research has shown that the most important influential environmental factors for exit choice are distance from the exits, queuing time, fire conditions (e.g. visibility of an exit) and indication by emergency lighting [41]. Different types of social influences can also affect exit choice leading to different behaviours: herding behaviour, leader-follower behaviour, cooperative behaviour and competitive/selfish behaviour [92]. Besides the environmental and social factors, personal factors can affect exit choice. The most influential personal factor is the familiarity of the decision-maker with an exit (place affiliation) [93].

C.5.4 Statistical data

Only little data is available on affiliation towards familiar exits during emergencies in case of fire. The most important experimental results regarding exit choice is discussed below. Experiments preceded by a number are already elaborated in the section on pre-movement times. Only the relevant information regarding exit choice is repeated.

1. Retail area (2000) [50]: From experiments in large retail areas in England it was observed that between 61% and 72% of the occupants chose a familiar exit when no additional safety measures were implemented. When additional safety measures were taken, in this case guidance of staff (50% alerted by staff) and

automatically opening of emergency exit doors, the majority of the people tended to evacuate towards the closest exit.

2. Furniture warehouse area (2001) [51]: Unannounced evacuation experiments were performed in three different Swedish IKEA warehouses with low occupant densities. People tend to use known exits in a very high degree. Many customers, therefore, walked very long distances before they came to an open exit. There were cases where people moved more than 75 meters even if they initially stood next to an emergency exit. In the evacuation from the Älmhult store some particular emergency exits were used by a high number of customers. What distinguish these exits from other emergency exits is that they are located so they face the customers as they walk along the path in the warehouse. The exits are in the line of sight and clearly visible as the customers arrive to the area.

3. Industry with office (2007) [52]: During experiments in an industry hall with offices was observed that the majority of the people chose the nearest exit. Only a very small part of the occupants chose the further familiar main exit. The reason for the observed exit was that the low population density and the occupants were properly trained and familiar with the exits.

4. Office and cinema (2008) [43]: From experiments in an office building and a cinema theatre it was observed that the majority of the occupants chose a familiar (main) exit (>80% for office and 100% for cinema) when no additional safety measures were implemented. When green flashing lights were implemented near the exits, more people were attracted to the emergency exits with flashing lights. The effect in the office building with high familiarity was limited. Only a small increase of 11% to 19% was observes. The effect in the cinema with low familiarity was significant. An increase from 0% to 100% was observed. This could indicate that the safety measure flashing lights is more affective for non-familiar occupants' types. For familiar occupant types other measures such as training could be more effective.

5. Hotel (2010) [42]: From experiments in a hotel it was observed that during evacuation trails without smoke people tend to take familiar exits (55%). While in similar trials with smoke people tend to go to the nearest exit (64%). In a third scenario with smoke and improved exit signage, it was observed that the majority of the people took the closets exit (75%). This could indicate that the perception of risk, related to smoke present, has an important impact on exit choice. Secondly, the effect of properly designed signage has an important impact on exit choice.

6. University (2013) [53]: During evacuation experiments in a university it was observed that people tend to evacuate towards the familiar route (>90%) when they are unaware of other available routes. When they are more familiar with the other exits they tend to evacuate towards the closest one.

7. University (2016) [54]: Evacuation experiments were performed in a university building. Results showed that people tend to evacuate towards the familiar staircase (62-87%). However, the impact of changing the configuration of alarm was significant.

C.5.5 Methods

In literature, three methods exist for exit choice modelling in evacuation models [49]:

- Agents (i.e. simulated evacuees) head towards exits predefined by the modeller (e.g. Pathfinder [94])
- Agents choose the closest exit (e.g. Simulex [95])
- Agents choose the exit considering environmental, social and personal factors (e.g. STEPS [96,97] JuPedSim [98], Building EXODUS)

The first method is the most basic because it does not consider any evolution of the evacuating scenarios and the choice is a user input rather than an output of the model. In the second method, the choice is context-dependent. However, it is static and only based on the building layout. The third and most complex approach considers that each agent evaluates the features of the simulated environment and takes decisions based on the perceived information. In these models, the chosen exit can change during the evacuation process if the evacuation conditions change and a range of factors can be considered (e.g. presence of smoke, visibility, familiarity with an exit). The simplest and most common model of the third category is the time-based one, in which the agents choose the exit that requires the lowest evacuation time [38].

A second classification of exit choice models is the difference between deterministic and stochastic approaches. Deterministic approaches have been derived from different decision theories, such as the game theory [99] or the utility maximisation theory [98]. The advantage of deterministic models is that they are efficient and reasonable accurate. The disadvantage is that they can only represent average behaviours. Stochastic models take the uncertainty of different parameters into account. In [100], an exit choice model as introduced in which the ‘base probability’ of using an exit is defined by the modeller. A second example is the Random Utility Theory (RUT) model developed in [49] which combines deterministic with random choice to take uncertainty into account. In the next paragraphs, analysis is done of several evacuation models and a literature study is performed regarding data with respect to exit choice.

C.5.6 Exit Choice models

C.5.6.1 Traditional models

The majority of modern numerical evacuation models requires the implementation of a user pre-defined exit selection in form of an exit familiarity (distribution) or unavailability (locked or smoke blockage). From research has observed that most evacuations models using this method predict similar evacuation times despite the use of different distribution laws of probability [78]. Examples of these models are JuPedSim, Pathfinder, Steps, etc.

C.5.6.2 MASSEgress model

The exit choice algorithm in MASSEgress is a rule based model taking multiple rules into account depending on the stress level [101]. When a low stress level is assigned, the occupant checks for the shortest familiar exit. If not found, the agent explores and takes the shortest exit. Under high stress levels, herding behaviour will become more important than familiarity.

C.5.6.3 SCT model

Social Comparison Theory Fridman proposed a theoretically-based crowd modelling algorithm whose development was inspired by Festinger's social comparison theory (SCT). The agents within this model base their decisions on the desire to be in and act as a group through comparison of their actions/attributes with those around them adjusting them accordingly [102]. Therefore, the behavioural driver is convergence to the social environment rather than an assessment of the perceived influence of the social, physical, procedural and environmental conditions.

C.5.6.4 FDS+EVAC model

In the FDS+EVAC model exit choice is based on four criteria: fastest route, visibility, familiarity of the exit and fire conditions [37]. The agents select an exit with the smallest preference number based on the familiarity and visibility. If two or more exits share the smallest preference, the decision between these is made by minimizing the estimated evacuation time. It is assumed that people change their course of action only if there is an alternative that is clearly better than the current choice, i.e. when an exit becomes visible or smoke appears from an exit.

C.5.6.5 Building EXODUS

The buildingEXODUS evacuation model is a grid based model composed of five core interacting models [89,103] These are the Occupant, Movement, Behaviour, Toxicity and Hazard models. In the behaviour model, the exit choice sub-model is implemented. The sub-model choses the fastest exit out of a set of predefined known exits. During the evacuation simulation, for every timestep, the occupant re-evaluates his/her exit choice based on the influence of dynamic factors such as population size and environmental factors (smoke signage, etc). The occupant may redirect due to higher expected queuing times or unavailability due to smoke. For a thorough appraisal to take place, the occupant has to be in visual contact with the exit, to examine the surrounding population, environmental conditions, etc. If the exit is not within visual range, the occupant has to rely solely on his recollection of exit details from memory, such as position and distance, or possibly from information communicated to them from the surrounding population or from a procedural influence such as an intelligent alarm system.

C.5.6.6 RUT Model

In the RUT framework, the decision-maker assigns to each route or exit an utility. The option with the highest utility is more likely to be chosen.

The validation results of case studies show that the method provides more accurate predictions of local exit choice. On the other hand, important factors such as number and position of the exits, affiliation, etc are not considered. Additionally, the model is only validated for very specific cases.

C.5.6.7 JuPedSim

The exit choice model in JuPeSim [98,104] applies a combination of the shortest and quickest path algorithm. The pedestrians are first routed using the shortest path, global or local depending on their knowledge about the location. Depending on the visibility of an exit, familiarity, travel time and queueing time a cost benefit analysis is performed to determine whether the occupant should reroute its exit choice. The algorithm is being extended by means of interaction of smoke [105]. Exits blocked by smoke are less favoured than other exits depending on the optical density of the smoke.

C.5.6.8 Real-time evacuation model

A real-time evacuation model was developed for sparsely populated enclosures such as industry halls [106]. The implemented model determines the most optimal evacuation based on the route that produces the minimum evacuation time, while keeping occupants away from the hazard. The advantage of the model is that it takes the location of the fire into account. The disadvantage is that no queuing times due to bottlenecks (e.g. exits) nor smoke spread are considered.

D SENSITIVITY ANALYSIS

D.1 The purpose of sensitivity analysis in fire safety engineering

Challenging building designs and complex regulations drive engineers towards quantitative risk analysis (QRA). An important aspect of quantitative risk methods concerns taking into account the variability of the design parameters. In QRA for life safety in case of fire, one of the main reasons to take probability and variability into account is to analyse a sufficient number of deterministic fire scenarios in order to give an acceptable representation of reality. These objectives implicate two key research challenges, i.e. the extensive number of different variables and the complexity of the multiple submodels. It is of importance to determine the most influencing input parameters. Therefore, a significant part of the risk assessment is the preceding sensitivity analysis (SA). This is expected in order to reduce the number of variables within the submodels. In the present study, several methods are suggested which are able to deal with high demanding computational models. Focus is put on SA methods from other fields of research. The evolution from calculating the elementary effects with the Morris method towards radial design with Sobol sampling is investigated.

D.2 Introduction to sensitivity analysis

Generally, sensitivity analysis (SA) are performed to determine how uncertainty in the model output can be attributed to different sources of uncertainty in the model input [107]. The main objective of the preceding sensitivity analysis in fire safety risk assessment is to reduce the dimensionality of the problem formulation [108,109]. The larger the number of random variables, the more the increase in the amount of necessary solver evaluations. Considering the computational effort of several submodels, such as CFD and evacuation models, the dimensionality of several submodels needs to be reduced.

Before discussing different techniques in sensitivity analysis. Two main types can be considered [107,110,111]:

- Local sensitivity analysis is carried out to determine the local impact of parameters in the model (Figure D.1). The partial derivatives of the output function are determined with respect to each input parameter. This can be analytical or numerical by means of One at a Time (OAT) measures. Usually, local SA is practicable only when the variation around representative values of the input factors is small. The main drawback of this approach is that interactions among factors cannot be detected, since they become evident when the inputs are changed simultaneously. A possible way to overcome this problem is to include multi-dimensional averaging of local effects [112–114]. This type of analysis will not be used because the local effects will be modelled with the discussed surrogate model. The results of these experiments can be visualised in tornado diagrams [115].

- In global sensitivity analysis, the emphasis is on apportioning the output uncertainty to the uncertainty of the input factors. Global measures offer a comprehensive approach to model analysis, since they evaluate the effect of a factor while all others are varying as well, exploring efficiently all dimensions of the input space. A wide range of global SA methods is available, ranging from qualitative screening methods [112,116,117] to quantitative techniques based on variance decomposition [118,119]. Secondly, techniques can be used to determine interaction effects between input factors. This is important to completely assess the model prediction. The former mentioned method aims at giving an indication of the correlation effects between input parameters.

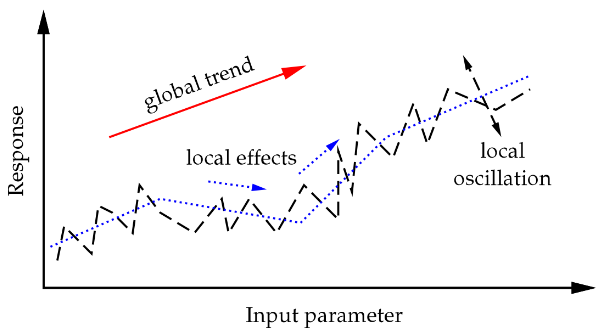

Figure D.1: Schematic decomposition of the responses for the one-dimensional case. The dotted line represents the smoothed responses. Taken from [120].

The choice of an appropriate sensitivity analysis technique depends on several factors [121]:

- Computational cost of running the model: CFD models take much more time than zone or network models.
- The number of input factors: In early stage of the design many factors are possibly of interest. Factorial and screening design can be used to determine the most important parameters.

- The degree of complexity of the model coding.
- The amount of analyst's time involved in the sensitivity analysis.
- The objective of (the analysis (e.g., factors' fixing, mapping, etc.).

In Figure D.2, a graphical representation is given for choosing an appropriate type of sensitivity method. At the first stage of the analysis, the model is located in the top right corner of the graph because of the high number of variables and the extensive computational time per evaluation. The suggested automated differentiation is not suitable for numerical models such as CFD. This because of the time and geometry dependence and the implicit problem formulation of the submodel equations [122,123]. Fractional factorial as used in [124] is a possibility however, a high number of solver evaluations would be necessary to have an interest in interaction effects. Therefore, a radial design and/or screening designs is suggested. In the next chapters, this type will be analysed. After reducing the number of variables, the type can be switched to meta-modelling in order to perform reliability analysis on the studied models. In [110] variance based methods are investigated. However, the application was studied on zone-models which are significantly less computationally expensive in comparison to CFD models.

Another way to deal with the issue of computational effort is to initially use simplified models (Chapter V). The location shifts in Figure D.2 then form top right to top middle.

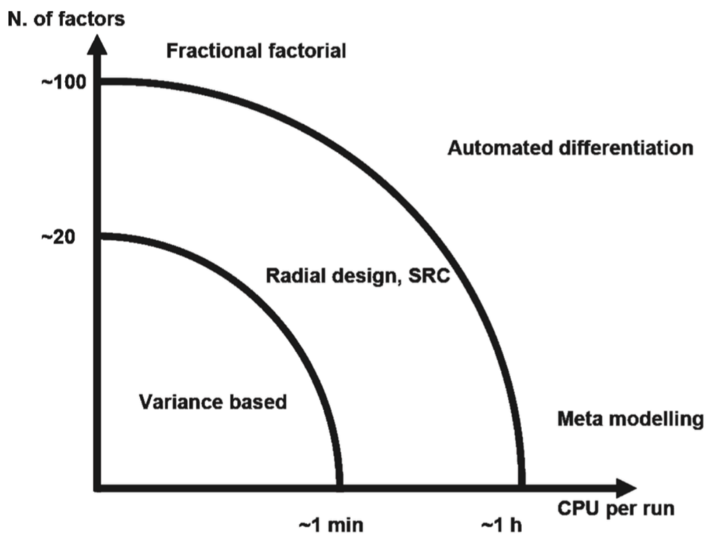

Figure D.2: Representation of the balance between sensitivity analysis and computational efficiency. Taken from [121].

D.3 The elementary effects methodology

The elementary effect method (EE) is a simple but effective factor screening method which can be used for computational affording models [125]. This because the total number of runs is a linear function of the number of examined factors. This in contrast to other schemes such as fractional factorial design or central composite design. The method is considered as good practice by experts in the field [111].

D.3.1 Methodology

D.3.1.1 The Morris method

The method is designed by Morris [112] and is composed of individual randomized designs, in which the impact of changing the value of each factor is evaluated in turn. The region of experimentation Ω is a k-dimensional unit cube (standardized) over which the input vector x is uniformly distributed. This is achieved by means of the probability integral transformation [126]. In the simulation each of the components x_i takes one of the p values $\{0, 1/(p-1), 2/(p-1), \ldots, 1\}$ with equal probability. Morris defines the elementary effect of the i^{th} factor at a given point x as:

$$EE_i = \frac{y(x_1, \ldots, x_{i-1}, x_i + \Delta, x_{i+1}, \ldots, x_k) - y(\boldsymbol{x})}{\Delta} \quad \text{(D.1)}$$

with Δ a predetermined multiple of $1/(p-1)$ and **x** is any value in *Ω* selected in such a way that the perturbed point $\boldsymbol{x} + \Delta$ is still in *Ω*. Δ can be chosen as $1/[2(p-1)]$. This choice has the advantage that, although the design sampling strategy does not guarantee equal-probability sampling from distribution, at least a certain symmetric treatment of inputs is ensured [116,125]. The distribution of elementary effects can be denoted as F_i and can be obtained for the i^{th} input factor is by sampling x from *Ω*. The mean μ and standard deviation σ are calculated:

$$\mu_i = \frac{1}{r} \sum_{j=1}^{r} EE_i^j \quad \text{(D.2)}$$

$$\sigma_i^2 = \frac{1}{r-1} \sum_{j=1}^{r} \left(EE_i^j - \mu\right)^2 \quad \text{(D.3)}$$

where r is the number of trajectories. A high mean indicates a factor with an important overall influence on the output. A high standard deviation indicates either a factor interacting strongly with other factors or a nonlinear factor. The main disadvantage of the method is that individual interactions among factors cannot be estimated. It can provide an overall measure of the interactions of a factor with the rest of the model, but it does not give specific information about the identity of the interactions.

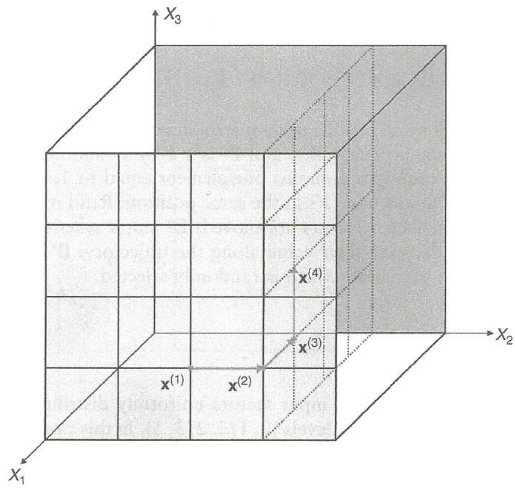

Figure D.3: Morris's OAT design in k = 3 dimensions with p = 10 trajectories. Taken from [112].

D.3.1.2 Improvement by Campolongo

Campolongo et al. [116] proposed replacing the use of the mean μ with μ*, which is defined as the estimate of the mean of the distribution of the absolute values of the elementary effects:

$$\mu_i^* = \frac{1}{r}\sum_{j=1}^{r}\left|EE_i^j\right| \tag{D.4}$$

The purpose of μ^* is to prevent Type II errors which fail to identify a factor with considerable influence on the model [116]. This in case the model is non-monotonic or has interaction effects.

D.4 Sampling strategy

D.4.1 Basic strategy

In order to estimate the sensitivity measures for the distributions F_i and G_i, the design needs to sample a number r of elementary effects from each F_i. In theory if the computation of each sampling point requires two sampling points, the design would require $2rk$ sample points. Morris suggested a more efficient design that builds r trajectories of $k + 1$ points for the input space, each providing elementary k effects, which gives in total $r(k+1)$ evaluation points. The design produces a trajectory of $(k+1)$ sampling points $\boldsymbol{x}(\mathbf{1}), \boldsymbol{x}(\mathbf{2}), \dots, \boldsymbol{x}(\boldsymbol{k}+\mathbf{1})$ with the key properties that two consecutive points differ only in one dimension and that every dimension is addressed at least once to increase by Δ. An example of a trajectory for $k = 3$ is illustrated in Figure D.3.

The technical scheme to generate the sampling trajectories can be seen in the form of a matrix, $\boldsymbol{B}^*$, with dimensions $(k+1)\ x\ k$, whose rows are the vectors $\mathbf{x}^{(1)}, \mathbf{x}^{(2)}, \dots, \mathbf{x}^{(k+1)}$. The first step is to build the matrix $\boldsymbol{B}$ with same dimensions and holds 0's and 1's and the property that for every column index $j, j = 1, \dots, k,$ there are two rows of $\boldsymbol{B}$ that differ only in the jth entry. A convenient choice for B is a strictly lower triangle matrix of 1s.

$$\boldsymbol{B} = \begin{bmatrix} 0 & 0 & 0 & \dots & 0 \\ 1 & 0 & 0 & \dots & 0 \\ 1 & 1 & 0 & \dots & 0 \\ 1 & 1 & 1 & 0 & \dots \\ \dots & \dots & \dots & \dots & \dots \end{bmatrix} \tag{D.5}$$

The matrix $\boldsymbol{B'}$ is given by

$$\boldsymbol{B'} = \boldsymbol{J}_{k+1,k}\ \boldsymbol{x}^* + \Delta \boldsymbol{B} \tag{D.6}$$

where $\boldsymbol{J}_{k+1,k}$ is a *(k+1) x k* matrix of 1's and $\boldsymbol{x}^*$ is a randomly chosen base value of $\boldsymbol{X}$, is a potential candidate for the desired matrix, but it has the limitation that the k^{th} elementary effect is produces would not be randomly selected. A randomized version of the sampling matrix is given by:

$$\boldsymbol{B}^* = (\boldsymbol{J}_{k+1,1}\ \boldsymbol{x}^* + \left(\frac{\Delta}{\mathbf{2}}\right)\left[\left(\mathbf{2}\boldsymbol{B} - \boldsymbol{J}_{k+1,k}\right)\boldsymbol{D}^* + \boldsymbol{J}_{k+1,k}\right])\ \boldsymbol{P}^* \tag{D.7}$$

Where $\boldsymbol{D}^*$ is a k-dimensional diagonal matrix n which each element either +1 or -1 with equal probability, and $\boldsymbol{P}$ is a k by k matrix random permutation matrix.

D.4.2 Campolongo improvement by maximizing distance

Campolongo [116] suggested an improvement of the sampling strategy which increases the scanning of the input domain without increasing the amount of solver evaluations. The trajectories are selected in a way to maximize their spread in the input space. The design is executed by first generating a high number of trajectories and then selecting the subset of r with the highest spread in terms of distance d_{ml} between a pair of trajectories m and l:

$$d_{ml} = \begin{cases} \sum_{i=1}^{k+1} \sum_{j=1}^{k+1} \sqrt{\sum_{z=1}^{k} \left[X_z^{(i)}(m) - X_z^{(j)}(l)\right]^2} & m \neq l \\ 0 & Otherwise \end{cases} \quad \text{(D.8)}$$

Where k is the number of input factors and $X_z^{(i)}(m)$ indicates the z^{th} coordinate of the i^{th} point of the m^{th} trajectory. d_{ml} is the sum of the geometric distances between all the pairs of points of two trajectories. The most optimal trajectories are selected by maximizing the distance d_{ml} between possible pairs of trajectories belonging to a certain combination. In the figure below, two samples are given of four trajectories in which the left figure shows a set of four random trajectories and the right figure shows an optimized subset from a larger set of trajectories.

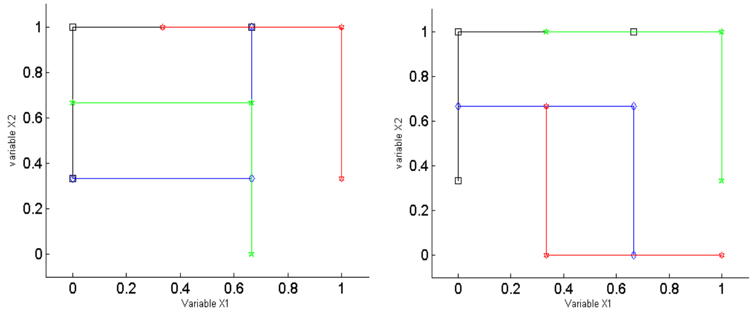

Figure D.4: (left) Original vs (right) optimized trajectory (p=4,r=4 & m=6).

D.4.3 Suggested improvement by optimal spread of sample points

After implementing the method, it is observed that using the optimization of Campolongo does not always give the most optimal configuration of the input trajectories. In the figure below, the optimization is used with all possible combinations. Due to the maximum distance criteria, the trajectories are pushed to the outside. This does not give a satisfying spread of input trajectories.

In order to deal with the problem stated above, a second criterion is advised in which a penalty method is used to spread out the input trajectories. The method starts from an Optimal Grade Spread (OGS):

$$OGS = \frac{(k+1) * r}{p} \quad \text{(D.9)}$$

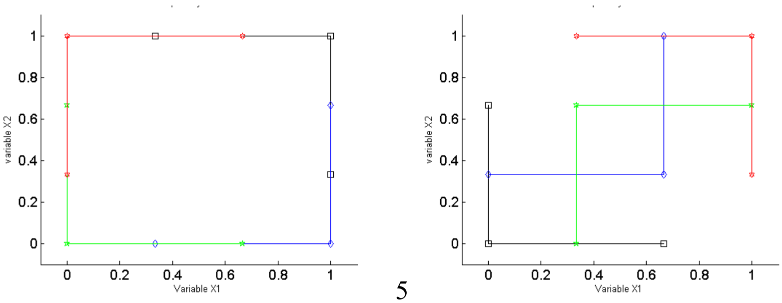

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Figure D.5: Optimized trajectory with all possible combinations (left) trajectories pushed to the outside (right) optimized trajectories with second criterion (p=4,r=4 & m=6).

In the above equation, the numerator gives the total number of samples. Next, all possible combinations of trajectories are determined by r and m. For every combination of trajectories, each possible coordinate, determined by p, and each variable, the OGS is subtracted from the number of times that coordinate is used. From this, a penalty matrix ($C_r^m\ x\ 1$) is determined which gives the penalty for every possible combination of trajectories.

$$PEN_{EE} = \sum_{i=1}^{C_r^m}\sum_{j=1}^{k}\sum_{l=1}^{p}\sum_{n=1}^{r}\sum_{z=1}^{k+1}\left(abs(OGS - \#Co)\right)^2 \tag{D.10}$$

Where $\#Co$ is the number of combinations. The combination with the lowest penalty gives the most optimal spread. The quadratic exponent is used to optimize the spread. In practise, often, multiple combinations will give the lowest penalty score. Therefore, the criterion of Campolongo can be used as second criterion. In the figure above, the method is put into practise. In this way, the spread of coordinates is optimal. The left configuration gives a penalty of 8 and a maximum distance of 16.05 units while the right configuration gives a penalty of 0 and a maximum distance of 18.46 units. Because of this result for the maximum distance, the first criterion is recommended to be the penalty method. The method selects first the combination of trajectories based on the lowest penalty. In case multiple trajectories have equal lowest penalty, the second criterion of distance can be used.

D.4.4 Graph theory sampling

The original method doesn't give a clear indication of second order effects. Campolongo [127] suggested an update to the Morris method. In addition to the 'overall' sensitivity measures, the new Morris method offers estimates of the two-factor interaction effects. The second order elementary effects are calculated by:

$$SEE_{ij}(x) = \frac{\left[y\left(x + e_i\Delta_i + e_j\Delta_j\right) - y(x)\right]}{\Delta_i\Delta_j} \tag{D.11}$$

The local measure of the magnitude of the effects on the output, due to the interaction between the i-th and j-th input factors, is given by the two-factor interaction effects:

$$TFE_{ij}(x) = \left|SEE_{ij} - \frac{1}{\Delta_i}EE_i - \frac{1}{\Delta_j}EE_j\right| \tag{D.12}$$

To determine these effects, the sampling strategy is revised and updated by means of the 'handcuffed prisoners [127]. The method defines the sampling matrix in such a way that the interaction effects of each couple of variables can be determined (see figure).

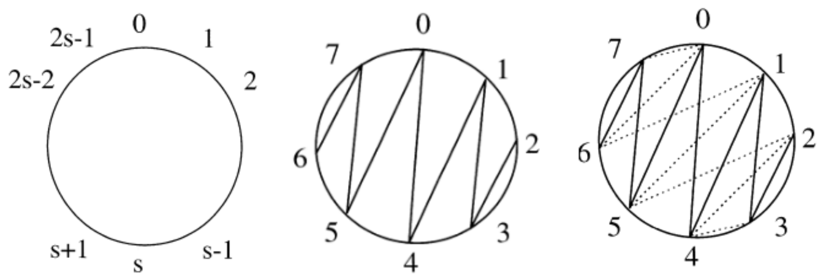


Figure D.6: The handcuffed prisoners method for sampling techniques [127].

D.4.5 Radial sampling

Radial design has been firstly presented in [128] and further investigated in [111,129]. Both radial and the former discussed trajectory sampling (Morris) are represented in the table below. The table shows how, starting from the first row made of elements from matrix **A**, a step in the X_1 direction (second row) is generated by drawing a row from the re-sample matrix $\mathbf{A}^{(1)}$, where all entries are from **A** but the first which is from **B**. Likewise the third row is from matrix $\mathbf{A}^{(2)}$, the fourth from $\mathbf{A}^{(3)}$ and so on till the last row is selected from matrix $\mathbf{A}^{(k)}$. In this way k steps have been generated in directions from X_1 to X_k. All steps involve the first point $(a_{1,1},a_{1,2},a_{1,3},...,a_{1,k})$. A full sensitivity analysis will be composed by N such blocks, the total cost of the analysis being thus $N_{tot} = N(1 + k)$. From the described method can be concluded that a radial design is nothing else than an iterated 'One factor at a Time' (OAT) approach. OAT is a radial design of size one.

Table D.1: Difference between radial and trajectory sampling for k random variables.

Radial Sampling	Step	Trajectory sampling
a1,1,a1,2,a1,3,...,a1,k		a1,1,a1,2,a1,3,...,a1,k
b1,1,a1,2,a1,3,...,a1,k	X1	b1,1,a1,2,a1,3,...,a1,k
a1,1,b1,2,a1,3,...,a1,k	X2	b1,1,b1,2,a1,3,...,a1,k
a1,1,a1,2,b1,3,...,a1,k	X3	b1,1,b1,2,b1,3,...,a1,k
...		...
a1,1,a1,2,a1,3,...,b1,k	Xk	b1,1,b1,2,b1,3,...,b1,k

The radial strategy can be combined with random sampling and one of the above motioned improvements in terms of maximizing distance. However, in [111], a sampling strategy based on Sobol's numbers [130] is suggested. This sampling method allows performing screening experiments first and then, if the computational cost of the model allows it, moving towards a quantitative experiment without the need to discard any model run. In the figure below, the difference is shown between random sampling and Sobol sampling. From research has been shown that the Sobol's sequences outperforms crude Monte-Carlo sampling for estimation of multi-dimensional integrals [129].

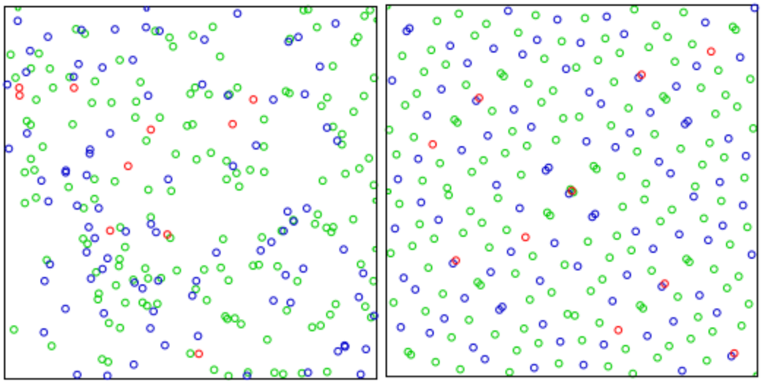


Figure D.7: Random vs quasi-random sampling with Sobol. Adapted from [25].

The vector matrices $\boldsymbol{a}$ and $\boldsymbol{b}$ for r repetitions are obtained by designing an r x 2k Sobol matrix. The left half is used for matrix $\boldsymbol{A}$ and the right half is used for $\boldsymbol{B}$. It is suggested to discard the first 4 rows of the auxiliary matrix $\boldsymbol{B}$ in order to prevent repetition in the coordinate samples [111]. In the figure below, an example input plot is shown for a two-dimensional case. Notice that compared to the Morris sampling strategy discussed before, the random points a and b are such that the steps taken by different factors can be different.

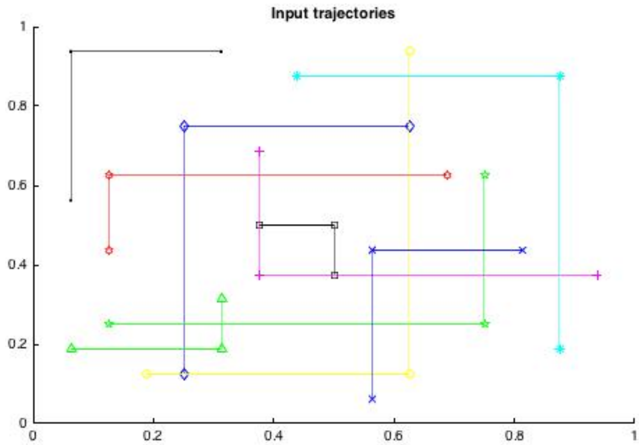


Figure D.8: Input 'star' plot with Sobol sampling for k = 2.

As mentioned above, unlike the traditional elementary effects method, in radial design each effect is computed over a different step size, equal to the distance between e.g. $x^{(u)}x^{(u))}$ and $x^{(v)}x^{(u)}$ which is to say the difference between $x^{(u)}$ and $x^{(v)}$, where u and v denote two rows of the sampling matrix chosen as described above. Under this notation, the absolute value of the elementary effect has been computed as [111]:

$$EE_i = \left| \frac{y(x_i^{(u)} x_{\sim i}^{(u)}) - y(x_i^{(V)} x_{\sim i}^{(u)})}{x_i^{(u)} - x_{\sim i}^{(V)}} \right| \tag{D.13}$$

The measure μ^* can be taken as the average r of these effects. If the computational cost of the model allows it, the modeller can increase r, the number of repetitions, up to achieve a sample size compatible with the estimation of the Total sensitivity index (ST). In this case one must replace the estimator for the EE method with an estimator for ST:

$$S_{Ti} = \frac{V_{Ti}(Y)}{V(Y)} = \frac{E_{X_{\sim i}}(V_{X_i}(Y|X_{\sim i}))}{V(Y)} \tag{D.13}$$

The estimator for ST can be calculated by means of the Janssen estimator [131]:

$$E_{X_{\sim i}}\left(V_{X_i}(Y|X_{\sim i})\right) = \frac{1}{2*r}\sum_{j=1}^{r}\left(y\left(a_1^{(j)}, a_2^{(j)}, \dots, a_k^{(j)}\right) - y\left(a_1^{(j)}, a_1^{(j)}, \dots, b_i^{(j)} \dots, a_k^{(j)}\right)\right)^2 \tag{D.14}$$

D.4.6 Sobol filtering for analysing limit state design

If a particular region in the space of the output, e.g. above or below a given threshold is of interest, then Monte Carlo filtering can be applied [107]. This is the case for the targeted situation with the aim for limit state design [132]. FED values close to and larger than unity are of interest. Therefore, it is not relevant to perform a sensitivity study on the entire input space. It is suggested to perform the sensitivity analysis with samples in the input space which obtain results for FED values between 0.9 and 1.1. No higher value because those sensitivities are not of relevance anymore because of high probability of fatality.

The radial sampling method can be used for generating samples. However, samples not located in the expected region of interest (Figure D.9) should not be evaluated. The method starts with evaluating the sample y1. The result is not in the region of interest. Therefore, samples in the blue forward hatched zone will not be further evaluated. Similar, results higher than the forward red hatched zone will not be evaluated. This way, the zone of interest is analysed this will reduce the number of necessary solver iterations.

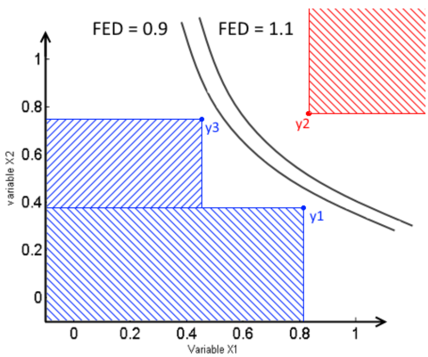


Figure D.9: Sobol filtering method.

E PROBABILISTIC FRAMEWORK DETAILED EXAMPLE

In this part of the thesis, a worked out example is give of the framework discussed in Chapter IV and the challenging case study in Chapter VII. The different steps are discussed and elaborated more in detail. The fire safety design with sprinklers and smoke and heat control is chosen to elaborate.

The start is chosen at step 5.1 of the probabilistic framework presented in figure IV.3. Three representative design scenarios are considered (Figure E.1): a fire in the open commercial area (1); a fire in a small storage room (2); and a fire in the restaurant (3). The main reason for the differentiation between 1 and 2 is to consider different ventilation conditions and delayed second detection. Additional design scenarios can be a scenarios of fires in evacuation routes, staircases and technical rooms. For reasons of simplification, this is not considered. For the remainder of this example the first design scenario is explained.

Figure E.1: Example of the setting for three different design scenarios.

For evacuation, only one main design scenarios are considered. This is a scenario where both the shopping mall and restaurant are open. Other scenarios with one out of two open are not considered in the analysis.

The input variables (step 5.2) are all taken from table IV.1. For the restaurant and the storage rooms different fire growth rate, HRRPUA, Max area, occupant density and pre-evacuation time.

In step 5.3 the bow-tie model is developed. The bow-tie model for the design scenario retail is constructed from the following variables which are considered discrete variables:

- Location: 3 locations per floor and 5 floors gives 15 locations
- Detection: optimal detection (fast 2 detections) and delayed detection is considered.
- Sprinkler activation: Failure and success is considered
- Smoke and heat control: Failure, 50% success and 100% success are considered
- Ventilation conditions: In case of small room the limited ventilation conditions are taken into account.
- Smoke barrier: in case of compartmentation, the connecting doors can be considered open or closed. Similar to the staircases. The door barrier can fail. However, the latter is not taken into account.

In total are 180 scenario for the first five discrete variables should be analysed. However, several scenarios were taken together to reduce the number of event tree scenarios so that only 64 event tree branches were analysed. The scenario of a fire on the ground level in the lower left corner of the floor, with sprinkler failure and SHC activation at 0% performance is taken into account. No limited ventilation conditions are considered.

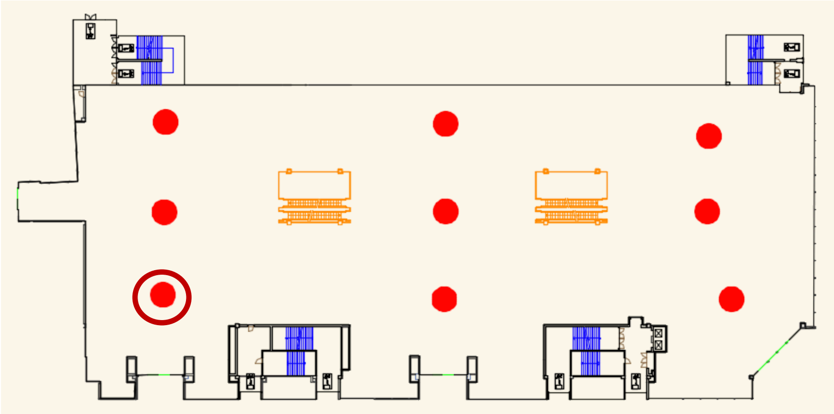


Figure E.2: Location of the fire.

As discussed in Chapter VII, an important boundary condition of the case study is that the staircases are considered smoke free during the evacuation for all scenarios. This is a limitation of the model because failure of a fire door causes smoke leakage into the staircase, which will have a major impact on the safety level.

The fire frequency, necessary as input for the event tree, for the whole building was based on the estimated fire frequency for retail and restaurants: The fire frequency for the retail is estimated at 0,05 fires per year and for the restaurant 0,012 fires per year. This gives a total of 0,062 fires per year.

The probabilities associated with the elaborated branch scenario is presented in the table below. It should be noted that the other scenarios might have the same outcome in terms of smoke spread. For example, when detection initially fails, the SHC system does not activate.

Table E.1: Frequencies and probabilities for the corresponding scenario.

Event tree section	Freq. or prob. [1/year]
Fire frequency analysed zone	$\frac{0,05 * 5000}{23000 * 3} = 0,0036$
Detection success	0.99
Alarm success	0.8
Sprinkler failure	0.05
SHC failure	0.4
Fuel controlled fire	0.9
Total	$5.13 * 10^{-5}$

In step 5.4 the RSM is chosen. For this case the IMLS model is chosen. Next the support points are generated in step 5.5. the limits and values suggested in table IV are used. No correlation is applied. In step 5.6 the support points are deterministically evaluated by means of the CFD model FDS. The results of the deterministic scenario for the sample combination α=0,12 kW/s^2, HRRPUA = 450 kW/m^2 and A_{max} = 100 m^2 is presented in the figure below.

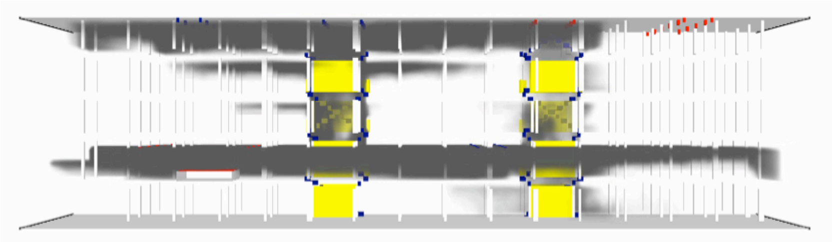


Figure E.3: Deterministic evaluation of a fire scenario on the ground floor in the smoke spread model.

The IMLS model elaborated in section IV.4.7.2 is applied to determine the RSM. The same number of coefficients are implemented. The toxicity, temperature and radiation concentrations are calculated at multiple locations.

Next, the DoE experiments are determined to obtain a uniform representation of the analysed domain (step 5.8). The Sobol Sampling method is chosen. For each scenario 100 samples are simulated in step 5.9. The results are provided as input for the evacuation analysis (loop to step 5.5). The support points for the evacuation RSM are generated (step 5.5) based on the support points discussed in table IV.8. The sample is analysed by means of the evacuation model Pathfinder (step 5.6). The results of the deterministic scenario for the sample combination of fast second detection, affiliation = 50/50 and occupant density = 1pp/3m^2 is presented in the figure below.

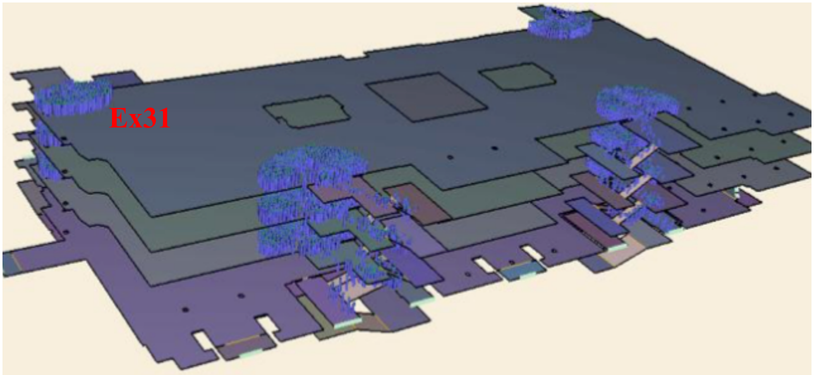


Figure E.4: Deterministic evaluation of an evacuation scenario time around 480s.

Next the results of the evacuation analysed locations data is coupled with toxicity, temperature and radiation data from obtained from the RSM for smoke spread. For every deterministically simulated evacuation scenario (4^2), the results of the 100 Sobol samples are analysed. This means that up till now about 1600 scenarios represent the chosen branch scenario. For every occupant in every scenario, the model obtains a minute by minute dosage of all the concentrations, temperature and radiation.

In step 5.8 DoE is generated for the probabilistic consequence analysis. In total 100 sobol samples for the variables CO-yield, HCN-yield, HoC, susceptibility and V_E rate are generated. This means that now about 160 000 samples are generated. Next the FID values are calculated in step 5.9. For every occupant in every scenario, the model calculates the FID a for heat and toxicity.

The result of one of the sample cases for the top exit (Ex31) indicated on figure E.4 is presented in figure E.5. For every exit such an FID curve is generated. Typically, the results obtained for the FID values do not provide a smooth line. Therefore a curve fit is performed and presented by means of the blue line.

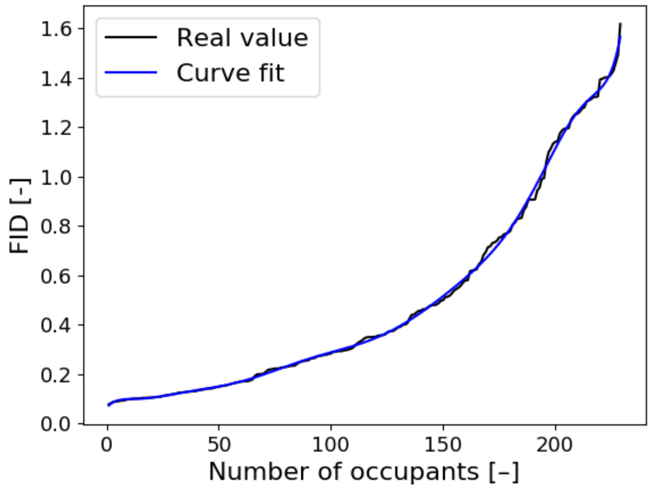


Figure E.5: Example of continuous increase in FID values for a group of people at an exit door.

The FID-curves of exits connecting to a staircase are then taken together in one FID-curve. This means that for every sample in the current case study, in total 4 FI-curves (stairs) and 4 FID-curves for the other exits on the ground floor are generated.

Once the curve fitting is performed, the procedure loops back to step 5.7 and the RSM for evacuation is developed. The RSM is applied in two phases for the evacuation data. Firstly, the RSM is conducted for determining the number of people evacuating towards each exit. Secondly, the RSM is applied for implementation of the other variables.

In the first phases the RSM is applied to de determine how many people will evacuate at each exit for each sample scenario. This is determined by evaluating the number of people evacuating at each exit for each support sample. For every new sample generate from the Sobol sampling technique, the number of people are determined by searching for the corresponding point on the RSM. This has to be done first to continue. Otherwise interpolation will be done between different population sizes.

Next, for every exit in every support sample scenario, the FID curves are rescaled to the number of occupants estimated before. An example for a set of six support points is given in Figure E.6. Originally, these curves were fitted for different occupant sizes. However, interpolation between them would not be possible. Therefore, a scaling algorithm is implemented to rescale every curve to the desired number of occupants.

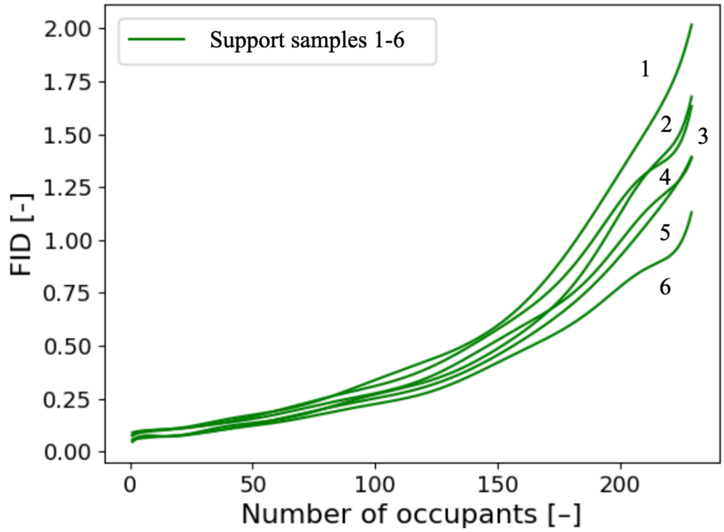


Figure E.6: Rescaled FID curves for a support sample of a particular exit and scenario.

In step 5.8, the DoE is generated for the probabilistic evacuation analysis. This means that samples are generated for the parameters occupant density and affiliation by means of Sobol sampling. Only a part of the domain is analysed as discussed in section IV.4.16. Samples with low occupant densities will not give a significant added valued to the results. Therefore, it is chosen to narrow the domain and give a weight to the results. The weight factor is later on multiplied by the branch probabilities. In total are 10^6 Sobol samples are generated for the chosen branch scenario.

Once the input combinations are chosen, the samples are evaluated by means of the response surface model for evacuation in step 9.9. In Figure IV.21 E.7 an example is given of the estimation of an FID curve by RSM. The red line is the estimated curve and the blue line is the real value. Two support samples are presented in green to illustrated that the new samples are interpolated between the support samples.

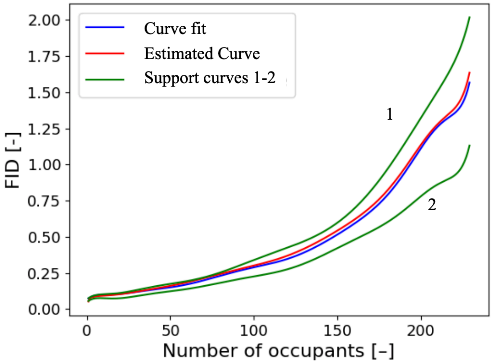
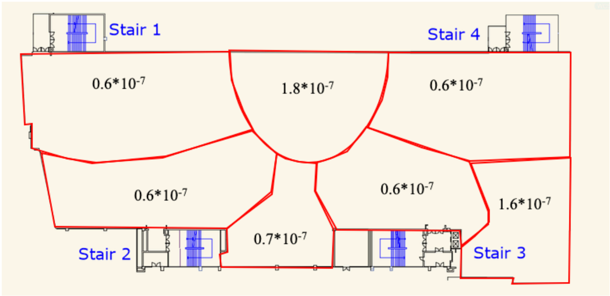


Figure E.7: Estimated FID curves for a new sample for a particular exit and scenario.

In the next step, the total risk is calculated by, calculating the number of occupants with FID ≥ 1 for every sample and multiplying the consequence of every sample by the actual frequency of the corresponding branch scenario which is in this case 2.12 * $10^{-12.}$ The branch frequency divided by 10^6 and multiplied by the weighting factors $WF_{SS} = 0.044$ and $WF_{Evac} = 0.94$. The risk of all the samples is summed to obtain the total risk for that branch scenario. The risk of the branch scenario is about $2.5*10^{-8}$.

In order to calculate the failure probability of the branch scenario, the number of samples with FID ≥ 1 is summed and divided by 10^6. A failure probability for this branch scenario is calculated of about $1.5*10^{-8}$.

To calculate the individual risk, the IR is calculated on the probable worst locations (in principle the most distant from the exit). An example of IR for different zones on a floor is given in figure E.8. The IR for the specific branch scenario is not calculated because it does not give a good representation of that locations. The final IR are presented in Chapter VII.



E.1 Zoning of individual risk.

F MOVEMENT DYNAMICS

Occupant movement is an important factor in evacuation modelling. Two main parts can be considered significant parameters for evacuation time modelling [136]. These are the (free) movement and flow through constraints. Both are influenced by individual characteristics, building layout and environmental conditions (e.g. smoke, visibility, etc.). Both movement and flow are considered from an individual and a group dynamic point of view.

In general, in case of low densities, travel speed is more important for evacuating towards an exit. When high occupant densities and bottlenecks are expected, flow dynamics become more important.

F.1 Movement

Walking speed of occupants has been extensively studied in the past [35]. In [137], a review of walking speeds in different models is performed. The main influence factors for walking speed can be divided in internal and external factors. Internal factors are due to the occupant individual characteristics (age, fitness, focus, etc.). External factors are mainly due to occupant's density, visibility/toxicity in smoke and building configuration (Slope, stair, etc.). The effect of these parameters gives a wide range of possible average walking speeds between 0.5 and 1.7 m/s applied in evacuation models. This as a fixed value or a probability distribution [35].

F.1.1 Importance of movement in evacuation modelling

From research is observed that a change in walking speed has a significant impact on the evacuation time [136]. In the study, a sensitivity analysis is performed with a mean walking speed of 1.19 m/s and a variation between 0.3 - 1.9 m/s (Figure F.1). For high walking speeds, the effect is low. This because the limiting factor for higher walking speeds are the bottlenecks and flow becomes important. However, for lower walking speeds, the variation is far more significant (up to 400%).

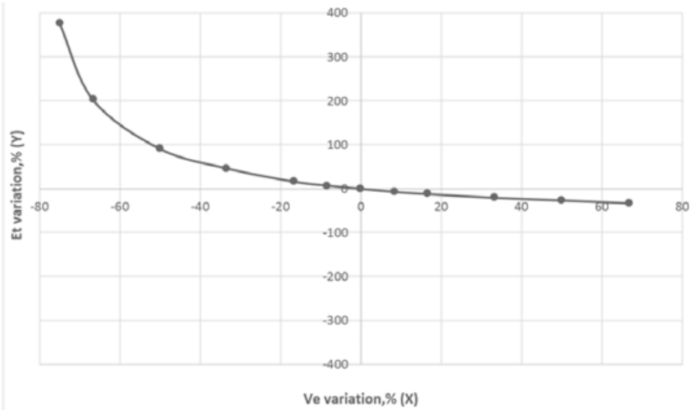


Figure F.1: Variation of evacuation time. Taken from [136].

F.1.2 Effect of occupant characteristics

The impact of occupant characteristics in evacuation modelling is generally implicitly taken into account by providing an overall walking speed distribution. This walking speed distribution should represent the entire occupancy type. However, for specific occupancy types (schools, elderly homes, ect.), an adjusted distribution is more appropriate. In this section, three parameters are analysed that have an important effect on walking speed. These are age, body size and impairment.

F.1.2.1 The impact of age

Age is directly related to a deterioration in physical, mental and neurological functions which impacts negatively on individual movement, e.g. speed and stride length [138]. Figure F.2 is shows that 'elderly' (over 65s) walk approximately 20–25% slower than adults in the age range 18–40 years. A study from NIST [139] indicates that the rate at which elderly people descend stairs (assisted or unassisted) can be much lower. Estimates are at a 50% reduction compared to healthy adults. Also for young people (< 10 year), reduced average walking speeds are observed.

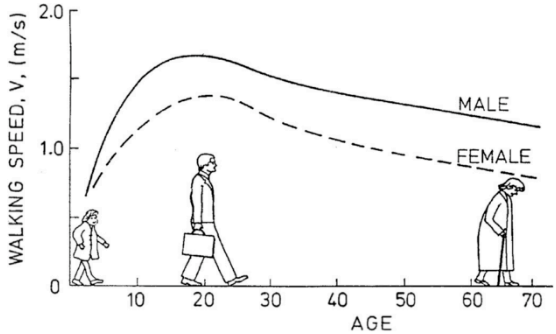


Figure F.2: The relationship between walking speed and age on a level surface. Taken from [138].

Recent studies [140] have quantified the impact of population age on crowd speed (Figure F.3). Three population types were included in the study: adults, children and elderly. The figure shows reduced speeds for elderly and children.

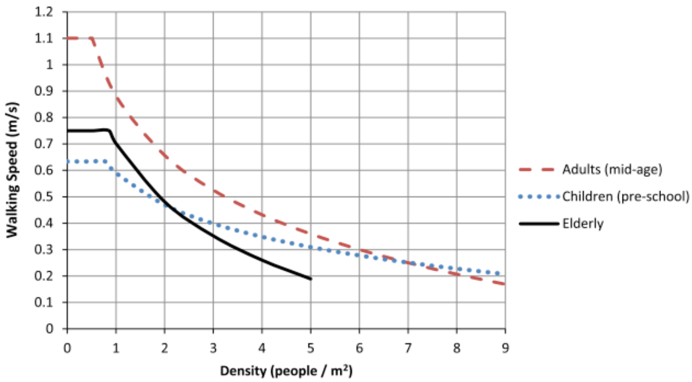


Figure F.3: Walking speed vs density for different age demographics, from Kholshenikov data. Taken from [140].

F.1.2.2 The impact of body size

The effect of body size on walking speed has been proven to have significant impact on walking speed dynamics [140]. The actual impact of the increasing proportion of obese people has yet to be properly considered with respect to crowd movement. However, from initial research [35,141], it is estimated that increased body size can reduce the movement speed and flow rate up to 25%.

F.1.2.3 Impairment

Research has shown that about 15% of the population live with some form of disability and that between 2-4% have very significant difficulties in functioning [142]. Impairments in the form of visibility, hearing, physical impairments, etc. have an important impact on human behaviour and movement dynamics. From past incidents it is observed that in case of emergency a large part of people with disabilities will attempt to use stairs irrespective of their limitations [143]. This is of particular importance because these people will cause bottlenecks which will slow down the evacuation of other people.

It is suggested to take these effects into account by analysing specific scenarios with special attention for evacuation of people with reduced mobility and scenarios of people with highly reduced mobility in which evacuation through of stairs is not possible [35].

F.1.3 Effect of occupant density on horizontal and vertical walking speed

Extensive research has been conducted regarding the effect of occupant density on walking speed [35]. Experiments show an inverse relationship between the two parameters. The waking speed decreases as the occupant density increases (Figure F.4). An important limitation of this relationship is the exclusion of body size. The real density might vary depending on the body size (small children vs obese adults). A possible adaption could be to represent the correlation in terms of occupant coverage per square meter.

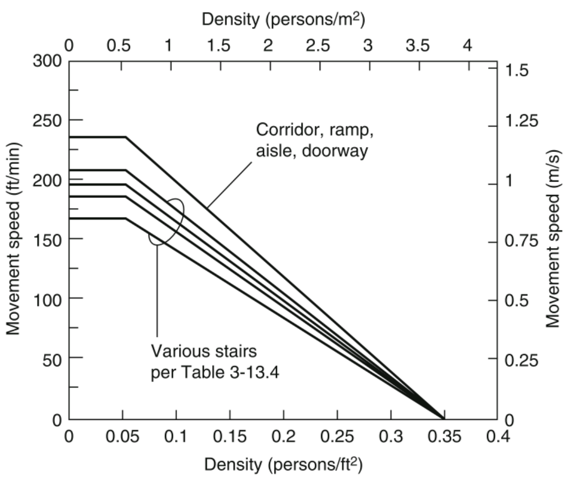


Figure F.4: Relation between walking speed and density through doors, on stairs and slopes. Taken from [35].

Movement on slopes, stairs and escalators presents a different challenge than horizontal movement, given the extra degree of freedom available in the movement. The constraints imposed by the stair design and the additional effort required to traverse the stair component. Extensive research was done in [144], [145], giving a wide range of results depending on density and floor levels. A mean movement speed of 0.48 m/s ± 0.16 m/s was obtained in [145]. In Figure F.4, several correlations for walking speeds on stairs are suggested. Distribution is recommended for application.

F.1.4 Effect of smoke on movement

The presence of smoke during an emergency has been shown to have a range of different effects upon evacuee performance [35,146]. These effects may be psychological, physiological and physical and affect the performance in a number of ways: recognition and response (pre-evacuation), redirection for movement (exit choice), reduced movement ability and posture change (crawling). The effect of reduced movement ability is studied below.

The main principle of the empirical correlation between the smoke extinction coefficient and walking speed is to lower the walking speed of the evacuating occupant due to the direct effect, i.e. lower visibility and irritancy of the gases. Due to the lower walking speeds, the occupant will be longer exposed for a longer time to the asphyxiant gases such as CO, HCN, etc. (see consequence model) which will have an additional negative effect on movement and decision making.

The effect of smoke on upright walking speed has been analysed in multiple experimental studies [147–156] of which only the first one is performed in smoke from actual fires. The other experiments are performed in artificial smoke in which sometimes irritancy products are added. Additional studies have analysed and reviewed these data sets [157–160]. From this research is concluded that the main factors influencing walking speed are:

- Occupant characteristics (internal): Different occupants have different characteristics which result in a different response to the external factors. This causes differences in reduced walking speeds and differences in minimum walking speeds. Fitness is an important parameter for performance and susceptibility. In [151] is observed that elderly people walk slower in dense smoke compared to younger people.
- Smoke density (external): Reduced visibility by increased smoke density is proven to have a negative impact on walking speed (Figure F.5.). Literature shows that walking speed is reduced by increasing extinction coefficient up to a certain point ($Cs = 1\text{-}2\ m^{-1}$) [154]. It is argued that after this point, the effect might be flattened out.

- Smoke irritancy (external): Irritating effects of smoke have a negative impact on walking speed mainly due to loss of visibility (closing eyes) and trying to cope with the irritating effect itself [147].
- Presence of guidance and complexity of the building (external): The presence of guidance by a wall or handrail has a positive effect on walking speed and wayfinding [35,161]. In [147] was noted that most subjects moved for part of the distance by feeling their way along the walls, and that those subjects doing this for more than 2/3 of the total distance had a greater average speed. It is proven that without visibility and guidance, occupants unfamiliar with the building get easily lost [35]. Especially in buildings with complex layout. Therefore, guidance is considered critical for obtaining a minimum walking speed in dense or/and irritating smoke.

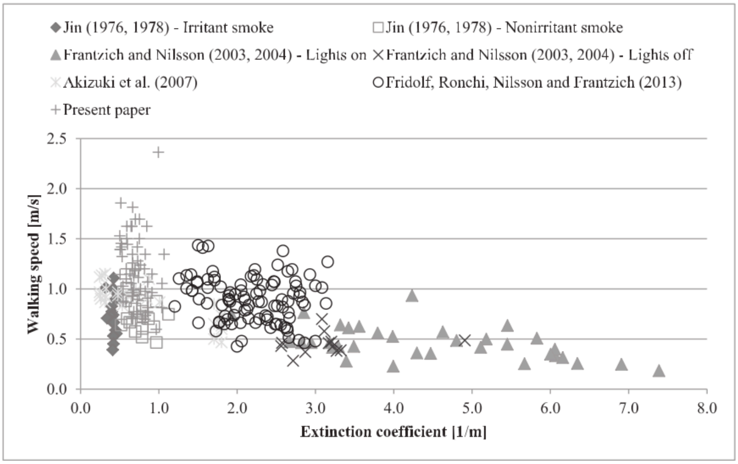


Figure F.5: Velocity as a function of the extinction coefficient for different experiments. Taken from [149].

In [157], research is conducted regarding the modelling of walking speeds in smoke conditions. Two sub and three main parameters are analysed. The sub parameters are walking speed (0.25 - 1.25 m/s) and extinction coefficient (0.5 - 1 m^{-1}). The main parameters are: two data sets [147,148], five modelling techniques (correlation interpretation) and six evacuation models. The results showed a minor effect of different evacuation models for different walking speeds and extinction coefficients when the same data set and coloration interpretation method is applied. However, a major impact is observed when different data sets and coloration interpretations were varied (factor 2). For lower initial walking speeds (0.25 - 0.5 m/s), the correlation method is the most sensitive parameter. When larger initial walking speeds (>0.75) are implemented, the data set is the most sensitive parameters for different extinction coefficients.

In [149,158], is recommend that walking speed in smoke is represented as a distribution considering the uncertainties in the data (Figure F.5.), i.e. using both mean values ± and standard deviations for defined extinction coefficient.

F.2 Flow and congestion

Flow of occupants through geometrical constraints has been extensively studied in the past [35]. The main influence factors affecting flow performance can be distinguished in internal and external factors. Internal factors are due to the occupant individual characteristics (age, fitness, focus, etc.). External factors are mainly due to occupant density, merging and building configuration (slope, stair, etc.). The effect of these parameters show a wide range of possible average flows between 0.0 and 2.0 pp/m/s applied in evacuation models [35].

F.2.1 Importance of flow in evacuation modelling

Research observed that flow properties have a significant impact on modelling evacuation time for higher occupant densities [136]. This because exits and stairs create bottlenecks causing longer exposure of occupants.

F.2.2 Effect of occupant characteristics

F.2.2.1 The impact of age

Experimental studies have quantified the impact of population age on crowd flow rates studies [140]. Three population types were included in the study: adults, children and elderly. Figure F.6 shows reduced flow rates for elderly people. For children, an increased flow rate is observed due to the smaller body sizes.

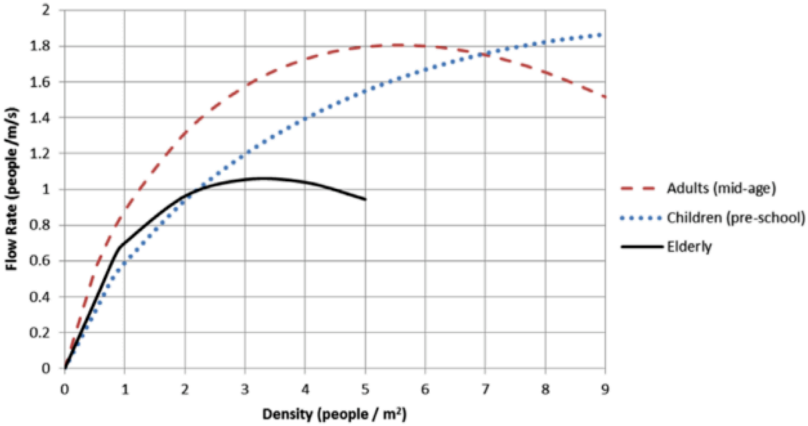


Figure F.6: Crowd flow rate vs density for different age demographics, from Kholshenikov data. Taken from [140].

F.2.2.2 The impact of body size

Research observed that a change in boxy size has a significant impact on modelling evacuation time. In [136], a sensitivity analysis is performed with a mean body size of 0.46 m diameter and a variation between 0.3 - 0.7 m (Figure F.7). For smaller body sizes, the effect was small. For larger body sizes, a variation up to 50% for higher body size is expected. This because the flow is heavily reduced.

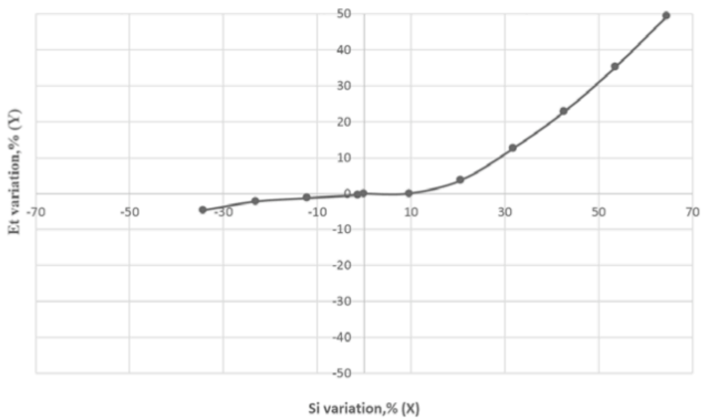


Figure F.7: Sensitivity analysis to size. Taken from [136].

The impact of significantly higher proportions of obese people has yet to be properly considered with respect to crowd movement. However, from initial research [35,141], it is estimated that increased body size can reduce the movement speed and flow rate up to 25%.

F.2.3 Effect of occupant density on horizontal and vertical flow

Experiments show a parabolic relationship between occupant density and flow. The flow first increases from low to medium densities up to 2 p/m^2. Secondly, the flow decreases from a maximum value to 0 for higher densities around 4 p/m^2.

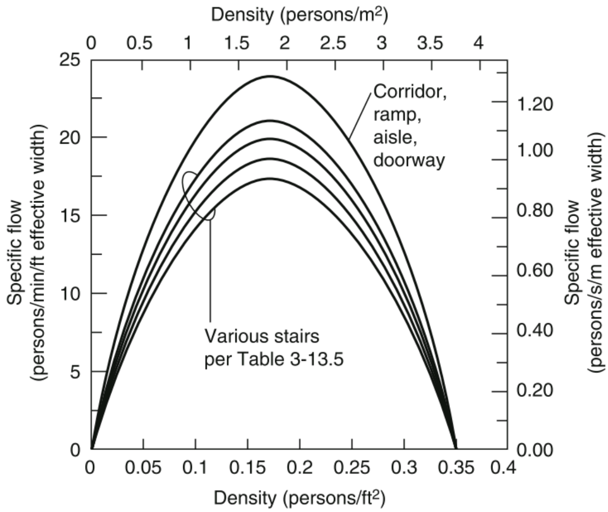


Figure F.8: Specific flow as a function of population density. Taken from [35].

The effect of different merging dynamics in staircases can have a significant impact on the exposure time of occupants in the incident compartment to the effluents of a fire. In [90] is described that most experiments show merging flows in the order of a 50:50 ratio. In these circumstances the top floor empties first and then the other floors, from bottom up, will be evacuated. In [162] was found that in the case of low occupant load and low densities, stair mergers seem often having priority over floor mergers (in the order of 60-70:40-30). A fictive example for different ratios is shown in Figure F.9. In [163] is discussed that the majority of the evacuation models approximate a 50:50 percentage ratio for most stair configurations.

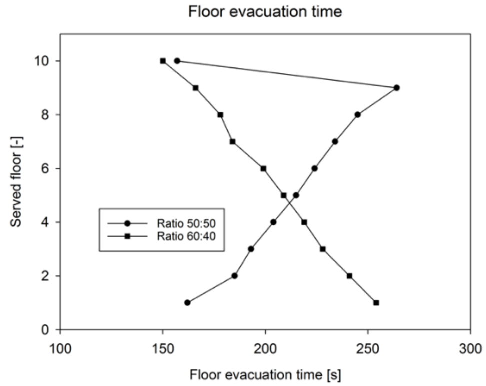


Figure F.9: Floor evacuation time. Talen from [162].

F.3 Uncertainty and limitations in evacuation modelling

F.3.1 Uncertainty

In [164] uncertainties are distinguished in three different parts in evacuation modelling. These are the definition of the input, the evacuation modelling and the analysis of the output. Input uncertainty is associated with scenarios and input parameters. It encompasses the definition of relevant scenarios (e.g. occupant type, exit availability, fire conditions affecting evacuation behaviours, etc.) and parameters (walking speeds, occupant load, affiliation, etc.). The former is considered by developing proper evacuation scenarios for specific occupancy types and activities. The latter is tackled by implementing a probability density function in the models.

The second type of uncertainty is associated with evacuation modelling which reflects intrinsic uncertainty (i.e., the uncertainty caused by the physical, mathematical, and modelling assumptions in use). This uncertainty is linked with the validity of the underlying equations or rules adopted by an evacuation model to represent movement and human behaviour. These uncertainties are validated by means of experiments.

The last set of uncertainties are associated with analysis of the output (behavioural uncertainty) [165]. This uncertainty is associated with the impact of the range of possible behaviours of individuals on the simulation results. In [165], a functional analysis method is developed to analyse the convergence of the evacuation modelling.

F.3.2 Limitations

An important limitation in evacuation modelling is lack of data considering human behaviour. While movement and flow are fairly well modelled, decision analysis regarding pre-evacuation and exit choice modelling is a large uncertainty. In the majority of the evacuation models pre-evacuation behaviour is implicitly modelled, while exit choice explicitly modelled. Both are user input and thus dependent on the FSE expertise.

A second important limitation is the (mis)use of default values. In order to keep complex models practical, most models are provided with pre-defined default values. Although, this might make the modelling more efficient, these defaults are most of the time input values for optimal conditions (e.g. smoke free walking speed, nearest exit, etc.) which might give unrealistic results. [166]. In order to deal with this problem, in [167], a new approach was suggest to provided conservative default values so that the modeller needs to understand and physically change the values.

An important limitation of the current use of data is the lack of quantification of the changing population distribution [140]. Legislation, guidelines and numerical models still implement correlations for movement speed, flow rates, occupant densities, smoke effect, etc. developed more than 50 years ago [35], [168]. Experts in the field criticize that this data collected in the past might not be relevant anymore. The loss of confidence in the use of this older 'uniform' data is due to the recognition of the ever increasing proportions of elderly, obese and mobility impaired in our society [140,169,170]. From research is expected that by 2050, the ratio of people older than 65 years and people between 15-65 years will be about 50% [171]. Some recent studies have reviewed flow data and formulae for people of different ages on stairs [139]. The indications are that, while basic flow values for uniformly 'healthy adult' groups may not have yet changed significantly, there is a very significant drop in flow rate for primarily 'elderly' populations. These factors of change to age distribution, population physical size (overweight and obesity rates) and presence of disability are not accounted for in currently implemented speed and flow rate correlations for evacuation models and fire safety designs. In fact, this is still early research and should be studied in future perspective [140].

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