Quantifying Risk for Deemed-to-Satisfy Apartment Buildings

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Abstract
Is it possible to quantify the risks associated with building design compliant with Deemed-to-Satisfy provisions? Prescriptive regulations can be said to provide an acceptable level of safety. Developments in the field of fire safety engineering have provided probabilistic methods for safety verification. It was theorized that by applying such methods to Deemed-to-Satisfy compliant case study buildings, an estimate of the risks associated with Deemed-to-Satisfy provisions could be derived. An event tree based QRA method together with a developed fire risk analysis framework was used to quantify the risks to individuals within apartments. The study was limited to Australian and Swedish building codes.

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"As far as the laws of mathematics refer to reality, they are not certain, and as far as they are certain, they do not refer to reality."

- Albert Einstein

"Only madmen are absolutely sure."

- Robert Anton Wilson

Summary

One purpose of building codes is to provide a high level of safety to occupants. Traditionally, safety was prescribed by a set mandatory provisions also known as prescriptive or Deemed-to-Satisfy provisions. As such, complying with these prescriptive regulations was considered achieving a sufficient level of safety.

When performance-based codes were introduced, this opened up for more flexible designs as no restrictions were put on the design if it could be verified that sufficient safety is achieved. Because a deviation from the Deemed-to-Satisfy provisions alters the level of safety, the design becomes subject to verification. Methods shown in Figure 1 provide different approaches to verify safety in fire safety engineering assessments.

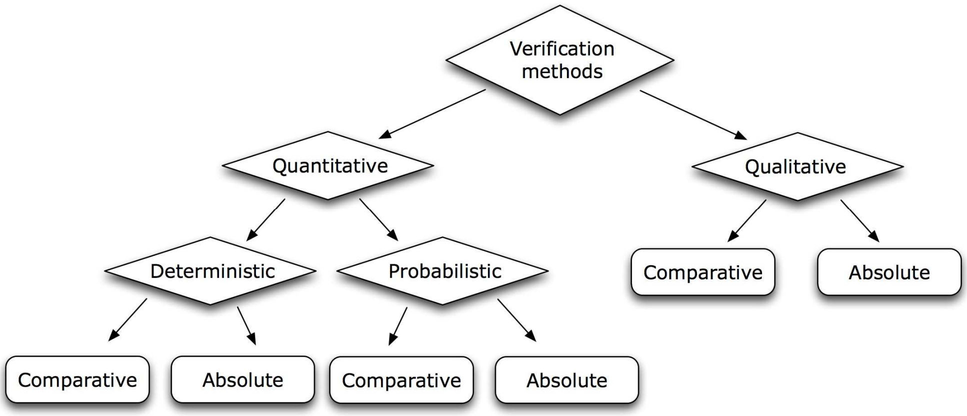


Figure 1 Verification methods in fire safety engineering

Quantitative methods refer to different approaches where the safety is verified by an estimated quantitative measure. Quantitative methods can further be divided into deterministic and probabilistic methods. In fire safety engineering, a deterministic approach normally corresponds to verify safety by trial of a set of fire scenarios. By also taking into account the probability or frequency of such scenarios occurring, the method becomes probabilistic. When frequency or probability and consequences are described in probabilistic terms, this is usually denoted risk.

By applying such probabilistic fire safety engineering methods to buildings designed according to prescriptive provisions, it was theorized that a quantitative measure of these provisions could be estimated. Also applying minimum requirements set out by the prescriptive provisions, a minimum level of safety required by the building code was sought to be quantified. The study was limited to apartment buildings and two prescriptive codes (Australia and Sweden).

Fire risk assessment frameworks and quantitative methods for fire risk analysis were studied to identify suiting approaches to the risk quantification process. A standard Quantitative Risk Analysis method was considered being most appropriate for the aims of this thesis. To structure the risk quantification process, the method was adopted to a framework. However, none of the studied frameworks were judged being directly applicable and therefore a model customized model for the purpose of this thesis was derived, see Figure 2.

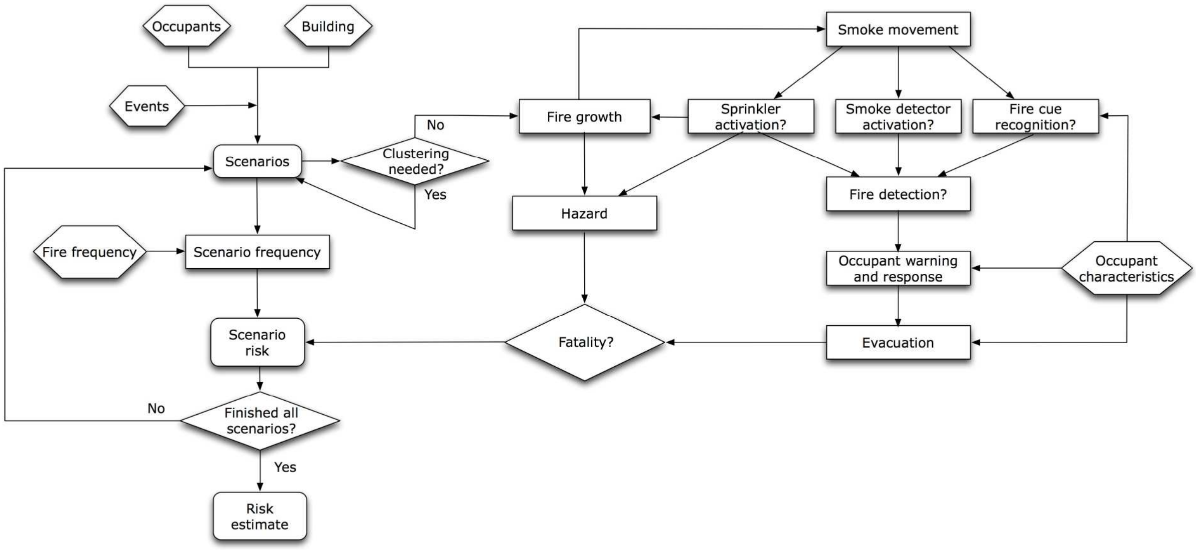


Figure 2 Applied fire risk analysis model

The model utilizes a scenario-based approach in which both frequency and consequences for each scenario are estimated. The product of frequency and consequence are used to estimate the risk associated with each scenario. Consequences are defined as fatalities and are calculated using a *Fractional Effective Dose* (FED) methodology. By estimation of Carbon Monoxide (CO) concentration and smoke layer temperature within the considered volume, FED can be estimated for occupants. If the dose received by an occupant reaches a certain level, they have been assumed to become fatalities.

Two building types (one mid-rise and one high-rise) were designed in accordance with prescriptive provisions of each country specific building code. Applying the model presented to these buildings it was possible to estimate the risk to occupants.

During this study it was concluded that determine minimum levels of safety achieved by the building codes is not addressable as the code allow for designs, even with installation of fire safety systems, would result in very large risks to occupants. As such the minimum level of safety achieved by common designs was sought.

The quantified levels of individual risk achieved by the different building code designs and apartments ranged from $3.44 \cdot 10^{-5}$ (lowest) to $9.08 \cdot 10^{-4}$ (highest), the difference being a factor of approximately 26. Generally the results generated in this study were of an order of magnitude equal to 10^{-4}. Compared to other studies reviewed, the risk estimated in this report were generally higher. However, considering that a conservative approach to the standard QRA was adopted which should generate higher risks, this is expected. A sensitivity study of the model variables showed that the model overestimates the risk if the input is to be considered conservative.

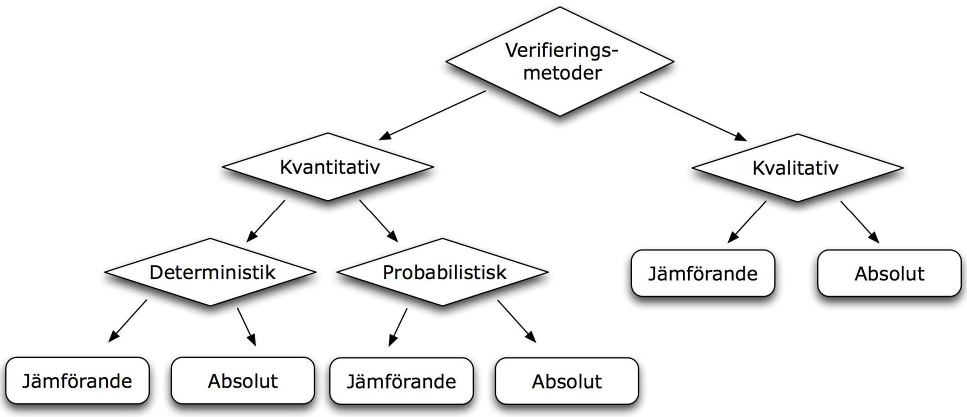
The provision of sprinklers did not show any significant lowered risks. It is theorized that sprinklers reduces the risk for the building in a holistic perspective, however this has not been investigated in this study. In contrary, variables associated with smoke detection had a major influence on the estimated risk. .

With the current state of knowledge regarding the variables that affect the risk, the uncertainties associated with method and input deems that the results should be considered with care. Also, there are variables that are very difficult to quantify and have therefore been investigated as control parameters. In reality, these are all associated with different probabilities, a factor that remains unknown.

Sammanfattning (Summary in Swedish)

Ett av syftena med byggregler är att upprätthålla en hög nivå av säkerhet för invånare. Traditionellt sett har säkerheten tillgodosetts genom att följa detaljkrav vilket även kallas preskriptiva föreskrifter. Att följa dessa föreskrifter ansågs tillgodose en tillräcklig nivå av säkerhet.

Då funktionsbaserade byggregler introducerades öppnade detta upp för mer flexibla lösningar då inga restriktioner längre sattes på byggnadsdesignen så länge det kunde verifieras att säkerhetsnivån var tillräcklig. Eftersom en avvikelse från de preskriptiva kraven förändrar säkerhetsnivån måste den alternativa designen verifieras avseende säkerhet. Olika brandtekniska metoder för att verifiera säkerhet visas i Figur 1.

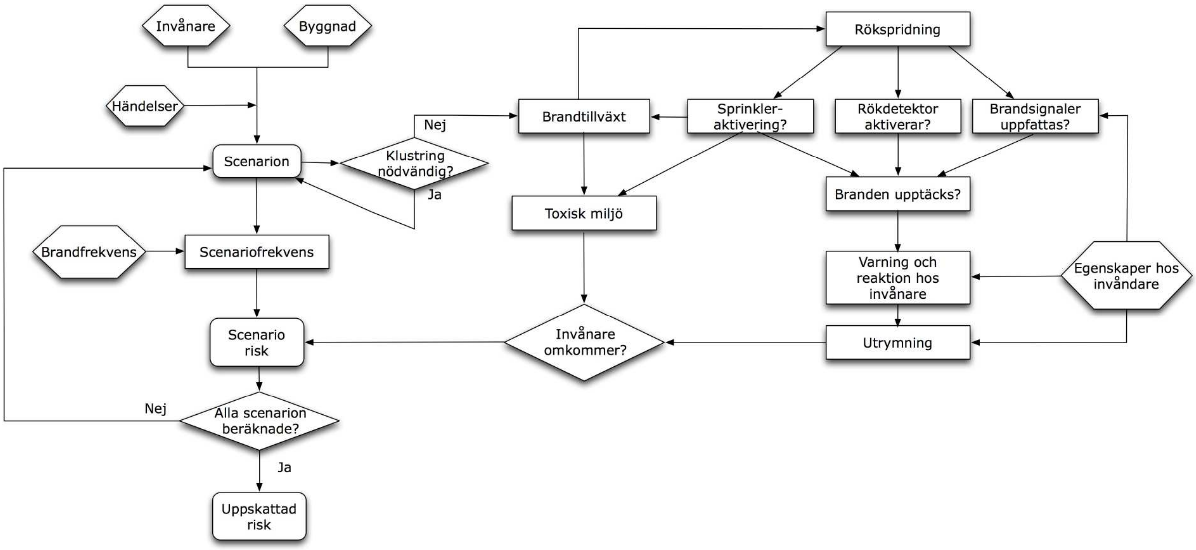


Figur 1 Brandtekniska metoder för att verifiera säkerhet

Med kvantitativa metoder verifieras säkerheten genom uppskattning av numeriska värden. Dessa kan vidare delas upp i deterministiska och probabilistiska metoder. I brandtekniska användningsområden brukar deterministiska metoder normallt sett innebära att säkerheten verifieras genom att ett antal scenarion utvärderas. Genom att också ta hänsyn till sannolikheten eller frekvensen för sådana scenarion övergår metoden till ett probabilistiskt angreppsätt. Det är också vanligt att sannolikhet och konsekvenser som beskrivs i probabilistiska termer kallas för risk.

I denna studie teoretiserades det att genom att applicera probabilistiska brandtekniska metoder på byggnader som är designade enligt preskriptiva krav, kunde ett kvantitativt mått på säkerheten hos preskriptivt designade byggnader uppskattas. Det teoretiserades också att genom att försöka identifiera miniminivån av preskriptiva krav ställda av byggreglerna kunde den lägsta nivån av säkerhet som dessa uppnådde kvantifieras. Studien begränsades till flerfamiljshus och två länders byggregler (Australiensiska och Svenska).

Olika ramverk för brandteknisk riskbedömning samt metoder för brandteknisk riskanalys studerades i syfte att identifiera lämpliga angreppssätt till kvantifiering av risken. En så kallad ”standard Quantitative Risk Analysis” ansågs vara mest lämplig för denna studie. För att strukturera riskkvantifieringen utfördes denna enligt ett ramverk. Dock ansågs inget av de studerade ramverken vara direkt applicerbart till problemet och därför togs en modifierad modell fram, se Figur 2.



Figur 2 Modell för brandteknisk riskanalys

Modellen använder ett scenariobaserat angreppssätt och uppskattar både frekvens och konsekvens för varje scenario. Produkten av frekvens och konsekvenser används för att beräkna risken associerat med varje scenario. Konsekvens är definierat som omkomna människor vilket har uppskattats genom en så kallad ”*Fractional Effective Dose*”-metodik (FED). Genom att uppskatta koncentrationen av kolmonixid (CO) och brandgaslagrets temperatur, kan FED uppskattas för invånarna i det berörda utrymmet. Då en viss dos har ackumulerats i en människa har dessa antagits omkomma till följd av exponering.

Två typer av byggnader (ett medelhögt och ett högt hus) designades enligt preskriptiva krav från de två ländernas respektive byggregler. Genom att applicera den tidigare presenterade modellen var det möjligt att kvantifiera risken för invånarna.

Under studien så noterades det att försöka att bestämma en minsta nivå på säkerheten hos preskriptiva byggregler inte är adresserbar. Detta beror på att även om det är möjligt att bestämma en minsta nivå av säkerhet genererad av brandtekniska krav ifrån byggreglerna så finns det variabler som är kopplade till risken som ej regleras av samma regelverk. Därför inriktades arbetet istället på att försöka uppskatta risken i vanligt förekommande byggnadsdesigner.

Risken som uppskattades för de olika byggnaderna och landsspecifika designerna varierade mellan $3.44 \cdot 10^{-5}$ (lägsta) och $9.08 \cdot 10^{-4}$ (högsta) per år vilka skiljer sig med ungefär en faktor av 26. De flesta av resultaten var dock i storleksordningen 10^{-4}. Jämfört med andra liknande studier är den uppskattade risken generellt högre. Dock skall detta hållas i åtanke att med det konservativa förhållningssätt som användes i den kvantitativa riskanalysen är detta resultat förväntat. Känslighetsanalysen av modellens variabler visade att modellen tenderar att överskatta risken om indatan kan anses vara konservativ.

De designer där sprinkler var ett krav uppvisade inga signifikant minskade risker. Det teoretiserades att sprinkler minskar risken för invånare i byggnaden i ett holistiskt perspektiv men detta har inte undersökts i denna studie. Å andra sidan hade de olika variablerna associerade med rökdetektorer en stor inverkan på den uppskattade risken.

Med hänsyn till den nuvarande kunskapsnivån relaterat till variablerna som påverkar risken, osäkerheterna förknippade med metoden och indatan skall resultaten användas med försiktighet. Det finns också variabler som är mycket svåra att kvantifiera och har därför behandlats som kontrolparametrar. I verkligheten är dessa också förenade med sannolikheter, detta är dock något fortfarande kvarstår som okänt.

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Writing this thesis has been a long and bumpy road into unknown land. It's been filled with new experiences, feelings of despair and problems that require creativity. In the end, it has been a very challenging but rewarding journey.

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At last, a thanks to all of you who have in some way dedicated a few minutes of your life to me.

I hope you enjoy my gift to humanity.

Ulf Carl Johansson

Melbourne, November 2010

Terminology and Definitions

Definitions

Alternative solution (alternative design)
A building solution that complies with performance requirements by other methods than satisfying prescriptive requirements.

Analytic design
Term found in Swedish building regulations. Designs which deviate from the building code by using other methods or solutions to verify safety (incl. alternative designs).

Available Safe Egress Time
Describes the time from fire ignition to time to escape is no longer possible for a specific scenario.

Building class
Describes a specific part of the building code only relevant to a specific building type (e.g. office buildings)

Canton
Political or local government area

Coefficient of determination
A statistical term for how well a statistical model describes the data set.

Convergence
A statistical term describing a function approaching a definite value when performing a large number of iterations.

Control parameter
A control parameter is a variable found important to account for in quantitative terms. The control parameter describes a specific state for a variable (e.g. a door set to 'Open')

Deemed-to-Satisfy
Prescriptive compliance with the building code.

Deterministic
Refers to methods to verify safety by achieving a specific state through modelling of 'a set of circumstances' that will result in a single outcome, deciding if the design is safe or not.

Dose (toxicology)
The accumulation of (harmful) species an individual is exposed to.

Dose-response
The change of effect in an individual caused by different levels of accumulated dose of (harmful) species.

Effective height
The height to the floor of the topmost storey from the floor of the lowest storey providing direct access to road or open space (ABCB, 2010b).

Event
Defined as a factor significantly changing the state of the system (e.g. sprinkler suppression in a fire)

Event tree
A graphical representation of possible sequences of events following an initiating event (e.g. a fire)

Expected Risk to Life
A risk measure describing the expected number of fatalities over a buildings lifetime (Yung, 2008).

Exposure time
Time for which an individual is exposed to toxic levels of species.

Fire scenario
A fire scenario is a qualitative, time-sequence-based description of a fire, identifying key events that characterize the fire and differentiate it from other possible fires. A fire scenario is therefore a fire incident characterized as a sequence of events (SFPE, 2006).

FN-curve (Frequency-Number curve)
A statistical measure to present societal risk. The curve the probability of frequency of causing X or more fatalities per year.

Monte Carlo analysis
A method to perform random sampling to compute predictions of mathematical models.

Occupant Warning System
Refers to any system that provide occupants with a warning signal of a fire hazard.

Performance-based code
A type of building code in which compliance can be achieved by verifying that sufficient levels of performance are achieved.

Prescriptive code
A type of building code in which compliance is achieved by following explicit requirements.

Probabilistic
Refers to methods that incorporate the probability of events occurring.

Probabilistic Risk Assessment
A method to evaluate the risks associated with a specific system. The risk is characterized by the magnitude of consequences and the likelihood/probability/frequency of those consequences occurring.

Quantitative
Refers to numerical methods.

Quantitative Risk Analysis
A method to identify and estimate the risks associated with a specific system. The risk is characterized by the magnitude of consequences and the likelihood/probability/frequency of those consequences occurring.

Required Safe Egress Time
Describes the time from fire ignition to the time when occupants are in a place of safety.

Risk analysis
The systematic use of available information to identify hazards and to estimate the risk to individuals or populations, property or environment (IEC, 1995).

Risk assessment
Evaluation (comparison with acceptable levels of risk) of estimated risks from risk analysis

Risk aversion
Describes the reluctance among individuals to accept a risk with larger uncertainty than one with smaller uncertainty, although both of them have the same expected outcome.

Risk triplet
Refers to the Kaplan & Garrick (1981) definition of risk. By answering the questions "What can go wrong?", "How likely is it that that will happen?" and "If it does happen, what are the consequences?" risks can be described.

Simplified design
Term found in Swedish building regulations.

Societal risk
A risk measure to the society as a whole.

State
A set of characteristics of a system

Stochastic
Natural variability (e.g. 'wind speed at any given moment' is a stochastic variable)

Ventilation controlled fire
A fire for which the heat release rate is controlled by the availability of oxygen

Abbreviations

AFO	Apartment of fire origin
ANFO	Apartment of non-fire origin
ARD	Average Rate of Death
ASET	Available Safe Egress Time
BBR	Boverkets Byggregler (Swedish building regulations)
BCA	Building Code of Australia
CO	Carbon Monoxide
ERL	Expected Risk to Life
FED	Fractional Effective Dose
IR	Individual Risk
PRA	Probabilistic Risk Assessment
QRA	Quantitative Risk Analysis
RSET	Required Safe Egress Time
RTI	Response Time Index
SOU	Sole Occupancy Unit

List of symbols

$[CO]$	concentration of CO [ppm]
A_F	building floor area [m^2]
A_f	floor area [m^2]
A_O	area of opening [m^2]
A_T	total area of internal surfaces [m^2]
C	concentration
c_i	consequences of scenario 'i'
c_p	specific heat capacity for air[kJ/kg·K]
D	smoke obscuration [m^{-1}]
D_{act}	smoke obscuration required for detector activation [m^{-1}]
D_g	mass optical density [m^2/g]
d_{esc}	distance from location to 'safe place' [m]
d	enclosure material thickness [m]
E	energy [kJ]
$E(X)$	expected value of X
FED	fractional effective dose
FID	fractional incapacitating dose
$F_c(x)$	cumulative density function, X or less fatalities per year
$f_c(x)$	probability density function, X fatalities per year
G	supply capacity
H	ceiling height [m]
H_c	heat of combustion [kJ/kg]
H_O	height of opening [m^2]
h_k	heat transfer coefficient [kW/(m^{2}K)]
IR	individual risk [year^{-1}]
IR_a	average individual risk [year^{-1}]
IR_l	location specific individual risk [year^{-1}]
L	length [m]
L_f	flame height [m]
$l_{corridor}$	corridor distance between AFO and place of relative safety [m]
$\ln(X)$	normal logarithm of X
K	flame base diameter [m]
M	safety margin
$\dot{m}_s$	mass loss rate of fuel [g/min]
$\dot{m}_a$	mass flow rate of air [kg/s]
Δm	mass loss [g]
$N(\mu,\sigma)$	normal distribution with mean value μ and standard deviation σ
OD	optical density [m^{-1}]
P_d	probability of death
p_p	probability of occupants present

p_i	probability of scenario 'i' occuring
$\dot{Q}$	heat release rate [kW]
$\dot{Q}''$	heat release rate per unit area [kW/m²]
$\dot{Q}_{VC}$	ventilation controlled peak HRR [kW]
$\dot{Q}_{sprinkler}$	sprinkler controlled heat release rate [kW]
$\dot{Q}_{act}$	heat release rate at sprinkler activation [kW]
q	radiant heat flux [kW/m²]
R	risk triplet
r	radial distance from fire plume [m]
RMV	respiratory minute volume [l/min]
RTI	response time index of device [$m^{1/2}s^{1/2}$]
S	demanding capacity
s_i	scenario 'i'
T_a	ambient temperature [°C]
$T_{\exp}$	exposure temperature [°C]
T_d	device temperature [°C]
$T_{d,act}$	device activation temperature [°C]
T_g	upper layer temperature [°C]
t	time
t_d	time until occupant becomes aware of hazard [s]
$t_{d,a}$	time until alarm sound notifies occupant [s]
$t_{d,fc}$	time until fire cues are perceived by occupants [s]
t_{esc}	time from starting evacuation until reaching a 'safe place' [s]
$t_{\exp}$	time under exposure
$t_{I_{rad}}$	time to fatal exposure from radiation [min]
$t_{I_{conv}}$	time to fatal exposure from convective heat [min]
t_{pre}	pre-movement time [s]
t_{ten}	time until untenable conditions occur
u	velocity of the ceiling jet [m/s]
V	volume [m³]
V	volume of smoke [m³]
$Var(X)$	variance of X
VCO_2	respiratory minute volume correction factor [-]
v_{esc}	walking speed of the occupant [m/s]
W_i	dose of 'i' required to achieve the sought effect
W_{CO}	incapacitating dose for CO [%]
w	width [m]
X	combustion efficiency [-]
y	yield [kg/kg]
z	smoke layer thickness [m]
α	fire growth rate [kW/s²]

δ	fatality rate of exposed occupants [min^{-1}]
ε	emissivity
Φ	configuration factor
ϕ	uncertainty of probability
λ	fire frequency [year^{-1}]
λ_B	fire frequency, Barrio's correlation [year^{-1}]
λ_R	fire frequency, Rutstein's correlation [year^{-1}]
λ_i	frequency of scenario 'i' [year^{-1}]
μ	mean value
ρ_{air}	air density (approx. 1.2 kg/m^3) [kg/m^3]
σ	standard deviation
σ_B	Stefan Bolzmann constant ($5.67 \cdot 10^{-8}$) [Wm^{-2}K^{-4}]
Ψ	distance between surfaces [m]
ζ	uncertainty of consequences

Table of Contents

Chapter 1 - Introduction

This thesis constitutes a joint finalization of a Master of Science in Risk Management and Safety Engineering and Bachelor of Science in Fire Protection Engineering at Lund University, Sweden. The introduction is intended to provide the reader with background to the problem, describe the aims and objectives but also specify limitations and boundaries of the thesis. The overall goal with the thesis is to quantify the risk to occupants in apartment buildings designed in accordance with prescriptive provisions. A comparison is also made between the risks achieved by two country specific building codes.

1.1 Background

The purpose of a building code is to ensure a minimum level of acceptable safety in buildings. The regulations in the code are reflections of criteria set out by societal norms regarding internal layout, safety, hygiene, etc. (Boverket, 2008)

Traditionally fire safety regulations in building codes have been prescriptive, i.e. compliance was explicitly stated and expressed as a set of safety measures and limitations in design. This has its advantages for certain target groups with limited knowledge about fire safety, such as architects and building surveyors (Hadjisophocleous et al, 1998). As these prescriptive provisions per definition meet the level of safety demanded by society, they allow for the design of 'safe' buildings without pre-existing fire safety knowledge, and provide easy design guidelines for non-complex buildings where advanced analyses are not considered cost-effective.

However, prescriptive codes have been argued to put undesirable constraints on building design (ABCB, 2005). New complex types of buildings created a demand for new regulations as these could not be constructed in a prescriptive manner. This has lead to the introduction of performance-based codes, which allow for more cost effective and flexible designs (Bénichou & Hadjisophocleous, 2000). Instead of complying with specific provisions, a design can either follow the prescriptive provisions or *perform* according to criteria.

AustraliaIn 1994 the Australian Building Code Board (ABCB) requested a performance-based Building Code of Australia (BCA). This permitted cost-savings by (ABCB, 2010a):

- permitting the use of alternative materials, forms of construction or designs to the prescriptive requirements;
- the innovative use of materials, forms of construction or designs;
- permitting designs to be tailored to a particular building;
- giving clear information on what the BCA is trying to achieve;
- allowing the designer flexibility in the use of materials, forms of construction or design provided that the intent of the BCA is met (in other words, allow for flexibility provided the performance required by the BCA is met); while still allowing acceptable existing building practices through the deemed-to-satisfy provisions.

When converting the old prescriptive building codes into one performance-based, various parts from the eight different state and territory codes were combined to form the new national regulations. Many of the old prescriptive codes had regulations based on historical events. To set requirements for performance, codes were written in a bottom-up manner – being constructed from what the prescriptive provisions already demanded. After sent out on public comment, the final version of the new performance-based BCA was released in late 1996. The structure of the present (BCA 2010) code can be seen in Figure 1.1.

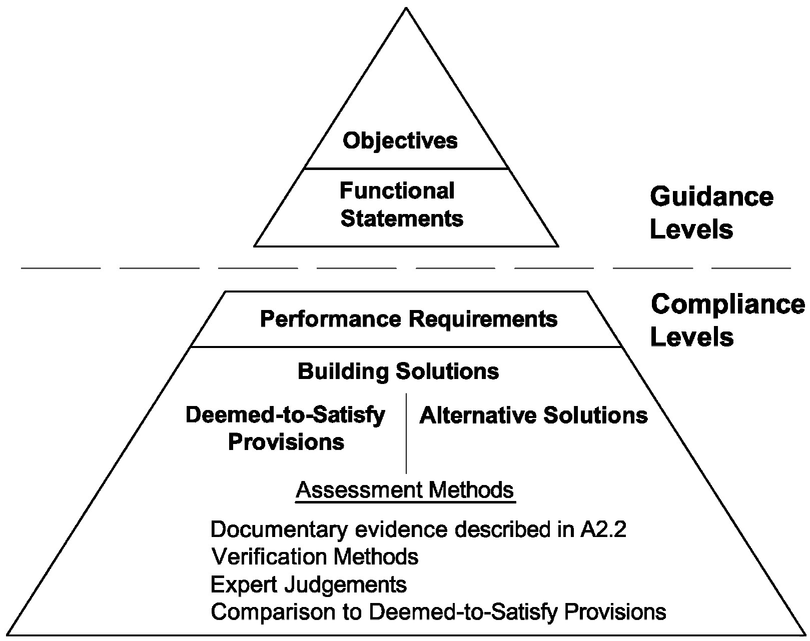

Figure 1.1 BCA Structure (ABCB, 2010b)

The new BCA made way for the opportunity to make use of alternative solutions. This meant that there are no more restraints on the design if it can be verified that the building still provides sufficient performance. In practice this resulted in a few new ways to comply with the building code. Section A0.5 in the BCA states (ABCB, 2010b)

> *"Compliance with the Performance Requirements can only be achieved by –*
> *(a) complying with the Deemed-to-Satisfy Provisions; or*
> *(b) formulating an Alternative Solution which –*
> *(i) complies with the Performance Requirements; or*
> *(ii) is shown to be at least equivalent to the Deemed-to-Satisfy Provisions; or*
> *(c) a combination of (a) and (b)"*

As clearly stated in the quote above, complying with the Deemed-to-Satisfy provisions is equivalent to complying with the Performance Requirements. But compliance can also be achieved by applying an Alternative Solution. However, by deviation from the Deemed-to-Satisfy provisions, the solutions become subject to verification.

1.1.1 Sweden

Fire safety requirements in Swedish building regulations can be found in the Planning and Building Act (PBL 1987:10), the Ordinance on Technical Requirements for Construction Works (BVF 1994:1215) and the Act on Technical Requirements for Construction Works (BVL 1994:847). BVF § 4 states:

> *"Construction works must be designed and built in such a way that in the event of an outbreak of fire:*
> *(1) the load-bearing capacity of the construction can be assumed for a specific period of time;*
> *(2) the generation and spread of fire and smoke within the construction are limited;*
> *(3) the spread of the fire to neighbouring construction works is limited;*
> *(4) people inside the construction works on fire can leave it or to be rescued by other means;*
> *(5) the safety of rescue teams is taken into consideration."*

Up until 1994, building regulations in Sweden were basically prescriptive (structural performance-based design had already been introduced) and design had to be carried out in accordance with the detailed provisions. But on the 1st of January new performance-based Swedish building regulations (BBR) were introduced.

Compliance with BBR can be achieved by either following the prescriptive requirements in BBR or by use of alternative solution as described in Figure 1.2.

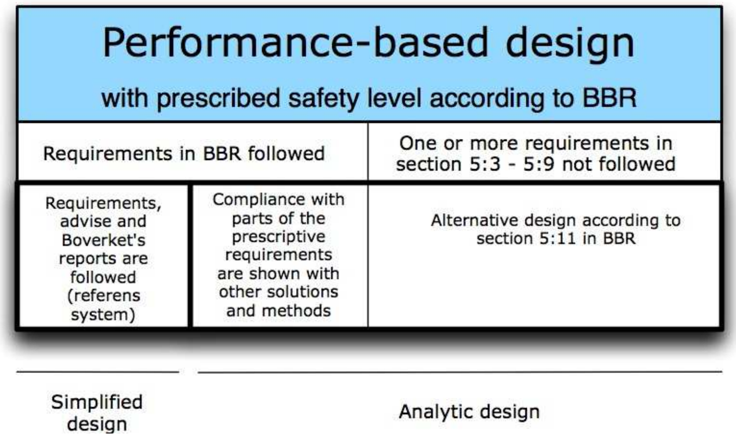

Figure 1.2 Swedish performance-based code (recreated and translated from Bengtson et al. (2005))

BBR separates *requirements* and *advice*. Requirements *must* be followed while advice only suggests that they *should* be. If all requirements and advice in the BBR are followed, this is denoted a *simplified design* or Deemed-to-Satisfy in international terms. When one or several Deemed-to-Satisfy provisions in the BBR are not followed or other methods than prescribed by the regulations are used to show compliance, this is called an *analytic design*. The design now becomes subject to safety verification by fire safety engineering methods. The extent of the verification depends on the deviation from the prescriptive regulations. If the analytic design is the result of using other methods or solutions than prescribed, safety verification requirements are usually low. However, if an *alternative design* is applied, i.e. requirements in the BBR are not followed, the regulations require extensive verification of the safety level (e.g. in the BBR; risk analysis).

1.1.2 Need for verification

The introduction of performance-based codes also increased the need for verifying that safety is achieved when prescriptive regulations are not followed. A few approaches to this have been introduced to assist the designer. In fire engineering terms, an alternative solution is usually described as *qualitative* or *quantitative*, *comparative* or *absolute*, and *deterministic* or *probabilistic* (ABCB, 2005).

A *qualitative* approach may be performed when the analysis contains small deviations from the Deemed-to-Satisfy provisions. Such an approach requires use of sound logic and appropriate references. When the complexity arises, it is suggested that a *quantitative* method is applied. This implies that the analysis includes some form of quantification of the safety, i.e. safety is described as a measure.

The acceptance criteria of an approach can either be *comparative* or *absolute*. When performing a comparative analysis, elements, sub-systems or the entire system is compared to the safety level achieved by a Deemed-to-Satisfy compliant design. If *absolute* criteria are applied, the design is usually evaluated directly against the performance requirements or quantified risk criteria.

Deterministic or *probabilistic* refers to the method to evaluate the fire safety achieved by the design. In a *deterministic* approach, one or a few so called 'worst credible' fire scenarios are used to verify sufficient level of safety is achieved. A common method for this is a so-called ASET/RSET analysis. For more detailed information, see section 2.1. In contrast to a deterministic analysis, the *probabilistic* approach also accounts for the probability of a scenario occurring. The combination of probability and consequence is usually considered a form of risk measure.

In Sweden, the requirement of verification of an analytic design is expressed in paragraph 5:13 in BBR (Boverket, 2008):

> *"5:13 Analytic design*
>
> *Analytic design and, where relevant, an associated risk analysis shall verify the fire safety and the evacuation safety in buildings where fire may cause great risk of human injury. Analytic design may be calculations, testing or special tests designed for the individual project or combinations of these.*
>
> *If design of fire protection is based on calculations, calculations shall be based on carefully selected design values and shall be performed in accordance with a model which gives a satisfactory description of the problem at hand. The calculation models selected shall be stated."*

In Australia, the BCA gives the designer some assistance in compliance assessments. Guidance is given in clause A0.9 in the BCA for which assessment methods that may be used for verifying compliance. These acceptable methods are (ABCB, 2010b):

> *"(a) Evidence to support that the use of a material, form of construction or design meets a Performance Requirement or a Deemed-to-Satisfy Provision as described in A2.2*
>
> *(b) Verification Methods such as-*
>
> *(i) the Verification Methods in the BCA; or*
>
> *(ii) such other Verification Methods as the appropriate authority accepts for determining compliance with the Performance Requirements.*
>
> *(c) Comparison with the Deemed-to-Satisfy Provisions*
>
> *(d) Expert Judgment"*

Lundin (2004) concluded that although the BBR allows for the designer to use different methods to comply with the performance requirements, methods to verify safety are very limited. He found that a comparison with the Deemed-to-Satisfy provision was the only way to show compliance (cf. (c) in BCA Clause A0.9 above). This problem arises as the fire engineering community has accepted certain methods to show compliance but the development of acceptance criteria as a method of verification has not followed. Frantzich (1998) noted that there are still no quantitative measures of performance objectives to compare with and Bénichou & Hadjisophocleous (2000) points out that one of the biggest challenges with the performance-based codes is to define criteria to comply with the code and develop the necessary tools to quantify these criteria.

1.1.3 Risk as a measure of performance

In the absence of quantified measures of the performance requirements, designers are often left with the only option of comparison with the Deemed-to-Satisfy provisions. As performance-based codes were introduced in Sweden 1994, Lund University started a pilot project for investigating quantitative methods that may be used in fire safety engineering applications (Magnusson et al., 1995). Risk was already a concept used in different areas of engineering and as the authors expressed it "there seems to be a general consensus that performance-based design equals risk-based design". Hence, it can be theorized that the performance requirements equals a corresponding risk.

One of the objectives with the Fire Code Reform Project in Australia aimed to make the first initial steps towards quantitative performance-based objectives. In this process they acknowledged that in order to do that, there was a need to investigate the level of safety of the current Deemed-to-Satisfy provisions. As a result of this initiative, the cost-risk assessment model CESARE-Risk was developed (ABCB, 2001). Thomas et al (2005) presented a paper in which an attempt to quantify the risk to life in apartment buildings was made using CESARE-Risk. In Sweden, Nystedt (2003) estimated the risk to occupants in a typical Swedish apartment. In order to do so he created a model to estimate the risk of death due to fire. Results were presented as absolute risks. However, as there is no general accepted method for fire risk analysis in the fire engineering community, there is still a need to strengthen the base for which decisions on quantitative criteria are made.

Method (c) in Clause A0.9 (see above) gives an interesting statement since it provides an opportunity to make use of engineering methods to compare a Deemed-to-Satisfy compliant design with an alternative solution. By using a quantitative, probabilistic approach to perform this analysis, the Deemed-to-Satisfy provisions may be converted into a corresponding risk measure. As clause A0.5 (a) states that the Deemed-to-Satisfy provisions are compliant with the BCA, this implies that there are methods to quantify the provisions.

1.1.4 Performance of Deemed-to-Satisfy provisions

Before the introduction of performance-based codes, the provisions were developed slowly based on past experience (Bengtson et al., 2005). When the BCA was rewritten to a performance-based code, the performance requirements were constructed from what the Deemed-to-Satisfy provisions already was demanding. No analysis was carried out to check that the provisions were in accordance with acceptable levels of societal risk. As a result, the absolute level of safety remains unknown. Furthermore, since the prescriptive codes were not developed from acceptable societal risks, it brings up the question: how good is the level of safety achieved by the Deemed-to-Satisfy provisions?

1.2 Aim

This thesis aim to investigate the concept of using quantitative fire safety engineering verification methods to quantify the level of safety achieved by prescriptive building code regulations.

By applying such methods to a number of case study buildings, quantified risk to life achieved by the prescriptive building code provisions for apartment buildings in Australia and Sweden can be estimated. By applying the minimum allowed prescriptive provisions, it is theorized that the risk imposed on occupants can be maximized. These quantified measures are also used to compare the levels of safety between the countries.

Quantified measures of the prescriptive regulations could be used as a benchmark when evaluating the safety of similar buildings. This thesis will also highlight some of the difficulties and problems associated with such an analysis.

1.3 Limitations

A wide variation of building types exist with varying characteristics and use. This thesis has been limited to investigate risk associated with apartment buildings. Even though entire apartment buildings have been included, the estimated risks are for occupants residing in individual apartments, i.e. a joint estimated risk for entire buildings have not been sought to be quantified.

Buildings and building classes also vary between nations due to traditions, climate and culture. This thesis is limited to investigate risks associated with apartment buildings in Australia and Sweden.

Some limitations are also made for the risk calculations performed in this thesis. For instance, no consideration has been taken to effects of fire brigade intervention which commonly assist in providing extra means of escape, rescue services and mitigating fire hazards. Occupant mobility constitutes another factor that has been shown to affect the estimated risk significantly but is not accounted for in this study (Nystedt, 2003; Thomas et al, 2005).

Worth noting is that in the Swedish building regulations some of the prescriptive provisions are formulated as something that 'must' be implemented. However, there is a slight difference between provisions that 'must' and 'should' be followed, see section 1.1.1. As for this thesis, it has been assumed that the 'should' implies that this is the equivalent minimum level of safety.

1.4 Method

This thesis consists of two parts. *The first part* is a review of existing literature on previous research, methods to verify fire safety, risk assessment methods and quantitative methods for fire risk analysis. The literature study aims to identify methods that jointly can be used as a model to quantify the risk in apartment buildings and the necessary background information in order to perform such an analysis. The term quantification here relates to applying mathematical and statistical methods (Backman, 2008).

In Chapter 2 an introduction is given to verification methods in fire safety engineering. The concept of using risk as a verification method is introduced and the differences between deterministic and probabilistic assessments is explained.

In Chapter 3, the concept of risk leads to further exploration of quantitative methods for fire risk analysis. This includes a review of methods with a description intended use and applicability. Included is also a summary of previous studies on fire risk analysis and risk to life quantification literature judged being relevant to this thesis. The gathered knowledge will form the model, which allow for quantification of risk.

The last section of the first part (Chapter 4) concerns building codes and prescriptive regulation. It describes how the prescriptive provisions are treated and implications with addressing a minimum safety level. As such, an alternative approach is formulated.

The second part presents the model for quantification of risks associated with apartments, more detailed description is found in Chapter 5 - Quantifying building code risk to life. This chapter briefly describes the method for calculating the risk associated with a prescriptive design of a building. The calculations were carried out in Microsoft Excel spread sheets together with the risk analysis software @Risk.

In a broad perspective, the Deemed-to-Satisfy provisions provide different safety measures for a wide range of buildings. The estimation of the risk imposed on the occupants (and to an extent, society) is determined by the type of building(s) analysed. Naturally, a large number of buildings would be preferred as this provides more information on the distribution of the risk. However, this is not an efficient approach as it is very time consuming. Therefore the level of safety, or risk, will be determined by a number of buildings that will be assumed representative for the range of buildings within the building class, i.e. the analysis will be carried out as a case study. Chapter 6 describes how the case study buildings have been chosen and criteria when designing these according to prescriptive provisions of the building code. It also presents the case study buildings that have been chosen to represent the broad spectrum of buildings with the appropriate Deemed-to-Satisfy provisions applied.

In Chapter 7 the necessary input data, models and assumptions for the quantitative analysis is presented. These form the body of the model and provide it with the necessary information to calculate the risk.

Chapter 8 presents the estimated quantified risk generated when applying the model (Chapter 5) to the case study buildings (Chapter 6) and with input and sub-models (Chapter 7). A risk estimate is calculated for each country-specific design and a comparison between the countries is made. Discussion of the results and method leads to conclusions and suggestions to further research from the thesis.

1.4.1 *Literature search*

The literature review carried out prior to the analysis in this thesis was mainly focused to give background information on the problem, search the field for previous studies and acquire state-of-the-art knowledge on fire risk analysis.

1.4.1.1 Type of literature used

Quality of the literature is important for the credibility of this report. Therefore only references with sufficient quality assurance procedures have been included. As a general guideline, these kind of scientific research reports have been considered quality resources:

- Papers in peer-reviewed academic journals
- PhD theses/dissertations
- Academic research reports
- Books
- Official guidelines/handbooks/manuals

To certain extent also:

- Student theses

1.4.1.2 Acquiring literature

Literature was gathered in mainly two ways; thorough examination of academic publications on website and search in online databases. The examination of academic publications was mainly carried out on websites of the Department for Fire Safety Engineering and Systems Safety (2010) at Lund University, the Department of Civil and Natural Resources Engineering (2010) at University of Canterbury and the Department of Fire Protection Engineering (2010) at Worcester Polytechnic Institute.

The online search was conducted mainly through Lund University access to ELIN (Electronic Library Information Navigator). This electronic library houses a large amount of papers and articles from scientific journals, databases and e-books.

The International Association of Fire Safety Science keeps an online database of the proceedings from their regular conferences as well as the local Asia-Oceania Association for Fire Science and Technology. These two databases was also used to support this thesis.

The author has also been given access to Philip Chun's library which contains a wide variety of books, guidelines, building codes and research reports.

1.4.1.3 Keywords

For reasons of being able to re-create this thesis, certain keywords were used when performing the search for literature. Usually these keywords were not directed towards any specific part of the literature (e.g. title, author, keywords, etc.). It should also be noted that the author discovered that some of the journals in ELIN have not been indexed properly, and therefore it was not possible to find certain articles through the search function. However, some reports were therefore found through searches on Google or by examining references in other articles and with the knowledge of the exact indexing in the journal, it was possible to acquire these.

Keywords that were used in the literature search were as follows: fire risk analysis, risk analysis, probabilistic, quantification, quantified, QRA, quantitative risk analysis, performance-based, risk criteria, acceptable risk, risk to life.

Chapter 2 - Verification methods

In Chapter 1 two different options to fulfil building code requirements were introduced; either by following prescriptive Deemed-to-Satisfy provisions which is defined as a 'safe' design or by applying an alternative solution. This is the basic structure of a performance-based code.

A building code aims to provide an acceptable level of safety to occupants and therefore a building design fully complying with Deemed-to-Satisfy provisions is, by definition, a method to verify that an acceptable level of safety is achieved. However, as the development of the prescriptive regulations is based on historical events rather than scientifically derived safety measures, the actual level of safety remains unknown. It may also be theorized that the level of safety varies for different designs within a building code but on an overall level performs according to societal acceptable norms. For example, night club fires have caused incidents with large number of fatalities world-wide whereas office buildings fires seldom are associated with large consequences.

Not following the prescriptive regulations in the building code, an alternative solution must provide the necessary information to verify that an acceptable level of safety is achieved by the design. Fire safety engineering (FSE) tools and methods are science-based approaches to such verification.

In section 1.1.3, it was theorized that applying Deemed-to-Satisfy provisions equal a corresponding risk. This chapter aims to provide information on how fire safety engineering methods commonly used to verify the safety of alternative solutions, may also be used to present a quantitative measure of risk of Deemed-to-Satisfy designs. Together with knowledge of prescriptive regulations of building codes presented in Chapter 4, a model to quantify the risk of prescriptive designs is presented in Chapter 5.

2.1 Fire safety engineering methods for safety verification

In section 1.1.2 'Need for verification', a short introduction was given to different approaches for analysis that may be taken on to verify the safety of a design, which are shown in Figure 2.1.

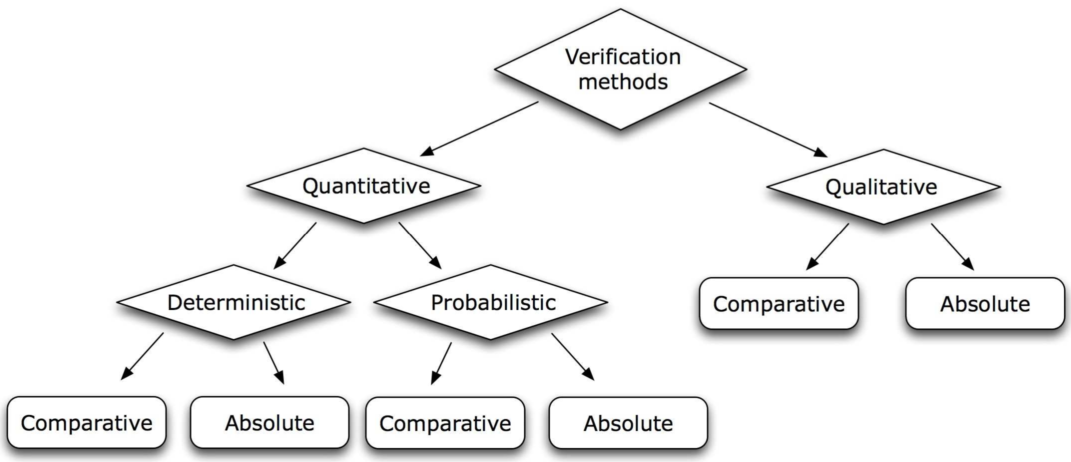

Figure 2.1 Different verification methods in FSE

The different approaches shown in Figure 2.1 are distinguished by the comprehensiveness of treatment of uncertainty. In some analyses, such as small deviations from the building code, an extensive analysis may be unnecessary as verification method. Paté-Cornell (1996) describes six levels of uncertainty treatment in analysis with Level 0 being the crudest in relation to explicit treatment. The six levels are:

- Level 0: Identification of hazards or system failure
- Level 1: 'Worst case' approach, comprises of a scenario which aim to provide information of worst possible outcome
- Level 2: 'Worst credible cases', taking into account that the Level 1 treatment may be so unlikely that it is meaningless evaluating that scenario and instead provide a reasonable upper bound of worst plausible scenarios
- Level 3: Best estimates or central values, using mean or median values of the outcome distribution can be argued to provide a more realistic representation of loss
- Level 4: Probabilistic risk assessment (single risk curve), taking into account different probabilities of the analysed system being in specific states allows for presentation of the risk as distribution of losses
- Level 5: Probabilistic risk analysis (multiple risk curves), similar to Level 4 but separates uncertainty due to knowledge or stochastic randomness

In Figure 2.1, a distinction is made between *qualitative* and *quantitative* methods, where the latter usually is associated with higher levels of uncertainty treatment. A qualitative approach relies on the author to verify the safety by use of sound logic and sufficient references. Examples of qualitative assessments could be a reliable source performing a very similar analysis or by showing that the alternative solution comprises small deviations from the building code and due to the nature of the use of the building, these deviations will have very small adverse effects on the level of safety. The qualitative approach can either be absolute or comparative, where absolute refers to complying with performance requirements. In a comparative solution, the alternative solution is qualitatively compared to a Deemed-to-Satisfy compliant design. A qualitative absolute method is commonly evaluated against performance requirements. This approach should be used with caution and is not suitable for complex analyses (ABCB, 2005).

Qualitative methods per definition can not explicitly measure the level of safety achieved by a design and is therefore of lesser interest in relation to the aims of this thesis. Using explicit measures of safety is equivalent to a *quantitative* approach. In Figure 2.1, quantitative approaches are divided into *deterministic* and *probabilistic* methods which in turn can be either comparative or absolute.

2.1.1 Deterministic methods

Magnusson et al. (1995) defines deterministic modelling as 'a set of circumstances' that will result in a single outcome, deciding if the design is safe or not. More generally, it can be argued that a set of circumstances correspond to a specific scenario. This presumes that at least one given fire scenario is evaluated, i.e. a Level 1 analysis. For evaluating fire safety in a building, a Level 1 analysis is supposed to provide the worst possible outcome, which in a life safety perspective would result in all occupants becoming fatalities. This is an extremely unlikely scenario and it can be argued that no design is entirely 'safe', as expressed in the International Fire Engineering Guidelines (ABCB, 2005):

> *"The goal of 'absolute' or '100%' safety is not attainable and there will always be a finite risk of injury, death or property damage"*

Therefore, in fire safety engineering it is more common to include a number of scenarios and seek 'worst credible' outcomes, which can be assumed to be a Level 2 analysis. As the safety is verified by scenarios, it relies on the designer being able to identify sets of circumstances that are likely to present 'worst credible' outcomes yet not being associated with insignificant probabilities. This is not a straightforward task and it becomes rather subjective. For example, assume that we know that a design is 'safe'. The design is being evaluated by a deterministic approach. If the selected scenarios fail to estimate the largest credible consequence, verification is flawed as the consequences are underestimated. On the contrary, if a scenario is selected so that consequences are very high, this suggests that sufficient safety is not achieved by the design when in reality is considered safe.

To bridge this problem, traditionally uncertainties in deterministic analyses are dealt with by conservative assumptions and safety factors. An example of a deterministic analysis is a so-called ASET/RSET analysis, comparing the evacuation time with the time until untenable conditions (Nelson & Mowrer, 2002). If the analysis shows that sufficient time margin is present for all considered scenarios, safety is verified.

A limitation with deterministic models is that no emphasis is put on how probable the scenarios are. In the above example, the 'worst credible' scenario might be highly unlikely but within reason. However, because of the deterministic approach, the acceptance criteria (e.g. all occupants evacuate safely) must be assessed against the consequences of the 'worst credible' scenario. If the deterministic analysis shows that this criterion cannot be achieved, the effect might be that the design has to be supplemented with an additional fire safety system to reduce the consequences of that specific scenario. This could for example be a sprinkler system. Problems arise when assessing the benefits of such a system in a deterministic analysis. Since fire safety systems are not without a probability of failure, even with an installed sprinkler system, the worst possible consequence remains the same in this example. However, in reality, the *probability* of this worst scenario occurring has been significantly reduced.

2.1.2 Probabilistic methods

To bridge the problem introduced in the previous section, scenario probability may be included in the analysis. Such methods are commonly denoted *probabilistic*. By deriving probabilities associated with the different scenarios, the information required to evaluate whether a scenario is insignificant or not can be evaluated. This mitigates the problem presented above with deterministic methods, where the probabilities of the evaluated scenarios are unknown.

The benefit of a probabilistic method is that more information regarding the safety can be produced. Where a deterministic analysis in essence answers the question of a design being 'safe' or not, a probabilistic analysis can express how likely it is that safety is achieved from a large range of scenarios. Depending on the level of separation of uncertainty, this type of analysis corresponds to either a Level 4 or 5 treatment of uncertainty (see section 2.1). Both comparative and absolute acceptance criteria may be used together with a probabilistic method to verify the safety. Further information on acceptable levels of risk is given in section 3.3.

Evaluating both consequences and probability for scenarios is considered a form of risk measure and such a probabilistic method is usually called risk analysis.

2.1.3 Risk analysis

IEC (1995) defines risk as "[the] combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event" and risk analysis as "[the] systematic use of available information to identify hazards and to estimate the risk to individuals or populations, property or environment." From this definition it can be concluded that risk analysis provides a framework to estimate frequency or probability and consequences from identified hazards. A wide range of risk analysis methods are available which can be linked to all levels provided by Paté-Cornell (1996) shown in 2.1.

Risk analysis is usually a part of the *risk management* process, see general framework shown in Figure 2.2. In the risk management process, risk analysis is used to identify and estimate the risks of a system. Together with a *risk evaluation*, i.e. comparing it to acceptable levels risk or other criteria, this comprises of what is commonly denoted as a *risk assessment*. In essence, this is a method to verify the safety of a system. If the result of a risk assessment is that the risks are unreasonably large, *risk reduction* or *risk control* may be necessary.

IEC (1995) provides guidance to what should be included in a risk analysis. Some major parts are:

- Scope definition (describe reasons for risk being analysed, define the system, define boundaries, define assumptions and limitations, define acceptance criteria)
- Hazard identification and consequence evaluation
- Risk estimation
- Verification

Because risk analysis is a multi-disciplinary science the process is very general and customized risk analysis/assessment methods and frameworks are common within individual disciplines. For fire safety engineering, such methods and frameworks are presented in section Chapter 3. No definition of risk has reached a general consensus among practitioners and it is therefore necessary to define what is meant by risk in the analysis. Depending on the definition and the system analysed, risk may be presented as different measures. A short introduction to different quantitative risk measures are given in section 3.2. Once risk has been estimated, verification can take place by comparing it to acceptable levels.

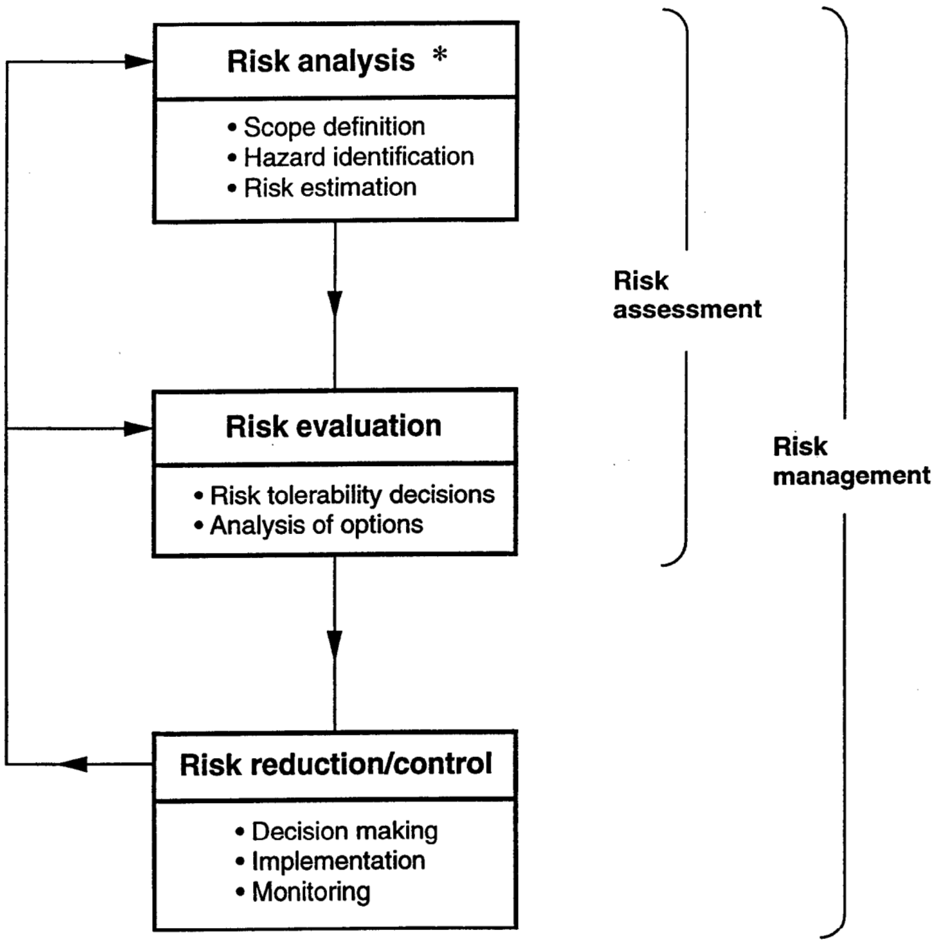

Figure 2.2 Risk management process (IEC, 1995)

Chapter 3 - Risk analysis in fire safety engineering

This chapter aims to provide information on how risk analysis may be used as a tool to verify safety in fire safety engineering, present previously developed frameworks for risk quantification and the necessary background information needed when performing fire risk analyses.

An introduction to fire risk analysis is given below. This is followed by a brief overview of quantitative methods identified (section 3.1) and a more detailed description of methods found suitable for the purpose of this thesis (sections 3.1.1 & 3.1.2). Different risk measures that may be used to present risk are described in section 3.2. A short introduction to risk evaluation is given in section 3.3. The estimated risk will be dependent on how the analysis is carried out. Therefore, different risk assessment frameworks for buildings were studied in section 3.4. These were also later used to customize a model for the purpose of this thesis (see Chapter 5). The risk assessment frameworks provided information regarding necessary knowledge needed to perform a fire risk analysis. Sections 3.5 - 3.9 aim to provide background information on these areas. The final part of this chapter (section 3.10) summarizes a few previous studies on quantitative measures of risk to occupants.

The concept of risk has been introduced in different forms in the field of fire safety engineering. One example is the measure of expected risk to life (ERL) as described by Eq. 3.1 (Yung, 2008).

$$ERL = p \cdot c \qquad \textbf{(Eq. 3.1)}$$

P denotes the probability and *C* the consequence. Magnusson et al. (1995) found that since the fire safety engineering disciple commonly utilizes scenario methodology, the risk triplet as defined by Kaplan and Garrick (1981) provided a useful definition of risk. The risk triplet essentially answers the following questions:

- What can go wrong?
- How likely is it that that will happen?
- If it does happen, what are the consequences?

The risk triplet is usually presented in the form

$$R = \{(s_i, p_i, c_i)\}$$

where s_i is the scenario description, p_i probability and c_i consequence for the scenario *i*.

Using the risk triplet, the ERL concept can therefore be expanded into a probabilistic approach as described by Eq. 3.2.

$$ERL = \sum_i p_i \cdot c_i \qquad \sum_i p_i = 1 \qquad \textbf{(Eq. 3.2)}$$

where *i* represents an individual scenario. Because the scenario methodology is deeply rooted in fire safety engineering, a scenario based risk analysis provides a good method to verify safety. In BBR it is stated that safety for certain building designs must be verified by a risk analysis (Boverket, 2008).

In reality, *i* consist of an infinite pairs of probabilities and consequences. This is an important understanding since it proves that it will never be possible to reproduce reality. However, using engineering techniques to identify key events for the course of the fire is a very important task in fire risk analysis. These key events lead to different 'states', i.e. events that have *major* effect on the outcome. One example of such an event is sprinkler activation which will significantly influence the consequences as it highly likely to mitigate the hazardous conditions.

3.1 Quantitative methods

Rasbash (2004) presents a simple method to estimate the fatality risk in dwellings. In the case of a fire, it may be assumed that the probability of fatality increases for time spent in the building. By use of statistics and time-exposure relationships, parameters may be estimated for this type of assessments. In the method, the total time needed for successful escape, Δt_{esc}, is compared to time until the fire has produced critical conditions which commonly arises from heat, smoke, radiation, etc. This time is denoted Δt_{ten}. If the difference

$$\Delta t_{esc} - \Delta t_{ten} = \Delta t_{\exp} \qquad \textbf{(Eq. 3.3)}$$

is positive, then there are occupants exposed to critical conditions. In BSI (2003), the probability of death for an occupant exposed to critical conditions is then described by Eq. 3.4.

$$P_d = \delta \cdot (\Delta t_{esc} - \Delta t_{ten}) = \delta \cdot \Delta t_{\exp} \qquad \textbf{(Eq. 3.4)}$$

where

δ is the fatality rate of exposed occupants [min^{-1}]
P_d probability of death

Using statistics, a fatality rate for exposed occupants may be derived as an analytical expression. However, this measure is crude as it does not account for building variations (other than described by statistics) and individual occupant variation. For the purpose of the thesis, this method was discarded as it was considered too crude.

More sophisticated methods for estimating risk and quantifying uncertainties for fire safety engineering purposes were described by Magnusson et al. (1995). The result of their study presented five approaches shown in Figure 3.1.

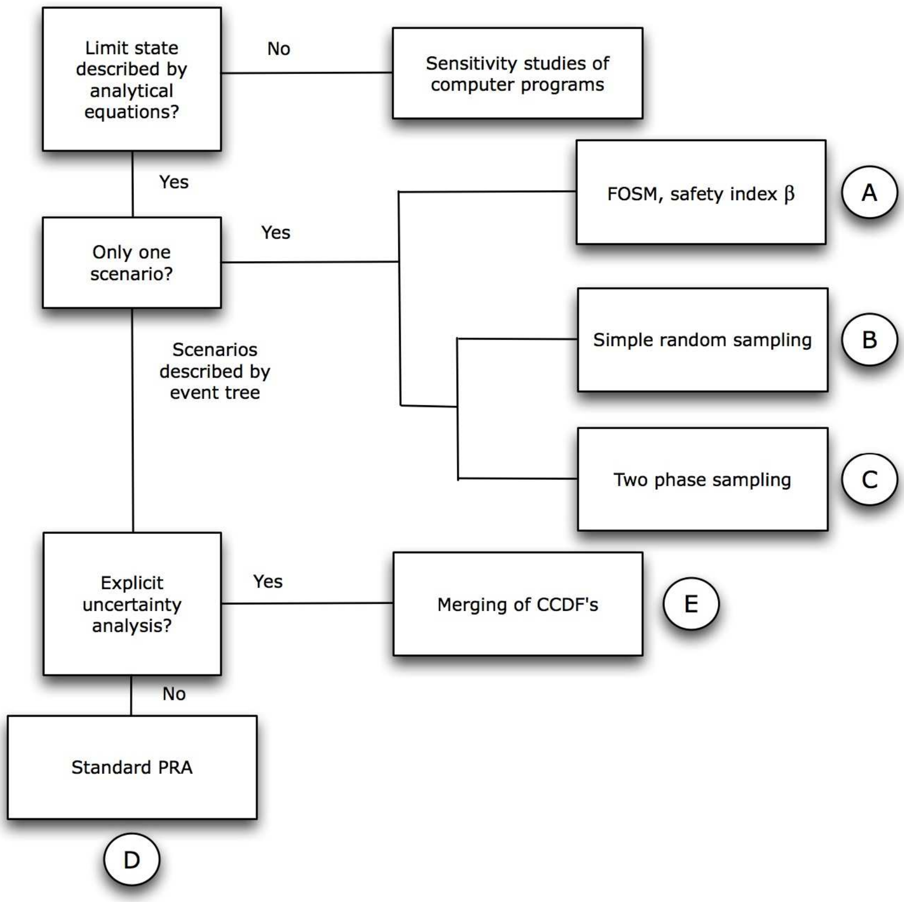

Figure 3.1 Taxonomy of methods of analysis. Reproduced from Magnusson et al. (1995)

Depending on the purpose and level (e.g. component, system) of the analysis, the choice of methodology and approach for quantifying the risk will differ. In Magnusson et al. (1995) these are divided into five categories:

1. FOSM, safety index β. (A in Figure 3.1)
2. Simple random sampling. (B in Figure 3.1)
3. Two phase sampling. (C in Figure 3.1)
4. Standard PRA. (D in Figure 3.1)
5. Extended PRA (E in Figure 3.1)

The first presented method (A in Figure 3.1) is a so-called First-Order Second-Moment (FOSM) approach to describe the safety of a system. This method is also know as safety or reliability index β method and has its roots in reliability engineering (Magnusson et al, 1995). The method is based on a supply-demand relationship which usually is expressed as

$$M = G - S \qquad \textbf{(Eq. 3.5)}$$

where G denotes the supply capacity , S the demand and M the safety margin. One of the earliest uses of the method in fire safety engineering was performed by Magnusson (1974) applying it to fire exposed steel structures.

A benefit with using this method is that the design point, i.e. the highest probability of failure is automatically generated as output (Frantzich, 1998; Magnusson et al., 1995). There are several limitations with this method. One is that the function (Eq. 3.5) only describes one scenario and evaluating several scenarios will result in high work-load. A more detailed explanation of applying this to fire safety engineering problems may be found in Magnusson et al. (1995) and Frantzich (1998).

Instead of solving an analytical expression (e.g. FOSM method), Monte Carlo based methods can be used to propagate uncertainties through the analysis. Methods B and C in Figure 3.1 present two such approaches with the main difference that knowledge uncertainty and stochastic uncertainty are separated in a two-phase sampling. This method may also be useful in situations when the analytical expression may not be solved directly. Similar to method A, this method is limited to describing one scenario.

Methods D and E in Figure 3.1 refers to a so-called Probabilistic Risk Assessment (PRA). This type of assessment is also known as Probabilistic Safety Assessment and Quantitative Risk Analysis/Assessment (Paté-Cornell, 1996). Probabilistic methods have been explained in section 2.1.2. The main difference from the other methods is that several scenarios may be evaluated in an event tree based approach. Using the same approach, method D and E different means to treat uncertainty and they are synonymous with Level 4 and 5 analyses respectively as described in section 2.1.

Frantzich (1998) gives guidance on how to determine which method is suitable for the analysis by asking the following questions

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

By answering those questions, a suitable method of analysing the problem is given by the flow chart seen in Figure 3.2. In this figure, the denomination QRA is used instead of PRA.

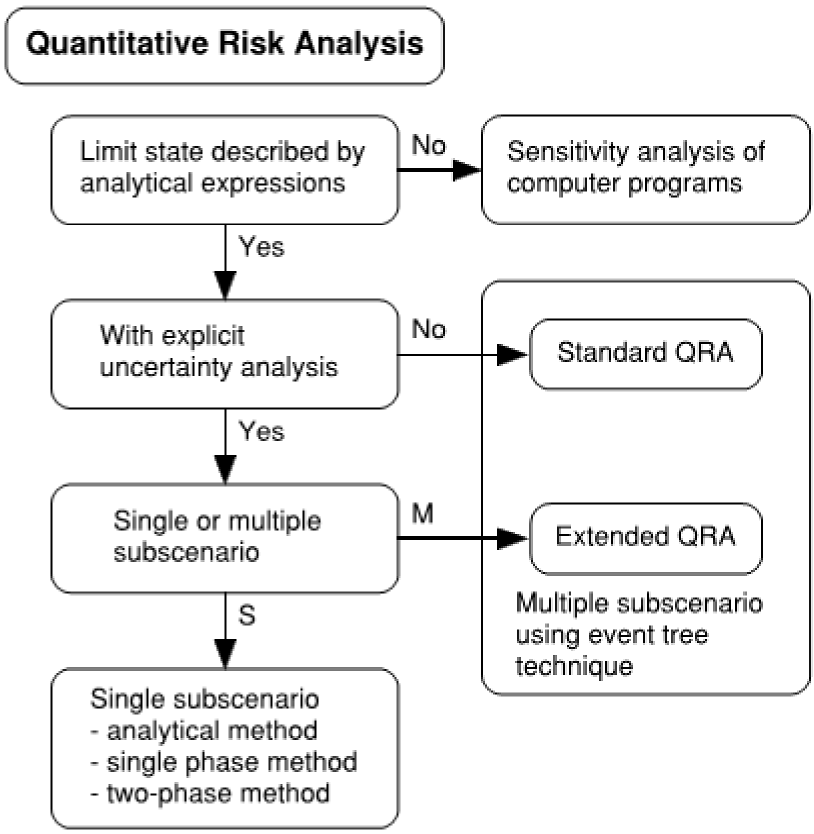

Figure 3.2 Flow chart for quantitative methods (Frantzich, 1998)

A review of methods for estimating probability and consequences for the purpose of this thesis suggested that the safety could be expressed as an analytical expression. Further, it was argued that a single scenario is not sufficient to describe the safety for the purpose of this thesis. Following the flow chart in Figure 3.2, the remaining alternatives are a standard QRA or an extended QRA, which are described in the following sub-sections.

3.1.1 Standard Quantitative Risk Analysis

Using the risk triplet as definition of risk it follows that a quantitative measure of risk can be represented by a number of scenarios for which the probability and consequences are determined. Since a large number of scenarios need to be evaluated and structured in a logical way, event trees are a good method to represent this in a graphical manner (Frantzich, 1998). The event tree always starts with an initiating event; in this case that a fire has occurred. The event tree is then further divided into sub-trees by events that represent important factors that change the course of the fire scenario (e.g. fire detection, sprinkler activation, blocked emergency doors) or stochastic variables (e.g. occupant awake/sleeping, night/day). A simple example of an event tree can be seen in Figure 3.3.

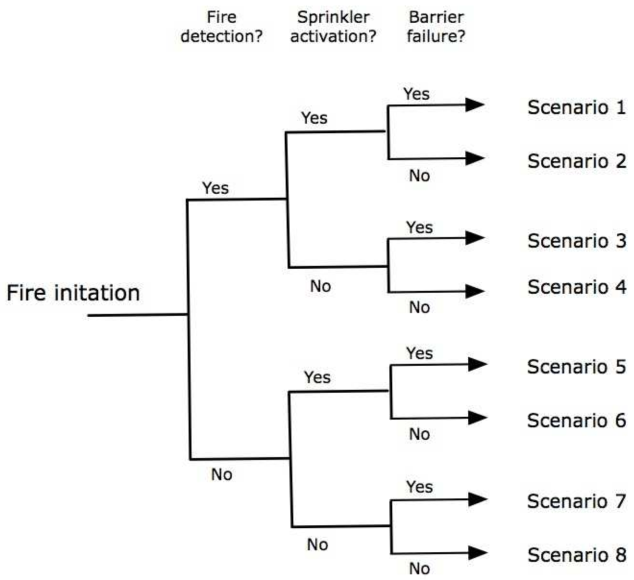

Figure 3.3 Simple event tree

The amount of events will determine the number of scenarios. Since every event has a probability associated with it, the probability of a scenario occurring can be calculated as a product of probabilities (or complementing probabilities). Every scenario is also associated with a unique state described by the chain of events leading to it. To assess the consequences, the end state has to be described in quantitative terms. In fire safety engineering this is commonly done by calculating when untenable conditions arise. However, risk analyses are commonly carried out with the consequence outcome is death (Frantzich, 1998). Untenable conditions are usually describing when an escape route is no longer available for escape. This doesn't necessary mean that occupants subjected to these conditions are lethal. It is important to distinguish these terms since it will severely affect the calculated risk.

While not treating uncertainties explicitly in a standard QRA, it is important to realize that the used estimates of different variables (e.g. fire safety system effectiveness, fire growth rate) must be selected with care. One may argue that the mean values may be a good representation of an 'average' distribution of consequences. However, if the safety margin is very small, this implies that safety is only achieved in approximately 50 % of the time. Magnusson et al. (1995) compared the safety margin between using mean, median and upper bounds of variables in a standard QRA. The result showed that what initially by using mean or median values could have been considered a 'safe' design actually lead to a negative time deficit in all scenarios for the 80th

percentile. When assessing safety, it is necessary to see to that safety is achieved with a high probability. Deterministic values used in a standard QRA should therefore be derived from upper bounds to ensure that acceptable levels of safety are achieved. Guidance is seldom given since providing an acceptable level of the upper bound requires

(a) knowledge on the distributions; and

(b) setting an acceptable level of risk

The knowledge about the difference between using mean, median and upper bounds can only be gained by having knowledge of distribution of the variable. In situations where this information is lacking, estimating the upper bounds is not without uncertainty.

Point (b) refers to the ambitions set out by regulatory instances. Assume that the 95th percentile would be set as criteria for 'safe' design. As a risk analysis considering life safety usually considers death as the consequence, this implies that in 5% of the cases it is acceptable with one (or more) fatalities. This is in contradiction with for example the objectives stated in Boverket (2008).

3.1.2 Extended Quantitative Risk Analysis

As the standard QRA only uses point estimates, information is lost on how certain and credible the results are. To estimate the risk this way is flawed in several ways, for instance some variables naturally contain randomness.

Frantzich (1998) uses the term 'random variability' to describe the natural stochastic variability caused by nature and randomness due to knowledge uncertainty. For systems, the variables describing it are not always well known and therefore it should be assigned variability instead of a constant. This suggests that there is uncertainty involved. Random variability is also why it is practically impossible to eliminate all risk, i.e. make a building entirely 'safe'. Even if major precautions are taken, there is still a probability for scenarios with adverse outcomes, for example a rapid fire scenario occurs at the same time as a high occupancy load.

As both the probability and consequences of a scenario are subject to uncertainties and therefore the Kaplan and Garrick's (1981) risk triplet may be modified to

$$R = \{(s_i, p_i(\phi_i), \zeta_i(c_i))\}$$

where ϕ_i and ζ_i represent the uncertainty of probability and consequences.

By assigning distribution functions to both probability of occurrence and consequences, uncertainties may be propagated through the analysis. Whereas a standard QRA gives a point estimate of the risk or a single cumulative function, the extended QRA provides information on the distribution of the estimate or a number of cumulative functions.

3.2 Risk measures

From a set of frequencies and consequences, it is possible to present this data in different ways. This section provides a short introduction to a few of these.

3.2.1 Individual risk

Individual risk (IR) usually describes the risk of death per year from one or a few risk sources. Davidsson et al. (1997) explains a few variations of expressing individual risk. *Average individual risk* is expressed as

$$IR_a = \frac{Number \quad of \quad fatalities \quad per \quad year}{Number \quad of \quad people \quad at \quad risk} \qquad \textbf{(Eq. 3.6)}$$

This measure is usually calculated from historical data. Another measure is also *location specific individual risk,* which expresses the risk of death for a (fictive) person being at the same location for a period of time. This measure is commonly used in chemical industries or around hazardous activities but may as well express the risk of a fictive person being located in an apartment. A variation of individual risk may also be expressed by calculating the combined risks that an individual is exposed to over a period of time. However, as this incorporates examining the risks an individual is exposed to during a specific period of time and hence many different risk sources, this is not relevant for this thesis as it is focused on the risks imposed on occupants in apartment buildings. The interested reader is referred to CPQRA (2000).

Frantzich (1998) used an event tree approach to calculate the individual risk in a building. Each of the scenarios has a probability and consequence and therefore associated with a specific individual risk. This type of IR may be calculated by summarizing all scenarios with a consequence of at least one death as described by Eq. 3.7.

$$IR_l = \sum_i^n p_i \qquad c_i > 0 \qquad \textbf{(Eq. 3.7)}$$

where

IR_l	location specific risk [year^{-1}]
p_i	probability of scenario 'i' occuring [-]
c_i	consequences of scenario 'i' [-]

As individual risk can be represented simply by a single number, there are some downsides with using this measure. For example, the IR is indifferent to how many people that are affected.

In buildings it may be hard to determine boundaries for effect zones. For example, Frantzich (1998) considered a fire being confined to a fire compartment and with this assumption it was possible to assume that the IR is constant within the fire compartment. However, if this assumption is not true, the effect zone may be much larger due to fire spread and the IR may be underestimated.

3.2.2 Societal risk

As mentioned previously, IR does not account for multiple fatalities. However, major accidents with multiple fatalities is of great concern to the society as we tend to be risk averse, i.e. tolerance for large accidents are lower than for smaller ones even if the expected number of fatalities over a period of time is the same (Davidsson et al., 1997). Therefore, risk measures such as IR may not provide sufficient information for decision making.

If the Kaplan and Garrick triplet (see section 3.1.1) is used, the information is sufficient to produce societal risk measures. A simple societal risk measure is *average rate of death (ARD).* This measure is estimated by calculating the product of each scenario frequency and consequence and then summarizing them as per Eq. 3.8.

$$ARD = \sum_i^n p_i \cdot c_i \qquad \textbf{(Eq. 3.8)}$$

The ARD is very similar to the location specific IR measure presented previously, however it accounts for multiple deaths as a consequence.

The FN curve is a commonly used risk measure for presenting societal risk in a more informative manner. The advantage of using a FN curve over a single number measure such as the ARD, is that the society's risk aversion can be taken into account. Kaplan and Garrick (1981) argue that a single number is not enough to "…communicate the idea of risk". By arranging the risk triplet in increasing consequence, a cumulative curve answering the question "How likely is it to be worse than this?" is created (Frantzich, 1998). As the curve describes the probability of exceedance, it can be described by Eq. 3.9 (Jonkman et al., 2003).

$$1 - F_c(x) = P(c > x) = \int_x^\infty f_c(x) \qquad \textbf{(Eq. 3.9)}$$

where $f_c(x)$ is the probability density function for the number of fatalities per year. Since the output from a standard QRA is not commonly a continuous function, it follows that the FN curves is highly dependent on the number of scenarios evaluated in the analysis as each scenario generates a 'step'. The number of steps will determine the 'smoothness' of the risk curve or as Kaplan and Garrick (1981) puts it; "…the staircase function should be regarded as a discrete approximation of a continuous reality".

Frantzich (1998) outlines a method for creating a FN curve from scenario-based QRA presented in Table 3.1.

Table 3.1 Method for creating a FN curve (Frantzich, 1998)

s_i	p_i	c_i	Cumulative p_i
s_1	p_1	c_1	$1 - p_1$
s_2	p_2	c_2	$1 - \sum_1^2 p_i$
-----	-----	-----	------
s_{n-1}	p_{n-1}	c_{n-1}	$1 - \sum_1^{n-1} p_i$
s_n	p_n	c_n	0

As the step function is an approximation of the 'continuous reality', it is necessary to be aware of the errors produced. The consequences included in the analysis is based on the scenarios derived from the events considered and it is uncommon that these 'steps' form a complete series, i.e. $c_i = 1,2,3,..,c_n$. Instead, the magnitudes of the consequences are usually randomly distributed. Lack of information is evident when an analysis fails to estimate the probability in the space between two consequences where at least one discrete step is missing. For example, consider Table 3.1 as the result of a standard QRA. If there are scenarios that fills the criterion

$$c_i - 1 \neq c_{i-1}$$

then there is information lacking. To explain this further, it is obvious that since there is a scenario that generate the consequence c_i, there must surely be a set of circumstances that can produce the consequence

$$c_i - 1$$

since

$c_i - 1 < c_i$

Frantzich (1998) suggest that without a high number of scenarios, the FN curve will underestimate the risk. Lundin (2004) suggests that since it is not always reasonable to evaluate a high number of scenarios, these must be categorized and then represented by a design scenario from each category, cf. clustering in 3.6.

3.3 Acceptable level of risk

Magnusson et al. (1995), Frantzich (1998), Rasbash (2004) all present methods to quantify the risk. However, quantified risk is not very useful unless safety can be verified. In a *comparative* design the prescriptive design is described by the used method and then compared to the alternative solution. Olsson (1999) provides an example for how an event tree based QRA is used to create tolerable risk criteria for hospitals in Sweden. It was based on the assumption that the safety level provided by the prescriptive building codes is considered 'safe'.

However, in more complex designs, where no prescriptive regulations are applicable, there has been a need for *absolute* levels of risk that serves as criteria for acceptance. Most acceptable risk criteria have been developed for various types of hazardous operations (Davidsson et al., 1997). This may for example be chemical industries or ADR transports.

Davidsson et al. (1997) carried out a study on acceptable risks used for different areas of use world-wide which may be found in their report. Risk acceptance criteria may be presented as a single threshold value but a more commonly used approach is to divide it into three different 'zones';

- Unacceptable risks. The contribution of the risk source will under no circumstances be considered acceptable. Risk mitigation is needed.
- As Low As Reasonably Practicable (ALARP). Risk reduction measures are considered in relation to the cost and as such cost-utility analysis is a necessary tool.
- Acceptable risks. Risks are very low and no mitigating actions have to be taken.

These kinds of measures are describing the risks imposed on individuals or society from <u>one</u> source, e.g. chemical plant. Therefore, an individual living in an area with multiple hazardous industries may be exposed to higher risk, even though all the industries not exceeding any of the prescribed acceptable levels of risk.

However, the risk imposed on buildings by hazardous activities and the risk from fires within a building differs considerably. For example when New South Wales Department of Planning (2008) advises on acceptable risk levels for residential areas, the risk is assumed to be external to that area. It can therefore be questioned if the above presented guidelines are applicable for fire risks associated with apartment buildings. For they are rather acceptable levels for the total risk an individual may be exposed to.

Lundin (2004) aimed to investigate if it was possible to determine acceptable criteria for engineered solutions in fire safety designs. He points out the fact that there are no ambitions of increasing the level of safety provided by the Swedish regulations and trying to adopt absolute criteria from other activities (such as the ones previously mentioned) may result in an increased or decreased level of safety. He also suggest that there is no need for absolute fire risk criteria for buildings, effort should be put into creating methods for determining what is sufficient fire safety. Quantitative analysis is a good tool for comparing different designs, but uncertainties in input, construction, etc. makes an absolute level hard to implement.

Even though the community appears to accept the levels of risk imposed on occupants by the building codes, the information of distribution of risk within society remains unknown, i.e. the average level of safety is acceptable, however some constructions may very well expose occupant to unreasonable high risks. This is related to the principle of equal distribution of risk (Davidsson et al., 1997). This principle suggests that risks imposed on society should not vary considerably within the population. However, without any holistic approach to quantify the safety level of the building code, no such information will be shed light on, and the distribution of the risk will remain unknown. While some argue that the methods for quantifying level of safety are not sufficiently accurate due to uncertainties, etc. (Lundin, 2004), these may very well be evaluated in a comparative manner.

3.4 Risk assessment frameworks

In order to bring structure and transparency to a risk analysis, a framework providing a graphical representation of how the different parts of the risk analysis are linked together might be beneficial. This section aims to provide some of the frameworks found in literature.

3.4.1 Risk-cost assessment model

This (see Figure 3.4) framework has its roots in the concepts presented by Beck (1991) and the framework was described first by Beck & Yung (1994). The framework has been implemented in the risk-cost assessment models FiRECAM (see Yung et al. (1999)) and CESARE-Risk (see ABCB (2001)). Since the model also includes a cost assessment model, it contains parts that are not of interest, as this thesis is limited to life loss.

As can be seen in Figure 3.4, the model uses a methodology to evaluate the risk associated with a specific scenario. In essence the model calculates the probability of life loss for each scenario and when all scenarios have been evaluated, an overall Expected Risk to Life (ERL) is estimated (Yung et al., 2002).

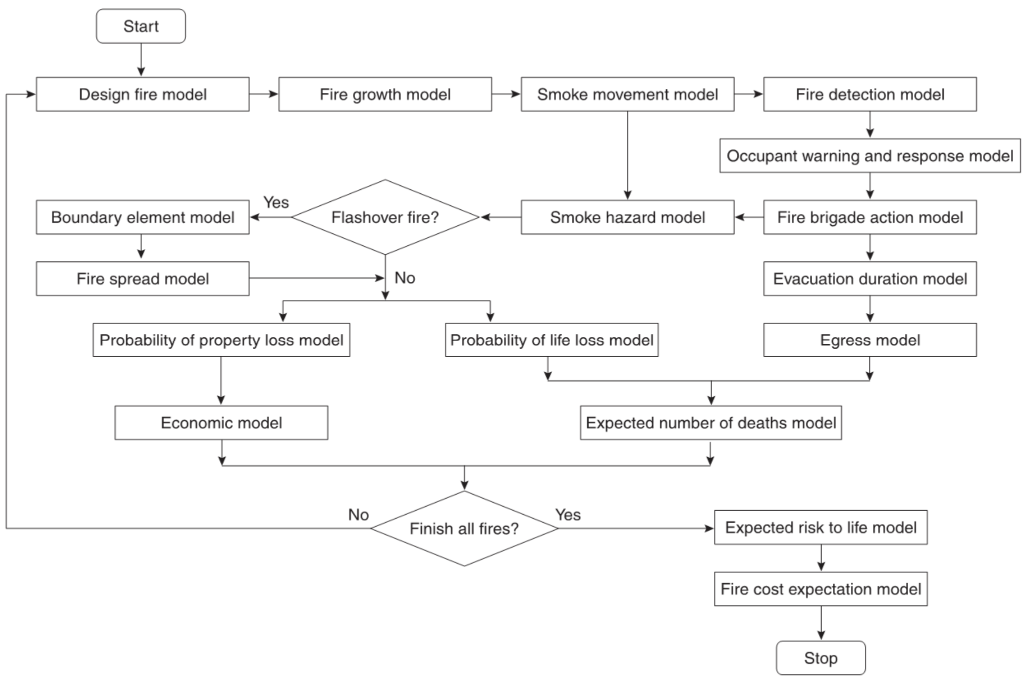

Figure 3.4 Framework for cost-risk assessment (Meacham, 2002)

3.4.2 SFPE Fire Risk Assessment

Society of Fire Protection Engineers (2006) have released an engineering guide for Fire Risk Assessment in which they suggest a process shown in Figure 3.5. As it describes a risk *assessment* methodology, the framework includes certain parts that relate to risk acceptance criteria.

Similar to the cost-risk assessment model presented in the previous section, the scenario methodology is also found in this framework. But instead of evaluating a large number of scenarios, a clustering of scenarios is suggested with one representative scenario for each cluster. Overall, compared to the framework presented in Figure 3.4, it provides less detail regarding for example exact method to determine consequences which, although some guidelines are given, are left to the engineer to decide.

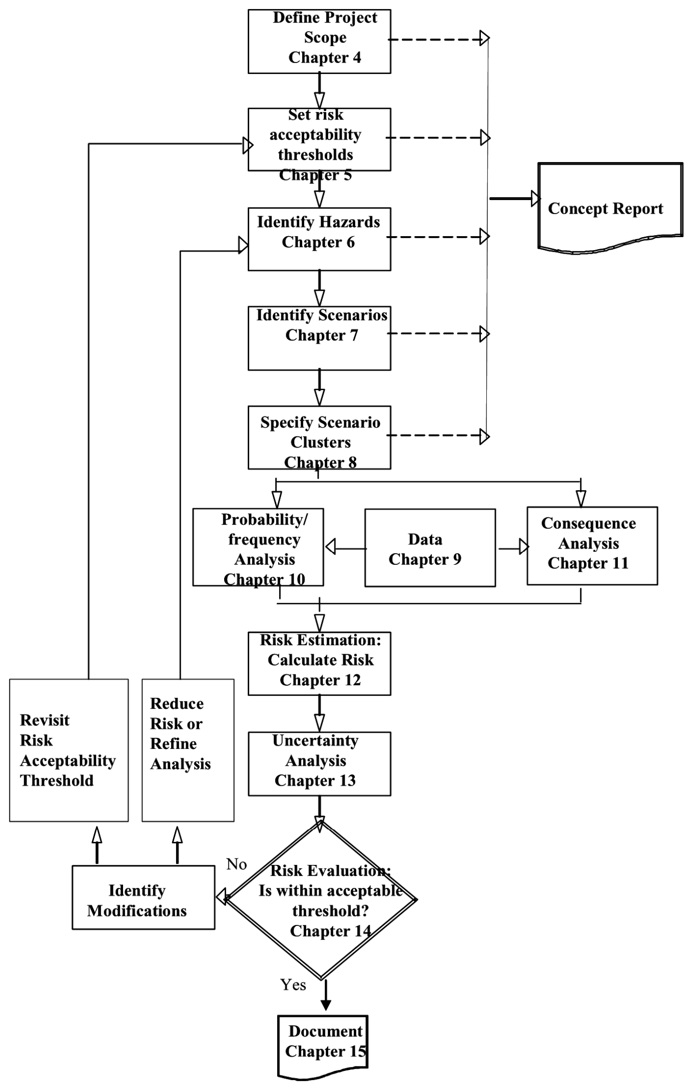

Figure 3.5 Fire Risk Assessment Flow Chart (SFPE, 2006)

3.4.3 U.S fire risk assessment method

Rasbash (2004) describes a fire risk assessment model developed in the United States. The risk is calculated by estimating the probability and consequences for a large number of pre-determined scenarios. The consequence is determined as number of deaths for that scenario and the risk measure is presented as deaths per fire. Focus in this method has been put to how different fire properties (e.g. ignitability, HRR, toxic potency) affects the risk to life of occupants in case of fire. The flow chart for the framework is shown in Figure 3.6.

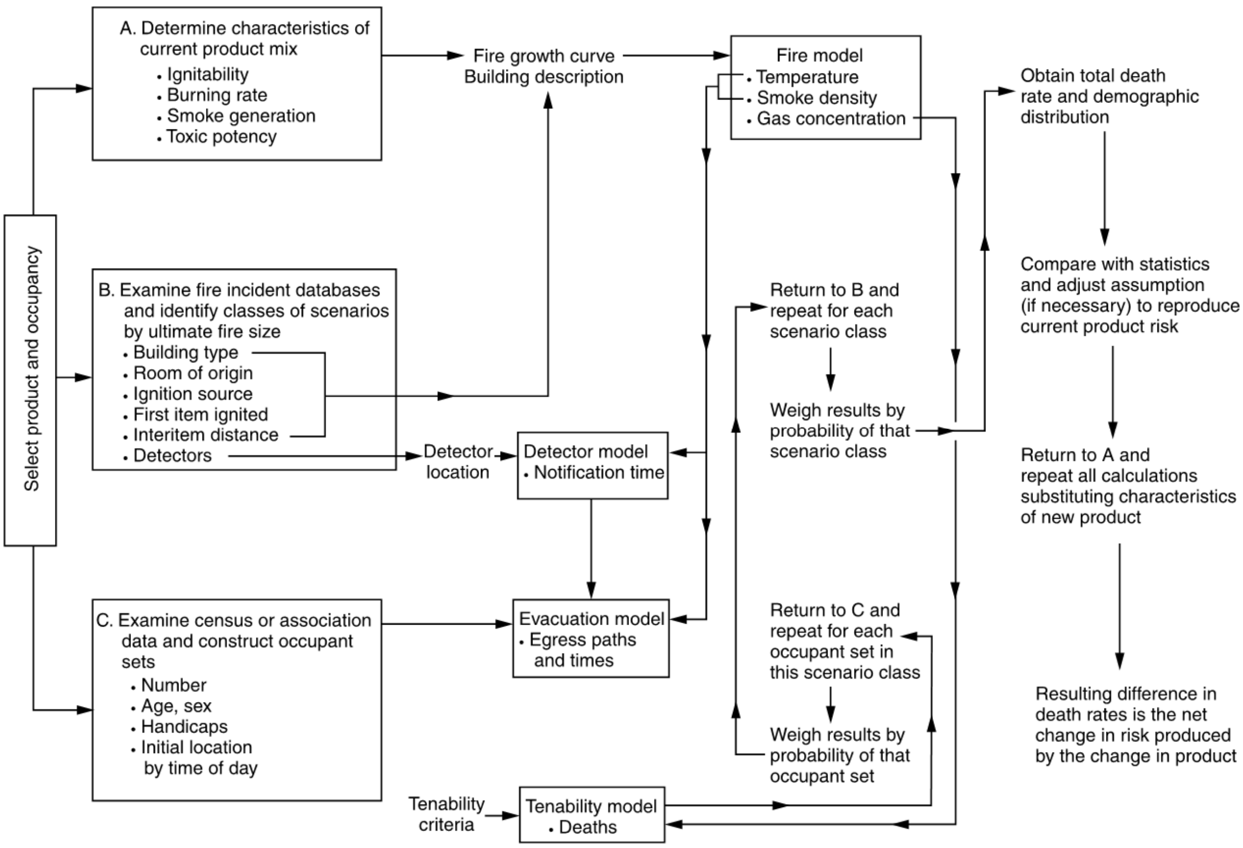

Figure 3.6 Flow chart of U.S risk assessment method (Rasbash, 2004)

3.4.4 Principles of Fire Risk Assessment in Buildings

In his book 'Principles of Fire Risk Assessment in Buildings', Yung (2008) presents both qualitative and quantitative methods to perform fire risk assessments. He also states a preferred 'fundamental' approach.

> *"Fundamental approach involves:*
> *(1) construct the possible fire scenarios that a fire initiation may develop into*
> *(2) the construction for each fire scenario of a sequence of fire events that follow the course of an actual fire development ;and*
> *(3) the mathematical modelling of these fire events to predict the outcome of occupant fatalities and property loss."*

Without detail of the different sub-sections of the approach, he proposes the method seen in Figure 3.7 for assessing risk to life of building occupants.

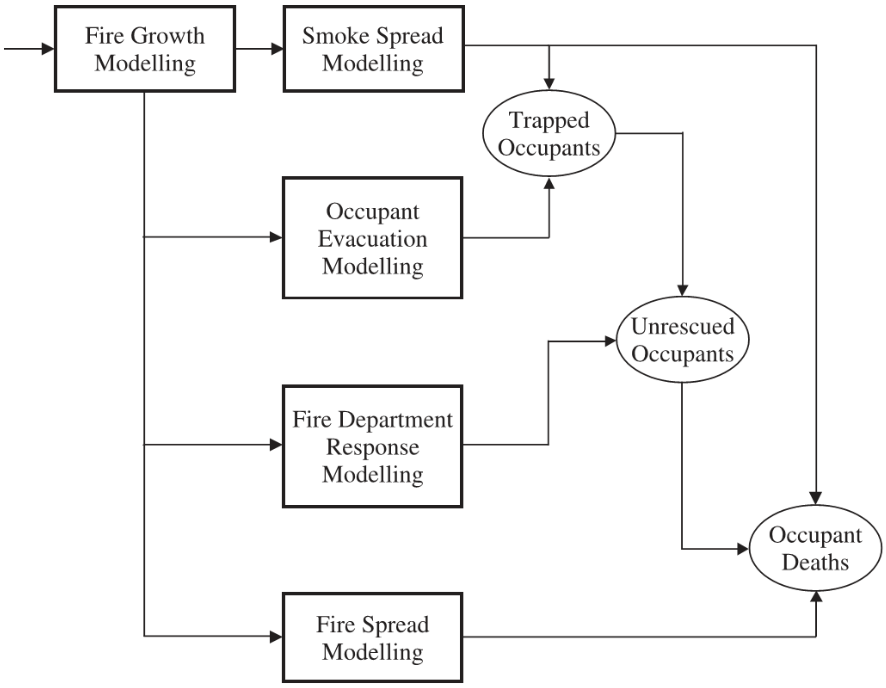

Figure 3.7 Risk to life modelling (Yung, 2008)

3.4.5 Summary

A few different frameworks for quantifying the risk have been presented. Except for the last model for assessing fatalities by Yung (2008), some similarities can be found in the frameworks. All of them use scenario methodology to identify the different possible end states. Some, such as the cost-risk assessment models, use a large number of scenarios whereas the 'SFPE Fire Risk Assessment method' suggest scenario clustering.

The determination of scenarios will seriously affect the calculated risk, since it is to say 'which events or pre-ignition set conditions should represent the universe of combination of events?'. Some guidance is given in these models, for example consideration must be taken to building layout, possible fire locations and ventilation conditions, first item ignited, etc.

To estimate consequences, two main components can be found, the development of the fire and human behaviour. The developments of the fire controls how long time it takes until critical conditions arise, both in the room of fire origin and in external spaces due to fire spread. But also the characteristics and behaviour of occupants will form an important part of estimating the risk. Parts related to fire characteristics and development can be found in sub models such as

- Fire growth
- Fire and smoke spread
- Temperature and toxic gas prediction
- Flashover and barrier failure
- Fire brigade intervention

and models relevant to occupant response and behaviour usually consist of

- Fire detection
- Occupant warning
- Evacuation
- Occupant characteristics (age, sex, mobility status, location, intoxication)

The interaction between humans and fire is a complex process. To make estimations of risk or exposure to critical conditions, tenability criteria is usually adopted to make this translation, e.g. 'which dose of CO will incapacitate an occupant?'. Therefore the models need to have human tenability criteria.

Subject to the reviewed frameworks, sections 3.5 - 3.9 aims to provide background information to relevant parts of the fire risk analysis. Section 3.5 describes how natural fires may be modelled and includes mathematical descriptions of the different stages of the fire judged necessary to include. This is followed by description of methodology to identify and cluster scenarios in section 3.6. Human behaviour and response modelling is described in section 3.7 and methods to estimate fire frequency in buildings in section 3.8. Finally, a method to describe consequences to occupants is presented.

3.5 Design fire

Staffansson (2010) provides a method for creating design fires. It can be said that a typical fire follows the development as shown in Figure 3.8.

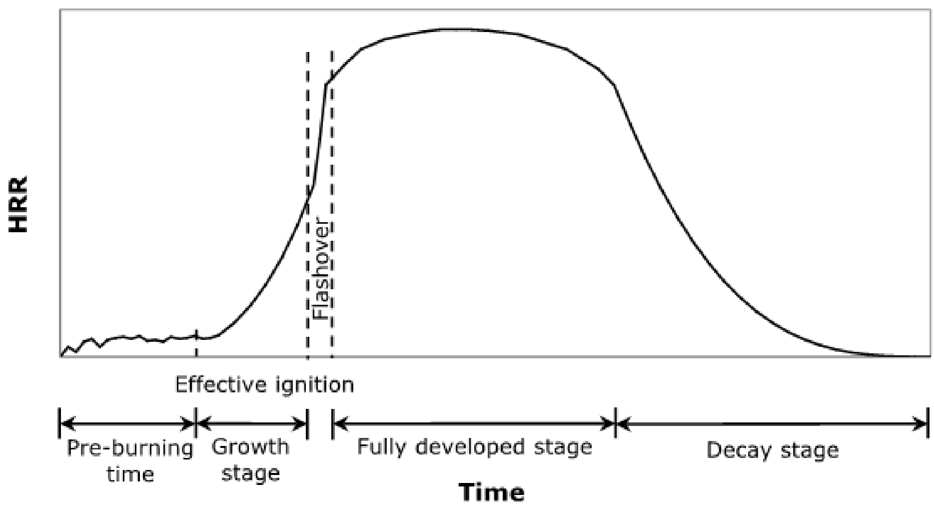

Figure 3.8 Fire development (Staffansson, 2010)

To model a natural fire development, it is suggested to use a curve similar to Figure 3.9.

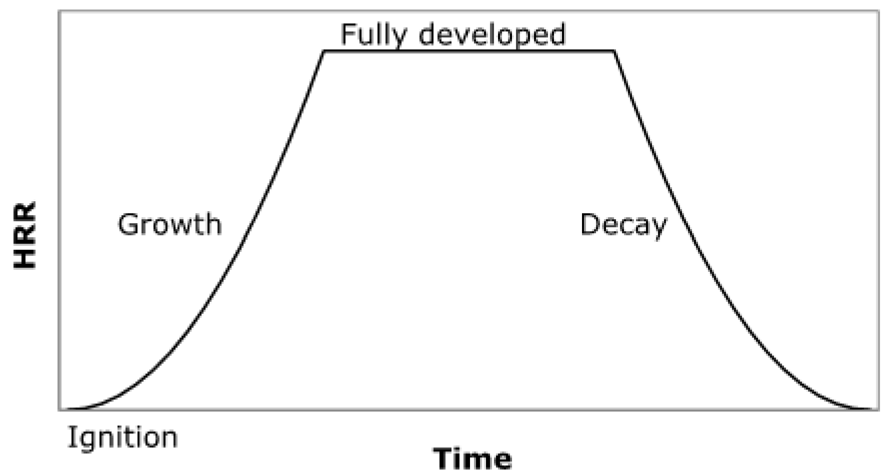

Figure 3.9 Design Fire (Staffansson, 2010)

To create a design fire, it requires modelling of

- The growth phase
- Fully developed or controlled phase
- Decay phase

3.5.1 Fire growth

Fire growth is one of the most important variables in fire hazard calculations. However, it is also one of the most difficult to give a realistic representation due to the random behaviour of a fire. For example, in a typical apartment there are multiple sources of ignition and hence multiple starting locations of a fire. Generally a distinction is made between flaming and smouldering fires for which production of heat and toxic yields will vary significantly.

3.5.1.1 Smouldering fires

Not only by lacking flames, smouldering fire distinguish themselves from flaming fires by the amount of heat and production of species. As the generated heat is significantly lower, it is not likely that the smouldering fire will pose any threat by generation of heat. Instead, a slow release of toxic species may undergo a long time due to smoke detectors/alarms which may create an toxic atmosphere in the surroundings.

Staffansson (2010) provides an expression to calculate the mass loss rate of a smouldering fire,

$$\dot{m}_s = \begin{cases} 0.1t + 0.0185t^2 & 0 < t < 60 \\ 73 & 60 < t < 120 \end{cases} \qquad \textbf{(Eq. 3.10)}$$

where

$\dot{m}_s$	mass loss rate of fuel [g/min]
t	time [min]

Together with yield of toxic species, a toxicity assessment can be made for smouldering fires.

3.5.1.2 Flaming fires

A widely used and commonly accepted representation of a fire's heat release rate (HRR) is the 't-squared fire' (Karlsson & Quintiere, 2000).

$$\dot{Q} = \alpha \cdot t^2 \qquad \textbf{(Eq. 3.11)}$$

Where

$\dot{Q}$	heat release rate [kW]
α	fire growth rate [kW/s²]
t	time [s]

The t-squared fire has been shown to give a good representation of a fire after the incipient stages and before flashover (see Figure 3.8), after which the t-squared fire is no longer valid. To give an example on this, consider a typical apartment. Common characteristics are high fuel load density and relatively small openings. Hence, it is likely that the fire at some stage will become ventilation controlled. The t-squared fire does not take any of these effects into account.

Deterministic modelling

In reality, many factors will govern the complex process behind the produced heat release rate. At the same time, assuming fire growth constitutes a crucial part of fire engineering assessments.

In the classic deterministic approach, it is therefore necessary to ensure that the fire growth rate is not underestimated. Table 3.2 shows common categories used when assessing burning items against certain growth rates. Karlsson & Quintiere (2000) suggest a medium t-squared growth rate for dwellings.

Table 3.2 Fire growth rates parameters for t-squared fires (Karlsson & Quintiere, 2000)

Growth rate	α [kW/s²]
Slow	0.003
Medium	0.012
Fast	0.047
Ultra fast	0.19

Experiments have provided fire growth rates for different materials and objects, for example see Custer et al (2008), or more detailed HRR curves as can be found in Särdqvist (1993). This in combination with fire brigade intervention reports that record statistics of first item ignited may be used to assign probabilities to different fire growth rates based on the available data from individual experiments. Also the upper percentile of the fire growth rates presented by Holborn et al. (2004) (see below) may be a good representation of deterministic values. This information is found in Table 3.3.

Stochastic modelling

Another aspect that should be noted is that the t-squared fire is usually used to represent the first item ignited. A more realistic representation of a fire in, for example an apartment, is to assume that more items will be involved in the fire. It has been suggested that a more natural representation of fires should contain several fire growth curves (Holborn et al, 2004).

Holborn et al. (2004) used the t-squared fire when approximating the fire growth for different premises and therefore investigating a more holistic approach to enclosure fire growth. The data collected were also fires with significance, e.g. fires with casualties, large in size or suspicious circumstances for instance. The (average) fire growth parameter was estimated by comparing the fire size on time of discovery and on fire brigade arrival. With the time interval given and knowledge of the fire sizes, the average fire growth rate can be calculated with Eq. 3.12.

$$\alpha = \frac{\dot{Q}''(A_1 t_1^2 + A_2 t_2^2)}{t_1^4 + t_2^4} \qquad \textbf{(Eq. 3.12)}$$

where

$\dot{Q}''$	heat release rate per unit area [kW/m²]
$A_{1,2}$	fire area at time t_1 and t_2 respectively [m²]

The fire growth parameter is dependent on the HRR per unit area. For residential premises Holborn et al (2004) assumed this value was 250 kW/m². Their results showed that fire damage size and fire growth rates can be approximated reasonably well with a log-normal distribution. Eq. 3.13 - Eq. 3.15 can be used to approximate the fire growth rate.

$$\Gamma = \ln(\alpha) \in N(\mu, \sigma) \qquad \textbf{(Eq. 3.13)}$$

$$E(\Gamma) = \exp\left(\mu + \frac{\sigma^2}{2}\right) \qquad \textbf{(Eq. 3.14)}$$

$$Var(\Gamma) = \left(\exp(\sigma^2) - 1\right)\exp(2\mu + \sigma^2) \qquad \textbf{(Eq. 3.15)}$$

where

$N(\mu, \sigma)$	normal distribution with mean μ and standard deviation σ
$E(\Gamma)$	expected value of Γ
$Var(\Gamma)$	variance of Γ

They plotted the data against the log-normal curve and examined the goodness of fit. Deviations were found in the distribution tails which indicated that very small growth rates occur more frequently than predicted by the log-normal curve and large fire growth rates are over estimated. The results for fitting the data for residential premises to log-normal curves is shown in Table 3.3. *n* denotes the sample size.

Table 3.3 Log-normal fire growth parameters (Holborn et al., 2004)

Fire growth parameter, α	n	μ_α	σ_α	$E(\alpha)$	$\alpha_{0.95}$
All dwelling fires	481	-7.00	1.98	0.006	0.024

Andersson & Wadensten (2002) used statistics on first item ignited provided by Swedish Rescue Service Agency to create categories of items. For these categories a study on different available data on growth rates made it possible to estimate a mean value along with a min-max interval.

Table 3.4 Fire growth rates for different items (Andersson & Wadensten, 2002)

Category	Item(s)	α_{mean}	$min \leq \alpha \leq max$
A	Interiors	0.030	0.01 – 0.06
B	Sauna heater, TV, HiFi, fan/vent installations, transformer	0.027	0.01 – 0.04
C	Flue, fire place, tumbler, cabinet drier	0.037	0.01 – 0.1
D	Dish washer, coffee percolator, stove, refrigerator, washing machine, iron, light bulb	-[1]	-[1]
E	Trash container	0.052	0.02 – 0.1
F	Car, other vehicles, train	0.050	0.01 – 0.1
G	Explosives, flammable liquids and vapours	0.19 [2]	-
H	Heating installation, other electric installations	0.0030	0.001 – 0.005

[1] Items in category contain very little combustible materials and very low fire growth rate
[2] Approximation, equals ultra fast fire growth rate (see Table 3.2)

Höglander & Sundström (1998) used CBUF (Combustion Behaviour of Upholstered Furniture) data in a statistical approach to give a representation of peak HRR and time to peak HRR for single burning items. They included a safety factor for use in design calculations. An adjusted correlation without safety factors was derived by Nystedt (2003) and is shown in Eq. 3.16.

$$\dot{Q} = a \cdot \exp(-0.4(t-b)^2) \qquad \textbf{(Eq. 3.16)}$$

The parameters *a* and *b* are normally distributed according to Table 3.5.

Table 3.5 Parameters according to adjusted correlation by Nystedt (2003)

Parameter	Description	μ	σ
a	Peak HRR [kW]	1278	719
b	Time to peak HRR [s]	339	278

3.6 Scenario identification

As it is impossible to incorporate the universe of possible outcomes of fires, one or multiple scenarios are usually used to describe time sequenced events following ignition. Yung (2008) defines a fire scenario as

> *"A fire scenario is a sequential set of fire events that are linked together by the success or failure of certain fire protection measures"*

This definition suggests that there are certain events that will be determined by the reliability of safety measures such as fire barriers, sprinklers, fire alarms, etc. Society of Fire Protection Engineers (2006) expands this definition to

> *"A fire scenario is a qualitative, time-sequence-based description of a fire, identifying key events that characterize the fire and differentiate it from other possible fires. A fire scenario is therefore a fire incident characterized as a sequence of events."*

In their definition, the events are not only linked to fire safety measures. For example, in residential buildings, "Occupants present?" is an event that will affect the range of possible outcomes of the fire but is not characterised by any fire safety measures. Therefore, the scenario methodology relies on the designer to identify the important variables describing the system.

Scenarios are developed based on the identified hazards (SFPE, 2006). Since this thesis only considers life loss, only the hazards that may be realized as life loss should be considered, i.e. it is not of interest to consider fires not posing a threat to life. Given that hazards have been identified, SPFE (2006) provides guidance on how to identify important events and thus construct scenarios by answering the following questions:

- *(a)* *What are the initial heat source, initial fuel source, and point of fire origin, including proximity to potential secondary fuel packages? Include the possibility that there are multiple points of origin involving multiple fuel sources and possibly multiple heat sources.*
- *(b)* *Based on (a), is there a smoldering phase? Include the duration of this phase, and include duration for each successive phase as well.*
- *(c)* *Based on (a) and (b), is there a small open flaming phase, in which the first fuel source is the only object burning?*
- *(d)* *Does the fire spread to secondary objects or, where applicable, is there considerable flame spread over the surface (e.g., along a wall or over the top of a couch)?*
- *(e)* *Does the fire reach flashover and/or full involvement of the first compartment or enclosed space (e.g., passenger cabin of an airplane)?*
- *(f)* *Does the fire spread to a second room, compartment or space (e.g., concealed space, exterior)?*
- *(g)* *Does the fire spread to a second floor or level (e.g., upper deck of a bus)?*
- *(h)* *Does the fire spread beyond the building, structure, vehicle or other object of origin?*
- *(i)* *Does the fire decay at the end or is it actively extinguished?*
- *(j)* *What are the statuses of all relevant passive fire protection features and active fire protective systems? This will in part reflect maintenance, inspection, and enforcement or the lack thereof. At any point, is there a complete or partial failure of a feature or system? The performance of features and systems is not normally part of the scenario specification but is calculated.*
- *(k)* *Apart from fire effects, will the initial conditions change during the course of the fire (e.g., wind direction and speed)?*
- *(l)* *What other events (e.g., human behavior such as evacuating or firefighting) occur that affect either the course of the fire or the exposure of people to fire effects? If there are any behavioral events, what are the states of knowledge, skills, attitude, belief, vulnerability, and location of the occupants and other relevant individuals when fire*

begins? Knowledge, skills, attitudes, and beliefs will reflect training and the larger safety culture or the lack thereof.

(m) What are the fire outcomes (e.g., who and what are exposed to fire and what is the severity of the harm)?

Yung (2008) suggests that scenarios are to be constructed by evaluating events around different aspects of the system. These aspects are

- Fire initiation scenarios
- Fire growth scenarios
- Smoke spread scenarios
- Occupant evacuation scenarios
- Fire Department Response scenarios

It is likely that following guidance given in the above references will result in identification of a large number of scenarios. Evaluation of all these might be an unmanageable task and therefore it is necessary to find representative scenarios. SFPE (2006) denotes this process scenario clustering, which allow for scenarios with similar characteristics to be grouped. The group is then represented by a single scenario but with the joint probability of all the scenarios within the group. As an example of this, they write

> *"As an example of the difference between scenarios and scenario clusters in level of detail, a scenario might be specified with an initial heat source of a match and a point of origin as the top of a cushion on an upholstered chair against an outside wall of a living room. A scenario cluster might be specified as any initial heat source that is a small open flame and any point of origin in a normally occupied room."*

The representative scenario must be chosen being aware of some of the fallacies associated with this. The most difficult scenarios involve high-consequence as these will have a large effect on the calculated risk. If these are included in a cluster with much lower consequence for the other scenarios, the effect is likely to be underestimated. However, an attempt to cluster scenarios with high-consequence may lead to a joint very low probability, hence suggesting that it is negligible, biasing the result (SFPE, 2006)

3.7 Human behaviour and response

In the case of a fire, human response and behaviour will play an important part in assessing the risk. The total time for an occupant to escape from a building to a safe place is usually denoted as time for successful escape, t_{esc}. However, the escape time is commonly divided into three different phases of egress; detection and alarm time, time for response and reaction, and travel time, see Figure 3.10.

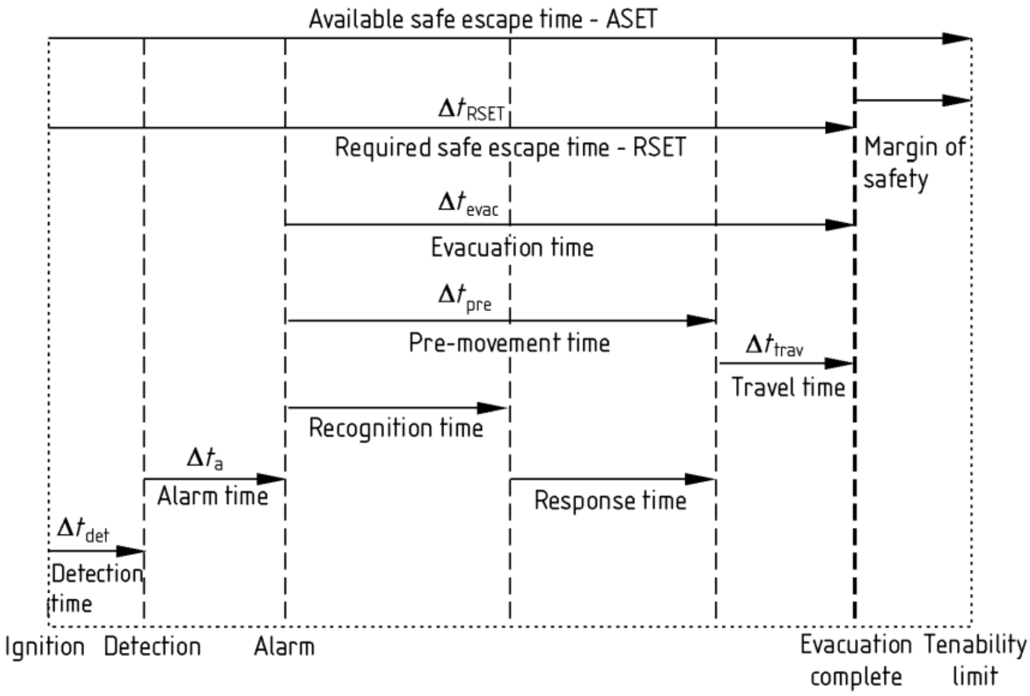

Figure 3.10 Schematic of escape time (BSI, 2004)

Detection and Alarm timeDetection and alarm time refers to the time until the occupant(s) receives information of the fire hazard. Literature suggests that there are two main ways for occupants being informed, either directly by fire cues or by an alarm or warning system.

3.7.1.1 Fire cues

A fire will result in increased amounts of heat and also combustion products being spread in the vicinity of the fire. From a human response perspective, the transient process will lead to an increased probability of occupants becoming aware of the fire hazard. Cues that notify occupants of fire hazard are heat, smoke and flames (Hadjisophocleous & Proulx, 1994). No research on criteria for thresholds where occupants become aware of the fire has been found.

3.7.1.2 Fire detection by fire safety systems

Residential smoke alarms, automatic smoke detection systems connected to a fire alarm or sprinkler systems interconnected with an occupant warning system provide occupants with a warning system of fire hazards. Activation of these systems can be estimated with hand calculations or computer software.

Pre-movement timeWhen an occupant has been notified by the fire hazard, either by alarm or fire cue, there will be a period of time in which the occupant is assessing the information at hand which (hopefully) finally leads to taking action (evacuating). Generally pre-movement can be divided into recognition and response time. Recognition time is the time for an occupant exposed to fire cues to process information and become aware of them. Response time is the delay between becoming aware of the fire hazard and starting to escape.

3.7.1.3 Recognition time

If the occupant is able to see the fire, it is evident that there is a fire hazard, which usually also significantly increases the willingness to evacuate. Frantzich (2001) suggests that the detection and alarm time in this case will be very short, given that people are awake and aware.

To adequately model cue recognition becomes important in apartment buildings, especially in the room or apartment of fire origin. Beck et al. (2006) provide a model for the apartment of fire origin (AFO) which can be seen in Figure 3.11.

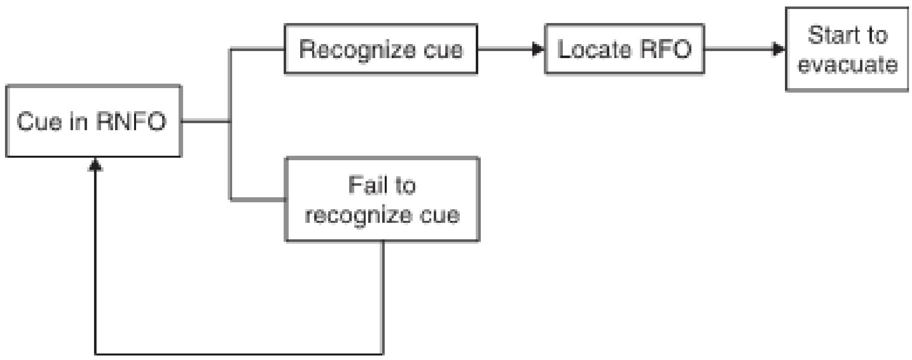

Figure 3.11 Response in AFO (Beck et al., 2006)

The model is fairly simple and straightforward; either the occupant fails to recognize the cue or the recognition leads to an investigation of the fire source and then evacuation. A similar model is explained in Hadjisophocleous & Proulx (1994).

Cue recognition probabilities are significantly affected by the occupant awareness status, for example if the occupant is either sleeping or awake. Beck et al. (2006) supports the theory that cue recognition is less likely in a sleeping state. In Hadjisophocleous & Proulx (1994), different fire cues are associated with different levels of certainty, which is linked to the response time following cue recognition.

3.7.1.4 Response time

The literature study concluded that there is a lack of information regarding response times for occupants in the apartment of fire origin for residential fires. Most studies are aimed at entire buildings and thus mostly apartments which are notified by external alarm signals. A brief description of some studies on overall response times are given here.

Brennan (1997) analysed the times between receiving the first cue and starting to evacuate after a residential fire in an 18 storey apartment building. The occupants were a mix of both permanent and temporary residents. Of the occupants interviewed after the fire, 66% were permanent residents. The data provided has been compiled in Table 3.6. Unreliable contributions of data have been left out.

Fahy & Proulx (2001) published a document intended to summarize (for the time) current knowledge regarding pre-movement time (i.e. recognition plus response time). Among the sources of information, the previously referred reports by Brennan (1997) and Fahy & Proulx (1997) is included. The summarized information for residential buildings is presented in Table 3.7.

Table 3.6 Delay time until start of evacuation after receiving fire cue. (data from Brennan (1997))

Time to start evacuation after receiving cue [min]	Cumulative frequency	Cumulative %
0	0	0
1	2	9
2	5	22
3	6	26
8	9	39
10	11	48
12	12	52
13	13	57
14	15	65
15	16	70
16	19	83
20+ [1]	23	100

[1] Includes occupancies were no evacuation was performed.

Table 3.7 Extracts of pre-movement times from Fahy & Proulx (2001). Time in minutes.

Building type	N	Min	1st Q	Median	3rd Q	Max	Mean	Comment
High-rise	219	0	N/A	187.8	N/A	720	190.8	Real fire,
High-rise	33	0.3	0.8	1.3	4.4	10.2	2.8	Drill, good alarm performance
High-rise	93	0.4	1.5	3.6	6.9	18.6	5.3	Drill, good alarm performance, winter
High-rise	27	1.0	2.0	8.0	14.0	>20	N/A	Real fire, less than half of occupants evacuated
Mid-rise	42	0.6	1.0	1.4	3.0	>14	2.5	Drill, good alarm performance
Mid-rise	55	>0.5	1.6	4.4	13.5	>21	8.4	Drill, poor alarm performance
Mid-rise	77	>0.3	1.2	2.5	3.7	>12	3.1	Drill, good alarm performance

Fahy & Proulx (1997) noted that factors such as time of the year and the audibility of the alarm system affected the pre-movement time. In the case where evacuation drills were performed in winter, these had an average of 2.5 minutes longer pre-movement time. The difference of poor and good alarm audibility in the same study showed that the poor system increased the average pre-movement time by approximately 5.5 minutes. Proulx (1995) found that for three of the four evacuation drills, around a quarter (17-25%) of the occupants were unable to hear the fire alarm.

Travel timeGiven that no queuing is likely to occur, the time for an occupant to travel from a place within the building to a 'safe place' is theoretically determined by the distance to the 'safe place' and the speed at which it can be assumed that the occupant travel with. An estimate of the travel time is given by Eq. 3.17.

$$t_{esc} = \frac{d_{esc}}{v_{esc}} \qquad \textbf{(Eq. 3.17)}$$

where

t_{esc}	the time from taking action until reaching a 'safe place' [s]
d_{esc}	distance from location to 'safe place' [m]
v_{esc}	walking speed of the occupant [m/s]

Eq. 3.17 is a theoretical estimate of the travel time for a best case scenario as other factors may increase the travel time such as complexity, way finding, etc. For example, in buildings where the occupant is not very familiar with the environment, way finding may have a significant effect on the travel time. As this thesis is focused on apartment buildings, it may be assumed that the occupants have good knowledge about the building layout. Another factor for which the real escape time may deviate from the theoretical one is alternative paths. In a building with more than one stair for example, occupants may try to escape through one stair in which they encounter smoke and have to turn back. Naturally, this will affect the escape time significantly and involve large difficulties to estimate.

3.8 Fire frequency

In order to be able to estimate absolute quantitative risk, a credible estimate of fire frequency in the analysed building must be included. With the event tree technique it is then possible to derive the frequency of every scenario. There are a few methods for quantifying the fire frequency in apartment buildings.

A very simple estimate is given by BSI (2003) where the fire frequency for a dwelling (not considering the area) is estimated to be $3 \cdot 10^{-3}$ per year. Statistical databases can be used to compare the number of fires reported with the number of dwellings, as can be seen in Nystedt (2003). Note that the term 'reported' is important, as Nystedt (2003) found that a large number of fires that never get reported to the fire brigades. A distinction can therefore be made. Either the approach is to estimate the number of fires, disregarding the severity of the fire initially and include this factor as an event in the event tree. The other approach is to estimate the frequency of fires that actually grows into large fires.

There has been a long history on theories regarding ignition frequency and in the 1960-70's the first estimates for correlating the fire occurrence frequency with floor area and type of occupancy was presented (Keski-Rahkonen & Rahikainen, 2004). This theory has been proven somewhat successful as more studies with similar types of mathematical expressions followed.

Area-dependant estimateJohansson (1999) presents Rutstein's model for estimating the fire frequency in a building according to type of activity and total floor area. British statistics were used to derive the power law correlations as described by Eq. 3.18.

$$\lambda_R = a \cdot A_F{}^b \qquad \textbf{(Eq. 3.18)}$$

where

λ_R	fire frequency [year^{-1}]
A_F	building floor area [m^2]
a, b	occupancy type specific constants[-]

Johansson (1999) also mentions that as this correlation was derived from fairly old British statistics, it should be used with care due to changing conditions with time. He also mentions that these are based on reported fires to the Fire Brigade.

Comprehensive studies on ignition frequency have been carried out at the VTT University in Helsinki, Finland. These are based on fire statistics collected in the accident database Pronto. Only fires reported to the fire brigade are inserted into the database and therefore the distinction previously mentioned done by Nystedt (2003) has to be kept in mind. These figures represent fires that actually grow into significant fires.

Keski-Rahkonen & Rahikainen (2004) used Pronto data to fit a mathematical model. They found that a model previously suggested by Barrios using two power law functions resulted in a good fit. For residential buildings, the correlation quite accurately described the data for buildings up to 100 m^2 but underestimated the ignition frequency for larger buildings. The generalized Barrios model can be expressed as

$$\lambda_B = c_1 \cdot A_F{}^r + c_2 \cdot A_F{}^s \qquad \textbf{(Eq. 3.19)}$$

where

λ_B	fire frequency [year^{-1}]
A_F	building floor area [m^2]
c_1, c_2, r, s	empirically derived constants [-]

Tillander (2004) summarized derived parameters for the Barrios model fitted to the Pronto data, the parameters for residential buildings are shown in Table 3.8. The coefficient of determination was 0.84, suggesting a reasonably good representation of the data.

Table 3.8 Barrios generalized model parameters (Tillander, 2004)

Building type	c_1	c_2	r	s
Residential	0.010	5 x 10^{-6}	-1.83	-0.05

Although with earlier publishing date, Keski-Rahkonen & Tillander (2003) presented an article which aimed to aid previous study by Keski-Rahkonen & Rahikainen (2004). By closely examining the deviations from the Barrios model, it was found that a better representation could be achieved by describing ignition frequency with an expression consisting of two log-normal functions and one Pareto distribution. Unfortunately, the information given in the above references were not sufficient to describe the usage of the mathematical model.

Fontana et al. (1999) used insurance statistics to make estimations of fire loss, frequencies, etc. from a database collecting all of the fire loss claims in the Canton of Berne (Switzerland) during 1986-1995. Nearly 40 000 fires were collected during this period. For dwellings the overall fire occurrence was $33.3 \cdot 10^{-6}$ /m^2 $\cdot$ year. When comparing the insurance statistics with the fire brigade statistics they concluded that the only 40% of the fires reported to the insurance company was also attended by the fire brigade.

3.9 Consequences

Fire deaths in dwellingsBuilding fire safety measures appeal to different aspects of safety. However, consulting statistics will reveal that most fire related casualties occur during the early stages of a fire and the victims are usually found within the room or apartment of fire origin. It is very rare that structural collapse results in deaths (Rasbash, 2004; Bengtson et al, 2005). The main reason for this is that structures are designed to withstand fires longer than what is required for evacuation or fire brigade intervention.

Dwelling fires contribute to the major part of fire related deaths. Nystedt (2003) concludes that in Sweden, 90 % of the fire related deaths occur in dwellings. Other characteristics for dwelling fires are that it is not common to have more than one death per lethal fire and fatalities are usually intimately related to the fire (Nystedt, 2003). Multiple deaths are usually a consequence of the fire or smoke compartmentation being penetrated, for example a door being left open. Rasbash (2004) gives a summary of location of casualties for British statistics between 1978 – 1991 shown in Table 3.9.

Table 3.9 Location of casualties (from Rasbash (2004))

Location	Sole occupancy	Multiple occupancies
Room of fire origin	0.582	0.668
Elsewhere on floor of origin	0.20	0.234
Floors above the floor of fire origin	0.208	0.094
Floors below the floor of fire origin	0.004	0.028
Total	1.0	1.0

Another interesting conclusion drawn by Nystedt (2003) is that a certain percentage of the fire related deaths may not be able to be reduced by increased fire safety measures. The reason for this is that they are very intimately related to the fire.

Lethal conditionsLethal conditions in fires is the result of a transient process where fire products, such as heat and toxins, increases the lethal potency of the fire environment. Three key stages of the fire can be identified for toxicity assessment of occupants (Brennan & Thomas, 2001; Purser., 2002);

- Growth phase. Fire is growing and not yet affecting occupants. Detection, perception and interpretation of information, and behaviour are important factors during this stage.
- Exposure. Victim is exposed to smoke, heat and toxic products. Escape capability may be affected by smoke and heat. Pre-fatality incapacitation may also occur.
- Death. Intoxication and burns are the most common factors for death in fires.

Ultimately, it is of interest to assess how the combustion products affect an escaping occupant and when incapacitation occurs (Purser, 2002). An incapacitated occupant who does not receive assistance or help will become a fatality as the dose increases.

3.9.1 Modelling incapacitation and death

There are many complex mechanisms interacting when a human is exposed to smoke and toxic products, however the two most important variables are concentration *(C)* and exposure time *(t_{exp})*. The product of concentration and time is denoted dose *(W)*.

$$W = C \cdot t_{\exp}$$ **(Eq. 3.20)**

In reality, more factors than these two will affect the outcome of the exposure, such as respiratory minute volume (i.e. breathing rate) and particle sizes. For example, the lethal dose is usually higher for longer exposure to lower concentrations compared to short exposure of higher concentrations. However, it can be assumed that the lethal dose is constant as a crude estimate.

Traditionally, when determining doses (incapacitating, lethal, etc.) these are made conservative for two reasons,

(a) uncertainties in predictability of exact dose-response relationship

(b) uncertainties due to demographic differences (age, sex, physiology, etc.)

In reality these uncertainties would lead to a variation of tolerance levels and therefore a more correct representation would be a probability distribution of dose-response relationships. This is clearly shown for Carbon Monoxide (CO) in Figure 3.12.

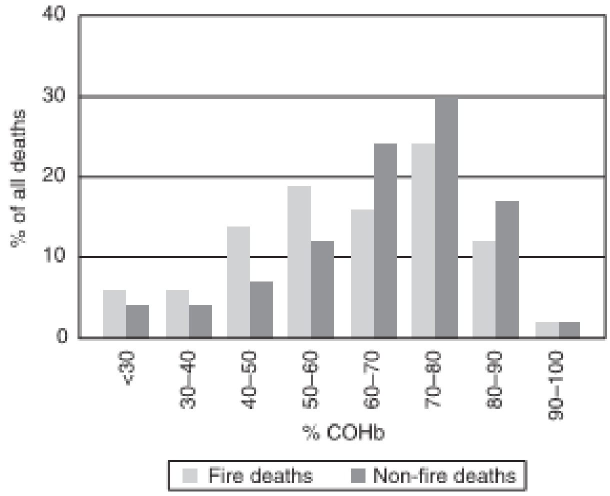

Figure 3.12 Lethality sensitivity to carbon monoxide (Purser, 2002)

Also notable in Figure 3.12 is the difference in levels of CO in the blood for fire related deaths and other reasons where CO was the only source of death. Fire related deaths generally are correlated to lower levels of CO, and thus indicating that CO is not the only contributor to incapacitation/death.

A commonly used method for assessing effects from different hazards is the so-called Fractional Effective Dose (FED). It may be used for estimating the incapacitation or lethality from exposure to one or several toxic gases and heat exposure (Purser, 2002). The FED is estimated as described by Eq. 3.21.

$$FED = \int_{t_0}^{t} \frac{C_i(t)}{W_i} dt$$ **(Eq. 3.21)**

where

C_i	is the concentration of 'i'
W_i	is the dose required to achieve the sought effect (e.g. death)
i	factor causing effect (e.g. toxic substance or heat)

Incapacitation and death occur at different doses which have been estimated for different toxic substances and/or heat. When a dose for incapacitation is used, this is called *Fractional Incapacitating Dose (FID)* and similarly *Fractional Lethal Dose (FLD)* describes when lethal doses are used. Time of predicted effect occur when the FED equals 1.

The model can also take into account for effects of multiple factors. An occupant exposed to hazardous fire environment is likely to be exposed to multiple sources of harm, for example heat and carbon monoxide (CO). In an assessment, FED can be calculated for both heat and carbon monoxide and the sum will predict when incapacitation or death occurs.

$$FED = \sum_i FED_i \qquad \textbf{(Eq. 3.22)}$$

Death is predicted to occur at 2 – 3 times the dose required for incapacitation (Purser, 2008). However, incapacitation leads to an occupant becoming immobile and if this happens in a toxic environment this increases the risk for the occupant becoming a fatality. This leads to further uncertainty regarding lethal doses required for death.

3.9.1.1 Generation of toxic species in fires

In order to predict when lethal conditions occur at different locations within the building, it is necessary predict the concentration of toxic gases (e.g. CO) which serves as input for the model.

The yield of toxic gases will depend on the type of fire (smouldering, flaming, flashover), material(s) burning, ventilation conditions, etc. Compartment fires usually occur in relatively small spaces and due to the limited number of vents and openings, it is likely to become ventilation controlled (Purser, 2000).

3.10 Previous studies on quantifications of life safety

Kristiánsson (1997) used a safety index method described in Magnusson et al. (1995) to investigate the level of life safety achieved by the Icelandic prescriptive building code. Among the analysed buildings were a dance hall, a sporting hall and a hotel. The reliability index ß method presents the quantified risk as a failure probability. Since the equations are derived from so-called critical conditions, the failure probability equals the probability of one or more occupants being exposed to critical conditions. From a risk to life point of view this is a conservative approach. Key findings in the report were that the Icelandic prescriptive building regulations contain a large span of risk depending on type of building, fire growth rate plays an important role in scenarios with absence of sprinklers and alarms, and risk is decreasing with increasing floor and height of the building. It should be noted that there are many assumptions associated with this quantification of the risk that is not presented explicitly to the reader. For example, sprinklers are assumed to activate at a specific time (which in reality is subject to stochastic variability and uncertainty) and after that reduce the HRR to 10% of the effect at activation time. As mentioned by the author these assumptions must be questioned and the calculated risk should be used in a more comparative manner until more reliable input is available.

Nystedt et al. (2002) explored an event tree method combined with standard QRA methodology in an attempt to quantify the safety achieved by the Danish prescriptive regulations. Denmark introduced performance-based codes in 1998 with two guidelines to assist in designing, one Deemed-to-Satisfy and one for alternative solutions. The latter lead to the formulation of a hypothesis that the prescriptive regulations could be quantified in order to create acceptance criteria for risk-based designs. To represent the span of buildings they analysed a hotel, two types of elderly homes, a school and an office building. In the process they acknowledged the problem of effort versus accuracy in assessing risk with QRA methods, i.e. the calculated risk is only as good as the number of scenarios evaluated. In their case by using a standard QRA method, scenarios are the only source of variation and no consideration is taken to the stochastic nature of many of the parameters describing a fire scenario.

With the results from their study they argue that the methodology lacks of reliability. In addition to their risk profile they present variation in input data representing, according to them, a thousand engineers performing the same risk analysis. However, this is more an indirect method of assessing uncertainties in the methodology as outlined as an extended QRA in Frantzich (1998). It is important to realize that a risk analysis will describe a degree of credibility according to our current knowledge and available data, not reality. Of interest would be the information regarding the number of events considered in their assessment. The information given in the paper is presented in FN curves and by examining the 'steps', it gives reason to believe that no more than 10 scenarios have been considered in the analysis. When the FN curve is represented by a small amount of scenarios, a single variation of a parameter results in large deviations. If the analysis would have been carried out as an extended QRA instead, the credibility of the analysis could be expressed as confidence intervals (Frantzich, 1998).

Thomas et al. (2005) used the fire risk assessment model CESARE-Risk (ABCB, 2001) in an attempt to quantify the risk of apartment buildings (class 2) in Australia. As a background to this analysis they stated that there were currently no quantified performance requirements in building codes in terms of life safety. As a first step to building a base from which such performance requirements can be constructed, the current level of safety from the prescriptive codes are investigated.

The risk was quantified in a probabilistic-deterministic manner, event tree methodology combined with deterministic fire modelling. The output of the model presents the number of fatalities per 1000 fires which is a combination of the risk of the occupants intimately related to the fire in the apartment of fire origin (AFO) and other occupants in apartments of non-fire origin (ANFO). They included 12 different types of apartment buildings in their investigation with different characteristics. It was found that low-rise buildings had an average fatality rate per 1000 fires of ≤ 0.2, mid-rise 3.3 to 3.4, and high rise (i.e. more than 25 meters) 1.7 to 2.1. The decrease in fatality rate in high-rise buildings is mainly explained by the mandatory provision of sprinklers in this type of building.

Some other results from their study concluded that when using CESARE-Risk, the risk of becoming a fatality within the room of fire origin was independent of the room size (one and two bedroom apartments were modelled). Another remarking result was that no fatalities were observed for awake occupants in normal condition. Comparing this with results presented by Sekizawa (2005) which shows that a significant number of the fire fatalities were in normal condition (although this includes both sleeping and awake), it seems as the model underestimates the risk for persons in normal condition. For low rise buildings, the major contribution to the average fatality rate comes from the risk within the apartment of fire origin. However, for medium and high rise buildings, the major contribution comes from fatalities outside of the fire apartment due to fire spread. The only explanation given is that a large number of fatalities occur in corridors when doors are left open, a variable which is difficult to quantify.

The analysis predicts the risk decreasing with increasing building height. Considering that becoming a fatality from structural collapse and due to the nature of fire spreading upwards this seems reasonable. However, the top floors of the medium and high rise buildings show a significant increase in risk. The only explanation to this is stated as "(…) due to a non-responsive occupant (OG5) appearing on that storey in a systematic manner". This leads to the question if occupants have been randomly sampled or the same seed has been used in all simulations? Also, the increase in risk from a single non-responsive occupant is interesting. In building 9, the increase in risk from floor 8 to 9 is almost 60%. There is no real transparency in the analysis to explain this.

Chapter 4 - Building design from prescriptive codes

One of the aims with this thesis is to compare levels of safety achieved by different country specific building codes, it is necessary to ensure that the designs are comparable from a risk point of view. This can be demonstrated by an example. Consider a fictive apartment building which is a medium rise building of 5 floors with 10 apartments on each floor. The details of the different codes will impose different requirements. For example, building codes describe a minimum ceiling height to which apartments may be constructed. The height of the ceiling will affect the time until lethal conditions since it directly affects the smoke layer height, radiation, etc. These variables are correlated with the risk of death from a fire.

It should also be pointed out that this thesis *does not* aim to investigate the currently *overall* achieved level of safety, which can be assumed to be made up of a mix of old and new regulations. By using the newest editions of the building codes as the base for the analysis, the level of safety achieved by the *current* regulations are analysed and compared.

4.1 Minimum level of life safety

In Thomas et al. (2005) study of risk to life they applied a *minimum* level of requirements demanded by the 2005 BCA Deemed-to-Satisfy provisions. They acknowledge that this ‘minimum’ level was highly subjective and only an interpretation of the provisions. If there is such a thing as a minimum level of safety provided by the Deemed-to-Satisfy provisions, it is interesting from a designer point of view since it reflects what society seems to perceive as an acceptable level of risk.

So an interesting question arises: is it possible to determine which set of design criteria from the prescriptive codes result in a minimum level of risk? Regarding fire safety provisions, minimum requirements can be found in the ABCB (2010b) and Boverket (2008). Examples of these might be smoke alarms/detectors, self-closing doors, sprinklers, etc. However, there are other parameters not regulated in the building codes affecting the risk to occupants (e.g. floor area). Unregulated factors can be used to show that it is impossible to determine a minimum level as the designer is not restricted to any minimum criteria for floor area.

4.2 Addressing the minimum level of safety in common designs

As previously mentioned, it can be shown that there are certain ways of construction accordingly to Deemed-to-Satisfy provisions that would result in a high level of risk to occupants. Another example is considering the number of exits needed by the BCA from sole occupancy units (SOU). In general it is considered that one exit from a SOU is acceptable as long as the corridor travel distance is designed in accordance to this. However, in the BCA a SOU may stretch over a number of stories without an increased required number of exits. Obviously this will change the risk compared to a SOU confined to only one storey. (ABCB, 2010b)

However, such designs are rarely encountered in practise and therefore using these (although allowed by the Deemed-to-Satisfy) would give an unfair representation of the level of risk the vast majority of society is exposed to.

Examples given above show that is possible to design an apartment building that would result in very high risk while still following the fire safety provisions in the building codes. Therefore, it is instead proposed that by addressing what can be considered to be common designs for apartment buildings, the risk estimated is instead reflecting what large parts of society is exposed to.

4.3 Systematic approach to implement Deemed-to-Satisfy provisions

In order to find the minimum fire safety requirements for a design, this has to be performed in a transparent and systematic procedure. In an effort to restructure the BCA, FCRC (1996a, 1996b) performed a systematic mapping of building classes, sub-classes, fire provisions and performance requirements with corresponding acceptable solutions.

They identified 17 different system elements related to fire safety that are listed below (FCRC, 1996a):

- Structure (load bearing elements of building)
- Escape paths (exits, travel distance, stair dimensions, steepness, widths, handrails)
- Active smoke management (controls extent of smoke spread excluding smoke compartmentation)
- Fire suppression (sprinklers)
- Fire detection
- Warning (any system with the purpose of making occupants and fire-fighters aware of a fire)
- Building management (maintenance of essential services, etc.)
- Materials control (fire and smoke properties, fire load, linings, furnishings)
- Occupant fire-fighting (hose reels, fire extinguishers)
- Brigade fire-fighting (fire brigade intervention incl. hydrants, fire control rooms, etc.)
- Means of communication (e.g. intercom system)
- Smoke compartmentation (barriers that intend to confine smoke)
- Flame compartmentation (barriers that intend to confine fire, e.g. walls and wetting systems)
- Flame and smoke compartmentation
- Exposure control (everything that reduces external fire spread between buildings)
- Way finding (exit signs, lighting, exit location)
- Standby power supply (means to provide power to essential services in an emergency)

The above stated system elements cover all building classes and therefore each element is more or less applicable to for apartment buildings. A discussion follows on why some of these elements have not been included.

As this project was performed in mid 1990s, changes have been made to the building codes since then. Therefore the structure will be helpful, but identification of the current requirements will be amended from the current codes.

Following sections will deal with presented elements relate to estimating the risk in occupancies and provide an argumentation on how these will be assessed.

4.3.1 Structure
Structural fire safety relates to the building or building component ability to withstand fire exposure for a certain time without leading to a collapse. For smaller buildings, structural fire safety will provide more means to protect from property loss whereas in larger buildings, for which it takes longer time to evacuate, it may also become relevant from a life safety point of view. There are also situations in smaller sized buildings where structural resistance becomes important in life safety point of view, for example when the fire makes escape paths unavailable (Buchanan, 2001). As such, structural fire resistance will not affect the risk within the compartment in which the fire occurs but may be important for the safety of other occupants within the building depending on the fire severity. However, statistics show that historically, very few deaths are related to structural collapse caused by fire (Bengtson et al., 2005). As such, for the purpose of this analysis, risk from structural failure has not been considered.

4.3.2 Escape paths
In order to ensure a safe escape from a building, it is important that tenable escape paths are available. Provisions in the building regulations put requirements on number of exits, travel distance, stair dimensions, stair steepness, widths, handrails, etc. There are also differences to what are allowed as exits. The BBR allows windows to serve as exits up to certain heights in contrary to the BCA.

4.3.3 Active smoke management
Active smoke management for apartments may include apartment ventilation system. It is believed that this aims to limit fire and smoke spread to adjacent compartments and therefore this is not of interest for calculating risk within the apartment of fire origin.

4.3.4 Fire suppression
Suppression of a fire can significantly reduce the severity of a fire. In the BCA requirements are found for a sprinkler system to be installed in buildings over 25 meters effective height.

Handheld suppression may also mitigate the effect of the fire. However, this is reliant on occupant behaviour, knowledge, etc. Large uncertainties are associated with modelling manual suppression and has therefore been left out of the analysis.

4.3.5 Fire detection
Different systems for making occupants aware of the fire hazard are important aspects of increasing the safety. Minimum requirements according to the BBR states that each apartment should be fitted with a smoke detector close to the bedroom. In the BCA choice is given to either install a smoke detection system, smoke alarms or a combination of these. It has been assumed that smoke alarms provide the minimum level of safety.

4.3.6 Warning
As the risks are concerned with the apartment of fire origin, warning signals are given when activation of the fire safety systems.

4.3.7 Building management
Relate to maintenance, surveillance, etc. This has not been considered in the analysis.

4.3.8 Materials control
The building code provides regulations for how the apartments may be designed but no restrictions can be found for interior design of the dwellings. However, the unique internal content of an apartment will have a large effect on the course of a fire. The speed of which a fire grows and spreads will have a significant effect on the risk to life.

It can also be questioned what is reasonable to try to model when assessing the risk to life imposed by buildings. It may be argued that a high load of combustibles can be considered as a voluntary action, but it may also be a case of lack of knowledge. The fuel load from an occupant's belongings and furnishing is something that is not controllable. As such, no consideration will be taken to individual variation of furnishing.

4.3.9 Occupant fire-fighting

See section 4.3.4.

4.3.10 Fire brigade intervention

Are not considered due to limitations of this thesis.

4.3.11 Means of communication

Have been considered a variable hard to quantify and therefore no consideration has been taken to this.

4.3.12 Compartmentation

Fire compartmentation aims to prevent fire and smoke spread from the compartment of fire origin and therefore mainly to protect occupants in other connecting compartments. Therefore, this parameter has not been considered.

4.3.13 Exposure control

External fire spread is not considered due to limitations of this thesis.

4.3.14 Way finding

Have been considered as a variable hard to quantify and therefore no consideration has been taken to this.

4.3.15 Other

4.3.15.1 Compartment size

Compartment and room sizes have a major influence of the fire related risk as it strongly affects the time until untenable conditions (for example see Magnusson et al. (1995) and Kristiánsson (1997)). A smaller room will lead to a shorter time until untenable (and lethal) conditions and therefore this constitutes an important part of interpreting and designing from the prescriptive codes.

No restrictions can be found in limiting the designer to a minimum floor area for dwellings. As such, it can not be determined a minimum floor area and therefore the risk can not be maximized. As already described previously, instead of trying to address the minimum safety level possible (which may be infinite large), a minimum level among commonly designed and representative buildings is sought.

4.3.15.2 Construction material

Building traditions, climate and other factors have created differences in how buildings are generally constructed in different countries. This includes the preferred materials for exterior, interiors, foundations, etc. The construction material effect on heat transfer has been considered.

Chapter 5 - Quantifying building code risk to life

The previous chapters have focused on methods for performing fire risk analysis (Chapter 3) and gained knowledge of risk aspects of prescriptive building code design (Chapter 4). This chapter aims to provide a description of the model which has been used to estimate the risk for the chosen case study buildings presented in Chapter 6. The coarse model presented in this chapter refers to findings in the review of risk assessment frameworks (Chapter 3) and to more detailed sub-models given in Chapter 7, which also contains the necessary input and assumptions for calculating the risk.

5.1 Applied fire risk analysis model

To bring structure to the quantification process, different risk assessment frameworks have been studied (see section 3.4) and evaluated in relation to the objective with this thesis. It was found that none of the studied frameworks were directly applicable and therefore a new model was derived. The base structure was adopted from the Risk-cost assessment model (section 3.4.1) which was modified to fit the purpose of this thesis.

The adopted model is presented in Figure 5.1 describing the interaction between occupants, building and fire development in an apartment. More detailed description of the different parts of the model, such as fire growth and evacuation, are given in Chapter 7.

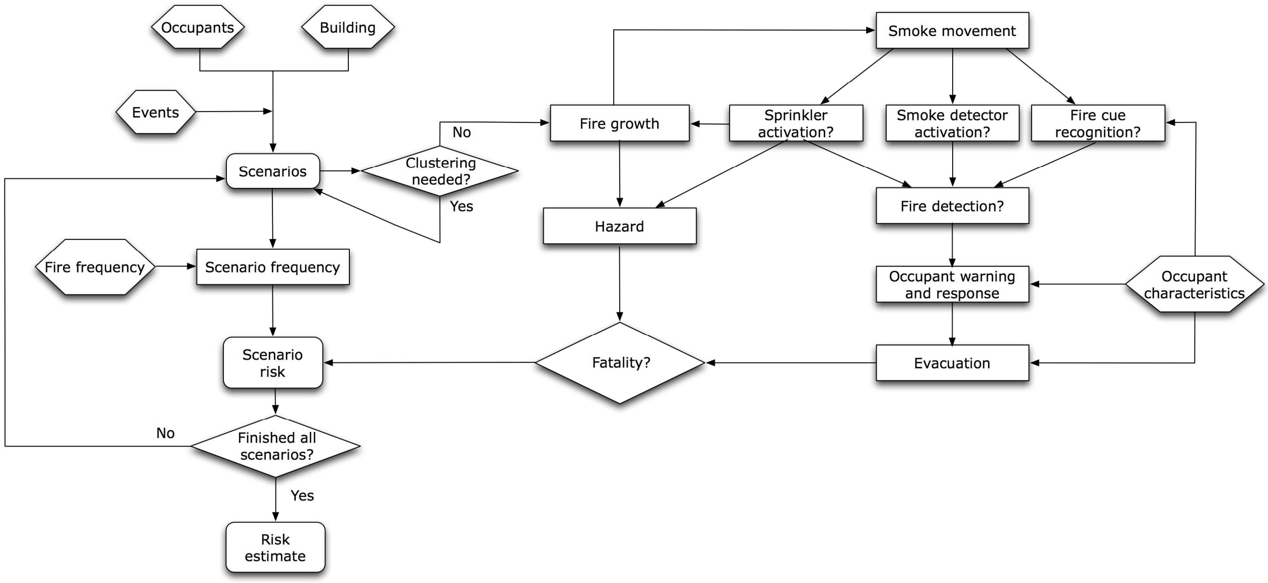

Figure 5.1 Flow chart of model used

The different parts of the risk analysis model applied are described in section 5.7.

In Figure 5.1 it can be seen that the model used for estimating risk is based on a scenario methodology. As it is not possible to incorporate all possible scenarios in an analysis, it was necessary to limit the number of scenarios considered (see section 3.6). This is described in section 5.5. Each scenario is associated with a certain frequency and consequence which together provides the necessary information to estimate the associated risk with the scenario. The literature review identified several methods to acquire a quantitative measure of risk. However, with guidance shown in section 3.1, it was found that a QRA provides a good method for estimating the risk in scenario-based analyses. Other benefits with this method were

(a) a complex system is to be analysed

(b) multiple scenarios can be analysed simultaneously

(c) it provides a flexible method for incorporation of explicit uncertainty study if found necessary

As such, a standard QRA methodology combined with an event tree approach was chosen. The event tree was used to structure the scenarios in a logic way. By estimating frequency and probability of events occurring (see Chapter 7), it was possible to derive frequencies for each scenario in the event tree. By calculating the consequences associated the scenarios with an FED methodology (see sections 3.9.1 & 7.6.1), it was possible to determine the risk in accordance with Eq. 5.1

Because definitions vary and it is possible to calculate different types of risk measures (see section 3.2) it is of importance to define what is meant by the term 'risk' (see section 5.2). The risk in turn is based on frequency and consequence for different scenarios. As such, it is necessary to communicate the definitions for these concepts which are done in sections 5.3 'Defining frequency', 5.4 'Defining consequence'. As the calculated risk is also dependent on the scenarios that have been included in the analysis, how these were derived has been described in section 5.5.

It is also necessary to define the system which is to be analysed (Frantzich, 1998). In fire engineering it is usually assumed that occupants escaping reach an area which is defined as a 'place of relative safety'. As it is assumed that beyond this point no consequences occur, this forms a boundary for which modelling should be carried out. The definition used in this thesis is provided in section 5.6.

5.2 Defining risk

In this thesis an individual risk measure calculated using the Kaplan and Garrick (1981) definition of risk (see Chapter 3) has been used. Risk is defined as the product of probability and consequences of unwanted scenarios that may occur within the apartment of fire origin or until occupant reaches a safe area. The individual risk measures presented in Chapter 8 have been calculated according to Eq. 5.1.

$$IR = \sum_i \lambda_i \qquad c_i > 0 \qquad \textbf{(Eq. 5.1)}$$

where

λ_i frequency of scenario 'i' [year^{-1}]

c_i consequence of scenario 'i' [fatalities]

i are the scenarios that have been included in the analysis, see section 5.5.

5.3 Defining frequency

As the model calculates the risk associated with apartments, the frequency should also describe the expected fire occurrence in the actual apartment analysed. Methods to estimate the fire frequency was presented in section 3.8 and the selected method is shown in 7.1.

5.4 Defining consequence

It is of interest to calculate the risk imposed on occupants, i.e. the risk of becoming a fatality from a fire in a specific occupancy. Instead of using criteria for untenable conditions, an approach to model death from different fire related causes is used.

5.5 Defining scenarios

The majority of the events identified and included in the analysis (see section 5.7.3) formed the structure of the event tree presented in Figure 5.2.

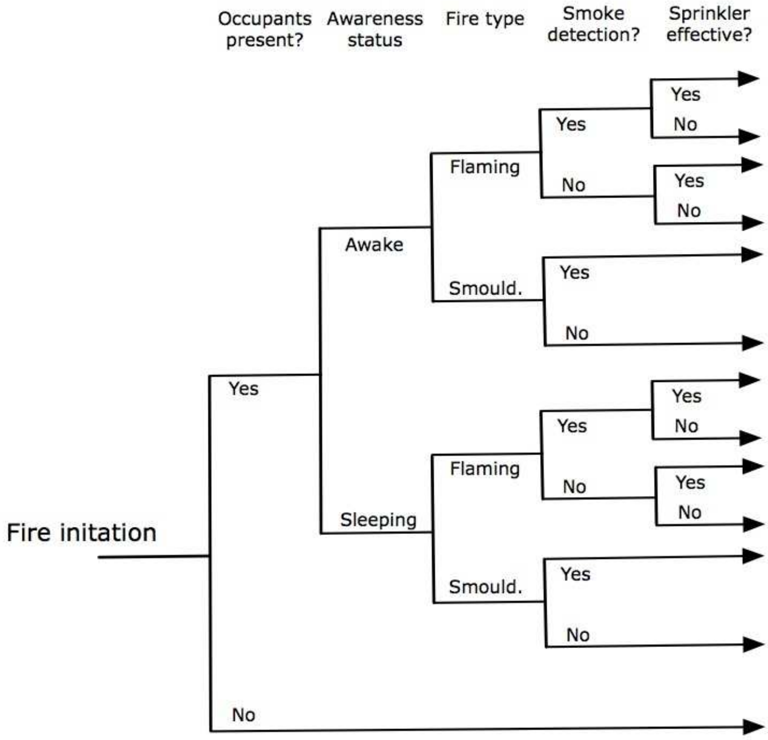

Figure 5.2 Model event tree

For reasons of avoiding creating a very large spreadsheet calculations, instead of including them in the event tree, some events were set as random variables and modelled with the Monte Carlo simulation software @Risk (Palisade corp., 2010). These were

- number of occupants
- occupant location
- fire location

Even though not displayed in the event tree, the @Risk modelling of these variables ensures that the different combinations are taken into account. By running sufficient amount of calculations the mean value reach convergence, i.e. not changing considerably for a set interval of iterations.

Some events identified as important for estimating the risk were not easily quantified, see 7.4. Not being able to quantify these parameters they were not included in the event tree or as randomized variables. These were instead taken accounted for by forming different sets of control parameters, see **Table** 5.1. To clarify, a 'set of control parameters' is a specific combination states for the parameters found difficult to quantify. For example, for the control parameter set 'C4' (see **Table** 5.1) the corridor door has the status 'Open', the window is 'Closed' and the internal doors are 'Closed'.

Table 5.1 Control parameters considered

Set of control parameters	Corridor door	Window	Internal doors
C1	Closed	Closed	Closed
C2	Closed	Closed	**Open**
C3	Closed	**Open**	Closed
C4	**Open**	Closed	Closed
C5	Closed	**Open**	**Open**
C6	**Open**	Closed	**Open**
C7	**Open**	**Open**	Closed
C8	Closed	**Open**	**Open**
C9	**Open**	**Open**	**Open**

Because it was not possible to quantify the probability of a certain set of control parameters occurring, a quantitative measure of the risk have been estimated for each set in Chapter 8.

5.6 Defining system boundaries

Entire buildings have been considered in the analysis but the model applies to single apartments. As such, the calculated risk measure provides information on the individual risk associated with occupants in a certain apartment.

For each individual calculation of a risk estimate, the physical boundaries are defined by the boundaries of the apartment, the corridor and the control parameters (see section 5.5). In case the corridor door is open, a 'place of relative safety' is assumed to be when reaching stairwell or similar.

5.7 Description of risk analysis model

The subsections are a short description of the parts of the model shown in Figure 5.1 if not already described above.

5.7.1 Building input

The building code is being represented by a number of representative buildings (see Chapter 6) which serves as input for the model. The geometry and layout of the apartment will be of importance for fire and smoke movement, fire detection, occupant evacuation, etc. The building code also requires certain fire safety measures for the different buildings that are assumed to affect the risk. Fire safety regulations for the buildings presented in Chapter 6 are described in detail in Appendix B.

5.7.2 Occupant input

As this thesis is only concerned with risk to life, a building without occupants would not be a concern. The number of occupants, their location, awareness status and movement are a few of the parameters that will determine the outcome of a fire scenario, and thus in extent will affect the risk.

5.7.3 Events

Events are defined as important variables significantly changing the state of the scenario. An example is sprinkler activation which will change the severity of the fire and also notify the occupants, two factors assumed to affect the risk. Using the scenario methodology described in section 3.6 and consulting risk assessment literature, a number of events where found, see Appendix A.

5.7.4 Design fire

Design fires are used to model the course of a fire over time. A method was presented in section 3.5 which was adopted (see section 7.3). It was concluded that modelling of the decay phase was not necessary. Therefore, the design fire only models fire growth and the peak heat release rate.

Fire growth is one of the most important variables to estimate in fire engineering calculations as it is strongly correlated to the time until lethal or untenable conditions occur. In section 3.5.1, a few methods were presented for modelling fire growth for both flaming and smouldering fires. The fire growth model output will work as input for calculating smoke detector and sprinkler activation, smoke movement, etc. The adopted sub-models to describe fire growth are presented in 7.3.1.

Peak heat release rate has been assumed to occur by either the fire becoming ventilation controlled or by activation of a sprinkler system. A more detailed description of this is provided in section 7.3.2.

5.7.5 Smoke movement and fire detection modelling

Smoke movement have been used to estimate fire safety system activation and occupant cue recognition as these two factors was suggested as the main causes to raised awareness of the fire hazard (see section 0). Smoke movement is (among other cues) used to estimate the time until occupants become notified of the fire hazard, i.e. the detection time (see sections 7.7, 7.6.1 & 7.9.1). However, in sprinklered buildings, activation of sprinklers will also alter the severity and growth of the fire.

If internal doors are closed, it has been assumed that the smoke will be confined to the room of fire origin. However, if the internal doors are open, smoke filling has been calculated for all interconnected spaces.

5.7.6 Occupant warning and response

When the occupant has received the information of danger, there follows a period where the occupant processes information. It is commonly denoted as pre-movement time, see section 0. The pre-movement time for an occupant will be influenced by the means of raised awareness (e.g. smoke alarm, temperature, flames) as these are associated with different levels of certainty. Also the occupant's level of awareness will affect the pre-movement time. Assumptions used in the analysis are presented in section 7.9.2.

5.7.7 Evacuation modelling

Once decision has been taken to evacuate, the final part of evacuation time begins. This is the travel time, i.e. the time it takes the occupant to move from its location to a place of safety. The literature study suggested a hand calculation method shown in section 0. This method utilizes travel distance from occupant location to the place of relative safety. Depending on the set of control parameters (see section 5.5) used, this may be either when exiting into the corridor or when reaching the end of the corridor.

5.7.8 Hazard

The transient fire creates a hazardous environment which is modelled by estimating concentration of toxic species and smoke layer temperature (see section 7.6). Using FED methodology (see sections 3.9.1 & 7.6.1) in combination with modelled occupant exposure, consequences can be assessed. Occupant exposure is determined by the time spent in the hazardous environment and is therefore dependent on for example time needed for escape. Also internal openings will determine exposure. For example, if an occupant is located in another room than the fire origin and internal doors are closed, exposure is assumed to begin when the fire has been detected and pre-movement time is over (≈ time to occupant walks into hazardous environment).

5.7.9 Scenario risk

The use of event trees and randomized variables presents the frequency of each scenario (section 5.3). Estimating the consequences of the scenarios (section 5.7.8), the scenario risk is calculated as described by Eq. 5.1.

5.7.10 Risk estimate

The calculation of scenario risk is repeated for all scenarios, which allows for calculation of the total risk estimate for each apartment and set of control parameters.

5.8 Sensitivity analysis

When performing the standard QRA, point values are used to estimate the risk. The different variables were assigned values equal to mean or upper bounds (more conservative), see Chapter 7. However, as uncertainty is not explicitly considered, the sensitivity of estimated risk introduced by the model and its input is unknown. A sensitivity analysis has therefore been conducted to provide this information. The parameters and variables analysed are shown in Appendix C and a summary of the results of the sensitivity analysis is given in section 8.3.

Chapter 6 - Description of buildings analysed

6.1 Current trend in apartment buildings

These sections contain an analysis to determine the current trend in construction of apartment buildings.

Statistics provided by the State of Victoria Building Commission (2010) shows the trend in current development in commenced apartment buildings in Victoria State, Australia. The histogram in Figure 6.1 shows the distribution of number of storeys among newly built apartment buildings in the period 2005 – 2009. In some instances, when information on number of storeys or number of dwellings was missing, this data was subtracted from the analysis. There were also a number of entries with only one dwelling, which is not considered fitting the data sought. The result was 989 entries into the database which were used in this analysis and this data is assumed to be representative for Australia.

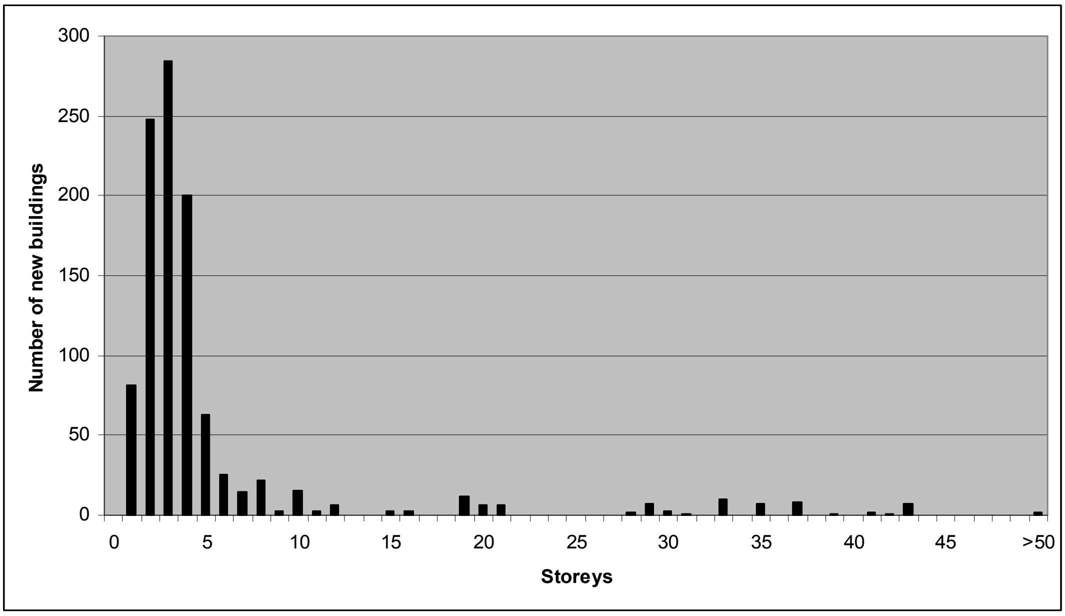

Figure 6.1 Distribution of number of storeys in newly built apartment buildings, 2005 - 2009 (State of Victoria Building Commission, 2010)

As clearly shown in Figure 6.1, the majority of apartment buildings built are one to five storeys high. To gain understanding on the layout of these apartment buildings, an attempt to show the distribution of the number of apartments per storey in different buildings was carried out. Since no detailed data was available, the apartments are assumed to be uniformly distributed within a building, i.e. if an entry into the database showed that the building has 5 storeys and 50 apartments, it is assumed that the building has 10 apartments per storey.

Table 6.1 Number of apartments by number of storeys (State of Victoria Building Commission, 2010)

	Total number of apartments in the building											
No of storeys	**2 - 5**	**5 - 10**	**11 - 20**	**21 - 30**	**31 - 40**	**41 - 50**	**51 - 100**	**101 - 150**	**151 - 200**	**201 - 300**	**301 - 400**	**> 400**
1	**61**	9	4	5	0	2	0	0	0	0	0	0
2	**149**	37	21	5	4	2	1	0	0	0	0	0
3	**116**	62	65	11	4	7	1	0	0	0	0	0
4	44	34	**45**	16	26	10	15	5	0	0	0	0
5	5	5	12	2	12	**13**	**13**	0	0	0	0	0
6 - 10	2	3	4	10	11	7	**23**	18	0	0	0	0
11 - 20	0	1	0	**12**	0	6	7	2	4	0	0	1
21 - 30	4	0	0	0	0	0	10	4	3	**17**	6	0
>40	0	0	0	0	1	0	1	7	0	0	0	2

The category with most entries has been highlighted as bold in the matrix shown in Table 6.1. It is obvious that there is some bias to the data as there are 5+ story buildings with only one or less apartments per storey. This may be due to the data being sensitive to database user input. The building can only be given a single BCA classification even though many buildings contain parts with different uses and as such multiple classifications.

The distributions of storeys are compared between Australia and Sweden for the years 2005-2006 in Figure 6.2. The comparison shows that Swedish multi-occupancy buildings are rarely constructed as one storey buildings whereas this constitutes about 10% in Australia. For both years, the distributions is skewed towards 2-4 storey high buildings in Australia while a more uniform distribution better describes Sweden.

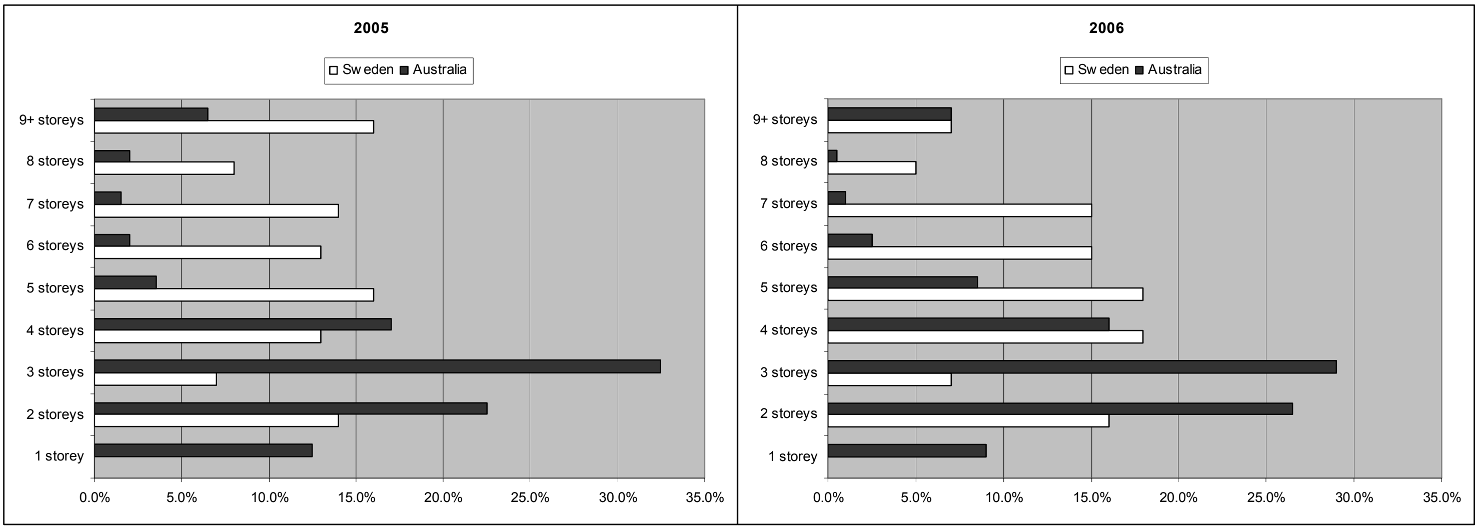

Figure 6.2 Comparison of storey distribution (SCB, 2010; State of Victoria Building Commission, 2010)

Regarding the number of occupants in the buildings, a distribution of the number of occupants in relation to apartment size is given in section 7.8.1.

6.2 Case study buildings

Variations in number of apartments, storeys, internal layout, etc. will lead to variations in risk to occupants. To give a credible representation of the risk to occupants, different types of apartment buildings should be included in the analysis, so that the risk is not represented by a single case. It was suggested[1] that at least a low-rise, medium-rise and high-rise building should be included due to the change in provisions. However, the analysis was limited to a mid-rise and a high-rise building due to these buildings judged being most interesting by the author since earlier studies (see for example Thomas et al (2005)) have shown that the risks associated with low buildings are significantly lower than mid- and high-rise. How these buildings are defined is described under each sub-section below.

To address common designs in these buildings, reference material was needed on internal layouts to determine commonalities in building design. For Australia, constructed buildings between 2003 and 2010 were investigated from the archives at Philip Chun, Melbourne. Examining building plans, it was noted which type shape the building had, if it contained apartments with similar or varied sizes, corridor/stair location and design.

For *mid-rise*, eight different buildings were examined. Commonalities in these buildings were:

- most buildings had somewhat uniform apartment sizes
- the shape of the building was usually rectangular
- internal corridor dominates the designs

For *high-rise*, only three buildings were found. Although the reference material was significant smaller, no real differences in design could be noted.

No investigation of Swedish buildings in a similar manner to the above described was carried out due to lack of material. Instead, when designing the buildings, it is sought to have similar base designs but adjust them according to what is allowed according to each country specific code. For example, dead end travel distance to exit differs. In Sweden, 10 meter travel distance is allowed while the BCA only allows 6 meters. However, to make the comparison fair, the floor area is strived to be kept constant.

6.2.1 Building 1 (Mid-rise)

As there is no clear definition of low-, mid- and high-rise buildings, it should be explained what is meant for the purpose of this thesis. Buildings with rise in 2 storeys or less will, according to both the BCA and the BBR, give concessions regarding stability and materials control. As such, the provisions increase for buildings at this height. The lower limit of a mid-rise building has therefore been defined as 3 storeys. An increase of provisions is found for buildings with effective height over 25 meters. The BCA then requires the entire building to be supplied with an automatic sprinkler system. Assuming 3 meters height increase per storey, this provision is required for buildings over 8-9 storeys. Therefore, the author has found a 5 storey building suitable to represent the mid-rise building category.

In Table 6.1 the distribution of number of apartments is given for the number of stories in the building. It is found that the categories '41 – 50' and '51 – 100' apartments are associated with the most likely number of apartments for 5 storey buildings. This suggests that, assuming that apartments are uniformly distributed among storeys, the number of apartments per storey ranges from 8 to 20. The Deemed-to-Satisfy solution only allows for 6 meters dead end travel distance. However, the statistics does not separate the buildings designed according to Deemed-to-Satisfy provisions and which ones that include alternative solutions. Furthermore, there is a concession given in the Victoria amendment to the BCA which allows for 12 meters of travel distance.

[1] Wayne Bretherton, Philip Chun Fire Pty, communication, 2010-07-28

Designing the building according to the Deemed-to-Satisfy provisions, suggests that the number of apartments (of reasonable size) is probably close to the lower boundary of the given interval. 12 apartments per storey have therefore been assumed. The appropriate fire safety regulations are presented in Appendix B.

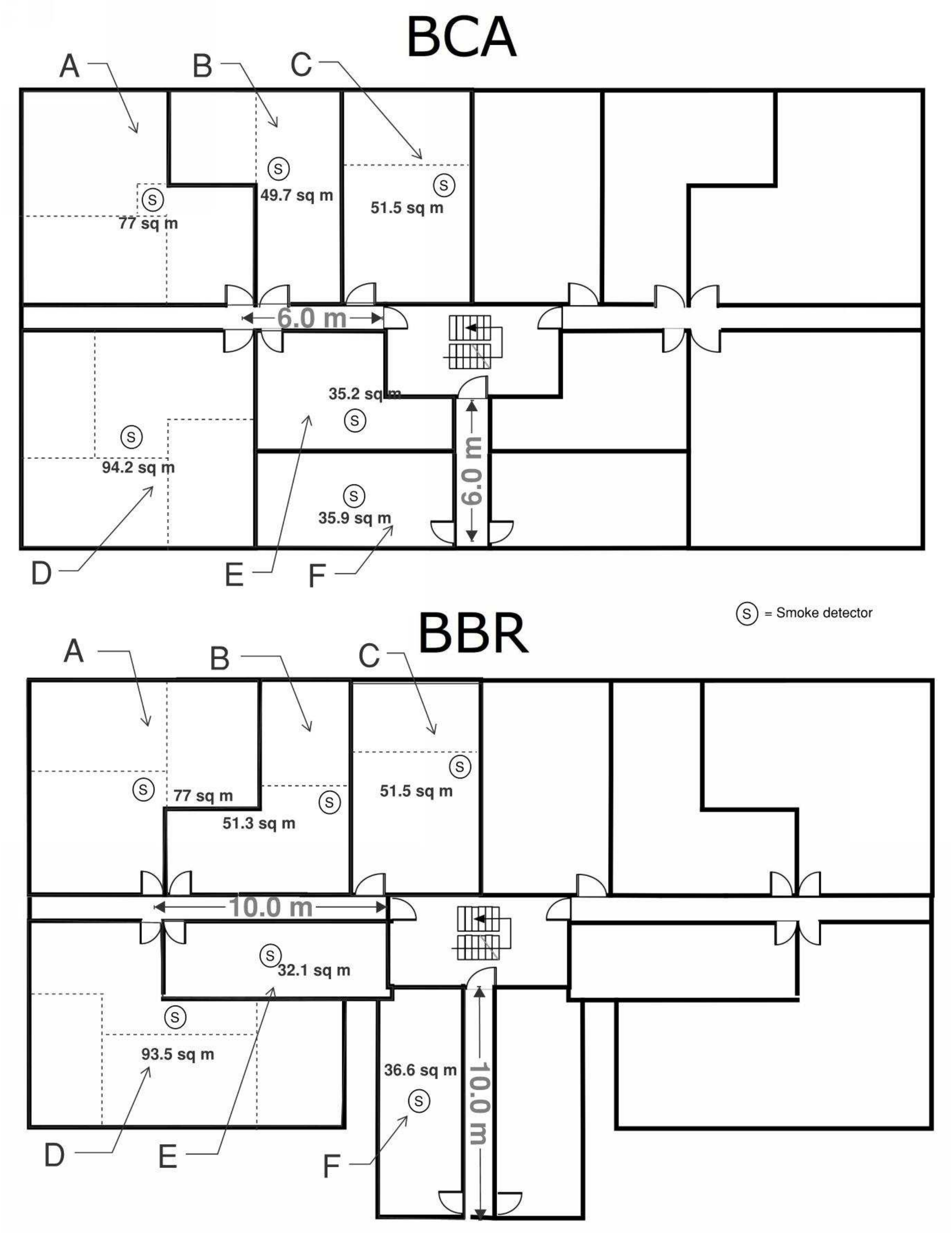

Figure 6.3 Building 1 layout designed according to BCA and BBR

Figure 6.3 provides an overview of apartment layout in Building 1 for both the design according to BCA and BBR. In Table 6.2, a short description of the different apartments modeled for the country specific designs are presented.

Table 6.2 Description of apartments in Building 1 designs

Building code	Apartment	# Rooms	Max. internal travel distance	Corridor travel distance
BCA	A	3	~ 20 m	~ 6 m
	B	2	~ 12 m	~ 5 m
	C	2	~ 12 m	~ 1 m
	D	4	~ 20 m	~ 6 m
	E	1	~ 12 m	~ 5 m
	F	1	~ 10 m	~ 6 m
BBR	A	3	~ 13 m	~ 10 m
	B	2	~ 15 m	~ 9 m
	C	2	~ 12 m	~ 1 m
	D	4	~ 16 m	~ 10 m
	E	1	~ 11 m	~ 10 m
	F	1	~ 12 m	~ 10 m

6.2.2 Building 2 (High-rise)

In this thesis, high-rise apartment buildings have been defined as buildings with an effective height over 25 meters, i.e. approximately 8-9 storeys. This definition was chosen mainly due to the increased provisions for buildings constructed at this height. In the BCA, over this height no more increases in provisions are found with increasing number of storeys. In the BBR, buildings over 16 storeys are required to analyse the safety analytically (Bengtson et al, 2005).

For high-rise buildings, layouts were examined for 8 to 12 storey high buildings. Therefore, building 2 has been assumed to have approximately 10 storeys. From Table 6.1 it is found that the categories '51 - 100' and '51 – 100' apartments are associated with the most likely number of apartments for 6 - 10 storey buildings. From these statistics, 16 apartments per storey were chosen as design criteria.

The high-rise building included in the analysis was adopted from common designs found and the highest (assumed) risk. For the BCA, this is assumed to be a travel distance of 6 m (dead end) + 22.5 m (two exits) from the apartment associated with highest risk. For the building designed according to BBR, the design became a bit more creative as it was assumed that only providing one stair was associated with highest risk. Thus, 16 apartments had to be fitted to a maximum corridor travel distance of 10 meters. The layouts of the high-rise building are shown in Figure 6.4.

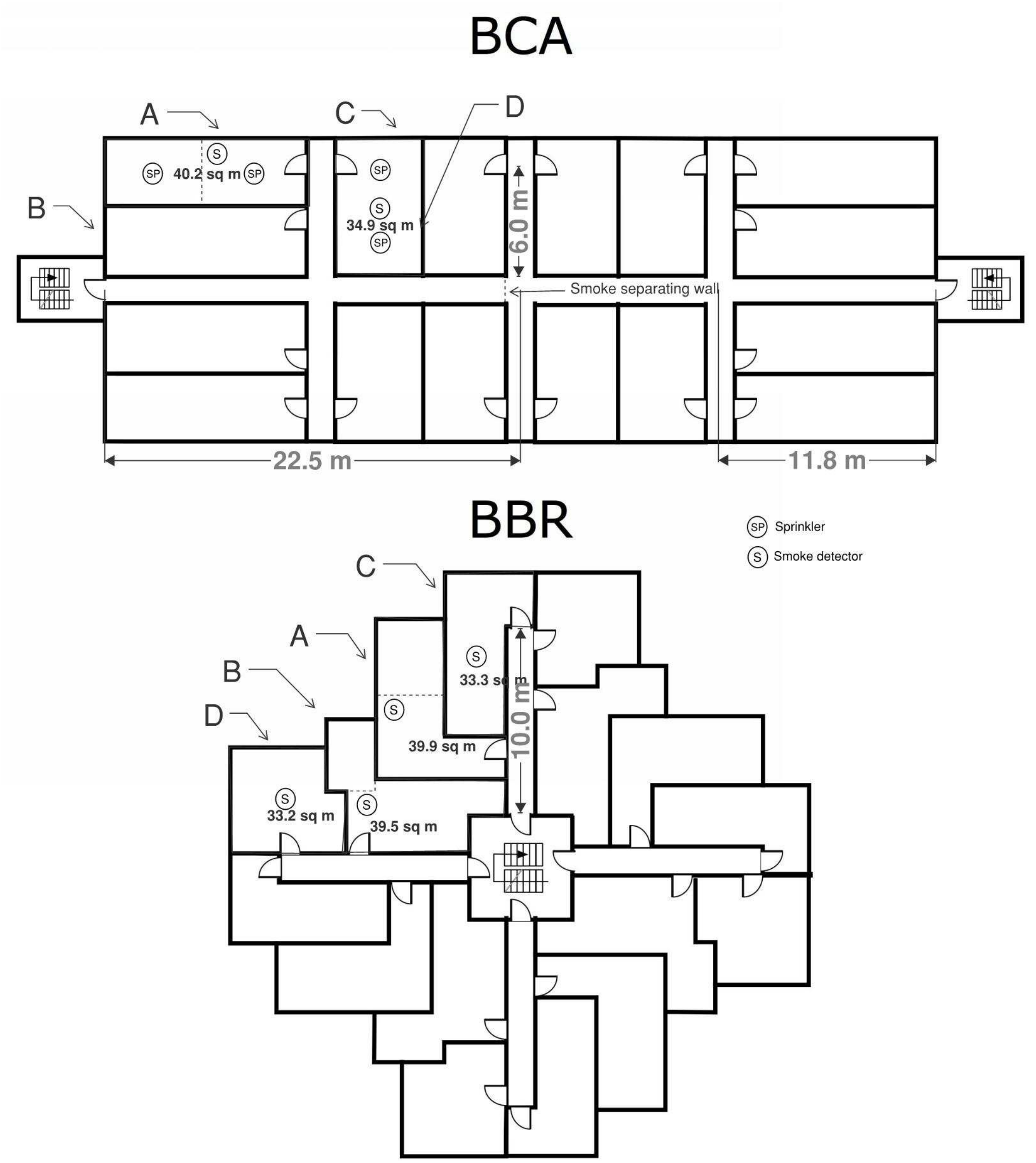

Figure 6.4 Building 2 layout designed according to BCA and BBR

In Table 6.3, a short description of the different apartments modelled for the country specific designs are presented.

Table 6.3 Description of apartments in Building 2 designs

Building code	Apartment	# Rooms	Max. internal travel distance	Corridor travel distance
BCA	A	2	~ 10 m	~ 16 m
	B	1	~ 8 m	~ 28.5 m
	C	2	~ 10 m	~ 13 m
	D	1	~ 8 m	~ 25.5 m
BBR	A	1	~ 8 m	~ 10 m
	B	2	~ 12 m	~ 4 m
	C	2	~ 9 m	~ 5 m
	D	1	~ 6 m	~ 10 m

Chapter 7 - Input, sub-models and assumptions

This chapter aims to show the models used so that the analysis becomes transparent as well as provide the necessary input and assumptions for the performed calculations.

7.1 Fire frequency

As it is intended to model all fires, not only the ones reported to the fire brigades, it can be argued that insurance statistics provide better estimates of the real fire frequency as pointed out by Nystedt (2003). The Swiss insurance statistics estimates provided by Fontana et al (1999) have been used since these are based on a large number of fires. The frequency of fire can therefore be described by

$$\lambda = 33.3 \cdot 10^{-6} \cdot A_f \qquad \textbf{(Eq. 7.1)}$$

where

λ fire frequency [$year^{-1}$]
A_f floor area [m^2]

It should be noted that this estimate based on Swiss statistics may bias the result as different cultures and building traditions as well as behaviour may affect the fire frequency. Further, it is assumed that no fires occur in corridors or stairwells. Fires are thus limited to apartment areas. Since Eq. 7.1 is based on floor area, it is also assumed that the fire frequency can be estimated for each apartment relative to its floor area. The fire frequency being estimated only by the floor area also neglects any differences in fire frequency that may exist between the two countries.

7.2 Fire statistics

7.2.1 Fire types (smouldering, flaming, flashover)

As noted in section 3.8, a fire may not grow into a flaming fire. Smouldering fires pose a different threat to the occupants as the yields of combustibles and heat from such fires differs significantly.

Yung & Bénichou (2002) provides guidance for the relation between smouldering, flaming and flashover fires in Australia. The percentage values are given for fires when sprinklers are not present. Similar Swedish statistics have not been found and therefore the Australian statistics have been assumed for the BBR buildings.

Table 7.1 Fire type according to statistics (Yung & Bénichou, 2002)

7.2.2	Australia
Smouldering	24.5 %
Flaming	60.0 %
Flashover	15.5 %

As the analysis considers life safety of occupants within the apartment of fire origin, flashover is not of interest. However, flashover fires are assumed to start as flaming fires and therefore a new derived probability distribution is shown in Table 7.2

Table 7.2 Assumed fire type probabilities

7.2.3	Australia
Smouldering	24.5 %
Flaming	75.5 %

7.2.4 Fire location

Fire location describes where the fire has started. This is of importance when compartmentation utilizes separations within the apartment. Together with the occupant location, the fire origin describes the occupants intimacy level with the fire. For Australia, Beck & Zhao (2000) describes the probability of fire location based on statistics. Similar probabilities for Sweden are found in Nystedt (2003).

Table 7.3 Fire location probabilities (Beck & Zhao, 2003; Nystedt, 2003)

Fire location	Kitchen	Bedroom	Living room
Australia	0.64	0.22	0.14
Sweden	0.28	0.30	0.42

As the sizes of the apartments differ, difficulties using these statistics for every case arise. Some assumptions are therefore made:

- The room connected to the corridor is the kitchen
- Toilets, bathrooms and smaller spaces have not been explicitly modelled
- A two room apartment is assumed to exist of a kitchen and a bedroom
- In case a certain room is missing in the apartment, the probability distribution will be calculated as the ratio between the existing ones. For example, if a living room is missing in an Australian apartment, the probability for a "kitchen fire" is thus

$$P(kitchen) = \frac{0.64}{(0.64 + 0.22)} = 0.74$$

- If there are several spaces that serve the same purpose, the probability is split. For example, a Swedish apartment containing two bedrooms. Each bedroom is then assumed to have a probability according to

$$P(bedroom) = \frac{0.3}{2} = 0.15$$

7.3 Design fire

The design fire modelled in the apartments have been done as described in section 3.5.

7.3.1 Growth phase

A few methods to model fire growth were found as can be seen in section 3.5.1. For flaming fires the growth phase have been assumed to follow a t-squared fire as described by Eq. 3.11. The fire growth rates derived by Nystedt (2003) are given for the first item ignited and no modelling of fire spread is being carried out, this method was discarded. Karlsson & Quintiere (2000) suggested a 'medium' (0.012 kW/s²) growth rate for dwellings. However, from Andersson & Wadensten (2002) it can be seen that the category 'interior' was associated with an expected fire growth rate of 0.03 kW/s², a significant difference. Holborn et al. (2004) applied a more holistic approach to apartment fire growth rates. From their analysis it was possible to derive percentiles of fire growth rates. The 95th percentile for residential fires (see Table 3.3) was calculated to 0.024 kW/s² which is also in more agreement with the fire growth rate suggested by Andersson & Wadensten (2002). For flaming fires, the fire growth rate used in the base calculations was therefore conservatively set to 0.024 kW/s².

For smouldering fires, the correlation described in Eq. 3.10 has been used.

7.3.2 Peak or controlled phase

It has been assumed that sufficient fuel is present within apartments for the fire always being able to reach a ventilation controlled state. Therefore, no consideration is taken to the compartment fire being limited due to the fuel present in the apartment.

In the case of sprinkler failure or no sprinklers present, the fire is assumed to become ventilation controlled (section 7.3.2.1). If sprinkler activates, the fire development have been modelled according to section 7.3.2.2.

7.3.2.1 Ventilation controlled fire

Karlsson & Quintiere (2000) describes a method to calculate the peak heat release rate in a ventilation controlled fire. It should be noted that this method assumes gas temperatures around 600°C and may therefore bias the calculations when this criteria is not fulfilled. Dimensions of openings in accordance with section 7.4 are used to calculate the maximum inflow of air into the compartment according to Eq. 7.2.

$$\dot{m}_a = 0.5 \cdot A_O \sqrt{H_O} \qquad \textbf{(Eq. 7.2)}$$

where

$\dot{m}_a$	mass flow rate of air [kg/s]
A_O	area of opening [m²]
H_O	height of opening [m²]

By assuming that the fire consumes all oxygen for combustion, the maximum heat release rate can be calculated as per Eq. 7.3 (Karlsson & Quintiere, 2000).

$$\dot{Q}_{VC} = 1518 \cdot A_O \sqrt{H_O} \qquad \textbf{(Eq. 7.3)}$$

where

$\dot{Q}_{VC}$	ventilation controlled peak HRR [kW]

$$E = 13100 \cdot V \cdot (0.23 - 0.1) \cdot \rho_{air} \qquad \textbf{(Eq. 7.4)}$$

E	energy [kJ]
V	volume [m³]
ρ_{air}	air density (approx. 1.2 kg/m³) [kg/m³]

7.3.2.2 Sprinkler suppressed fire

Staffansson (2010) discusses approaches to model affects on fire growth when sprinkler activation occurs. One approach is to try to model the reduction in HRR. However, such approach assumes that all fires are suppressed by sprinklers. Another approach suggests that the HRR at activation will determine the effect of the sprinkler. One such assumption which has been adopted is described by Eq. 7.5.

$$\dot{Q}_{sprinkler} = \begin{cases} \dot{Q}_{sprinkler} = 1/3 \cdot \dot{Q}_{act} & , \dot{Q}_{act} \leq 5MW \\ \dot{Q}_{sprinkler} = \dot{Q}_{act} & , \dot{Q}_{act} > 5MW \end{cases} \qquad \textbf{(Eq. 7.5)}$$

where

$\dot{Q}_{sprinkler}$	sprinkler controlled heat release rate [kW]
$\dot{Q}_{act}$	heat release rate at sprinkler activation [kW]

This is believed to provide a conservative estimate of the sprinkler effect as it is not unlikely that the fire will become completely suppressed.

7.3.3 Decay phase

Simple calculations show that the fuel load within a normal compartment exceeds by far the time frame for what may be of risk to occupants within the apartment of fire origin (Bengtson et al, 2005; ABCB, 2005). Any modelling of the decay phase has therefore been assumed unnecessary.

7.4 Openings

The availability of openings play an important part in the development of a fire in an apartment as it may be the difference between a fire that self-extinguishes and a flashover. However, the presence of openings (other than permanent) is difficult to estimate. Some examples are door blocked open, an open window or window breaking due to the fire, etc. This parameter significantly affects the calculated risk while at the same time it is difficult to quantify the probability of it occurring. These parameters have therefore been included as control parameters. The factors concerning openings that have been modelled this way are

- Corridor door open/closed
- Window open/closed
- Internal doors open/closed (for all rooms)

In case of doors and windows are open, the area which they allow flow through will vary according to the size of the opening and the effective open area. The minimum requirements provided in the BBR states very low criteria for allowing a window as an exit (Boverket, 2008). Normal sized windows are generally considerably larger than this minimum requirement. In the calculations, it has been assumed that a window have the dimensions 1.0 x 1.2 m (W x H). Similarly, door openings have been assumed to have the dimensions 0.9 x 2.0 m (W x H).

When there are no windows available in the specific room, this has been modelled as leak paths with the total dimension 0.1 x 0.1 m^2.

7.5 Temperature

In scenarios where openings are present (e.g. open door or window), temperature within the enclosure is calculated in accordance with Eq. 7.6 (McCaffrey et al, 1981).

$$T_g = T_a + 6.85\left(\frac{\dot{Q}^2}{A_O\sqrt{H_O}h_k A_T}\right)^{1/3} \quad \textbf{(Eq. 7.6)}$$

where

T_g	upper layer temperature [°C]
T_a	ambient temperature [°C]
h_k	heat transfer coefficient [kW/(m²K)]
A_O	area of opening [m²]
H_O	height of opening [m²]
A_T	total area of internal surfaces [m²]

The temperature rise calculated by Eq. 7.6 predicts an immediate temperature rise within the compartment, neglecting transport time for the hot gases. Therefore, the temperature rise within the smoke layer has been delayed with transport time calculated as described in section 7.7.1.2.

In the case where the fire is fully enclosed without any openings (other than small leakages), a different approach has been adopted to estimate the temperature within the apartment. Assuming that no energy transfer through the solid surroundings occurs and the room can be considered a homogenous zone, a simple estimate of the temperature is given by Eq. 7.7.

$$T_g = T_a + \frac{\int_{t_0}^{t} \dot{Q}dt}{V \cdot \rho_{air} \cdot c_p} \quad \textbf{(Eq. 7.7)}$$

where

c_p	specific heat capacity for air [kJ/kg·K]

7.6 Consequence assessment

The consequences of occupants in the apartment of fire origin have been estimated as per section 7.6.1. Some assumptions were necessary to enable for calculating estimates with hand calculations, such as

- If the fire is not recognized, either by fire cues or by failure of fire safety systems, the occupants are assumed to become fatalities.
- Volumes are controlled by control parameters. For example, internal doors being open or closed. The FED calculations have been carried out for the entire volume.

7.6.1 Fractional Effective Dose

Lethal doses of toxic gases produced in fires can be estimated with the Fractional Effective Dose method described in section 3.9. In the model, fatalities have been estimated by the expressions as follows. A few assumptions are made for this calculation, such as

- One zone model (concentration is uniform for all connected spaces)
- No consideration is taken to outflow through window
- Incapacitation and death is assumed to only rely on doses from heat and carbon monoxide (CO)

Following the concept described in section 3.9.1, fractional incapacitating doses are calculated for CO and heat. Fractional Incapacitating Dose (FID) is described by Eq. 7.8 (Purser, 2008).

$$FID = FID_{CO} \cdot VCO_2 + FID_{HEAT} \quad \textbf{(Eq. 7.8)}$$

where

VCO_2 respiratory minute volume correction factor [-]

7.6.1.1 Carbon Monoxide (CO)

The respiratory volume is a function of the concentration of carbon dioxide (CO_2) which is described by Eq. 7.9 (Purser, 2008).

$$VCO_2 = \frac{\exp(0.1903 \cdot \%CO_2 \cdot 2.0004)}{7.1} \quad \textbf{(Eq. 7.9)}$$

For CO, the FID is described by Eq. 7.10.

$$FID_{CO} = \frac{3.317 \cdot 10^{-5} \cdot [CO]^{1.036} \cdot RMV \cdot t}{W_{CO}} \quad \textbf{(Eq. 7.10)}$$

where

$[CO]$ concentration of CO [ppm]
RMV respiratory minute volume [l/min]
t time [min]
W_{CO} incapacitating dose for CO [%]

The dose and respiratory minute volume changes for different activities. It is suggested that a dose equal to 40% and RMW of 8.5 l/min is used for escaping occupants (Purser, 2008).

7.6.1.2 Heat

Purser (2008) also describes the FED from heat. Incapacitation or death can occur as a result of either heat stroke, skin burns or respiratory tract burns. However, tenability limits are lower for burns to occur on skin than respiratory tracts and therefore it is not necessary to consider both. The FED calculations concerning heat are described by Eq. 7.11 - Eq. 7.13.

$$FID_{HEAT} = \int_{t_0}^{t} \left(\frac{1}{t_{I_{rad}}} + \frac{1}{t_{I_{conv}}} \right) dt \quad \textbf{(Eq. 7.11)}$$

$$t_{I_{rad}} = \frac{16.7}{q^{1.33}} \quad \textbf{(Eq. 7.12)}$$

$$t_{I_{conv}} = 2 \cdot 10^{18} \cdot T_{\exp}{}^{-9.0403} + 10^{8} \cdot T_{\exp}{}^{-3.10898} \quad \textbf{(Eq. 7.13)}$$

where

$t_{I_{rad}}$ time to fatal exposure from radiation [min]
$t_{I_{conv}}$ time to fatal exposure from convective heat [min]

q	radiant heat flux [kW/m²]
T_{exp}	exposure temperature [°C]

Exposure temperature has been assumed to be the same as the smoke layer temperature which is a conservative assumption (at least in the initial stages of the fire). Radiant heat flux between two surfaces can be calculated as

$$q = \frac{\Phi \cdot \varepsilon \cdot \sigma_B \cdot \left(T_g^4 - T_a^4\right)}{1000} \qquad \textbf{(Eq. 7.14)}$$

σ_B	Stefan Bolzmann constant ($5.67 \cdot 10^{-8}$) [$Wm^{-2}K^{-4}$]
ε	emissivity (assumed to be 1.0)
Φ	configuration factor [-]

The configuration factor relates to the geometry of the emitting body (i.e. smoke layer) and is described by the following expression (Tien et al, 2002)

$$\Phi = 4 \cdot \frac{1}{2\pi}\left[\frac{X}{\sqrt{1+X^2}}\tan^{-1}\left(\frac{Y}{\sqrt{1+X^2}}\right) + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right)\right] \qquad \textbf{(Eq. 7.15)}$$

$$X = \frac{w}{2\Psi}$$

$$Y = \frac{L}{2\Psi}$$

where

w	width [m]
L	length [m]
Ψ	distance between surfaces [m]

Since equations Eq. 7.11 - Eq. 7.15 seek to determine the heat dose received by an occupant, we assume that the distance between the emitting surface (smoke layer) and an occupant by an average value. It has been assumed that the distance between emitting and receiving surface can be described by Eq. 7.16. This equation assumes that the average distance from the smoke layer to a human can be describes as the ceiling height minus one meter above floor (assumed average height of human).

$$\Psi = H - 1 \qquad \textbf{(Eq. 7.16)}$$

where

H	ceiling height [m]

Naturally, not all rooms have a completely rectangular shape. In designs where this was not possible, the viewing factor was estimated by a rectangular shape with the same area.

7.6.2 Yields

Nystedt (2003) suggested the following yields when assessing the risk in apartments.

Table 7.4 CO and CO_2 yields for flaming fires (Nystedt, 2003)

Ventilation conditions	Carbon monoxide, CO [kg/kg]	Carbon dioxide, CO_2 [kg/kg]
Well-ventilated	0.005	1.3
Ventilation controlled	0.19	0.8

For smouldering fires, yields differ from flaming fires. McKenzie et al. (1994) retrieved yields for wood seen in Table 7.5.

Table 7.5 CO and CO_2 yields for smoldering fires (McKenzie et al., 1994)

	Carbon monoxide, CO [kg/kg]	Carbon dioxide, CO_2 [kg/kg]
Wood	0.15	0.87

7.7 Fire safety systems

When assessing fire safety systems as events in a fire development, it is sought to estimate the probability of transition from one state to another. For example, consider a normal smoke detector. In the event of a fire, it is beneficial to know how 'often' the smoke detector is providing occupant warning. Commonly in fire engineering design, only reliability of the fire safety system is considered. However, as described in Gravestock (2008), there are more failure modes than just the component malfunctioning. Instead, he estimates system effectiveness based on

- Reliability – the probability of the component working as intended
- Unavailability – the probability of the system being unavailable due to repair time, no power source, etc.
- Efficacy – the probability of a fire safety component achieving desired effect

By use of fault tree methodology he was able to derive system effectiveness for different fire safety systems, which are later presented in Table 7.6 and Table 7.9.

7.7.1 Smoke detectors

Different smoke detectors are associated with varying effectiveness when detecting different types of fires (Gravestock, 2008; Geiman and Gottuk, 2003). In apartment buildings, the most common detector types are either photoelectric or ionizing. No statistics have been found concerning the use of certain detector types. However, the author have theorized that ionizing detectors are more commonly used in Sweden whereas photoelectric are dominating in Australia.

7.7.1.1 Effectiveness

Smoke detectors are a common protective fire safety measure in residential premises due to fire safety provisions in building codes. For smoke detectors, system reliability differs between ionizing and photoelectric detection mechanisms. It is also common separate effectiveness for both flaming and smouldering fires. This is mainly because the two types differ in the combustion products that are produced. In Table 7.6, system effectiveness is presented for different system configurations in apartment buildings.

Table 7.6 Smoke detection system effectiveness for apartment buildings. Reproduced with data from Gravestock (2008)

Design scenario		**Flaming**			**Smouldering**		
Detector type	Detectors	Expected	Lower	Upper	Expected	Lower	Upper
Photoelectric	Single	88.2 %	72.5 %	98.2 %	93.1 %	63.4 %	98.2 %
Photoelectric	Multiple	96%	87 %	99 %	96.5 %	82.4 %	98.9 %
Ionizing	Single	92.1 %	81.6 %	98.2 %	88.2 %	63.4 %	98.2 %
Ionizing	Multiple	97.5 %	89.7 %	99.1 %	95.1 %	82.4 %	98.9 %

7.7.1.2 Activation time

For the purpose of performing hand calculations, time steps of one second have been used. Smoke detector activation has been calculated using the obscuration created by the fire. The criteria for activation is given according to Eq. 7.17 (ABCB, 2005).

$$D > D_{act} \qquad \textbf{(Eq. 7.17)}$$

where

D smoke obscuration [m^{-1}]
D_{act} smoke obscuration required for detector activation [m^{-1}]

Assuming well mixed conditions, the smoke obscuration can be described by Eq. 7.18 (Mulholland, 2008)

$$D = \frac{D_g \cdot \Delta m}{V_s} \qquad \textbf{(Eq. 7.18)}$$

where

D_g mass optical density [m^2/g]
Δm mass loss [g]
V_s volume of smoke [m^3]

The mass optical density produced for different wooden and plastic materials are provided in Mulholland (2008), which have been used to create Table 7.7.

Table 7.7 Mass optical density (data from Mulholland (2008))

	D_m (mass optical density) [m²/g]		
Type of combustion	Min	Mean	Max
Pyrolysis	0.12	0.34	0.64
Flaming	0.12	0.54	1.4

For flaming fires, the fire is assumed to form a hot smoke layer under the ceiling. It is also assumed that all smoke produced is contained within this smoke layer. The smoke layer thickness can be calculated according to (ABCB, 2005)

$$\frac{z}{H} = 0.91 \cdot \left(\frac{t^{3/5} \cdot H^{2/5}}{\left(\frac{1055}{\dot{Q}} \right)^{1/5} \cdot A_f^{3/5}} \right)^{-1.45} \qquad \textbf{(Eq. 7.19)}$$

where

z	smoke layer thickness [m]
H	ceiling height [m]
$\dot{Q}$	heat release rate [kW]
A_f	floor area [m²]
t	time [s]

Eq. 7.19 combined with the floor area provides an estimate of the smoke layer volume for use in Eq. 7.18. For smouldering fires, it is assumed that the generated heat is not sufficient to form a hot layer and the gases are instead assumed to be well mixed within the room. Therefore, the volume has been assumed to equal the room volume when calculating smoke detector activation from smouldering fires according to Eq. 7.18.

The smoke obscuration is also dependant on the mass produced in the fire. For smouldering fires the mass loss can be calculated from Eq. 3.10. For flaming fires the mass generated at each time step can be described by

$$\dot{m} = \frac{\dot{Q}}{H_c \cdot X} \qquad \textbf{(Eq. 7.20)}$$

where

H_c	heat of combustion [kJ/kg]
X	combustion efficiency [-]

However, the mass released needs to be transported to the ceiling before forming a smoke layer. This time lag for the smoke layer formation is inherently built into Eq. 7.19. By extracting the time for which the smoke layer has formed, the smoke obscuration in the smoke layer can be adjusted according to this time lag. The mass flow is also dependant on the heat of combustion as can be seen in Eq. 7.20. In turn, the heat of combustion is dependant on the material(s) burning. Comparing table 3-4.16 in Tewarson (2008), it is concluded that materials assumed to be found in apartments (mostly wood and plastics) range between roughly 15 and 40 MJ/kg. It is assumed that 27 MJ/kg is representative of an apartment.

The smoke obscuration required for smoke detector activation has been shown to vary considerably by Geiman and Gottuk (2003). Their research provided a statistical base for determining smoke detector response according to smoke obscuration levels. The data was summarized in Custer et al (2008) which is shown in Table 7.8.

Table 7.8 Threshold values for smoke detectors (Custer et al, 2008)

Fire type	OD Alarm threshold	Ionizing detectors [m^{-1}]	Photoelectric detectors [m^{-1}]
Flaming	20 %	0.007 ± 0.004	0.031 ± 0.016
	50 %	0.021 ± 0.005	0.063 ± 0.029
	80 %	0.072 ± 0.027	0.106 ± 0.039
Smouldering	20 %	0.045 ± 0.028	0.032 ± 0.016
	50 %	0.113 ± 0.048	0.059 ± 0.019
	80 %	0.176 ± 0.052	0.110 ± 0.034

7.7.2 Sprinklers

Sprinklers have a significant impact on fires if working as intended. The effect of successful sprinkler activation is lower temperatures, production of less toxic gases and lower visibility.

7.7.2.1 Reliability and effectiveness

Malm & Pettersson (2008) conducted a comprehensive study on sprinkler reliability world wide. The analysis shows that there are large differences in sprinkler reliability, both on a national basis and compared world wide. For Australia, over 100 years of experience with automatic sprinkler systems provided a very reliable source of data up to 1986. An overall sprinkler reliability of 99.5% was reported for general building types in Australia by Marryatt (1988). A more detailed investigation of the statistics provided by Marryatt shows that during the period 1886 – 1986 only 33 fires were reported in sprinklered apartment buildings. All of these were reported being controlled by the sprinkler and no casualties were suffered. This sample should be used with caution since the sample size is relatively small and perhaps biased due to changing conditions since the analysis was performed.

Gravestock (2008) have summarized sprinkler system effectiveness, similar to the data presented for smoke detectors in 7.7.1. The data provided in Table 7.9 shows sprinkler effectiveness distribution given a flaming fire.

Table 7.9 Sprinkler system effectiveness (no smouldering fires) (Gravestock, 2008)

Design scenario		**Effectiveness**		
Water supply	Location	Expected	Lower	Upper
Single town main supply	Auckland	98 %	87 %	99.5 %
Diesel Pump and Tank Supply	Any	97.7 %	74 %	99.4 %
Dual supply: Diesel pump and tank; town main	Auckland	98.3 %	97 %	99.6 %

It has been assumed that the sprinklers will not activate in case of a smouldering fire.

7.7.2.2 Activation time

For *flaming* fires, time of sprinkler activation has been calculated as follows (ABCB, 2005).

The temperature rise in a ceiling jet is described by Eq. 7.21.

$$T_g - T_a = \begin{cases} \dfrac{16.9 \cdot \dot{Q}^{2/3}}{H^{5/3}} & , r/H \leq 0.18 \\ \dfrac{5.38 \cdot \left(\dot{Q}/r\right)^{2/3}}{H} & , r/H > 0.18 \end{cases} \qquad \text{(Eq. 7.21)}$$

where

T_g	upper layer temperature [°C]
T_a	ambient temperature [°C]
$\dot{Q}$	heat release rate [kW]
H	ceiling height [m]
r	radial distance from fire plume [m]

For the same ceiling jet, the velocity of the flowing gases at a given point can be calculated by Eq. 7.22.

$$u = \begin{cases} 0.95 \cdot \left(\dfrac{\dot{Q}}{H}\right)^{1/3} & , r/H \leq 0.15 \\ \dfrac{0.2 \cdot \dot{Q}^{1/3}\sqrt{H}}{r^{5/6}} & , r/H > 0.15 \end{cases} \qquad \text{(Eq. 7.22)}$$

where

u	velocity of the ceiling jet [m/s]

The response from a heat sensing device is described by Eq. 7.23.

$$\frac{dT_d}{dt} = \frac{\sqrt{u}\left(T_g - T_d\right)}{RTI} \qquad \text{(Eq. 7.23)}$$

where

T_d	device temperature [°C]
RTI	response time index of device [$m^{1/2}s^{1/2}$]
t	time [s]

Activation temperature and RTI of sprinklers are acquired by complying with minimum requirements of standards. The placement of sprinklers has been carried out according to minimum requirements of the building code and related standards.

7.8 Occupant characteristics

7.8.1 Number of occupants

The number of occupants and the location of these in relation to fire location and exit locations will affect the probability of the fire resulting in fatalities.

The number of occupants in an apartment can be said to somewhat correlated to the number of rooms (and size). From Australian Bureau of Statistics (ABS) census data from 2006 gives the distribution of number of occupants in apartments according to Table 7.10.

Table 7.10 Occupant distribution in apartments (ABS, 2010a; ABS, 2010b)

Number of persons usually resident	1	2	3	4	5	6+	**Total**
None (includes bedsitters)	2.02%	0.19%	0.02%	0.01%	0.00%	0.00%	**2.24%**
1 bedroom	18.25%	3.99%	0.33%	0.05%	0.01%	0.00%	**22.63%**
2 bedrooms	28.80%	20.48%	6.30%	2.42%	0.52%	0.15%	**58.67%**
3 bedrooms	4.21%	5.51%	2.80%	1.84%	0.54%	0.23%	**15.14%**
4 bedrooms	0.25%[1]	0.27%	0.18%	0.22%	0.12%	0.06%	**1.10%**
5 or more bedrooms	0.00%[1]	0.07%	0.04%	0.04%	0.04%	0.03%	**0.21%**
Total	**53.52%**	**30.51%**	**9.67%**	**4.59%**	**1.23%**	**0.48%**	**100.00%**

[1] For ABS 2 (2010) '4 or more bedrooms' was largest housing category

For the purpose of simplification, only apartments up to 4 bedrooms and up to 4 occupants were considered. This still constitutes 94.6 % of the apartments shown in Table 7.10. The adjusted table is shown in Table 7.11.

Table 7.11 Assumed occupant distribution

	Number of persons usually resident				
Apartment size	1	2	3	4	**Total**
1 bedroom	20.65%	4.26%	0.35%	0.06%	**25.32%**
2 bedrooms	29.34%	20.87%	6.42%	2.47%	**59.10%**
3 bedrooms	4.29%	5.61%	2.86%	1.88%	**14.64%**
4 bedrooms	0.25%	0.28%	0.18%	0.23%	**0.94%**
Total	**54.53%**	**31.02%**	**9.81%**	**4.64%**	**100.00%**

Given that the size of the apartment is known, occupant distribution can be described by Table 7.12.

Table 7.12 Occupant distribution given different apartment sizes

	Number of persons usually resident				
Apartment size	1	2	3	4	Total
1 bedroom	81.5%	16.8%	1.4%	0.2%	**100.0%**
2 bedrooms	49.6%	35.3%	10.9%	4.2%	**100.0%**
3 bedrooms	29.3%	38.3%	19.5%	12.8%	**100.0%**
4 bedrooms	26.8%	29.5%	19.6%	24.1%	**100.0%**

The occupant distribution presented here is assumed to describe both Australia and Sweden.

7.8.2 Occupant location

The model takes into account the level of intimacy with the fire and therefore assumptions must be made on this. This most significant difference is assumed to be due to level of awareness (sleeping/awake). The author was not able to find any statistics or research to support time spent in different parts of apartments and therefore this had to be made an assumption. The assumed probabilities for individuals being in the different parts of an apartment are shown in Table 7.13.

Table 7.13 Assumed occupant locations. Figures in bracket show probability during night.

	Kitchen	**Bedroom**	**Living room**
3 Rooms	0.2 (0.01)	0.05 (0.96)	0.75 (0.03)
2 Rooms	0.7 (0.02)	0.3 (0.98)	N/A
1 Room	1.0 (1.0)	N/A	N/A

7.8.3 Awareness level

The level of awareness (e.g. sleeping, awake, intoxicated) will be important when assessing the probability of an occupant is receiving warning of the fire hazard. The model takes into account if the occupants are awake or sleeping, however this is not modelled individually for each occupant. Therefore, scenarios where multiple occupants are present, these are only modelled as one status of awareness. This affects the cue recognition times and thus the time until fire detection.

To calculate occupancy load (see section 7.10.3) it has been assumed that occupants on average sleep 7 hours per night. This is based on the authors perception of what can be considered an average number of hours of sleep among healthy normal humans.

7.8.4 Walking speed

Walking speed varies for several reasons. There is a natural variation among people and it can therefore be considered being a stochastic factor. However, factors such as age, sex, mobility status, etc. will also affect the speed of movement.

Another factor that need to considered when estimating the time for escape is building occupant density in relation to available exits, there might arise situations where these exits work as 'bottlenecks' and thus determine the travel time. If the population density is less than 0.54 persons/m^2 of an exit route 1.85 m^2/person, the occupants will escape at their own (individual) pace (Nelson & Mowrer, 2002). 1.19 m/s is suggested as unimpeded maximum speed by an able-bodied occupant.

Fahy & Proulx (1997) provides some guidance on walking speed for occupants measured from evacuation drills as shown in Table 7.14.

Table 7.14 Walking speeds (Fahy & Proulx, 1997)

Occupancy type	Type	Mean speed [m/s]	Range [m/s]
High-rise	Drill	1.05	0.57 – 1.20
High-rise	Drill	0.95	0.56 – 1.12

It seems as 1.2 m/s is representing the upper bound of the distribution of walking speeds. If a more conservative approach is to be taken, the walking speed should be set to the lower bounds and thus representing a larger proportion of the distribution of the occupants.

7.9 Human behaviour and response

Human responses to fire cues and the resulting behaviour comprises of many complex interactions. A description of theory is given in section 3.7.

7.9.1 Fire detection

It is assumed that occupants can become aware of a fire from either direct perception of fire cues or by alarm signals. Time until fire detection occurs have been assumed to be described by Eq. 7.24.

$$t_d = \min\left(t_{d,fc}, t_{d,a}\right) \quad \textbf{(Eq. 7.24)}$$

where

t_d	time until occupant becomes aware of hazard [s]
$t_{d,fc}$	time until fire cues are perceived by occupants [s]
$t_{d,a}$	time until alarm sound notifies occupant [s]

7.9.1.1 Fire cues

There is a lack of information regarding criteria for fire cue recognition. Literature suggests that there is an increased risk when sleeping as the lower level of awareness increases the time until fire is detected (Tubbs & Meacham, 2007). In this thesis, fire detection through direct perception is assumed to come from hot smoke layer, radiation from smoke layer or sufficient large flame size according to Table 7.15. It should be noted that since there is a lack of data regerding fire cue recognition, criteria was assumed and therefore the magnitude of uncertainty introduced by the assumptions in Table 7.15 is unknown.

Table 7.15 Fire recognition criteria for fires

		Criteria	
Fire type	**Fire cue**	Awake	Sleeping
Flaming	Upper layer temperature	100 °C	130 °C
	Radiant heat flux	1.2 kW/m²	1.5 kW/m²
	Flame height	0.6 m	1.2 m
Smouldering	Visibility	100 m	N/A

Further, it is also assumed that at least one occupant have to be in the room of fire origin or in a connected space to be able to detect the fire. Direct perception of flame is assumed to only happen if at least one occupant is in the room of fire origin.

Flame height has been calculated as (Karlsson & Quintiere, 2000)

$$L_f = 0.235\dot{Q}^{2/5} - 1.02D \qquad \textbf{(Eq. 7.25)}$$

where

L_f	flame height [m]
K	flame base diameter [m]

The diameter is unknown and there by assuming that dwelling interiors produce a heat release rate equal to 250 kW/m² (Staffansson, 2010), the diameter can be correlated to the heat release rate by Eq. 7.26.

$$\dot{Q} = \dot{Q}'' \cdot \pi\left(\frac{K}{2}\right)^2 \qquad \textbf{(Eq. 7.26)}$$

By merging Eq. 7.25 with Eq. 7.26, the following expression is derived

$$L_f = 0.235\dot{Q}^{2/5} - 1.02\sqrt{\frac{4\dot{Q}}{250\pi}} \qquad \textbf{(Eq. 7.27)}$$

For smouldering fires, cue recognition is more complicated as they give away less cues and Beck et al. (2006) uses a time-based approach to the probability of an occupant successfully perceiving a fire cue. This seems natural for growing fire scenarios as time passes, fire cues becoming increasingly evident.

It has also been noted that many of the fire related deaths occur when only one occupant is present in the apartment. This suggests a decreased risk for occupancies where there are several occupants present. For awake occupants, this seems logic as it is more probable that the perception of the occupants cover a larger area. The model accounts for this as the people are distributed differently according to the time of day. For example, during the day people are more likely to be spread out in the apartment whereas during the night it is very likely that they are positioned in the bedroom(s). As it is assumed that occupants being in the room of fire origin are more likely to early detect the fire, more occupants in an apartment increases the probability of early detection.

7.9.1.2 Alarms

It is assumed that once any type of alarm has been successfully activated, the occupants immediately hear the signal and become aware. For apartment buildings this can be smoke detection systems, smoke alarms or sprinkler system (linked to occupant warning system). Effectiveness and time to activation has been presented in section 7.7.

7.9.2 Pre-movement time

Some background to pre-movement times are given in section 0. However, it must be distinguished that this will differ for the apartment of fire origin and the other dwellings within the building. Most research has been carried out for the entire building, i.e. measuring this time for all dwellings. For fire drills, this naturally implies that there is no pre-movement time for an apartment where a fire in a real world situation would occur.

For occupants being awake and aware, the recognition time is suggested to be short. For sleeping occupants this becomes more difficult to estimate. There are large uncertainties associated with occupants perception of fire cues or alarm signals. Literature suggests that it is indeed longer for sleeping than for awake occupants (Tubbs & Meacham, 2007).

For response time, it is assumed that occupants being awake and have recognized a fire cue, the response time will be very short. Being awake and receiving an alarm signal, it is assumed that the occupant first will perform an investigation before starting the evacuation. For sleeping occupants being exposed to fire cues and alarm signals, the time increases as there is a larger probability that the occupants have to get dressed, make others aware, etc.

The assumed pre-movement times are shown in Table 7.16.

Table 7.16 Assumed pre-movement time

	Awake	Sleeping
Direct perception of fire cue	15 s	100 s
Alarm signal	45 s	130 s

Further, it should be noted that in this model, fire cues are assumed to be registered when the criteria (Table 7.15) is satisfied. In reality, this is more likely to follow a probability distribution as pointed out by Beck et al (2006).

7.9.3 Travel time

The travel time has been calculated as described by Eq. 3.17. The travel distance to a 'safe place' has been set as the place where no further exposure is assumed to occur. Sets of control parameters where the corridor door is initially shut, the corridor becomes the place of safety. On the other hand, if the door is open, it is assumed that exposure also occurs in the corridor and the 'safe place' is assumed to be when the occupant has reached the end of the corridor.

If there is more than one occupant present in the apartment, it is assumed that the occupant with longest walking distance will determine the travel time. This is based on the assumption that occupants evacuate in groups and are unwilling to leave anyone behind.

7.10 Other

7.10.1 Day of week

Occupancy load will differ during the week which partially depends on which day of the week the fire occurs. Probability of occupants being present during weeks and weekends will vary.

7.10.2 Time

Time of the day is a variable that will affect occupancy load and awareness status. Assumption necessary to calculate occupancy load are given in section 7.10.3

7.10.3 Occupancy load

Occupancy load describes the percentage of the people living in the building are present at a given time. No data have been found regarding this and the following tables includes, by the author, assumed occupancy loads.

A fire occurring without any occupants present will not result in any consequences (for the AFO). Therefore, an estimate of the average time spent in the apartment becomes important. It should also be noted that there is a correlation between occupants present and fires that may need to be investigated more closely.

It is assumed that the average person spends the night (7 hours) plus afternoon/evening (7 hours) awake in their home during weekdays and the night (7 hours) plus 10 hours in their home during weekends. The average probability of being present at any given time is thus

$$p_p = \frac{5}{7} \cdot \frac{(7+7)}{24} + \frac{2}{7} \cdot \frac{(7+10)}{24} = 0.619 \quad \textbf{(Eq. 7.28)}$$

The conditional probability of being asleep is thus

$$P(sleeping \mid p_p) = \frac{5}{7} \cdot \frac{7}{14} + \frac{2}{7} \cdot \frac{7}{17} = 0.474 \quad \textbf{(Eq. 7.29)}$$

and naturally the conditional probability of being awake is

$$P(awake \mid p_p) = 1 - P(sleeping \mid p_p) = 0.526 \quad \textbf{(Eq. 7.30)}$$

7.11 Summary table

Table 7.17 provides a summary of the values and parameter settings used when estimating the risk in the different designs (see Chapter 8).

Table 7.17 Summary of variables used

Variable	BCA		BBR	
	Building 1	Building 2	Building 1	Building 2
Fire ignition [$year^{-1}$]	Estimated from Eq. 7.1			
Fire location (kitchen/bedroom/living room)	0.64 / 0.22 / 0.14		0.28 / 0.30 / 0.42	
Fire type (flaming/smouldering)	0.755 / 0.245			
Fire growth rate [kW/s^2]	0.024			
Heat of combustion [kJ/kg]	27 000			
Combustion efficiency [-]	0.7			
CO yield flaming (well ventilated/ventilation controlled) [kg/kg]	0.005 / 0.19			
CO yield smouldering [kg/kg]	0.15			
CO_2 yield flaming (well ventilated/ventilation controlled) [kg/kg]	1.3 / 0.8			
CO_2 yield smouldering [kg/kg]	0.87			
Detector type	Photoelectric		Ionizing	
Mass optical density [m^2/g] (flaming/smouldering)	0.54 / 0.34			
Smoke det. activation threshold, photoelectric [m^{-1}] (flaming/smouldering)	0.106 / 0.09			
Smoke det. activation threshold, ionizing [m^{-1}] (flaming/smouldering)	0.072 / 0.176			
Number of detectors	1 per apartment			
Sprinkler system effectiveness	N/A	0.977	N/A	N/A

Water supply system	N/A	Tank and pump	N/A	N/A
RTI [$m^{1/2}s^{1/2}$]	N/A	350	N/A	N/A
Activation temperature [°C]	N/A	68	N/A	N/A
Number of sprinkler	N/A	1 per 21 m^2	N/A	N/A
Compartment size	1 – 4 rooms	1 – 2 rooms	1 – 4 rooms	1 – 2 rooms
Number of occupants	1 – 4			
Occupant location(s)	See section 7.8.2			
Material	Concrete			
Opening areas (door/window)	2 x 0.9 m / 1.2 x 1 m (H x W)			
Occupants present (time of the day)	0.619			
Awareness (awake/sleep)	0.525 / 0.475			
Walking speed [m/s]	0.65			
Internal travel distance [m]	0 – 20	0 - 10	0 - 15	0 - 12
Corridor travel distance [m]	1 - 6	13 – 28.5	1 - 10	4 - 10
Cue recognition criteria, awake (upper layer temp./rad. Heat flux/flame height/visibility)	100 °C / 1.2 kW/m^2 / 0.6 m / 100 m			
Cue recognition criteria, sleeping (upper layer temp./rad. Heat flux/flame height/visibility)	130 °C / 1.5 kW/m^2 / 1.2 m / -			

Chapter 8 - Results

The model used to quantify the risk to occupants in apartments was outlined in Chapter 5. Applying this model to the case study apartment buildings presented in Chapter 6 together with the necessary input and assumptions provided in Chapter 7 (summary table of input and assumptions in section 7.11), risk estimates were calculated for each building, apartment and set of control parameters. C1 – C9 in the tables presented in this chapter refers to control parameters presented in section 5.5.

The individual risk calculated is presented both as an absolute risk, describing the annual risk (as defined in 5.2) for an individual residing in a specific apartment (e.g. rows in Table 8.1), and as a relative risk for which risk differences can be view in a normalized table (e.g. Table 8.2). Apartments consisting of only one room, sets of control parameters with 'internal doors' set to 'open' were not applicable and the risk was therefore not calculated. These are labelled in the below tables as 'N/A'.

A sensitivity analysis was also carried out to examine the output sensitivity to the model input and assumptions. Results from this analysis with discussion are found in section 8.3.

8.1 Building 1 (Mid-rise)

Building 1 was chosen as a 5 storey high building with 12 apartments per storey. The layout of the building designs according to both the BCA and the BBR can be seen in Figure 6.3.

8.1.1 BCA (Australia)

The estimated absolute risk for Building 1 designed according to the BCA is shown in Table 8.1.

Table 8.1 Estimated absolute individual risk (per year) for Building 1 designed according to the BCA.

Apartment	C1	C2	C3	C4	C5	C6	C7	C8	C9	Avg.
A	$6.67E^{-4}$	$2.70E^{-4}$	$4.97E^{-4}$	$2.82E^{-4}$	$2.69E^{-4}$	$2.13E^{-4}$	$2.85E^{-4}$	$2.61E^{-4}$	$2.13E^{-4}$	$3.29E^{-4}$
B	$3.82E^{-4}$	$4.89E^{-4}$	$3.81E^{-4}$	$1.74E^{-4}$	$4.09E^{-4}$	$8.45E^{-5}$	$1.71E^{-4}$	$4.08E^{-4}$	$8.42E^{-5}$	$2.87E^{-4}$
C	$4.34E^{-4}$	$5.20E^{-4}$	$4.31E^{-4}$	$1.84E^{-4}$	$4.36E^{-4}$	$1.26E^{-4}$	$1.00E^{-4}$	$4.34E^{-4}$	$1.26E^{-4}$	$3.10E^{-4}$
D	$7.78E^{-4}$	$4.53E^{-4}$	$7.76E^{-4}$	$3.25E^{-4}$	$4.27E^{-4}$	$3.34E^{-4}$	$2.38E^{-4}$	$4.39E^{-4}$	$4.24E^{-4}$	$4.66E^{-4}$
E	$3.37E^{-4}$	N/A	$3.37E^{-4}$	$1.12E^{-4}$	N/A	N/A	$1.12E^{-4}$	N/A	N/A	$2.25E^{-4}$
F	$3.45E^{-4}$	N/A	$1.15E^{-4}$	$1.15E^{-4}$	N/A	N/A	$1.15E^{-4}$	N/A	N/A	$1.73E^{-4}$

The maximum estimated individual risk is approximately 9 times the minimum. The average risk for each apartment has been calculated by equally weighting each estimated risk for C1 – C9. The lowest estimated average risk and the highest differ by a factor of 2. This suggests that the large differences are mainly due to the control settings.

The risk has been normalized by setting the estimated risk for apartment A and control parameters 'C1' as relative risk 1.0. Table 8.2 shows the relative relationship for the risks presented in Table 8.1.

Table 8.2 Relative risk (per year) for Building 1 designed according to the BCA

Apartment	C1	C2	C3	C4	C5	C6	C7	C8	C9
A	1.0	0.4	0.7	0.4	0.4	0.3	0.4	0.4	0.3
B	0.6	0.7	0.6	0.3	0.6	0.1	0.3	0.6	0.1
C	0.7	0.8	0.6	0.3	0.7	0.2	0.1	0.7	0.2
D	1.2	0.7	1.2	0.5	0.6	0.5	0.4	0.7	0.6
E	0.5	N/A	0.5	0.2	N/A	N/A	0.2	N/A	N/A
F	0.5	N/A	0.2	0.2	N/A	N/A	0.2	N/A	N/A

As can be seen in Table 8.2, the different control settings influence the risks significantly. It is also found that the largest risks are associated with the larger apartments. It is theorized by the author that this is mainly due to scenarios where there is a single or few occupants present in a large occupancy, resulting in a decreased likelihood for an early detection. A fire that grows larger before detection is more likely to produce a higher toxic potency in the apartment, so when an occupant begins to evacuate, even short exposure times may result in large inhaled doses.

8.1.2 BBR (Sweden)

The estimated absolute risk for Building 1 designed according to the BBR is shown in Table 8.3.

Table 8.3 Estimated absolute individual risk (per year) for Building 1 designed according to the BBR

Apartment	C1	C2	C3	C4	C5	C6	C7	C8	C9	Avg.
A	7.82E-4	3.22E-4	2.68E-4	3.88E-4	3.00E-4	2.73E-4	2.96E-4	2.96E-4	3.20E-4	3.61E-4
B	5.08E-4	5.10E-4	4.21E-4	2.48E-4	5.07E-4	2.51E-4	2.51E-4	5.08E-4	2.56E-4	3.84E-4
C	5.22E-4	5.22E-4	4.33E-4	1.68E-4	5.23E-4	2.56E-4	1.68E-4	5.23E-4	2.92E-4	3.79E-4
D	9.08E-4	3.96E-4	3.72E-4	4.97E-4	3.46E-4	5.04E-4	4.98E-4	3.38E-4	5.00E-4	4.84E-4
E	3.10E-4	N/A	9.45E-5	9.45E-5	N/A	N/A	9.45E-5	N/A	N/A	1.48E-4
F	3.48E-4	N/A	1.06E-4	1.06E-4	N/A	N/A	1.06E-4	N/A	N/A	1.67E-4

The maximum estimated individual risk is approximately 10 times the minimum. The lowest estimated average risk and the highest differ by a factor of 3. On average, the BBR design shows somewhat higher calculated risks compared to its BCA counterpart shown in Table 8.1.

The estimated risks in Table 8.3 are shown as relative risks in Table 8.4.

Table 8.4 Relative risk (per year) for Building 1 designed according to the BBR

Apartment	C1	C2	C3	C4	C5	C6	C7	C8	C9
A	1.0	0.4	0.3	0.5	0.4	0.3	0.4	0.4	0.4
B	0.6	0.7	0.5	0.3	0.6	0.3	0.3	0.6	0.3
C	0.7	0.7	0.6	0.2	0.7	0.3	0.2	0.7	0.4
D	1.2	0.5	0.5	0.6	0.4	0.6	0.6	0.4	0.6
E	0.4	N/A	0.1	0.1	N/A	N/A	0.1	N/A	N/A
F	0.4	N/A	0.1	0.1	N/A	N/A	0.1	N/A	N/A

8.1.3 Comparison

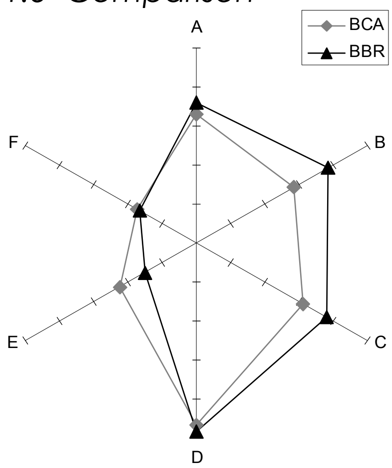

Figure 8.1 Comparison of average apartment risk

The estimated risk for the BBR is somewhat higher in almost every case compared to the building designed according to the BCA, see Figure 8.1. Studying the ratio between the estimated risk for each apartment and set of control parameters for the different country specific designs, it is found that the largest differences are found for scenarios where the corridor door is closed. This suggests that the travel distance is not the major contributor to the differences in the estimated risks.

8.2 Building 2 (High-rise)

Building 2 was chosen as a 10 storey building with 16 apartments on each storey. The layout of the building designs according to both the BCA and the BBR can be seen in Figure 6.4.

8.2.1 BCA (Australia)

The estimated absolute risk for Building 2 designed according to the BCA is shown in Table 8.5

Table 8.5 Estimated absolute individual risk (per year) for Building 2 designed according to the BCA

Apartment	C1	C2	C3	C4	C5	C6	C7	C8	C9	Avg.
A	$3.41E^{-4}$	$3.39E^{-4}$	$2.74E^{-4}$	$1.43E^{-4}$	$2.72E^{-4}$	$4.25E^{-5}$	$1.42E^{-4}$	$2.74E^{-4}$	$4.30E^{-5}$	$2.08E^{-4}$
B	$3.42E^{-4}$	$3.40E^{-4}$	$2.74E^{-4}$	$1.42E^{-4}$	$2.72E^{-4}$	$4.17E^{-5}$	$1.42E^{-4}$	$2.71E^{-4}$	$4.32E^{-5}$	$2.08E^{-4}$
C	$3.24E^{-4}$	N/A	$3.24E^{-4}$	$3.44E^{-5}$	N/A	N/A	$3.44E^{-5}$	N/A	N/A	$1.79E^{-4}$
D	$3.24E^{-4}$	N/A	$3.24E^{-4}$	$3.44E^{-5}$	N/A	N/A	$3.44E^{-5}$	N/A	N/A	$1.79E^{-4}$

The maximum estimated individual risk is approximately 9 times the minimum. The estimated average risks for the different apartments are similar.

The estimated risks in Table 8.5 are shown as relative risks in Table 8.6.

Table 8.6 Relative risk (per year) for Building 2 designed according to the BCA

Apartment	C1	C2	C3	C4	C5	C6	C7	C8	C9
A	1.0	1.0	0.8	0.4	0.8	0.1	0.4	0.8	0.1
B	1.0	1.0	0.8	0.4	0.8	0.1	0.4	0.8	0.1
C	1.0	N/A	1.0	0.1	N/A	N/A	0.1	N/A	N/A
D	1.0	N/A	1.0	0.1	N/A	N/A	0.1	N/A	N/A

8.2.2 BBR (Sweden)

The estimated absolute risk for Building 2 designed according to the BBR is shown in Table 8.7

Table 8.7 Estimated absolute individual risk (per year) for Building 2 designed according to the BBR

Apartment	C1	C2	C3	C4	C5	C6	C7	C8	C9	Avg.
A	$7.84E^{-4}$	$3.14E^{-4}$	$2.69E^{-4}$	$3.86E^{-4}$	$2.99E^{-4}$	$3.21E^{-4}$	$2.70E^{-4}$	$3.03E^{-4}$	$3.13E^{-4}$	$3.62E^{-4}$
B	$3.97E^{-4}$	$3.22E^{-4}$	$4.24E^{-4}$	$1.93E^{-4}$	$1.21E^{-4}$	$1.21E^{-4}$	$1.93E^{-4}$	$1.21E^{-4}$	$1.21E^{-4}$	$2.24E^{-4}$
C	$3.23E^{-4}$	N/A	$9.86E^{-5}$	$9.86E^{-5}$	N/A	N/A	$9.86E^{-5}$	N/A	N/A	$1.55E^{-4}$
D	$3.18E^{-4}$	N/A	$9.68E^{-5}$	$9.68E^{-5}$	N/A	N/A	$9.68E^{-5}$	N/A	N/A	$1.52E^{-4}$

The maximum estimated individual risk is approximately 8 times the minimum. The estimated average risks for the different apartments are fairly similar.

The estimated risks in Table 8.7 are shown as relative risks in Table 8.8.

Table 8.8 Relative risk (per year) for Building 2 designed according to the BBR

Apartment	C1	C2	C3	C4	C5	C6	C7	C8	C9
A	1.0	0.4	0.3	0.5	0.4	0.4	0.3	0.4	0.4
B	0.5	0.4	0.5	0.2	0.2	0.2	0.2	0.2	0.2
C	0.4	N/A	0.1	0.1	N/A	N/A	0.1	N/A	N/A
D	0.4	N/A	0.1	0.1	N/A	N/A	0.1	N/A	N/A

8.2.3 Comparison

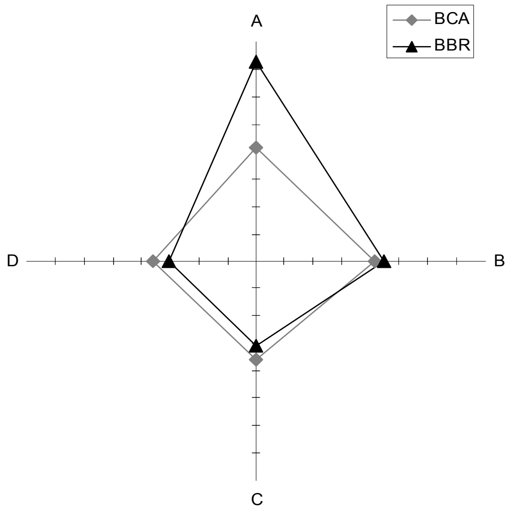

Figure 8.2 Comparison of average apartment risk

A comparison of the results from the Australian and Swedish designs shows some interesting results. The risk in the apartments designed according to the two codes are very similar which suggests that sprinklers designed according to minimum requirements do not reduce risks significantly for the occupants in the apartment of fire origin.

However, analysing the ratio between the estimated risk for each set of control parameters, apartment and building code; it is found that there are larger variations than for Building 1.

8.3 Sensitivity analysis

A sensitivity analysis was carried out to study the variation in output from the model in relation to input variables. The sensitivity analysis aims to identify the variables that introduce large uncertainties to the output.

BCA apartment A, Building 3 (see section 6.2.2) was chosen as base case (BC) for the sensitivity analysis. It comprises of a two room apartment with an approximate floor area of 40 m^2. As much information regarding influence from the different control parameters (see section 5.5) are presented in the above results section, only one set of control parameters (C9) were applied in the sensitivity analysis.

An initial test performed was to investigate the contribution of risk from flaming and smouldering fire scenarios respectively. For the base case it was found that flaming fires only represent ¼ of the total calculated risk.

The full sensitivity analysis of the variables can be found in Appendix C. A selection of variables is presented as relative risks below.

8.3.1 Fire growth rate

It is well known that fire growth rate constitutes a very important variable in fire safety engineering applications. Because it is correlated to the amount of heat and mass released and thus it was theorized that it would affect the risk. There was a significant variation in risk noted when the fire growth rate was varied, see Figure 8.3.

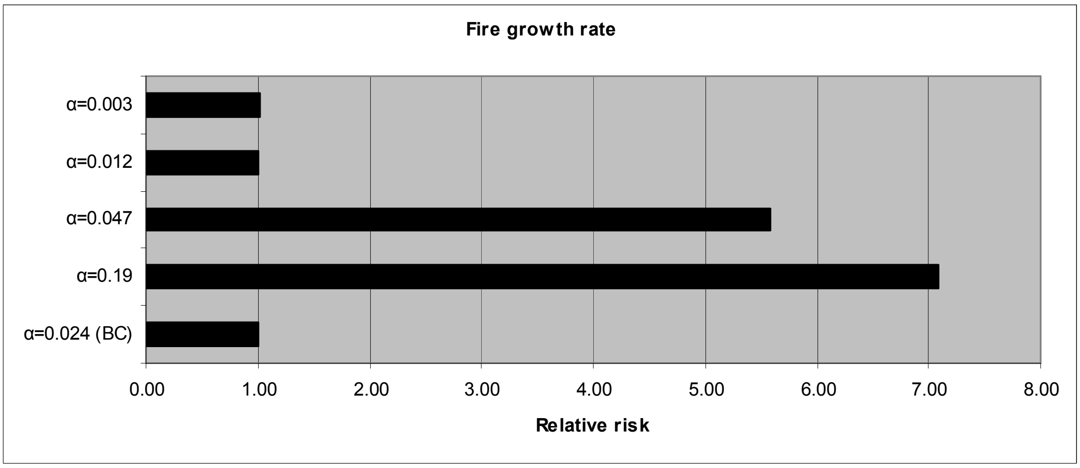

Figure 8.3 Sensitivity of fire growth rate

Setting the fire growth rates to 'fast' or 'ultra fast' has significant effect on the risk as it increases by a factor of 5.5 and 7 respectively. Reducing the fire growth rate to 'medium', reduced the risk by half. However, when reducing the parameter even further to a 'medium' or 'slow' growth rates, no reduction in risk was achieved. As this parameter only affects *flaming* fires, it is theorized that the majority of the fatalities predicted in general is caused by smouldering fires. However, it is not impossible that the risk for occupants in small enclosures remain the same or even increase for a slower growth rate. It is theorized by the author that this could be caused by more toxic gases being accumulated before occupants become aware of the fire and thus being exposed to larger doses before successful escape.

8.3.2 Heat of combustion

By its definition, heat of combustion provides a correlation between released energy and released mass. The sensitivity analysis of this parameter is shown in Figure 8.4. Increasing the heat of combustion will reduce the amount of mass released for a given quantity of heat produced which suggests that the risk will decrease with increasing heat of combustion. However, this may be a result of the construction of the model. It is theorized that there is a positive correlation between heat of combustion and heat release rate. Because these are not correlated in the model this may bias the result.

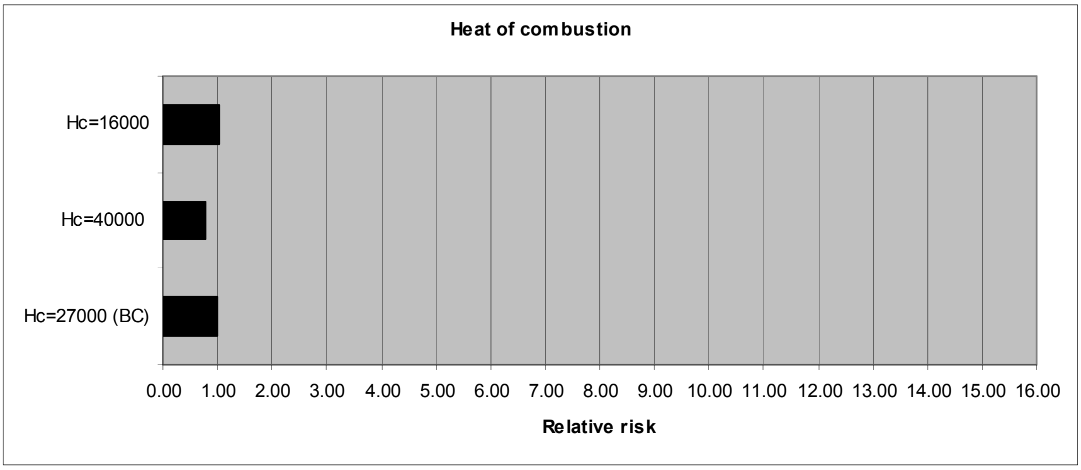

Figure 8.4 Sensitivity of heat of combustion

Interesting to note is that the model does not predict an increase in risk when heat of combustion is lowered.

8.3.3 Yields

Specified yields in the model directly affect the released CO and CO_2. While CO_2 was not modelled as a contributor to incapacitation and death, it affects the respiratory rate and thus the amount of inhaled toxins. However, the sensitivity analysis showed no significant increase or decrease in the risk for this parameter (see Appendix C section C.4).

In contrary, yield of CO showed large variations of the estimated risk for some conditions. In Figure 8.5 variations for well ventilated (fuel controlled) conditions and flaming fires are displayed. Very small or no variations in risk were noted for this particular setup. For ventilation controlled conditions the results of the sensitivity analysis were similar (see Appendix C section C.4). Again, as the base case indicated that the majority of the risk comes from smouldering scenarios, the risk contribution from changing parameters only affecting flaming scenarios is small.

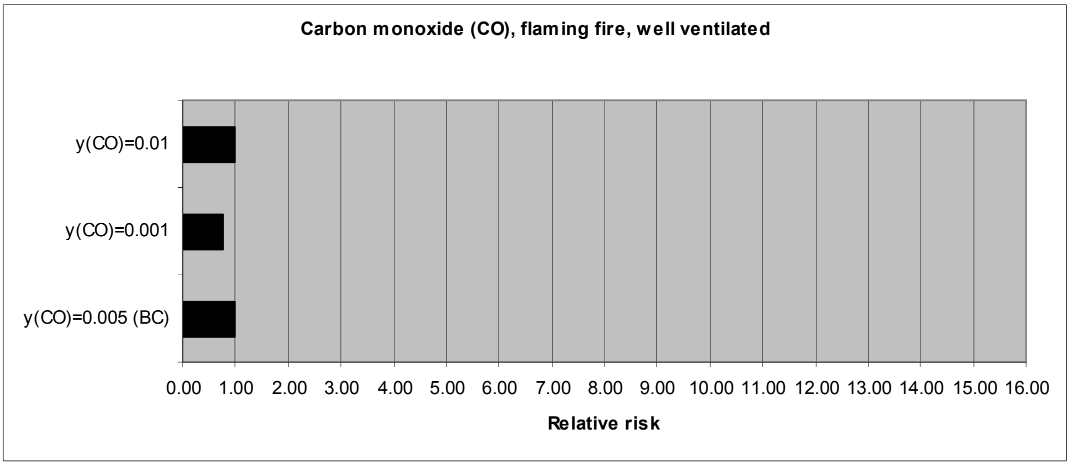

Figure 8.5 Sensitivity of carbon monoxide yield for flaming fires and well ventilated conditions

For smouldering fires a positive correlation was noted when increasing the yield of CO, see Figure 8.6. Both increasing and decreasing the parameter had significant effect on the estimated risk. Since only limited data was collected on CO yield for smouldering fires, it is suggested that this variable is introducing uncertainty. Also proven to affect the estimated risk significantly, it is unknown to what extent the used data relates to real world applications.

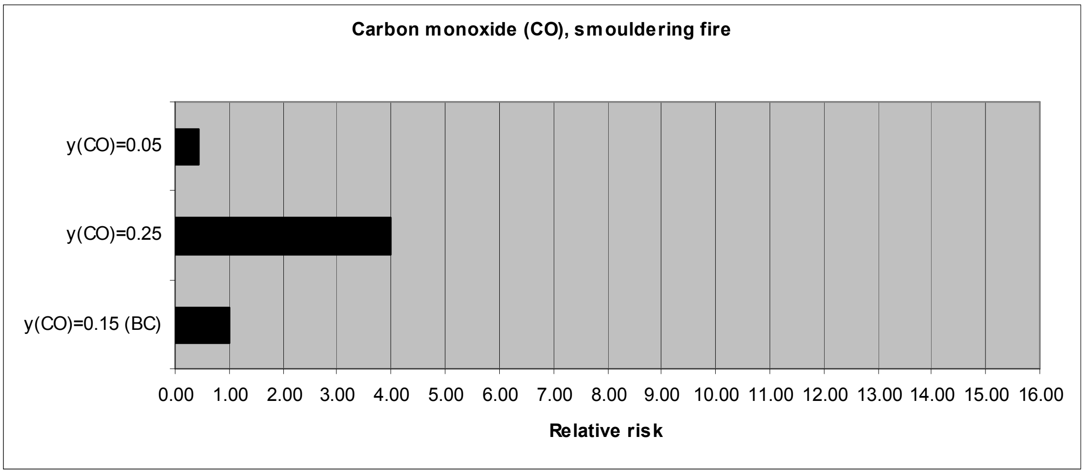

Figure 8.6 Sensitivity of carbon monoxide yield for smouldering fires

8.3.4 Smoke detection

The influence of different smoke detector type is shown in Figure 8.7. Using an ionizing detector increased the risk for the base case scenario. This may be explained by the decreased probability of detecting smouldering fires. Because of problems related to a specific smouldering fire scenario (see discussion in 9.1), an increase in smouldering fires not being detected will have a direct effect on the risk.

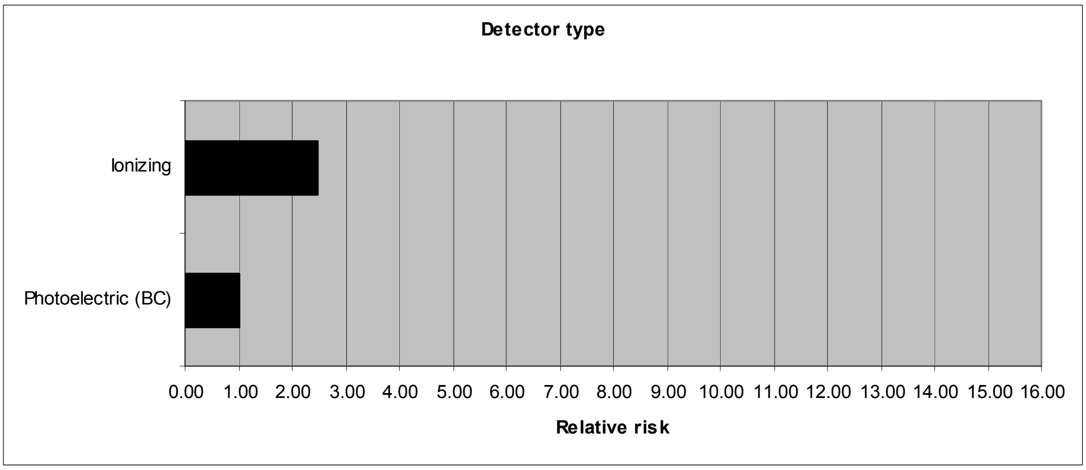

Figure 8.7 Sensitivity to detector type

Mass optical density describes the mass fraction of smoke produced for combusted fuels. In turn, optical density governs smoke detection. In Figure 8.8 it is shown that decreasing the mass optical density, i.e. producing less smoke per combusted fuel, increases the risk which is expected. In reality, it is theorized that this variable is correlated to yields and type of fuel. Neglecting this, the result may become biased. It can also be seen that increasing the mass optical density does not decrease the risk which could be expected. A possible reason for this is that the flaming scenarios in the base case do not contribute significantly to the calculated risk.

Sensitivity of mass optical density was also analysed for flaming fires. However, the same sensitivity was not noted for flaming fires.

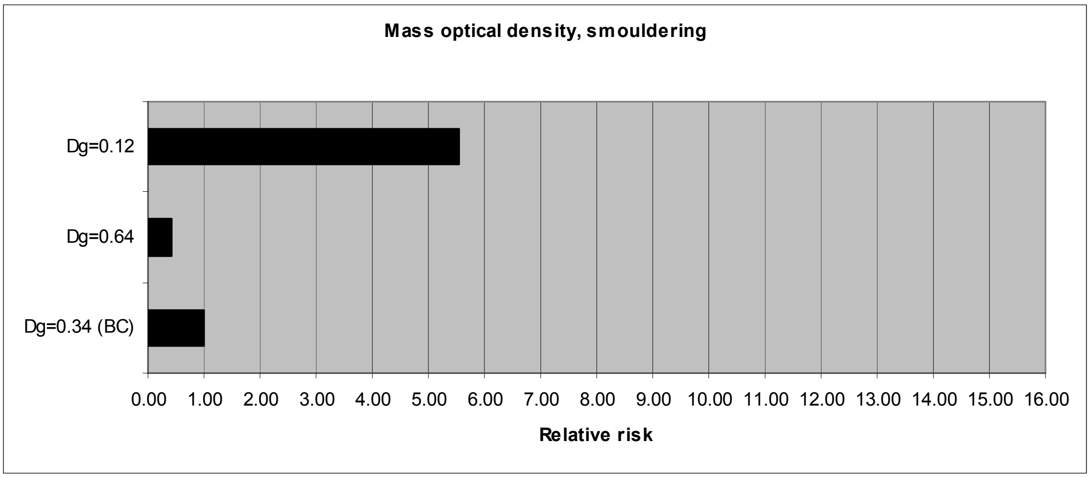

Figure 8.8 Sensitivity of mass optical density for smouldering fires

The effect on an extra smoke detector was also investigated as it was theorized that this would reduce the risk. The model predicts that for the base case, no reduction is achieved by this increased measure. However, it is theorized that more detectors become more important when the apartment size is large in relation to the number of present occupants.

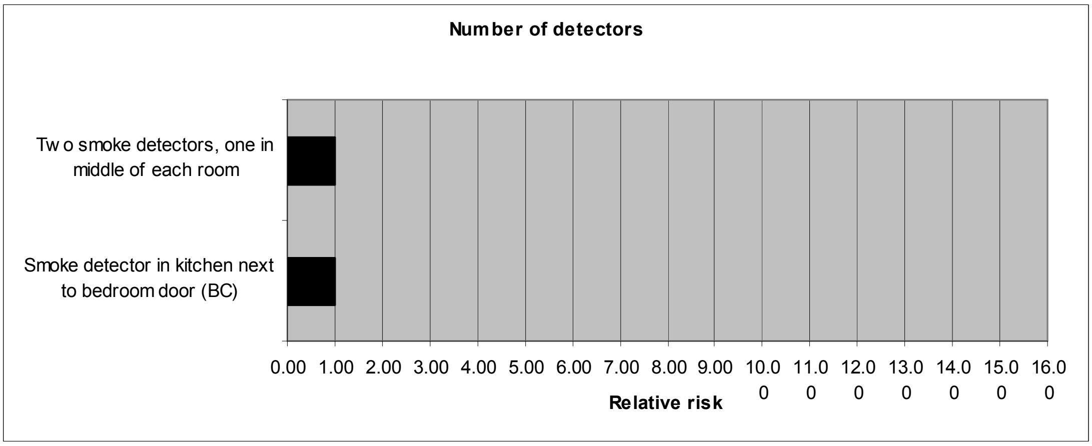

Figure 8.9 Sensitivity to number of detectors

8.3.5 Sprinklers

Model output sensitivity was also studied for sprinkler related variables. An interesting conclusion was that sprinkler effectiveness had little effect on the calculated risk, see Figure 8.10. This suggests that not many fatalities are avoided due to sprinklers according to this model.

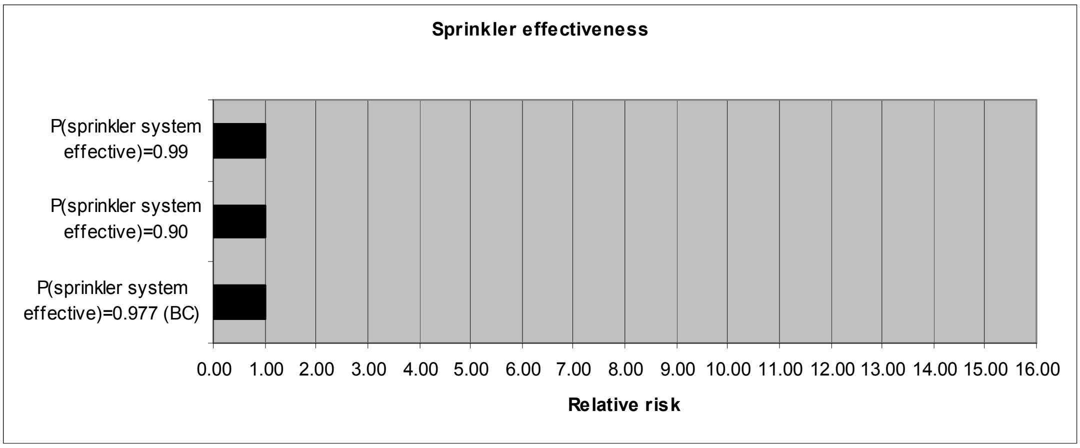

Figure 8.10 Sensitivity of sprinkler effectiveness probability

The presented results were calculated with maximum allowed RTI and activation temperature allowed by the building code. However, setting these parameters to more commonly found values, a reduced risk was achieved. The effects for varying the RTI is shown in Figure 8.11 and activation temperature in Figure 8.12. Using conservative values for these two variables, it is probable that this contributes to an overestimation of the risk compared to common design values.

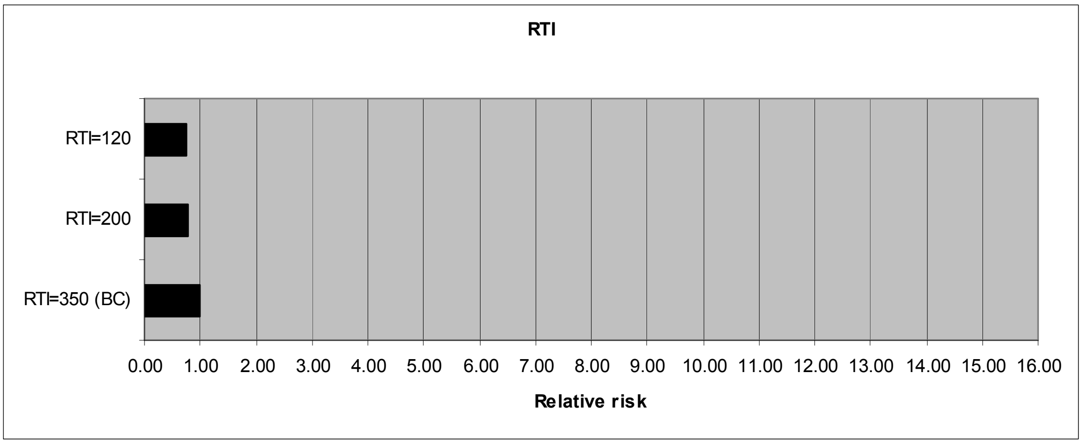

Figure 8.11 Sensitivity of sprinkler RTI

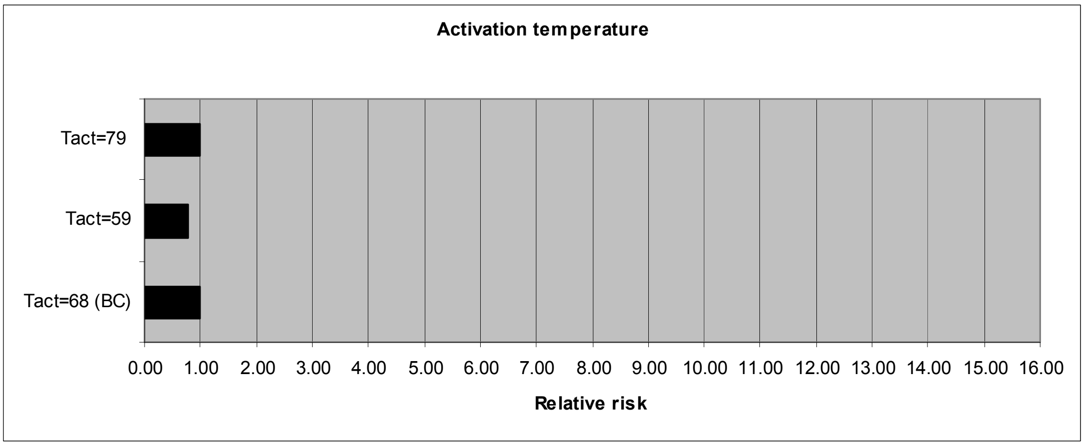

Figure 8.12 Sensitivity of sprinkler activation temperature

In the risk estimation, a conservative approach was also taken when setting horizontal sprinkler distance from the fire location. Maximum distance from sprinkler placing to any wall was assumed for this variable. Naturally, this is a function of where the fire occurs within the room, and in reality this will vary. Therefore, it was of interest to see how this affects the calculated risk. In Figure 8.13 it can be seen that decreasing the distance results in a lower risk as expected. However, increasing the distance does not result in an increased risk. Again, the sensitivity analysis suggests that actual sprinkler effectiveness does not decrease the risk. However, sprinklers do provide extra means of notification and a fire close to the sprinkler (in combination with successful sprinkler activation) will lead to early detection of the fire. When the sprinkler distance is increased, an explanation to the lack of increased risk may be that other means of detection mitigates risk increase.

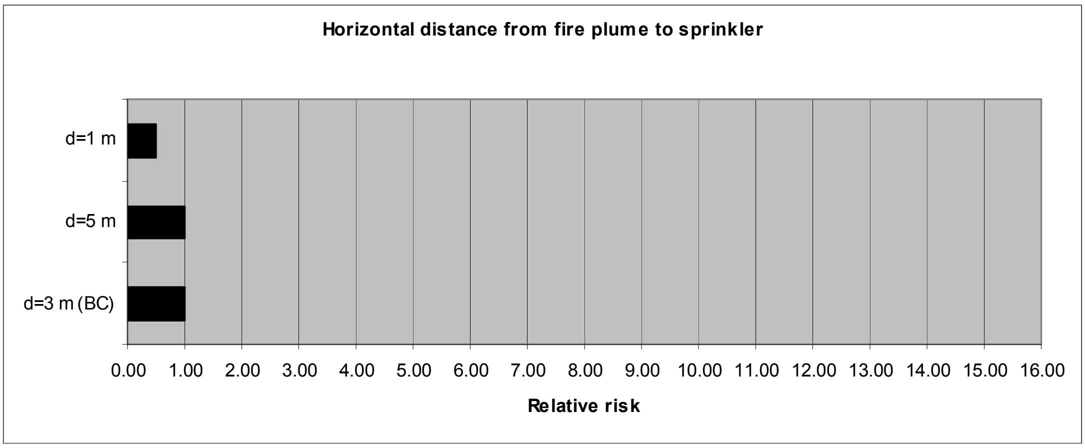

Figure 8.13 Sensitivity of horizontal distance to sprinkler

8.3.6 Material

Assuming different apartment enclosure materials showed a little variation in risk except for 'Lightweight concrete' which display among the largest variations found in the sensitivity analysis, see Figure 8.14. The material is utilized as input for the smoke layer temperature calculation which in turn is used to predict incapacitation and death from heat and radiation. In essence, the calculations assume different heat transfer coefficients which describe how much energy is lost to the surrounding boundary by Eq. 7.6. Clearly, the assumptions associated with this using this equation significantly affects the estimated risk as it is not likely that boundary materials will have a significant effect on the risk in the initial stages of an enclosure fire.

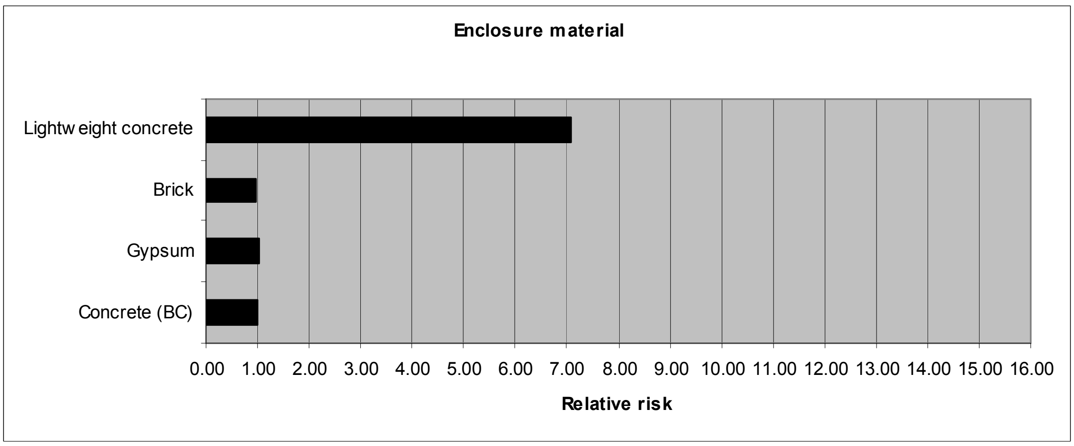

Figure 8.14 Sensitivity of enclosure material

8.3.7 Occupant characteristics

Assumptions were necessary when setting pre-movement times for occupants due to lack of available data. Generally, no large differences in risk were noted when the assumed pre-movement time was varied. However, in some cases, a significant difference was noted, see for example section C.8.9 in Appendix C. In reality, pre-movement time will be determined by a much more complex process than the model accounts for. For example, the pre-movement time is likely to differ depending on whether an occupant is in the room of fire origin or an adjacent room. This is not taken into account and will affect the risk.

8.3.8 Egress

Walking speed was conservatively assumed to be 0.65 m/s in the calculations, referring to the lower bound in Table 7.14. Comparing to the estimated risk to the suggested upper bound can be seen in Figure 8.15.

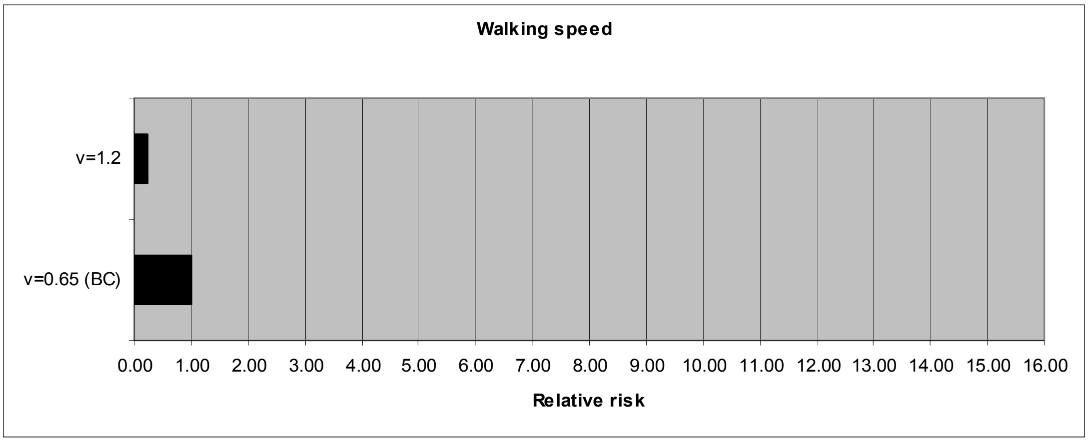

Figure 8.15 Sensitivity of walking speed

Walking speed and travel distance together determines the travel time to a place of relative safety. In Figure 8.16 and Figure 8.17 the effects of varied internal and corridor travel distance are shown. Interesting to note is that internal travel distance showed no variation in the estimated risk. It is believed that this is a result of this particular case, the time variation achieved by varying the internal travel distance does not result in more or less lethal scenarios for this particular case. However, this is calculated on a case to case basis and therefore choosing another room as base case could have shown variations in risk.

As an average concentration in the entire connected volume was assumed when calculating FED (see further discussion in section 9.3), the increase in risk for longer travel distances in the corridor may become overestimated. The sensitivity analysis shows tendencies that travel time will affect the risk for occupants in an apartment where the fire occurs.

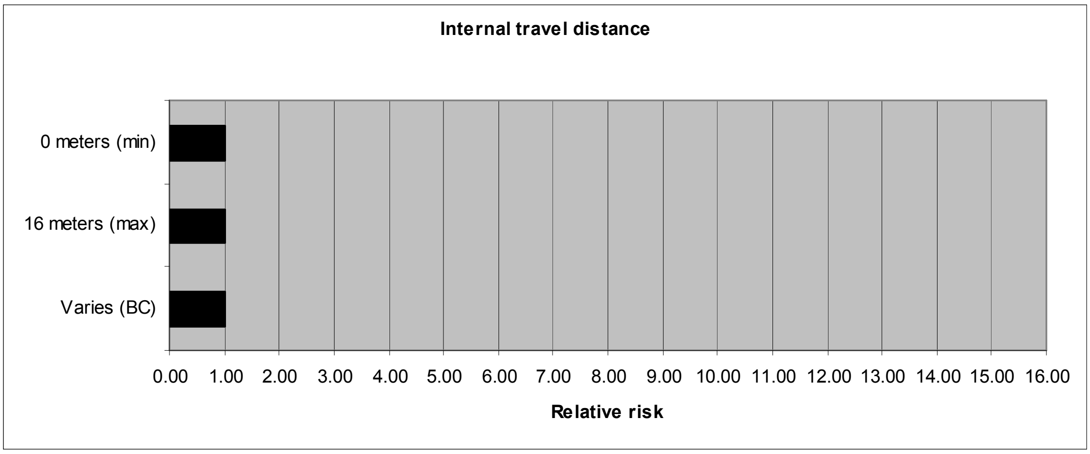

Figure 8.16 Sensitivity of internal travel distance

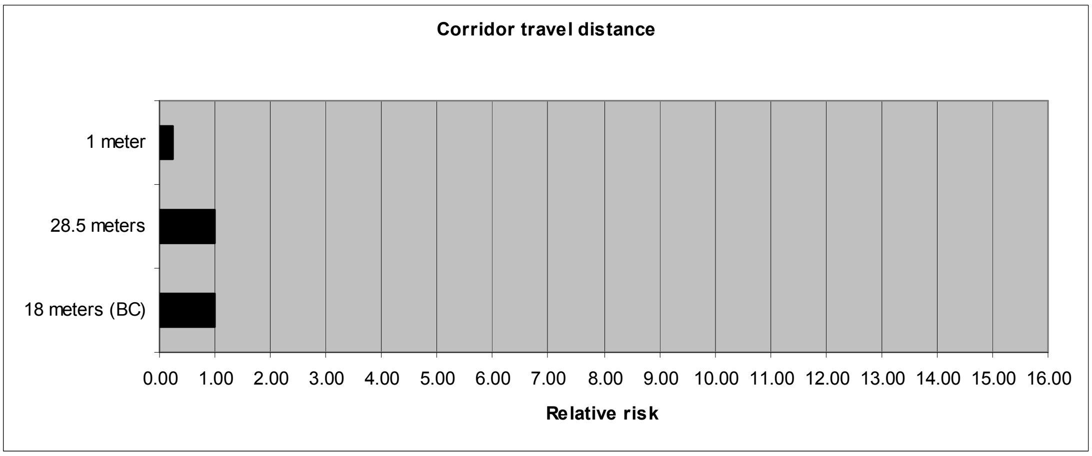

Figure 8.17 Sensitivity of corridor travel distance

In the above discussion it was theorized that concentrations affecting escaping occupants in the corridor biased the estimates, a sensitivity analysis was carried out on the effect of changing the corridor volume which can be seen in Figure 8.18. As expected, the risk is reduced with a increased volume. However, reducing the volume by half is not sufficient to increase the estimated risk. More accurately sub-modelling of concentrations in space and time would therefore be beneficial for this type of risk calculation.

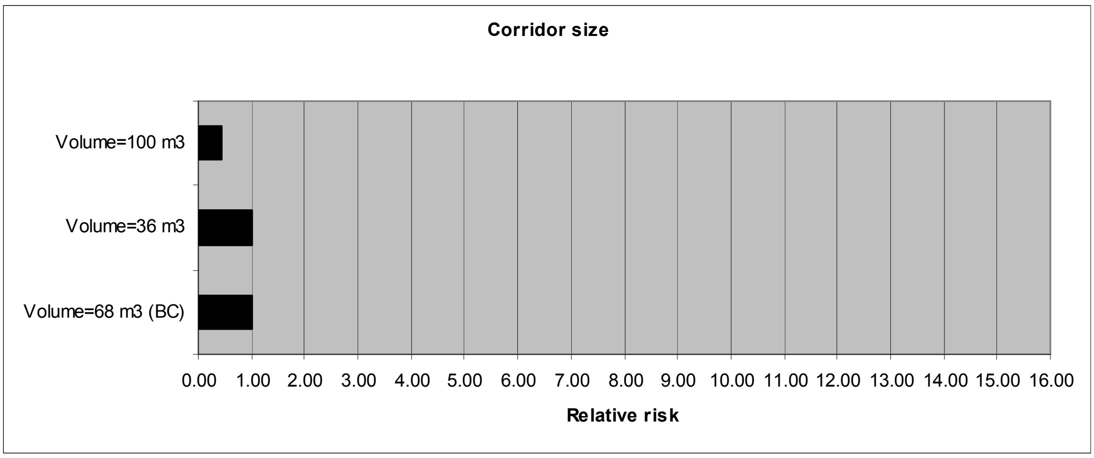

Figure 8.18 Sensitivity of corridor size

8.3.9 Concluding remarks

It is clear that this sensitivity analysis (and the results in general) may have become biased due to the large contribution in risk from smouldering scenarios. A more thorough investigation of different room configurations would have provided a better understanding of the model behaviour. However, this is subject to future research as it has not been possible to cover in this report.

Chapter 9 - Discussion

9.1 Discussion of results

9.1.1 Estimated risk and comparison

Studying the absolute risk levels achieved by the different building code designs, apartments and set of control parameters; it is evident that there are large variations in the estimated individual risk. These range from $3.44 \cdot 10^{-5}$ (lowest) to $9.08 \cdot 10^{-4}$ (highest) per year, the difference being a factor of approximately 26. To actually quantify the overall risk for a residential building is therefore a very difficult task in itself. An average risk was calculated by a weighted average for the nine sets of control parameters (C1 – C9). It should be noted that this in no way is an attempt to calculate an average risk, it is merely an attempt to provide an average for which it is easy to measure deviance for the individual sets of control parameters.

Based on Swedish statistics for the years 1996 – 2000, Nystedt (2003) estimated the probability of becoming a fatality in an apartment fire to the magnitude of $1 \cdot 10^{-5} – 2 \cdot 10^{-5}$ per year. It can be seen that the wide range of results in this study covers these statistics. Nystedt (2003) also developed a model to quantify the risk to occupants in an apartment and found that the annual death risk ranged between $2.75 \cdot 10^{-5} – 7.02 \cdot 10^{-5}$ depending on installed fire safety measures (i.e. smoke detectors, sprinklers). Given that a fire has occurred, Thomas et al. (2005) estimated the probability of death for mobile occupants in the apartment of fire origin to $1.4 \cdot 10^{-3}$ for mid-rise buildings and $1.3 \cdot 10^{-3}$ in high-rise buildings. Assuming an average annual fire frequency of $3 \cdot 10^{-3}$ (see section 3.8) the fatality risk is estimated to approximately $1.2 \cdot 10^{-6}$ per year for both mid and high-rise buildings in the Thomas et al. (2005) paper.

Generally the results generated in this study were of an order of magnitude equal to 10^{-4}. Compared to the above presented studies, the risk estimated in this report were generally higher. However, considering that a conservative approach to the standard QRA was adopted which should generate higher risks, this is expected. The sensitivity study showed that the model indeed overestimates the risk if the selected input (Table 7.17) is to be considered conservative. It is also believed that the model overestimates the risk from smouldering fires. It this is true, this may also mean that the risk from flaming fires in turn is underestimated.

Comparing the estimated risk in Building 2 (high-rise) for the different codes (see section 8.2.3) did not result in large differences in risk even though the BCA design was fitted with sprinklers. Similar results were achieved by Thomas et al. (2005) presented above, where the differences between mid and high-rise are very small in the apartment of fire origin. The study by Nystedt (2003) showed a slight reduction in the risk for mobile occupants. However, both these studies showed that a more significant reduced risk of death for immobile occupants, something that has not been accounted for in this study.

In the introduction part of this report (see section 1.1.4), a question of the performance levels of Deemed-to-Satisfy provisions of the BCA was raised. It is the author's opinion that the necessary knowledge and data is not sufficient to make such statements yet. A step towards making such statements is to investigate the overall safety level of entire buildings. Such projects have already been initiated in the development of FiRECAM (Yung et al, 1999) and CESARE-Risk (ABCB, 2001). However, this study has revealed that there are still areas where more research needs to be conducted and more reliable data must be gathered before such analyses can be carried out.

9.1.2 Result bias

The lowest estimated risk is found for one room-sized apartments. From a model point of view it is believed that this is due to the occupant being exposed to the full range of possible cues to detect the fire. As the cue recognition criteria are assumed, it is possible that they overestimate the time for detection. Further research is needed before any estimates on the bias achieved by this can be quantified. It should also be noted that no consideration has been taken to intoxicated or immobile occupants that are believed to be at higher risk in this type of occupancy. Earlier studies have determined that deaths related to these factors make up 30 % of the total fire related fatalities (Nystedt, 2003).

The calculated risk for the mid rise buildings were generally higher than high-rise. However, it should be noted that the composition of apartment types were different for these buildings. The highest risks are found for large apartments and by deducting these when comparing the results, these are only slightly lower.

As described in Chapter 5, when designing a building according to one building code and then adopting it to fit the minimum requirements of the other, it was sought to maintain the floor area and size of the apartments. The latter was maintained but the floor areas in the different apartments were not identical in both cases which affects the fire frequency and in extent, the risk.

Problems arose when estimating consequences for scenarios where occupants were not in the room of fire origin, internal doors were closed and all fire safety systems fail. It was assumed that these scenarios always lead to fatality, which is very likely to overestimate the calculated risk. This assumption resulted in that a smouldering fire during night time which was not detected by the fire safety systems always was modelled as a deadly scenario. Depending on which type of detector that was used, the probability of this scenario occurring differed. In the base scenario (photoelectric detector) for the sensitivity analysis, the frequency of this particular scenario was $6.67 \cdot 10^{-6}$. Changing to an ionizing detector the corresponding scenario risk becomes $1.15 \cdot 10^{-5}$. Comparing these figures to the results, it is concluded that these scenarios are of magnitude larger than what can be considered insignificant.

Another factor that affects the consequence estimation is the number of sources accounted for that may incapacitate an occupant. The model takes heat, carbon monoxide and also increased ventilatory response from carbon dioxide into account. Purser (2008) points out that carbon monoxide poisoning is one of the most common causes of death in fires and in small enclosures doses of heat will also become more significant. However, there are more other agents that are likely to contribute to incapacitation in fires as can be seen in Purser (2008). It is likely that this limitation in the model leads to a slight underestimation of the risk.

In the FED calculations it has also been assumed that an occupant is affected by both radiant and convective heat. However, in reality, convective heat transfer will only occur if the occupant is immersed in a hot zone. This may not be the case in all situations and as this is not accounted for, such an assumption may lead to an overestimation of the risk.

No consideration has been taken to investigate correlations in the model. As an example, the probability of fire ignition has been assumed to be evenly distributed over the 24 hours of a day. Consulting statistics it is found that the fire frequency is correlated to times where occupants are present in the apartment. As no analysis of this has been performed it is uncertain how the results are biased.

When calculating the risk for a specific apartment, only scenarios in which the fire starts in the actual apartment have been considered. However, the risk imposed on the occupants within the specific apartment can also be derived from other sources such as the surrounding apartments. This has not been considered in this thesis. It is theorized from other research that this risk is small in relation to the risks to occupants considered in this thesis.

9.2 Discussion of sensitivity analysis

It seems as the model is quite sensitive to the defined criteria as for example cue recognition is determined by a threshold and not an interval (which is theorized to be more accurate). The result is “jumps” in the risk. By extending the event tree and including more events and thus estimating the risk for more scenarios would probably result in less drastic changes in the estimated risk.

Some variables were reduced without a change in risk. This suggests that the parameter does not contribute significantly to the calculated risk (in the base case). For example, if the majority of the fatalities are associated with smouldering fires, it is obvious that a reduction of CO yield for flaming fires will not reduce the risk. However, increasing the yield in CO yield for flaming fires may alter the lethality for flaming scenarios, and an increase in risk may occur.

Another possible reason to this effect is that an increase or reduction does not affect the risk because it is no longer the determining factor. For example, consider an apartment with both smoke detector and sprinkler. Generally, smoke detection will occur earlier than sprinkler activation. Therefore, by varying sprinkler parameters, the time until sprinkler activation occurs is altered. However, if the time for sprinkler activation is greater (for all variations) than the time until smoke detection, the change in risk will be small or absent.

It should also be noted that the model showing sensitivity to certain parameters does not necessarily suggest that it is inaccurate. For example, it is likely that a rapid fire scenario (larger fire growth rate) will indeed result in an increased risk for any occupant present.

9.3 Discussion of method

One of the main aims with this thesis was to quantify the risk to life imposed on occupants in apartment buildings. During the project, it has been acknowledged that accurately estimating this comprises a very difficult task with the current level of knowledge as well as tools and methods. These factors can all be described as uncertainties that have not been possible to eliminate. Therefore, the absolute risks calculated in this thesis should rather be seen as a performance benchmark than an actual real world representation of the risk.

Great difficulties arose when the actions of occupants located outside the room of fire origin were being modelled. There are large uncertainties involved with the assumptions of pre-movement times and fire cue recognition criteria. The author has not been able to find any reliable data on the latter. It is suggested that more research is needed until the associated uncertainties can be reduced.

There are also uncertainties associated with the method for which death was modelled. It was necessary to make assumptions that are believed to affect the results significantly. One example is the assumption of a one-zone model. The concentration of toxic species was calculated by dividing the released mass with the volume. This means an average concentration is calculated each time step, ignoring real world concentration variations within the volume. The extent of the volume for which the FED calculations were performed can also be questioned. In the cases were control parameters were set to having the corridor door open, it was assumed that the toxic gases were averaged out in this volume as well. In some calculations volumes up to 200 m^3 were used and it is likely that those calculations are associated with large uncertainties and therefore questioning the accuracy of the results. With better models it will be possible to more accurately describe the toxic concentrations and thus, provide a better estimate of the risk for an occupant escaping. However, it is likely that problems regarding exact occupant positioning and movement will still be very difficult to estimate.

Further uncertainties associated with the FED calculations are criteria for lethal doses. Different scenarios can lead to different doses being sufficient for individuals becoming fatalities. One example is a single occupant escaping. If the individual becomes incapacitated due to the smoke and heat, it is likely that this person will become a fatality following further exposure while being unconscious. The same scenario for multiple people could mean that the same person becoming incapacitated may avoid becoming a fatality due to other occupants limiting the exposure by helping the incapacitated occupant escape. Further expanding on this, the toxic gases will affect individuals below the incapacitating doses and may impair physical ability to escape for example, a factor not accounted for.

All outflows of gases have been ignored in the FED calculations. This could either be an outflow produced by the fire or ventilation systems. This leads to an overestimation of the risk whereas calculating average concentrations may lead to an underestimation depending on the location and movement of an occupant. This is especially true for smouldering scenarios were the accumulation of toxic gases develops over a longer period of time. In the calculations, lethal conditions were achieved after approximately 20 minutes in the calculations. It is likely that this time is overestimated as the room ventilation would lead to lower gas concentrations.

Using only hand calculations, problems arose when modelling cue recognition in other rooms than the room of fire origin. Given that the door connecting the rooms are open, smoke filling of the adjacent room will not occur before the smoke layer has descended below the door height. This has not been taken into consideration in the model where the smoke layer is calculated for the entire open area. This is believed to underestimate smoke layer height and temperature in the room of fire origin and overestimating in the adjacent rooms. Only some considerations have been taken to transport times of hot gases. These are assumed to be of minor differences in small spaces and usually in the rooms of fire origin were no obstructions are believed to be present. However, when modelling smoke detection, etc. outside the room of fire origin, similar problems to what has been previously discussed above arises.

As the sensitivity analysis showed that the travel distance (both internal and in the corridor) being an important factor, a larger emphasis could have been put on more accurately addressing internal layouts in apartments which have only been assumed. This is also applicable for the entire building layout where some reference material was used but could have been expanded. The Swedish designs were adopted to the country specific regulations but no considerations were taken to differences in design and therefore it was assumed that the layouts were somewhat similar. The Swedish designs also become more 'creative' to fit the BBR regulations whilst maintaining minimum provisions and the same floor area. It is acknowledged that this may not accurately represent what is actually designed. On the other hand, in the way the model is constructed, this mainly influences the internal travel distances and the result thereof.

It can also be questioned if an absolute level of risk as design criteria is beneficial. As already mentioned, there will be large difficulties to determine such an acceptable level. For example, taking on a similar approach to this thesis, it will be found that factors such as the fire load, occupant behaviour and mobility will affect the calculated risk. Who should the apartment (or building) be designed for? If apartments initially are designed for mobile occupants but the usage of the building changes so that there are immobile occupants, the risk is changed for the building. The same result is achieved by variations in interior of an apartment. It is believed that an apartment with few combustibles and ignition sources will result in lower risks than one with very high fuel load and many ignition sources. It is not feasible to put constraints on the amount of furniture, etc. in apartments and therefore the occupants are to an extent determining the risk to which they are exposed themselves. The problem also relates to the definition of risk. Estimating the risk for occupants in an apartment is dependent on the occupant characteristics. But does the risk differ in "reality"? Are we not interested in the risk *imposed* on occupants *by* the apartment? Estimating risk without regards to specific occupant characteristics will require another definition and a set of criteria to measure against.

Although no absolute quantitative criteria may be desirable it is the authors opinion that a more holistic method suited for engineering applications is needed. Most engineering applications are trade-offs, verifying this deviation from the building code on an element or sub-system level. Uncertainties may arise regarding how the overall safety of the building is affected. This thesis only considers risks to occupants in the apartment of fire origin, but naturally other occupants are also at risk. Efforts have been put into cost-risk assessment models such as FiRECAM (Yung et al, 1999) and CESARE-Risk (ABCB, 2001) are not available to the public. Therefore, it is suggested that a consensus regarding such a holistic approach should be agreed on.

The model in this thesis is described by simple hand calculation (usually empirical) correlations. Naturally, by adopting more complex models it is possible to more accurately model the hazardous environment, human response and evacuation and perform more accurate consequence assessments. Attempts incorporating two-zone models have already been done with the development of FiRECAM (Yung et al, 1999) and CESARE-Risk (ABCB, 2001). As computational power increases quickly it may also soon be relatively easy to incorporate a field model using Computational Fluid Dynamics to describe the hazardous environment.

9.4 Future research

This study has identified a few areas for which future research will be beneficial for similar studies.

There seems to be a lack of information regarding criteria for human response to fires other than injuries and death. To accurately describe occupants' response it is of essence to be able to predict criteria for when occupants can be assumed to recognize fire cues. It has been suggested that different fire cues also are associated with different degrees of certainty, a concept that also need more research.

When assessing occupant response and behaviour in the apartment of fire origin, recognition and response times becomes important factors in the relatively small time frame that is available for escape. It can be said that there is a general lack of information regarding occupant behaviour within the apartment of fire origin. Such information would be beneficial to create more accurate response models and provide critical information to risk assessments.

This study estimates risks to occupants in individuals in the apartment of fire origin. However, this is not an accurate way describing the risk of the entire building. In a scenario where the occupant(s) in the apartment of fire origin successfully escapes may still pose a threat to other occupants in the building. Models such as FiRECAM (Yung et al, 1999) and CESARE-Risk (ABCB, 2001) are both approaches to a more holistic evaluation of risk to occupants in apartment buildings. However, as these are not commercially available, there is still a need for such an holistic method to evaluate how complex building design and risk mitigating measures (e.g. sprinklers, smoke detectors, stair pressurisation) alter the overall risk for the building.

Chapter 10 - Conclusions

During this study it was concluded that determine minimum levels of safety achieved by the building codes is not addressable as the code allow for designs, even with installation of fire safety systems, would result in very large risks to occupants. As such the minimum level of safety achieved by common designs was sought.

With the current state of knowledge regarding the variables that affect the risk, the uncertainties associated with method and input deems that the results should be considered with care. Also, there are factors that are very difficult to quantify and have therefore been investigated as control parameters. In reality, these are all associated with different probabilities, a factor that remains unknown. Therefore, due to the numerous uncertainties associated with this type of analysis, no statements regarding the overall performance achieved by the Deemed-to-Satisfy provisions of the investigated building codes are given.

The model used in this study estimated the risk for apartments to vary between $3.44 \cdot 10^{-5}$ and $9.08 \cdot 10^{-4}$ per year. Considering the conservative assumptions used, the results was within the order of magnitude of other studies. Variations found in investigated buildings and country specific designs, suggest that the increased provisions for high-rise buildings do not affect the risk for occupants in the apartment of fire origin significantly. The provision of sprinklers did not show any significant lowered risks. It is theorized that sprinklers reduces the risk for the building in a holistic perspective, however this has not been investigated in this study. However, it was concluded that the sensitivity analysis was very limited and further investigation of the model is needed before more detailed statements of the model's behaviour is given.

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Appendix A - Parameters and variables

To quantify the risk an event tree based QRA was used. To create an accurate estimate of the risk, important parameters and variables have to be considered in the analysis. By reviewing other sources and brainstorming, these parameters were documented in this appendix. Items in *italic* have been identified but not considered in the analysis. A reference refers to other reports in which this variable has been used or concluded important. Items without reference are either trivial or assumed important.

A.1 Building code

Parameter	References
Storeys	(Becker, 2000)
Exits	
Escape path width	
Travel distance	
Ceiling height	
Smoke detection system	(Becker, 2000)
Fire alarm	(Becker, 2000)
Sprinkler	
Smoke management	
Construction material(s)	(Becker, 2000)
Fire resistant construction	*(Becker, 2000)*
Fire compartmentation	*(Becker, 2000)*
Smoke compartmentation	*(Becker, 2000)*
Safety class	*(Becker, 2000)*
Availability for fire fighters	*(Becker, 2000)*
Type of exit	
Door type	
Stairs	*(Becker, 2000)*
Type of stair	*(Becker, 2000)*

A.2 Fire development

Parameter	References
Flaming/smouldering fire	(Nystedt, 2003)
Yields	(Nystedt, 2003)
Fire location	(Nystedt, 2003)
Openings available	(Nystedt, 2003)
Fire suppression	(Nystedt, 2003)
Door open/closed	(Frantzich, 1998)
Smoke spread	(ABCB, 2001)
Frequency	(Becker, 2000)
Flashover	
Glass breakage	*(ABCB, 2001)*
Flame spread rate	*(ABCB, 2001)*
Fire spread	*(ABCB, 2001)*
First item ignited	*(Nystedt, 2003)*
Barrier failure	*(ABCB, 2001)*

A.3 Fire safety systems

Parameter	References
Smoke detector	(Nystedt, 2003)
Sprinklers	(Nystedt, 2003)
Stair pressurisation	

A.4 Human response and behaviour

Parameter	References
Detection time	(Nystedt, 2003)
Alarm time	
Recognition time	
Response time	
Travel time	(Nystedt, 2003)

A.5 Human tenability

Parameter	References
Heat	(Nystedt, 2003)
Carbon monoxide	(Nystedt, 2003)
Oxygen deficiency	*(Nystedt, 2003)*
Other toxins	*(Nystedt, 2003)*

A.6 Occupant characteristics

Parameter	References
Location	(Nystedt, 2003; Miller, 2005)
Awareness level	(Nystedt, 2003; Miller, 2005)
Walking speed	
Age	
Mobility	*(Nystedt, 2003)*
Local knowledge	*(Becker, 2000)*
Evacuation strategy	*(Becker, 2000)*
Sex	*(Miller, 2005)*

A.7 Stochastic variables

Parameter	References
Occupancy load	Assumed
Day	Assumed
Time	Assumed

Appendix B – Deemed-to-Satisfy provisions

This appendix contains extracts of building code provisions which have been identified as important (Appendix A) when estimating the risk to occupants within apartments. The requirements have been identified for the case study building presented in Chapter 6. Clauses refer to the building code requirements in each code.

B.1 Building 1 (Mid-rise)

B.1.1 Design according to BCA

Element	Part	Clause(s)	Requirements
Type/Class		C1.1	Type A
Escape paths	Exits	D1.2	1 from each floor
	Travel distance (door to exit)	D1.4	6 m (20 m)[1]
	Travel distance (door to road or open space)	D1.7	
	Escape path width	D1.6	1 m
	Escape path height	D1.6	2 m
	No. of stairs	N/A	1
	Fire isolated stair	D1.3, D1.7	Yes
Fire suppression		E1.5	N/R
Fire detection	Sole Occupancy Unit	Table E2.2a, SpecE2.2a	Automatic smoke detection system, AS 3786 in other, mains powered
	Areas that may cause spurious signals		AS 1670.1
Sole occupancy unit	Compartment ceiling height	F3.1	2.4 m

B.1.2 Design according to BBR

Element	Part	Clause(s)	Requirements
Type/Class		5:21	Br1
Escape paths	Exits	5:311, 5:312	2 (one may be a window where allowed)
	Travel distance (SOU to door)	5:332	Max. 45 m (from worst place in SOU to escape path)
	Travel distance (door to safe place)	5:332	Max. 10 m (to stairwell)
	Escape path width	5:341	0.9 m
	Escape path height	5:341	2.1 m
	No. of stairs	5:311	1 (one is window)
	Door in escape path	5:6214	Need self-closer
Fire suppression			N/R
Fire detection	Sole Occupancy Unit	5:374	Smoke alarm (placed nearby bedroom)
Sole occupancy unit	Compartment ceiling height		2.4 m

B.2 Building 2 (High-rise)

B.2.1Design according to BCA

Element	Part	Clause(s)	Requirements
Type/Class		C1.1	Type A
Escape paths	Exits	D1.2	2 from each floor
	Travel distance (door to point of choice)	D1.4	6 m
	Distance between alternative exits	D1.5	Min. 9 m and max 45 m
	Escape path width	D1.6	1 m
	Escape path height	D1.6	2 m
	No. of stairs	D1.2	2
Fire suppression		E1.5, Spec E1.5 Clause 2	Yes, AS 2118.1
	Water supply system	Spec E1.5 Clause 7	Grade 1
	Sprinkler activation connected to OWS?	Spec E1.5 Clause 8	Yes
Fire detection	Sole Occupancy Unit	Table E2.2a, SpecE2.2a	Automatic smoke detection system, AS 3786 in other, mains powered
	Areas that may cause spurious signals	SpecE2.2a Clause 4	N/R
Sole occupancy unit	Compartment ceiling height	F3.1	2.4 m

B.2.2 Design according to BBR

Element	Part	Clause(s)	Requirements
Type/Class		5:21	Br1
Escape paths	Exits	5:311, 5:312	1
	Travel distance (SOU to door)	5:332	Max. 45 m (from worst place in SOU to escape path)
	Travel distance (door to safe place)	5:332	Max. 10 m (to stair)
	Escape path width	5:341	0.9 m
	Escape path height	5:341	2.1 m
	No. of stairs	5:311	1
	Door in escape path	5:6214	Need self-closer
Fire suppression			N/R
Fire detection	Sole Occupancy Unit	5:374	Smoke alarm (placed nearby bedroom)
	Areas that may cause spurious signals		
	Corridor/common space		
Sole occupancy unit	Compartment ceiling height		2.4 m

Appendix C – Sensitivity analysis

A sensitivity analysis of the variables used in the model was carried out in accordance with what is described in 8.3. This appendix includes the result of all the variables analysed.

C.1 Fire type

Parameter value	Absolute risk	Relative risk
P(flaming fire)=0.755 (base case)	4.30E-5	1.00
P(flaming fire)=0.855	2.98E-5	0.69
P(flaming fire)=0.655	5.42E-5	1.26

C.2 Fire growth rate

Parameter value	Parameter change	Absolute risk	Relative risk
$\alpha = 0.024$ (base case)	1.0	4.30E-5	1.00
$\alpha = 0.19$ (ultra fast, see section 3.5.1.2)	7.9	3.05E-4	7.10
$\alpha = 0.047$ (fast, see section3.5.1.2)	2.0	2.40E-4	5.60
$\alpha = 0.012$ (medium, see section 3.5.1.2)	0.5	4.30E-5	1.00
$\alpha = 0.003$ (fast, see section 3.5.1.2)	0.13	4.38E-5	1.01

C.3 Heat of combustion

Parameter value	Parameter change	Absolute risk	Relative risk
$H_c = 27000$ (base case)	1.0	4.30E-5	1.00
$H_c = 40000$	1.5	3.30E-5	0.77
$H_c = 16000$	0.6	4.40E-5	1.02

C.4 Yields

C.4.1 Carbon monoxide (CO), flaming fire, well ventilated

Parameter value	Parameter change	Absolute risk	Relative risk
$y(CO_{fc}) = 0.005$ (base case)	1.0	4.30E-5	1.00
$y(CO_{fc}) = 0.001$	0.2	3.27E-5	0.76
$y(CO_{fc}) = 0.01$	2	4.30E-5	1.00

C.4.2 Carbon monoxide (CO), flaming fire, ventilation controlled

Parameter value	Parameter change	Absolute risk	Relative risk
$y(CO_{vc}) = 0.19$ (base case)	1.0	4.30E-5	1.00
$y(CO_{vc}) = 0.09$	0.5	4.20E-5	0.98
$y(CO_{vc}) = 0.29$	1.5	4.30E-5	1.00

C.4.3 Carbon dioxide (CO_2), flaming fire, well ventilated

Parameter value	Parameter change	Absolute risk	Relative risk
$y(CO_{2,fc}) = 1.3$ (base case)	1.0	4.30E-5	1.00
$y(CO_{fc}) = 2.0$	1.5	4.30E-5	1.00
$y(CO_{fc}) = 0.1$	0.08	4.35E-5	1.01

C.4.4 Carbon dioxide (CO_2), flaming fire, ventilation controlled

Parameter value	Parameter change	Absolute risk	Relative risk
$y(CO_{2,vc}) = 0.8$ (base case)	1.0	4.30E-5	1.00
$y(CO_{2,vc}) = 1.5$	1.9	4.23E-5	0.99
$y(CO_{2,vc}) = 0.1$	0.13	4.29E-5	1.00

C.4.5 Carbon monoxide (CO), smouldering fire

Parameter value	Parameter change	Absolute risk	Relative risk
$y(CO_{sm}) = 0.15$ (base case)	1.0	4.30E-5	1.00
$y(CO_{sm}) = 0.25$	1.7	1.70E-4	3.95
$y(CO_{sm}) = 0.05$	0.3	1.95E-5	0.45

C.4.6 Carbon dioxide (CO_2), smouldering fire

Parameter value	Parameter change	Absolute risk	Relative risk
$y(CO_{2,sm}) = 0.87$ (base case)	1.0	4.30E-5	1.00
$y(CO_{2,sm}) = 1.5$	1.7	4.25E-5	0.99
$y(CO_{2,sm}) = 0.1$	0.11	4.28E-5	1.00

C.5 Smoke detection

C.5.1 Detector type

Parameter value	Absolute risk	Relative risk
Photoelectric (base case)	4.30E-5	1.00
Ionizing	1.07E-4	2.49

C.5.2 Detector effectiveness, flaming fires

Parameter value	Absolute risk	Relative risk
P(smoke detector effective)=0.882 (base case)	4.30E-5	1.00
P(smoke detector effective)=0.8	4.87E-5	1.13
P(smoke detector effective)=0.95	3.68E-5	0.86

C.5.3 Detector effectiveness, smouldering fires

Parameter value	Absolute risk	Relative risk
P(smoke detector effective)=0.931 (base case)	4.30E^{-5}	1.00
P(smoke detector effective)=0.8	5.51E^{-5}	1.28
P(smoke detector effective)=0.99	3.69E^{-5}	0.86

C.5.4 Photoelectric smoke detector threshold, flaming fire

Parameter value	Parameter change	Absolute risk	Relative risk
$OD = 0.106$ (base case)	1.0	4.30E^{-5}	1.00
$OD = 0.15$	1.4	4.30E^{-5}	1.00
$OD = 0.05$	0.5	4.25E^{-5}	0.99

C.5.5 Photoelectric smoke detector threshold, smouldering fire

Parameter value	Parameter change	Absolute risk	Relative risk
$OD = 0.09$ (base case)	1.0	4.30E^{-5}	1.00
$OD = 0.15$	1.7	1.09E^{-4}	2.53
$OD = 0.05$	0.6	1.91E^{-5}	0.44

C.5.6 Mass optical density, flaming

Parameter value	Parameter change	Absolute risk	Relative risk
$D_g = 0.54$ (base case)	1.0	4.30E^{-5}	1.00
$D_g = 1.4$	2.6	4.35E^{-5}	1.01
$D_g = 0.12$	0.2	4.34E^{-5}	1.01

C.5.7 Mass optical density, smouldering

Parameter value	Parameter change	Absolute risk	Relative risk
$D_g = 0.34$ (base case)	1.0	4.30E-5	1.00
$D_g = 0.64$	1.9	1.89E-5	0.44
$D_g = 0.12$	0.35	2.39E-4	5.56

C.5.8 Number of detectors

The configuration was changed so that a smoke detector was fitted in the middle of each room of the apartment. The maximum distance to the detectors was set to 3 meters for both rooms.

Parameter value	Absolute risk	Relative risk
Smoke detector in kitchen next to bedroom door (base case)	4.30E-5	1.0
Two smoke detectors, one in middle of each room	4.29E-5	1.0

C.6 Sprinklers

C.6.1 Effectiveness

Parameter value	Absolute risk	Relative risk
P(sprinkler system effective)=0.977 (base case)	4.30E-5	1.00
P(sprinkler system effective)=0.90	4.40E-5	1.02
P(sprinkler system effective)=0.99	4.30E-5	1.00

C.6.2 RTI

Parameter value	Parameter change	Absolute risk	Relative risk
$RTI = 350$ (base case)	1.0	4.30E-5	1.00
$RTI = 200$	0.57	4.30E-5	1.00
$RTI = 120$	0.34	4.25E-5	0.99

C.6.3 Activation temperature

Parameter value	Parameter change	Absolute risk	Relative risk
$T_{d,act} = 68$ (base case)	1.0	4.30E-5	1.00
$T_{d,act} = 79$	0.86	4.30E-5	1.00
$T_{d,act} = 59$	0.75	4.35E-5	1.01

C.6.4 Horizontal distance from fire plume to sprinkler

Parameter value	Parameter change	Absolute risk	Relative risk
$r_{sprinkler} = 3$ (base case)	1.0	4.30E-5	1.00
$r_{sprinkler} = 5$	1.67	4.30E-5	1.00
$r_{sprinkler} = 1$	0.33	4.14E-5	0.96

C.7 Boundary heat transfer

C.7.1 Enclosure material

Parameter value	Absolute risk	Relative risk
Concrete (base case)	4.30E-5	1.00
Gypsum	4.41E-5	1.03
Brick	4.13E-5	0.96
Lightweight concrete	3.04E-4	7.07

C.7.2 Material thickness

Parameter value	Parameter change	Absolute risk	Relative risk
$d = 0.3$ (base case)	1.0	4.30E-5	1.00
$d = 0.5$	1.67	4.21E-5	0.98
$d = 0.1$	0.33	4.26E-5	0.99

C.8 Occupant characteristics

C.8.1 Number of occupants

Parameter value	Absolute risk	Relative risk
Varies 1 – 4 (base case)	$4.30E^{-5}$	1.00
1	$4.12E^{-5}$	0.96
2	$4.30E^{-5}$	1.00
3	$4.38E^{-5}$	1.02
4	$4.57E^{-5}$	1.06

C.8.2 Occupant location

Parameter value	Absolute risk	Relative risk
Varies (base case)	$4.30E^{-5}$	1.00
Fixed, kitchen	$3.51E^{-5}$	0.82
Fixed, bedroom	$4.38E^{-5}$	1.02

C.8.3 Occupants present

Parameter value	Absolute risk	Relative risk
P(occupants present)=0.619 (base case)	$4.30E^{-5}$	1.00
P(occupants present)=0.7	$4.85E^{-5}$	1.13
P(occupants present)=0.5	$3.60E^{-5}$	0.84

C.8.4 Awareness

Parameter value	Absolute risk	Relative risk
P(awake)=0.525 (base case)	$4.30E^{-5}$	1.00
P(awake)=0.6	$3.60E^{-5}$	0.84
P(awake)=0.4	$5.37E^{-5}$	1.25

C.8.5 Walking speed

Parameter value	Parameter change	Absolute risk	Relative risk
$v_{esc} = 0.65$ (base case)	1.0	4.30E-5	1.00
$v_{esc} = 1.20$	1.84	1.00E-5	0.23

C.8.6 Pre-movement times, fire cue, awake

Parameter value	Parameter change	Absolute risk	Relative risk
$t_{pre} = 15$ (base case)	1.0	4.30E-5	1.00
$t_{pre} = 30$	2	4.30E-5	1.00
$t_{pre} = 0$	N/A	4.17E-5	0.98

C.8.7 Pre-movement times, fire cue, asleep

Parameter value	Parameter change	Absolute risk	Relative risk
$t_{pre} = 100$ (base case)	1.0	4.30E-5	1.00
$t_{pre} = 150$	1.5	4.30E-5	1.00
$t_{pre} = 50$	0.5	3.21E-5	0.75

C.8.8 Pre-movement times, alarm, awake

Parameter value	Parameter change	Absolute risk	Relative risk
$t_{pre} = 45$ (base case)	1.0	4.30E-5	1.00
$t_{pre} = 60$	1.33	4.30E-5	1.00
$t_{pre} = 30$	0.67	4.30E-5	1.00

C.8.9 Pre-movement times, alarm, asleep

Parameter value	Parameter change	Absolute risk	Relative risk
$t_{pre} = 130$ (base case)	1.0	4.30E-5	1.00
$t_{pre} = 160$	1.23	2.39E-4	5.56
$t_{pre} = 100$	0.77	1.90E-5	0.44

C.9 Travel distance

C.9.1 Internal

Parameter value	Absolute risk	Relative risk
Varies (base case)	$4.30E^{-5}$	1.00
16 meters (max)	$4.30E^{-5}$	1.00
0 meters (min)	$4.27E^{-5}$	0.99

C.9.2 Corridor

Parameter value	Parameter change	Absolute risk	Relative risk
$l_{corridor} = 18$ (base case)	1.0	$4.30E^{-5}$	1.00
$l_{corridor} = 28.5$	1.58	$4.30E^{-5}$	1.00
$l_{corridor} = 1$	0.06	$1.03E^{-5}$	0.24

C.10 Window size

Parameter value	Absolute risk	Relative risk
Window in bedroom 1.2 x 1.0 (base case)	$4.30E^{-5}$	1.00
Window in bedroom 1.5 x 1.2	$4.20E^{-5}$	0.98
Window in bedroom 1.0 x 0.6	$4.40E^{-5}$	1.02

C.11 Cue recognition criteria

C.11.1 Upper layer temperature, awake

Parameter value	Parameter change	Absolute risk	Relative risk
$T_g = 100$ (base case)	1.0	$4.30E^{-5}$	1.00
$T_g = 130$	1.3	$4.30E^{-5}$	1.00
$T_g = 70$	0.7	$4.30E^{-5}$	1.00

C.11.2 Upper layer temperature, asleep

Parameter value	Parameter change	Absolute risk	Relative risk
$T_g = 130$ (base case)	1.0	4.30E-5	1.0
$T_g = 160$	1.23	4.30E-5	1.00
$T_g = 100$	0.77	3.30E-5	0.77

C.11.3 Radiation, awake

Parameter value	Parameter change	Absolute risk	Relative risk
$q = 1.2$ (base case)	1.0	4.30E-5	1.00
$q = 1.5$	1.25	4.30E-5	1.00
$q = 0.9$	0.75	4.30E-5	1.00

C.11.4 Radiation, asleep

Parameter value	Parameter change	Absolute risk	Relative risk
$q = 1.5$ (base case)	1.0	4.30E-5	1.00
$q = 1.8$	1.2	4.30E-5	1.00
$q = 1.2$	0.8	4.30E-5	1.00

C.11.5 Flame height, awake

Parameter value	Parameter change	Absolute risk	Relative risk
$L_f = 0.6$ (base case)	1.0	4.30E-5	1.00
$L_f = 0.8$	1.33	4.30E-5	1.00
$L_f = 0.4$	0.67	4.30E-5	1.00

C.11.6 Flame height, asleep

Parameter value	Parameter change	Absolute risk	Relative risk
$L_f = 1.2$ (base case)	1.0	4.30E-5	1.00
$L_f = 1.4$	1.17	4.16E-5	0.97
$L_f = 1.0$	0.83	3.30E-5	0.77

C.11.7 Visibility, awake

Parameter value	Parameter change	Absolute risk	Relative risk
100 meters (base case)	1.0	4.30E-5	1.00
50 meters	0.5	4.77E-5	1.11
150 meters	1.5	4.17E-5	0.97

C.12 Corridor size

Parameter value	Parameter change	Absolute risk	Relative risk
$Volume = 68$ (base case)	1.0	4.30E-5	1.00
$Volume = 36$	0.53	4.30E-5	1.00
$Volume = 100$	1.47	1.88E-5	0.44

C.13 Room ceiling height

Parameter value	Parameter change	Absolute risk	Relative risk
2.4 meters (base case)	1.0	4.30E-5	1.00
2.0 meters	0.83	1.89E-5	0.44
3.0 meters	1.25	4.30E-5	1.00