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DEPARTMENT: Department of Flow, Heat and Combustion
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STUDY ON RISK ASSESSMENT MODELS FOR QUANTIFYING LIFE SAFETY IN BUILDINGS IN CASE OF FIRE

Khairunnisa

Promoter: Bart Merci
Co-promoter: Bart Van Weyenberge

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Abstract

Risk assessments have been extensively used to quantify life safety in a building in case of fire. In the last decade, the solely deterministic risk assessment approach is shifting to a broader risk-informed frameworks. The complication of this development lies in the integration of the probabilistic approach in current models. In current models, there are several sub-models evaluated. The risk model results are influenced by the sub-models modelling method, interactions and selection of input parameters value. The aim of this thesis is to investigate how the sub-models system work with the introduction of inputs distribution. An extensive literature study on previous risk assessment models has been carried out. From this, a general risk assessment framework is developed with the integration of input probability distributions stemmed from statistic data. The general framework gives flexibility to the users to select the suitable methods based on their intentions and resources availability. As an additional aid to choose the appropriate methods, selection criteria are defined. This way the most optimal combination of methods can be selected to estimate the risk outcome. The application of the framework proposed is demonstrated through a simple case study of an office building. The risk outcome is measured as fatalities per year per building.

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Abstrak

Analisis risiko telah banyak diterapkan untuk memperkirakan tingkat keselamatan hidup di sebuah gedung bilamana kebakaran. Dalam dekade terakhir, metode analisis risiko secara deterministik murni mengalami pergeseran yang lebih luas ke arah metode analisis berbasis risiko-informasi. Komplikasi pengembangan metode ini terletak pada integrasi pendekatan probabilistik dalam kerangka model. Dalam model risiko saat ini, ada beberapa sub-model yang dievaluasi. Hasil model risiko dipengaruhi oleh metode penghitungan dalam sub-model, interaksi antar sub-model dan pemilihan nilai masukan parameter. Tujuan tesis ini adalah untuk menyelidiki bagaimana sub-model dalam kerangka analisis risiko bekerja dengan menggunakan nilai masukan yang dijelaskan dalam bentuk distribusi probabilitas. Studi literatur yang ekstesif mengenai model analisis risiko terdahulu dilakukan. Berdasarkan studi tersebut, sebuah kerangka umum analisis risiko dikembangkan dengan mengintegrasikan distribusi probabilitas nilai masukan yang berasal dari data statistik. Kerangka umum analisis risiko memungkinkan pengguna untuk memilah dan memilih metode pemodelan yang tersedia. Sebagai tambahan bantuan untuk memilih metode yang tepat, kriteria penilaian telah ditetapkan. Dengan cara ini, kombinasi yang paling optimal dari berbagai metode dapat dipilih untuk memperkirakan hasil risiko. Penerapan kerangka umum yang diusulkan ditunjukkan melalui studi kasus sederhana mengenai sebuah gedung perkantoran. Hasil risiko studi kasus dinyatakan sebagai kematian per tahun per gedung.

Table of Contents

1. Introduction

The introduction Chapter consists of four Sections. The first Section captures the background of the problem. The objectives to meet and the scope of work of this thesis are described in the second and third Section, respectively. The last Section covers the methods used during the writing and summary of each Chapter.

1.1 Background

The performance-based approach to assessing building fire safety has been increasingly applied in many countries such as UK, the United States and Australia since 1980s (Meacham, 1996). It gives equal or even better safety fire level while still providing design flexibility comparing to prescriptive code solution. To demonstrate the building design performance, an appropriate risk assessment modelling is required to conduct.

There have been many acceptable approaches that can efficiently address and resolve the performance-based design issue. The most adopted technique in current practice is the scenario-based approach in which the outcomes are determined depending on deterministic modelling.

The deterministic approach relies on analysis or judgment based on physic and chemistry, or correlations derived from experiment (SFPE, 2007). It involves evaluation of a set of circumstances that will provide single outcome; i.e. the design will be either successful or not. The attached uncertainties are tackled by taking a conservative approach in the selection of input data. This way leads to a condition where the safety level acquired by a particular design remains unknown. In addition, the calculation answer to a specific problem produced by different engineers might exhibit a broad and inconsistent scatter (Magnusson, et al., 1995). The process of determining input data to be applied in the whole risk assessment becomes fundamental and needs to be performed in a responsible manner.

In reality, the input data are affected by factors that are probabilistic in nature. Therefore, in the last decade, the solely deterministic designs are shifting to a broader risk-informed frameworks. It is done by adding various probabilistic elements to create a hybrid of a deterministic-probabilistic model. In the probabilistic approach, a range of possible values for calculation parameters are used.

Risk assessment model is used to characterize the outcome of fire growth until untenable conditions reached. There are several sub-models evaluated. The sub-models included but not limited to fire growth and development, smoke spread, fire spread, human response and evacuation (Meacham, 1996). The extensive application of building fire risk assessment has encouraged the development of different modelling methods for in each sub-model. For instance is zone model or field model that can be selected to demonstrate the smoke movement during a fire condition. Each modelling method has different capabilities and limitations. The application can differ from one case to another depends on the fire, building and occupant characteristics. Some of the sub-models are maturely developed, and some of them are still under development.

Interactions between sub-models also influence the outcome of the consequences modelling. It creates relation in which the output of one sub-model can be main input data to other sub-models. Therefore, the integration of sub-models are important to consider.

Driven by the background described, the study on risk assessment model to quantify life safety in buildings in case of fire is performed.

1.2 Objectives

This thesis will support a larger study regarding the development of a quantitative risk assessment methodology for fire safety of people in complex buildings.

The objectives of this thesis are established to answer the problems explained in the background. First is to investigate the sub-models used in current fire risk assessment. The status, concept, parameters to adjust and modelling methods of the sub-models are studied to determine which method are most optimal to be applied in real life. The interaction between the sub-models and how the probabilistic approach introduced during input values selection are also highlighted.

The final objective is to propose conclusions on how the chosen sub-models can be improved to fit for implementation in a fire risk assessment model. With the knowledge gathered, a general risk assessment framework is developed and applied to a case study.

1.3 Scope and limitations

Referring to SFPE guidelines (2007), there are four types of fire safety goals. They are life safety, property protection, operation continuity and environmental protection. In this thesis, the goal is limited to life safety only. As a consequence, sub-models related to other than life safety will not be taken into account.

Magnusson et. al. (1995) have defined five different variations of a quantitative risk assessment study. They are (1) a fully probabilistic method for the single scenario example with application of the concept of reliability index β, (2) the single scenario example treated by a one-phase, simple random sampling Monte Carlo simulation study, (3) the single scenario example treated by a two-phase Monte Carlo simulation procedure, (4) multi-scenario event tree evaluated deterministically, (5) multi-scenario event tree evaluated with an uncertainty analysis included. This thesis is focused on the method number (4). The integration of the probabilistic part to the method is limited only to the application of statistical distribution to input parameters value. Other methods mentioned are therefore beyond the scope.

A wide variety of buildings can be object of fire risk assessment. Different type of building might have different characteristics and different fire safety measurements. The risk assessment in this thesis is assigned to low, medium or high buildings.

1.4 Methodology

There are two methods performed in this thesis. These are literature reviews and an application to a case study. The structure of the thesis is described below.

Chapter 1 describes the introduction of this thesis. It explains the background, the objectives, the scope and limitations and methodologies used. Chapter 2 provides deep review from previous studies on risk assessment model, either in general or specific. This Chapter is intended to acquire state-of-the-art of fire risk assessment. Uncertainty and reliability in fire safety system are also briefly discussed. Chapter 3 summarizes what elements from previous studies can be extracted and what can be improved. These are then used to develop a general fire risk assessment framework.

Chapter 4 provides deeper discussions on the types of fire risk assessment sub-models. The parameters and modelling methods are explained. Examples of available modelling software are listed. The comparisons based on their limitations and features are summarized. The author also proposes criteria to consider in choosing suitable modelling software for fire risk assessment. Chapter 5 presents the case study using the general fire risk framework proposed. This Chapter contains the input data, assumptions, and sub-models used. Simulation tools such as FDS and STEPS were used for the case study. Chapter 6 describes the results of the case study. Chapter 7 encompasses the discussion on the framework proposed and in the case study. Chapter 8 summarizes the conclusions of this thesis and suggestions for future research.

2. Fire Risk Assessment

Life safety is the value that shall be conformed in building design. Therefore, the process of risk assessment is fundamental to perform to decide if the building design is safe enough from fire safety point of view.

The terminology in studies of fire risk assessment can be different for one case to another. For example is the terms of fire risk analysis and fire risk assessment that can be used interchangeably with the same meaning. Based on SFPE definition (Jr. & Jr., 2002), risk analysis is the process of quantification of the probabilities and expected consequences for identified risks. Risk assessment is the process of establishing information regarding acceptable levels of risk for individual, group, society or environment. On the other hand, Yung (2008) describes comprehensive fire risk assessment as the assessment of all probable unwanted fire scenarios and their consequences are considered. In this thesis, the process of quantifying risk and the expected consequences is stated as risk assessment.

2.1 Risk definition

Risk is unavoidable in our life. It cannot be eliminated entirely. However, the probability or the negative consequences can be minimized. Risk is the potential for realization of unwanted, adverse consequences to human life, health, property or the environment (Jr. & Jr., 2002). Meacham (2002) describes fire risk as the possibility of an unwanted outcome in an uncertain situation, where fire is the hazard that may induce the loss or harm to valued objectives.

The concept of analysing risk has been defined quantitatively by Kaplan and Garrick (1981) as a set of triplets idea. These are the scenarios that can happen (i.e., what can go wrong?), the likelihood of the scenario to happen and the consequences if the scenario happens. Assessing risk is answering those three questions.

The risk triplet is presented in Equation (2.1):

$$R = \{< s_i, p_i(\phi_i), x_i >\} \tag{2.1}$$

Where for the scenario i, s_i is the scenario description, $p_i(\phi_i)$ is the probability density function of the frequency and x_i is the consequences.

2.2 Risk outcome

There are different ways to present the calculated risk level. The most used method is using individual risk or societal risk. Individual risk (IR) is defined as the risk to which of any individual is subjected at on the location defined by specific scenario. The ‘location’ term in the definition might limit the applicability of this measure for building risk assessment. In buildings, the fire is often assumed to be confined to the compartment origin resulting the same IR value at any point. If fire spread is likely to occur, the estimated risk will then be underestimated. Societal risk is defined as the risk subjected to a population based on the defined scenario. It is expressed as FN curve showing the exceedance curve of the event probabilities and the number of fatalities. Frantzich (1998) pointed out that FN curve will underestimate the risk unless a high number of scenarios is calculated. An example of FN curve is shown in Figure 2.1.

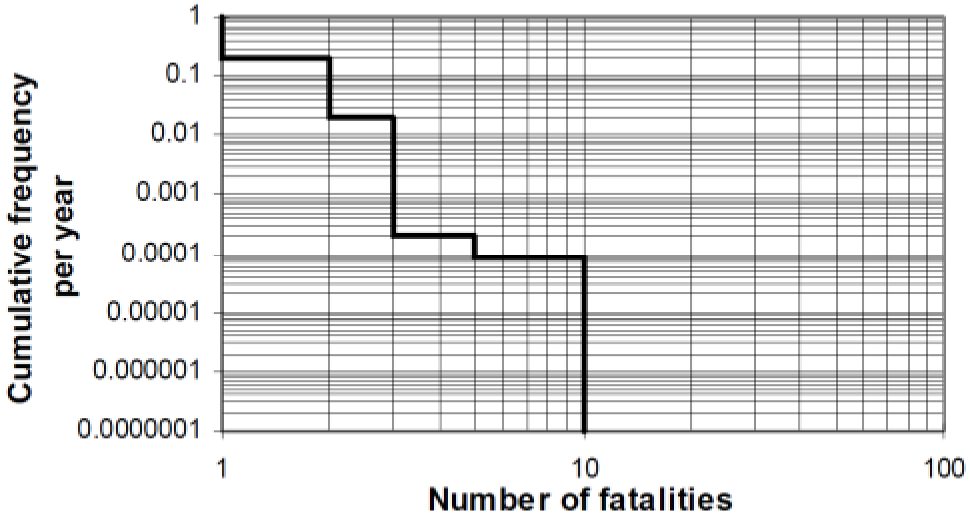

Figure 2.1 Example of FN curve

2.3 Fire risk assessment methods in general

In fire safety, risk assessment can take different approaches depending on the purpose and scope of the analysis. Data and resources availability also determine which assessment method is suitable to carry out. A schematic diagram of fire risk assessment method is shown in Figure 2.2.

The qualitative method relies on the personal judgment in analysing the hazards, likelihood and consequences. It does not involve any numerical value to determine the risk level. The risk level is defined into pre-defined categories, for instance extreme, moderate or low. Qualitative risk assessment is usually used in the preliminary risk analysis as screening methods (Frantzich, 1998).

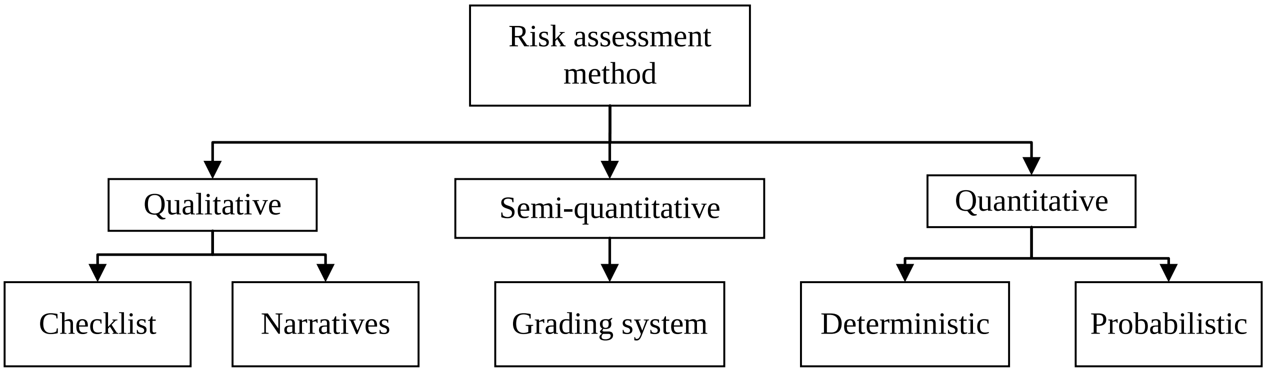

Figure 2.2 Schematic diagram of fire risk assessment method

As displayed in Figure 2.2, checklist and narratives belong to the qualitative method. Checklist is a common approach in fire safety that contains hazards list, usually with recommended practices. It is simple and easy to interpret. However, checklists do not consider the consideration of the logical development of fire events (Yung, 2008). Narratives consist of a series of recommendations related to fire risk and safety. They were not comprehensive with regard to hazards, and so they did not support a thorough review (Jr. & Jr., 2002).

The semi-quantitative method is used to determine the relative hazards associated with unwanted events by applying grade of the identified hazards according to a certain scoring system (Hadjisophocleous & Fu, 2004). One of the examples is indexing method. Fire risk indexing method assigns values to selected variables based on professional judgment and experience. The selected variables represent both positive and negative fire safety features. The assigned values are then operated on by some combination of arithmetic functions to arrive at a single value. This single value can be compared to other similar assessments or to a standard to rank the fire risk (Jr. & Jr., 2002).

In this thesis, quantifying fire risk in buildings is the primary interest. Therefore the qualitative and semi-quantitative method will not be studied further. The quantitative risk assessment method is discussed more detailed in Section 2.4.

2.4 Quantitative risk assessment

In building fire safety, quantitative risk assessment is the most employed method. It has been used for assessing the risk of various types of building such as residential buildings, commercial buildings, and office buildings. Quantitative fire risk assessment concerns quantifications of the probability a fire hazard, fire scenario occurring and the consequences. Comparing to the previous methods, it provides detail information about the assessed risk but also most labour intense. A generalized procedure of quantitative risk assessment is illustrated in Figure 2.3

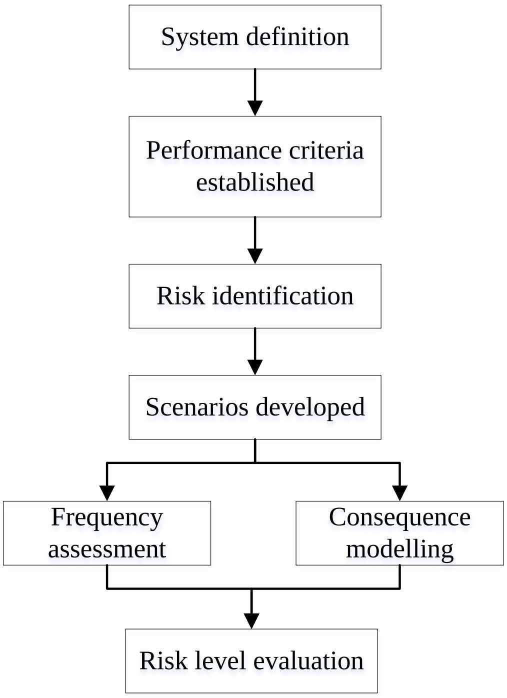

Figure 2.3 General procedure of quantitative risk assessment

The first step is defining the system. It includes defining the characteristic of the building and occupants and also the physical limitations. It is important to know the limit of the system assessed to determine what extent the analysis will be carried out. After the system has been clearly described, the performance criteria are established. The criteria represent the threshold value that needs to be met by the design. Potential hazards in the system are then identified. These are the basis used to develop credible scenarios. There are several tools to construct fire scenarios. The most convenient technique is using event tree.

As displayed in Figure 2.3, the quantification of the hazards divided into two branches: frequency assessment and consequence modelling. The frequency assessment is estimated using probabilistic model whereas the consequences are evaluated using deterministic approach. The fusion of the two steps is most desired because it provides more comprehensive information to evaluate the risk level. Depending on the variable uncertainty, Franzitch (1998) puts quantitative risk assessment (QRA) into two categories: standard QRA and extended QRA. If no uncertainties are taken into account, a standard quantitative risk assessment can be applied. The standard quantitative risk assessment defines the events in terms of deterministic point estimates. Because uncertainty is not explicitly considered, care should be taken during the selection of input data for each variable. Conservative approach is usually adopted to compensate the uncertainties.

An extended quantitative risk assessment needs to perform study the influence of uncertainties in the probabilities or variables. The extended QRA can be seen as a standard QRA performed in a large number of times (Hadjisophocleous & Fu, 2004). The uncertainty analysis determines how uncertainties the outcome probability and consequences are propagated (Frantzich, 1998). The extended quantitative risk assessment provides more information on the distribution of the estimate or number of cumulative functions (Johansson, 2010).

2.4.1 Deterministic approach

In the deterministic approach, the evaluation of a set of circumstances will provide a single outcome. Even so, the outcome of the deterministic model is still valuable in giving important insight to the safety level.

2.4.2 Probabilistic approach

The probabilistic method produce quantitative values. They are typically produced by methods that can be traced back through explicit assumptions, data and mathematical relationships to the underlying risk distribution that all methods are presumably seeking to address (Jr. & Jr., 2002). It does not give a single possible outcome but considers a number of 'chains' representing the nature steps of fire development. Time-dependent probabilities are utilized which were determined from knowledge of extensive experimental data and fire incident statistics. A common method is by constructing event tree as shown in Figure 2.4.

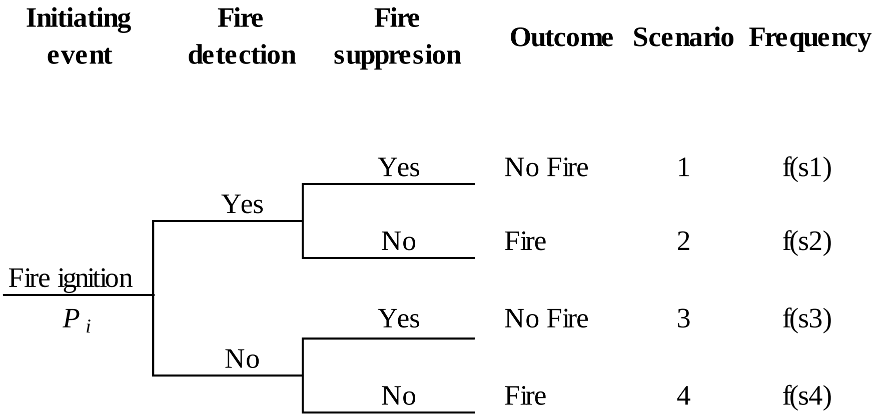

Figure 2.4 Example of simple event tree

Purely probabilistic methods do not make direct use of the physical and chemical principles involved in fires as deterministic approach do. Probabilistic models can be combined with deterministic models. Such procedures view fires as being deterministic once the fire is fully defined, but the inputs are assumed to follow probabilistic models. Thus, the inputs to the deterministic models are treated as random variables (Karlsson & Quintiere, 2000).

2.4.2.1 Distributions used in fire risk assessment

Variables can be described as distributions to compensate its random behaviour due to knowledge uncertainties. A probability distribution describes the interval of possible values that a random variable can fall and the probability that the value of the random variable is within that interval. The distribution interval can be opened or limited by outer bounds.

The followings are three common ways to represent distributions (Frantzich, 1998).

1. Probability Density Function (PDF). It shows the probability for the random variable to fall within a specific interval.
2. Cumulative Distribution Function (CDF). It shows the probability of the random variable, *X*, having value less or equal than *x* in the interval $-\infty < x < \infty$.

   The mathematical expression between the PDF and the CDF is shown in Equation (2.2).

   $$F_X(x) = \int_{-\infty}^{x} f_X(t)dt \qquad (2.2)$$

   where F_X is the cumulative distribution function, *X* is the continuous random variable, *x* is the random value, *f(x)* is the frequency distribution.

3. Complementary cumulative distribution function (CCDF). It shows the inverse cumulative distribution of the probability. In risk analysis, it describes how likely it is that the consequences are worse than a specified value. The mathematical terms for CCDF is shown in Equation (2.3).

   $$1 - F_X(x) = \int_{x}^{\infty} f_X(t)dt \qquad (2.3)$$

In fire risk assessment, the common approach establishing a distribution for random variables is described as follows (Frantzich, 1998).

- Establish the minimum and maximum values for each variable.
- Estimate the distribution parameters, for examples the mean values and the standard deviation.
- Choose a distribution form that has the highest degree of credibility.

2.5 Existing fire risk assessment framework

There has been numerous fire risk assessment models developed up to now. Each model has its framework that depicts what sub-models are evaluated and how the interactions between the sub-models are.

In an international context, risk predictive methods were increasingly applied to a broad range of practical problems in fire safety. It was shown that careful treatment of complex problems provided more reliable solutions than basing only on experts judgment. Countries like Japan, Australia, Sweden or United States have constructed their prototype of fire risk assessment system that demonstrates the ability to account for the complex interactions of fire, building, protection system and the occupants (Bukowski, 1992). There are also models developed by institutions. Some of the models are relatively matured such as FiRECAM^{TM}, FIERAsystem, CESARE-Risk, SCHEMA-SI and CRISP (Muller, et al., 2013). Some of them are still under development, e.g. CURisk (Hadjisophocleous & Fu, 2004). In this Section, FiRECAM^{TM} is selected as an example of existing risk assessment frameworks to describe further.

2.5.1 FiRECAM^{TM}

To assess the overall fire safety performance of a building, The National Research Council of Canada (NRCC) has developed a computer fire risk-cost assessment model called FiRECAM^{TM} (Yung & Bénichou, 2000). The outcome are presented as expected risk to life (ERL) and fire cost expectation (FCE). In its current application, FiRECAM^{TM} can be used for rehabilitation and refurbishment of apartment and office buildings (Yung, et al., 2000). The basic concept of FiRECAM^{TM} was derived from fire risk-cost assessment model developed by Beck. This concept was also used in CESARE-Risk and FIERAsystem (Hadjisophocleous & Fu, 2004).

FiRECAM^{TM} calculates the cumulative effect of all possible fire scenarios that could occur in the building. The total number of fire scenarios is defined as the product of the number of design fires and the number of floors in the building (Yung, et al., 2000). In FiRECAM^{TM}, there are six design fire whose probability of occurrence is determined based on statistical data (refer to Appendix A for details). In the case of an apartment building, the scenarios with occupants awake or asleep are evaluated separately. The six design fire are:

1. Flashover fire with open fire compartment door
2. Flashover fire with closed fire compartment door
3. Flaming (non-flashover) fire with open fire compartment door
4. Flaming (non-flashover) fire with closed fire compartment door
5. Smouldering fire with open fire compartment door
6. Smouldering fire with closed fire compartment door

There are fifteen sub-models in total used in FiRECAM^{TM} to simulate the dynamic interaction of fire, building and occupants during a fire condition. Both probabilistic and deterministic approach are used in the sub-models. Figure 2.5 shows the available sub-models in FiRECAM^{TM} and the linkage created by each sub-model. To be aligned with the objective of this thesis, only sub-models related to life safety are discussed further. They are summarized in Table 2.1. Details of the equations and data source can be found in Appendix A.

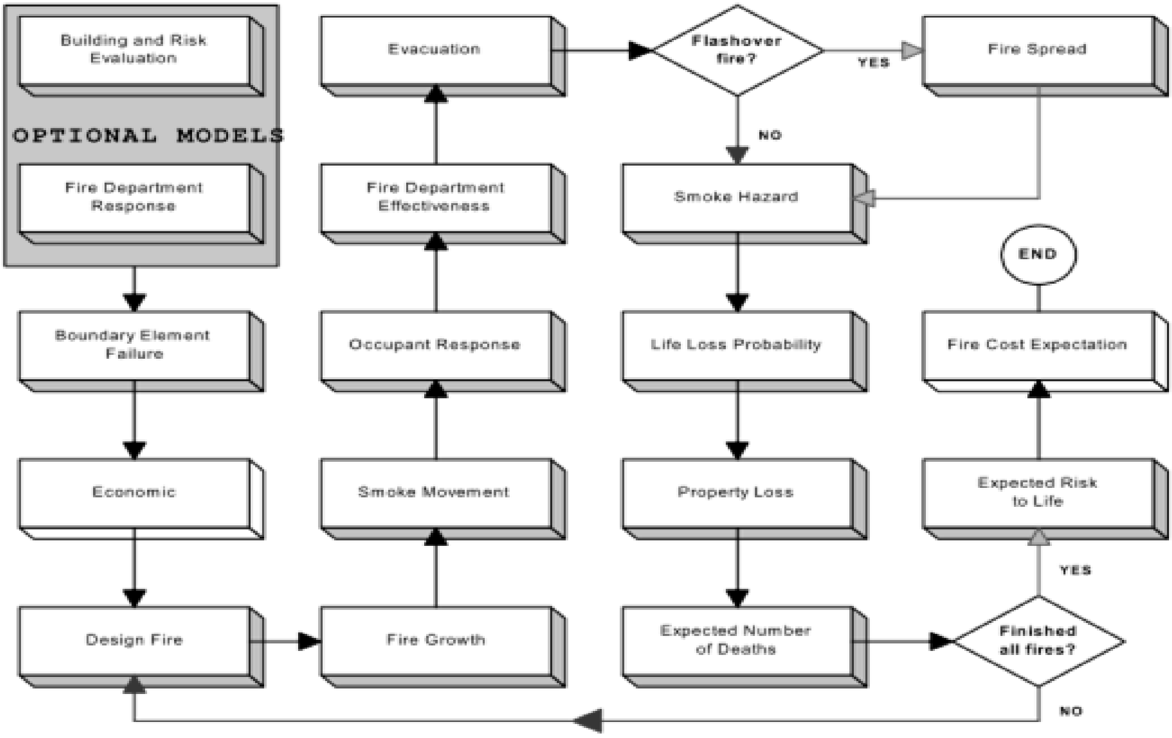

Figure 2.5 FiRECAM^{TM} risk assessment framework *(Yung, et al., 1999)*

Since FiRECAM^{TM} has been designed as a one fire risk assessment framework, every sub-model needs to be simulated using FiRECAM^{TM} modelling method. It cannot be combined with an external modelling program. In its implementation, FiRECAM^{TM} also has limitations as summarized below (Yung, et al., 2000).

- The maximum number of floor in the building is 30 floors
- The maximum number of exits is 15 exits
- The maximum number of occupants per floor is 600 people
- Fire origin is assumed to be in a compartment. Fire in stairwell or corridor is not taken into account
- Smoke spread to floor below fire compartment is considered to be zero
- Smoke hazard value in every location in the floor above fire compartment is the same

- All exits are located on the ground floor only

Table 2.1 FiRECAM^{TM} sub-models related to life safety *(Yung, et al., 2000)*

Sub-model	**Objective**	**Methodology**
Building Evaluation	To evaluate the fire characteristic of a building. Output: - Rate of fire occurrence - Probability of design fire scenario (if it is not typical building) - Probability of failure of detection and activation system	Statistical data information
Design Fire	To calculate the rates of fire occurrence and design fire scenario	- Statistical data information. - If it is not typical building, the probability of occurrence is adjusted from the Building Evaluation sub-model.
Fire Growth	To calculate the fire development in the compartment of fire origin and also to determine the timing occurrence of the different states of the fire development process. Output: - Time of fire cue (I) - Time of detector activation (II) - Time of sprinkler activation (III) - Time to flashover (IV) - Time of fire burnout (V)	Fire growth is calculated using mass loss rate of the combustion of representative fuel below. This sub-model assumed the furniture in the compartment as a single mass in the centre of the room with uniform properties. - Polyurethane foam for residential building - Wood cribs for office buildings
Smoke Movement	To calculate the smoke hazard in terms of temperature and CO and CO_2 concentration at different locations in the building	- The smoke spread is evaluated using one zone model. - The concentrations of CO and CO_2 are presented as FID values based on Purser's equation.
Occupant Response	To calculate the probability that building occupants will decide to evacuate from the building	The probability of occupant to response is based on the PIA process (Perceiving fire cue, Interpreting the cue as fire, Action to evacuate) and computed as follow (Proulx & Hadjisophocleous, 1994). The PIA process depends on 3 specific variables. 1. States of fire growth (I-V) 2. The occupant location (in fire compartment, on the level of fire compartment, other level from fire compartment) 3. The warning received by occupant
Occupant Evacuation	To calculate the evacuation time and the number of occupants who can evacuate the building	A network modelling approach is used where the compartment doors, corridors, stairwells and exits are represented as nodes (Proulx, et al., 1997).

Sub-model	**Objective**	**Methodology**
Fire Department Response	To calculate the response time of fire department	The response time is the sum of dispatch time, preparation time and travel time. The information of the time is obtained from statistical data (Bénichou, et al., 2002).
Fire Department Action	To calculate the probability of fire department arrival and the expected time of arrival	The probability of arrival is calculated as the combination of the probability of fire detection and probability of calling fire department by occupants.
Expected Number of Death	To compute the expected number of occupants that may die from the effects of toxic gases and heat	It calculates the expected number of deaths for the fire scenario being considered using the smoke hazard obtained from Smoke Movement sub-model. The probability of life loss is reduced if there is a refuge area nearby, such as a balcony, which the occupants can use to avoid the hazard.
Expected Risk to Life	To calculate the expected risk-to-life for the building	The total expected risk to life is computed as follow. $ERL_{total} = \sum_{scenario\ i}^{all\ scenarios} (ERL_{scenario} \times P_{scenario}) \quad (2.2)$

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2.6 Life safety criteria

The criteria that correspond to life safety should address the survivability of persons due to exposure to fire condition. They are also called as tenability criteria. In current methods, they are represented as toxicity, thermal effects, smoke layer height and visibility.

Toxicity

Toxic effects on human are caused by the combustion products. It reduces the individual ability to make a decision or to evacuate. In higher level toxicity, it may lead to fatalities. A common method to express toxicity is using the Fractional Effective Dose (FED) formulated by Purser (2002). The FED for each toxic gas can be computed using Equation (2.3).

$$FED = \int_{t_o}^{t} \frac{C_i(t)}{W_i} dt \tag{2.3}$$

where C_i is the concentration of toxic gas 'i', W_i is the required dose to achieve fatal effect and t is the exposure time.

The common toxic gases evaluated are CO, CO_2, O_2 and HCN. The FED total is the summation of all toxic gases FED. The threshold value for critical FED varies from 0.3 to 1.

Thermal effects

Heat radiation from the flame or heated gases can cause thermal injury to the occupants in building. Data from Great Britain fire statistics (Department for Communities and Local Government, 2012) show that 34% fatalities in case of fire are caused by toxicity and 25% are due to burns-severe. Referring to CFPA Guideline (2009), the allowable limit of radiant heat intensity for 30 s exposure is 2.5 kW/m^2. The tenable limit for air temperature for a short time in the event of fire is about 60^{o}C.

Smoke layer height

Smoke layer height is monitored due to its impact on occupants' ability to evacuate properly from the building. The common threshold value varies from 1.5 m to 2 m. Employing this performance criterion is deemed too conservative since it does not give a big impact on people evacuation or direct fatalities. In a real fire situation, the occupants are still possible to evacuate safely by ducking down under the smoke layer.

Visibility

Visibility through smoke can affect the occupant's ability to escape safely from the buildings by reducing their walking speed. The determining factors are the smoke optical density and the physiological effects on the eyes. The common threshold value used is 10 m.

2.7 Uncertainty

It is evident that uncertainties are unavoidable in risk assessment. There are two types of uncertainty: stochastic uncertainty and knowledge uncertainty. Stochastic uncertainties are caused by the randomness in nature. One of the way to tackle this uncertainty is by performing exhaustive studies or making a homogenous population of the variable. Knowledge uncertainty includes random error, systematic error or lack of an empirical basis in making estimation. It can be addressed by advancing knowledge of the process or better measurements.

Pate-Cornéll (1996) has defined six levels of treatment for uncertainties in risk analysis with level 0 as the crudest treatment.

1. Level 0: hazard detection and failure modes identification.
2. Level 1: 'worst-case' approach which based on the accumulation of worst-case assumptions without probability support.

3. Level 2: 'quasi-worst' cases and 'plausible upper bounds'. Conservative value which considered representing worst credible scenario is used.
4. Level 3: best estimates and central values that use mean or median value among a set of possible mechanisms.
5. Level 4: probabilistic risk assessment with single risk curve.
6. Level 5: probabilistic risk assessment with multiple risk curves so that the stochastic uncertainties are distinguished from the knowledge uncertainties. It is the extended version of Level 4 by using statistical distribution instead of point values as the input.

Relating to the previous Section, qualitative risk assessment method can be categorized in Level 0. Quantitative methods can fall between Level 1 to Level 5 depending on how uncertainties are reviewed. The scenario-based method with pure deterministic approach is considered as Level 2 due to the implicit treatment of uncertainties. Event tree and fault tree analysis are considered to be Level 4. Analysis on Level 3 and Level 5 are deemed to be inappropriate for design situation because of these reasons respectively: the possibility of underestimating risk and extensive workload.

One of the most applied technique to treat uncertainties is sensitivity analysis. Through sensitivity analysis, variables that are likely to have the greatest impact on the final results can be identified. Based on International Fire Engineering Guidelines (Nystedt, 2011), a sensitivity analysis should examine the following aspects:

- Input variation
- The reliability of technical systems
- The influence of simplification taken to risk outcome
- The influence of pre-defined events, e.g. door open

The first three points will be discussed later in Chapter 4. Due to the random nature of fire, the events happen can vary. They are presented as a probability as shown in Table 2.2. The variations depend on the fire type, building and occupant characteristic. The more the events defined, the more fire scenarios are developed.

Table 2.2 Examples of pre-defined events during fire and the probabilities

Events	Probability	References
Fire occurring during the day (apartment)	67%	(Frantzich, 1998)
Occupant awareness (apartment) ▪ Sleep ▪ Awake	 52.5% 47.5%	(Johansson, 2010)
Fire type Dwellings (n=481) ▪ Smouldering ▪ Flaming Offices (n=19) ▪ Smouldering ▪ Flaming Retail (n=37) ▪ Smouldering ▪ Flaming	 30% 60% 32% 68% 11% 89%	(Holborn, et al., 2004)
Door open ▪ Blocked fire door ▪ Self-closing door	 30% 20%	(British Standards, 2003)

2.8 Previous studies on quantifying life safety for specific building

A case study of 41-level office building performed by BHP Research Laboratories was featured in (Hasofer, et al., 2007). They carried out a risk-to-life analysis based on stochastic modelling to compare the safety of a building complying with existing requirements and that of an alternative design with improved sprinkler system reliability. Different scenarios were constructed using event trees analysis based on the activation and effectiveness of sprinkler system. For the fire scenario, only flashover (fully or partial) fire was considered. The sub-models used were smoke and flame management, fire brigade communication and response, and occupation communication and response. Based on those sub-models, consequence analysis was performed. The number of expected deaths per year in the building was obtained as the main outcome. It was shown that providing reliable sprinkler system will result in a safer level of risk-to-life in the office building.

Hultquist and Karlsson (2000) have studied fire risk assessment for multi-storey apartment building. The methods used were fire risk indexing, named as FRIM-MAB, and standard QRA. In FRIM-MAB, they defined 17 parameters, e.g. linings in an apartment, smoke control system, suppression system. A Delphi panel that consists of expert engineers with diverse expertise has given each parameter a weight. The parameter grade is multiplied by the weight, and all the weighted grades are added to give a final grade. For each parameter, specific sub-parameters were determined to be later graded according to grading schemes. For example is sub-parameter automatic sprinkler system for the suppression system that has grade range from 0 to 5. Grade 0 represents the worst grade that could lead to low safety index. On the other hand, the standard QRA was performed using event tree. The events considered are initial fire location, detection & suppression system, door condition, occupants' location and awareness level. Mean risk values were obtained showing the expected number of people exposed to critical conditions. Their results showed that the standard QRA gives similar risk level results to the fire index method. However, they emphasized that the responsible manner in performing fire indexing must be adhered to avoid subjectivity in giving bad ratings to the defined parameters. Moreover, the assumptions and simplifications taken when using QRA shall also be treated with care.

Johansson (2010) attempted to quantify the level of safety achieved by apartment buildings built based on prescriptive regulations in Australia and Sweden through quantitative risk assessment. A combination of standard QRA and event tree approach was chosen. He adopted the risk-cost assessment framework to describe the flowchart of the risk analysis. As the outcome, he used the concept of individual risk and societal risk. The results showed that the estimated risk was higher compared to several previous studies. He argued that this was due to conservative input selection. In the study, he acknowledged that uncertainties were great difficulties. The uncertainties come from the assumptions of pre-movement time and cue recognition criteria. Other sources of uncertainty arose from the model used. He stated that the utilization of one-zone model to simulate the smoke spread had led to questions about the accuracy of the results. Adopting more complex models to calculate the consequences more accurately was strongly suggested by the author.

Study on quantifying life safety in apartment building has also been carried out by Grunnesjö (2014). He aimed to determine to what degree the inclusion of passive and active systems compensates for the increased risk due to the extended travel distance for any given (non-compliant) building solution. The risk assessment method was defined in three steps: system definition (apartments and corridors), hazard identification and risk estimation (event tree analysis and ASET/RSET comparison). He used a comparative technique to compare the risk outcome to the deemed-to-satisfy solution. Advance modelling, e.g. FDS, was employed to simulate the fire and smoke development. He included uncertainty analysis by applying probability distributions to those variables that affected the result more than 10%. It was shown that the model overestimated the risk that indicates that the input data were not highly accurate. It was found that due to probabilistic approach, the increased number of dwellings provided led to a linear increase of probability of fire though in reality it was not always the case.

3. General Risk Assessment Framework Proposed

Fire risk assessment can be carried out in a number of ways. The structural framework required can be constructed and adjusted to meet the objective studies. A complete framework such as FiRECAM^{TM}, CRISP, FIERA. is convenient to adopt since it has already taken into account the interaction of all the sub-models with pre-defined simulation model. However, it brings limitation to a point where it does not allow the combination of different modelling theories.

In general, there are elements that can be adopted from developed frameworks in previous studies despite its application to particular buildings or theories background. They are summarized as follows. However, it is worth to note that the followings shall not be treated as an absolute list to follow. It is the author intention to point out what can be extracted for the purpose of this thesis.

- Risk can be evaluated by comparing to absolute criterion (ALARP, acceptable or unacceptable risk) or to acceptance criteria of similar building that complies with codes.
- For scenario-based analysis, event tree is convenient to adopt since it allows the combination of deterministic and probabilistic approach, leading to holistic quantitative risk assessment.
- Review of previous fire incidents is beneficial in identifying what events to be evaluated in the event tree. Common events found are the time of occurrence, location of the initial fire, fire type, door open, detection and suppression system reliability and occupant awareness.
- In general, the sub-models evaluated are fire growth, smoke spread, fire protection system (detection and suppression system), fire department intervention, fire spread, structural failure and occupant response and evacuation. However, the fire design objective limits which sub-models are accounted.
- Fire compartment origin can be determined based on fire statistic especially of room type with most casualties. It is helpful in defining fuel type as a base for fire growth sub-model giving a more realistic result.
- Toxicity is the most used and representative tenability criteria. Visibility, heat radiation and smoke layer height can also be chosen. However, they are considered to be not significant since their influences do not directly cause fatalities.
- Sensitivity analysis should not only be performed on the input variables but also to the modelling use, for instance, is the grid size used in fire field model.

Different fire risk assessment frameworks have been studied. It is shown that the frameworks have same goal – to quantify risk – but with a different approach. Some limitations of existing risk model are indicated in Chapter 2. In this thesis, a general fire risk assessment framework is derived. To improve the validity of the proposed framework, the author attempts to summarize following suggestions.

- When available, input for sub-models should be stemmed from fire statistics to reduce the uncertainties.
- To be more realistic, fire growth should be based on first item ignited instead of the item with highest heat release rate. Again this will strongly depend on the availability of fire statistic data.
- The smouldering fire should not be excluded from the fire type events although it is a slow growth fire. Taking into account smouldering fire lowers the probability of underestimating the risk.
- More than one tenable criteria should be used to lower the uncertainty level.
- Human behaviour should be taken into account more in occupant response and evacuation modelling. Setting life safety as the objective, occupants' ability to make different decisions has a huge impact on the level of risk outcome.
- Advanced technique or modelling software might help to simulate more realistic condition. However, it is important to remember that the engineer must not rely the final risk analysis based on simulation results only. The modelling software shall be regarded as a tool that gives output regardless what kind of input is provided. It is the engineer responsibility to distinguish

which input is appropriate or which one is not to obtain a realistic result. The choice of modelling method can vary depending on the level of detail and resources available. Further discussion on this topic is available in Chapter 4.
- The variable that is deemed to be sensitive from the sensitivity analysis should be investigated to its primary variable.

A general fire risk assessment model is developed as shown in Figure 3.1 (FESG, 2015). The proposed framework demonstrates available sub-models to evaluate and how the interactions between them. The modelling method for every sub-model remains open to enable flexibility in cooperating various methods. The dotted line indicates the frequency assessment part. The dashed line represents sub-models not related to life safety.

As shown in Figure 3.1, the first step is to define the system. It describes the scope of the risk assessment. Next step is to establish performance criteria. Later, it will be compared with the calculated risk at the final stage. It can be performed either using absolute or comparative criterion. Building characteristics includes the type of occupancy, room, geometry and boundary properties. Occupant characteristics include the gender, age, psychology condition and location distribution. Fire hazard identification determines potential ignition source and items ignited. Once the hazards are identified, scenarios can be developed. In this stage, the consequence analysis and the frequency assessment are performed independently.

Fire growth sub-model is evaluated using information from hazard identification. The output of this sub-model is used as the input for smoke spread and fire spread. If the suppression system is successfully activated, the heat release output will be decreased. Smoke spread interacts with almost all sub-models. The smoke properties obtained is used to determine when smoke detectors will be activated. When the detectors are activated, it gives warning for them to start to take action. Smoke spread sub-model also influences the fire department intervention and occupant evacuation in terms of walking speed and incapacitation. The performance of fire department relates to evacuation sub-model in evacuating trapped occupants (Yung, 2008). For instance, a disabled person who is taking refugee. Together with output from smoke spread sub-model – tenability criteria – evacuation time obtained in evacuation model are used to estimate the number of consequences.

In the frequency assessment, a probability is assigned to each event defined in the event trees. The frequency of each scenario is calculated by multiplying the event probability. This value is then multiplied by the number of consequences to having consequence per year. By summing up the consequence per year for all of the scenarios, the final risk outcome is obtained which later compared to pre-defined performance criteria.

Due to lack of time and resources, the proposed framework will not be completely followed in the latter case study. Details of its boundary condition are explained in Chapter 5.

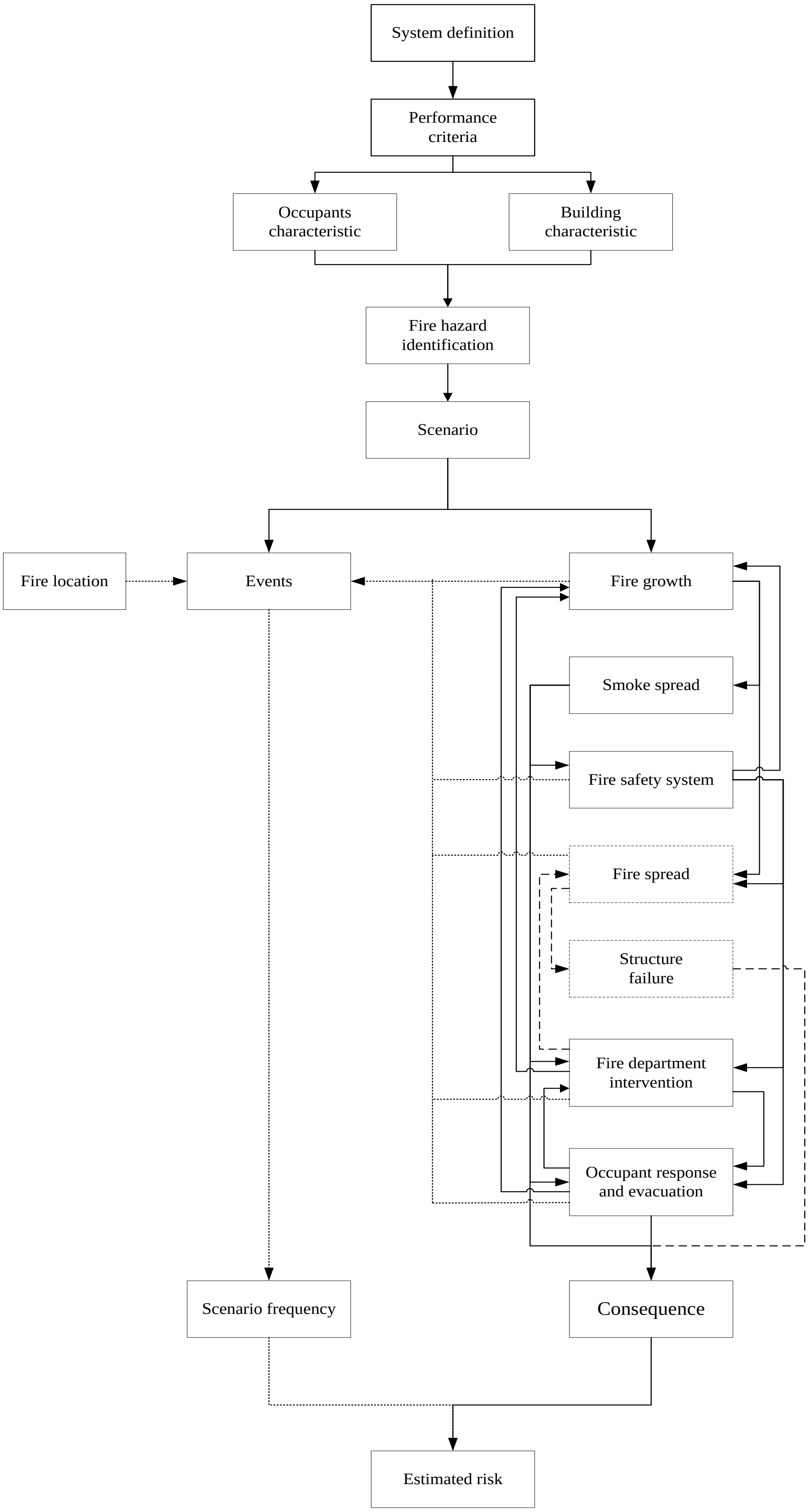


Figure 3.1 General fire risk assessment framework proposed

4. Fire Risk Assessment Sub-Model

There are two main components to estimate fire consequences in terms of life safety: the development of fire and human behaviour. The development of fire determines how long it will take to reach the untenable conditions. It bounds the available time for occupants to evacuate. On the other hand, how persons will response and react during the fire condition also plays an important part to evaluate the consequences.

In Chapter 3, sub-models commonly evaluated in quantitative fire risk assessment are pointed out. In this Chapter, each sub-model is reviewed by providing brief information of the background theory, parameters to adjust, applicability and limitations. Aiming life safety as goal considered in this thesis, only the associated sub-models will be discussed thoroughly. They are fire growth sub-model, smoke spread sub-model, fire safety system sub-model, fire department intervention sub-model, occupant response & evacuation sub-model.

4.1 Fire growth

Fire growth is the first sub-model to calculate in fire risk assessment. The output of this sub-model is heat release rate (HRR) which used later in other sub-models. Parameters related to fire growth sub-model is explained in Section 4.1.1. Existing different methods in estimating fire growth is described in Section 4.1.2.

4.1.1 Parameters of interest

The common approach to calculate heat release rate in the beginning is by using fire growth rate. It is usually illustrated in fire growth curve. When there is intervention from suppression system or fire department, fire growth is affected resulting in lower HRR. Table 4.1 summarizes parameters to adjust in calculating fire growth.

Table 4.1 Parameters to adjust in fire growth sub-model

Output	Parameter	Input	Values
HRR	Fire growth rate	• Occupancy type • Fuel type	Refer to Section 4.1.2
Modified HRR	Suppression system activation	• Activation time • System effectiveness	• Calculated in Smoke Spread sub-model • Statistic data from Fire Safety System sub-model
	Fire department intervention	• Extinguishing time • Extinguishing effectiveness	Statistic data from Fire Department Intervention sub-model

4.1.2 Modelling method

Speaking about fire growth is speaking about heat release rate. Babrauskas (1992) showed that heat release rate is the most sensitive parameter in the fire hazard. Due to the random behaviour of fire, defining the heat release rate to represent the fire growth stage appropriately is not an easy task.

4.1.2.1 Flaming fire

Deterministic method

The most widely used and accepted approach to quantifying fire growth is the alpha-t^2 relation (Equation (4.1)). The alpha-t^2 relation has been found to fit well with the growth rate developed by various different burning items after the incipient stages and before flashover. After that, the relation is no longer valid.

$$Q = \alpha t^2 \tag{4.1}$$

where
Q is heat release rate (kW)
α is fire growth rate (kW/s^2)
t is time (s)

NFPA has established four category of fire growth based on the fire growth rate as shown in Table 4.1 (Karlsson & Quintiere, 2000). In the classic deterministic approach, the heat release rate is calculated by selecting one value from this fire growth category.

Table 4.2 Fire growth rate value for alpha-t^2 relation

Fire growth rate	**α (kW/s^2)**
Ultra fast	0.19
Fast	0.047
Medium	0.012
Slow	0.003

The choice of the fire growth rate for building fire design depends on the occupancy and fuel characteristic. If there is sufficient and reliable information about the building contents, a suitable ignition scenario can be forecasted. The fire growth rate can then be calculated using heat release rate obtained from experimental data. The detailed heat release rate curve for various items can be found in Sardqvist (1993) and SFPE (2002). Another alternative is to determine based on the building type as listed in Table 4.3 (Karlsson & Quintiere, 2000).

Table 4.3 Fire growth rate category based on building type

Fire growth rate	**Building type**
Ultra fast	Shopping centre, entertainment centre
Fast	Hotels, nursing home, school, offices
Medium	Dwellings

There are infinite number of possible fire scenarios. Even in one type of building, fire can be initiated differently by various item. It is also worth to point out that there is never exactly similar arrangement for one case to another. For instance is defining fire growth rate for offices. According to Table 4.3, it will have fast fire growth rate class. It can be argued that there will be many types of combustible materials so that it is acceptable to choose the fast category. However, this is not going to be entirely true in reality. The fuel type, fire load, fuel arrangement or ventilation condition always vary. As a simplification, determining fire growth rate based on one single value is useful to give an insight on how bad the fire might be yet the outcome might not be realistic.

Representative fuel

In reality, information provided during the early phase of building design is limited. Fuel package is usually assumed to represent the fire room origin characteristic. In this approach, the representative fuel is assumed to represent the fuel type, fuel load and arrangement in the building with specific occupancy. This approach is for example used in FiRECAM^{TM}. In FiRECAM^{TM}, the fire growth sub-model for office building was developed based on wood cribs as burning item (Yung, et al., 2000).

Hadji and Zalok (2007) conducted a careful survey of fire loads and types of combustibles for a clothing store. They made probability distribution of the fire load density and took 661 MJ/m^2 as the representative value. They then constructed the fuel package for fire experiment in a standard room to generate the fire growth characteristics. The results showed that for clothing store with mostly clothes as the combustible material, the heat release rate peak achieved was 1.5 MW after 300 s. Comparing to the alpha-t^2 relation, the fire growth rate falls under the medium category.

Although the representative fuel approach seems more realistic than the traditional deterministic method, it still has uncertainties on whether the selected fuel package will be the ignited item. Adopting experimental result as data for the burning item properties is also problematic since there might not be any suitable information. The fuel arrangement also varies for every case. The calculation result thus is subjective depends on the selected item.

Statistics and experimental method

The alpha-t^2 fire is usually applied to describe only one burning object. Holborn et. al. (2004) has expanded the alpha-t^2 relation to a more holistic level. They argued that in reality for a given occupancy there will be a distribution of possible fire growth curves. Therefore, they proposed to use average fire growth rate value. It was estimated by performing a least square fit of a t^2 growth curve based on area of the fire when it was discovered and when the fire brigade arrived and the time intervals between ignition and discovery and ignition and fire brigade arrival. It was assumed that the fire area was zero at the time of ignition. The mathematical expression is shown in Equation (4.2).

$$\alpha = \frac{q''(A_1 t_1^2 + A_2 t_2^2)}{t_1^4 + t_2^4} \tag{4.2}$$

where q'' is the average heat release rate per unit area of the fire (kW/m^2), A_1 is the area of the fire when it was first discovered (m^2), A_2 is the area of the fire when the fire brigade arrived (m^2), t_1 is the time interval between ignition and discovery of the fire (s), t_2 is the time interval between ignition and fire brigade arrival (s).

The average heat release rate per unit area was 250 kW/m^2 for all types of building occupancy except retail and warehouses which has a value of 500 kW/m^2. Comparing to the conventional category of fire growth rate, their results added a very slow growth rate category to compensate cases with smouldering fire type. The calculated fire growth rate value is summarized in Table 4.4.

Table 4.4 Fire growth value category based on Holborn et. al. *(2004)*

Fire growth rate	Range of α [kW/s^2]
Ultra fast	> 0.1055
Fast	0.026375 – 0.1055
Medium	0.026375 – 0.006594
Slow	0.006594 – 0.000412
Very slow	< 0.000412

Table 4.5 Estimated fire growth rate value using log-normal distribution *(Holborn, et al., 2004)*

Building occupancy	α_{95} (kW/s^2)
Offices	0.016
Schools	0.019
Public buildings	0.045
Retail	0.101
Factories	0.100
Warehouses	0.405
Dwellings	0.024

A recent method for quantifying fire growth rate has been developed by Nilsson et. al. (2014). In the study, they estimated fire growth distribution for commercial building in Sweden. They broke down the building into a number of different rooms types and then divided again into possible first object ignited. Statistical data was employed to identify which room is common as fire origin and what object might be ignited first. The fire growth rate for the corresponding item was obtained from literature and experimental data. The principle of this method is depicted in Figure 4.1. Referring to Holborn et. al. (2004) study, their calculated fire growth rate was also presented in the log-normal distribution. For commercial building, it was found that the expected fire growth rate value is 0.011 kW/s^2 without considering arson.

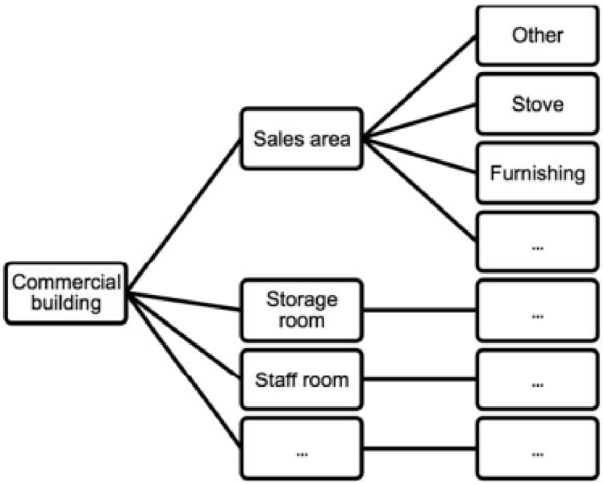


Figure 4.1 Fire growth rate determination based on Nilsson et. al. method *(2014)*

This approach is promising to apply since it provides flexibility to use for any type of fire scenario. In addition, it tries to capture all possible first ignited item in every room type hence representing more realistic fire growth rate value for the building. The challenge is on the work of dealing with plenty of possible ignition items. It also requires extensive well-recorded information about fire statistic that might be hard to implement in the countries where no such statistic is available.

One of the uncertainties sources of this approach comes from the statistical data. It is difficult to guarantee based on the recorded data that fire in one room, for an instance sales area, is caused by one specific item, for instance furnishing. Similar to the other method, uncertainties also comes from the utilisation of the experimental result. When choosing fire growth value for a specific item, there might not be any data at all or rough estimations have to be made.

4.1.2.2 Smouldering fire

In the conventional approach, heat release rate of smouldering is calculated using mass loss rate of fuel. For instance in FiRECAM^{TM} (Cooper & Yung, 1997), the fuel mass loss rate is estimated using Equations (4.3).

$$\begin{aligned} R_{ML} &= 1\,x\,10^{-8}(2.78t + 0.00856t^2) && \text{if } t < 3600 \\ R_{ML} &= 1.21\,x\,10^{-3} && \text{if } t \geq 3600 \end{aligned} \qquad (4.3)$$

where R_{ML} is mass loss rate (kg/s) and t is time (s).

In the statistical approach of fire growth rate determination proposed by Holborn et. al. (2004), smouldering fire is already covered under category very slow fire growth.

4.2 Smoke spread

The values required to calculate consequences to human are generated in smoke spread sub-model. They are temperature, smoke layer height, visibility, heat radiation and gas product concentration. The outputs of smoke spread sub-model are used to determine the fire safety system activation time. The outputs also affect occupant response and evacuation sub-model in estimating recognition time for direct cues, exit decision-making and change of walking speed. The parameters of smoke spread sub-model are strongly influenced by the output of fire growth sub-model and fuel and building characteristics.

4.2.1 Parameters of interest

The parameters and corresponding inputs of smoke spread sub-model are summarized in Table 4.6.

Table 4.6 Parameters to adjust in smoke spread sub-model

Parameters	Values	Output	Influencing (in other sub-model)
Enclosure characteristic • Dimension • Openings • Wall properties Fuel properties • Heat of combustion • Combustion efficiency Surrounding condition • Temperature ambient Heat release rate	Defined • Statistic data • Defined Defined Calculated in fire growth sub-model	Layer properties • Hot gas temperature • Heat radiation • Visibility • Smoke layer height	• Suppression system activation time • Detection system activation time • Notification time to fire department • Incapacitation • Walking speed • Exit choice decision • Walking speed • Occupant recognition time (direct cues)
Fuel properties • Heat of combustion • Product yield • Combustion efficiency Surrounding condition • Oxygen concentration	• Statistic data • Statistic data • Defined Defined	Gas product concentration	• Incapacitation • Walking speed

4.2.2 Modelling method

Due to constantly changing surrounding condition during a fire, the equations are expressed in the form of differential equations. A complete set of equations can compute the conditions produced by the fire at a given time in a specified volume of air. Referred to as a control volume, the model assumes that the predicted conditions within this volume are uniform at any time. As a consequence, the control volume has one temperature, smoke density, gas concentration, etc. (Jones, 2001). Up to date, there are three approaches used in modelling smoke spread in enclosure (Mowrer, 2002). They are distinguished by the degrees of sophistication and detail in defining the fire development.

Analytical model

The analytical model is the simplest model. It consists of closed-form equations that can be solved directly without iteration. The equations are derived from the overall mass and species conservation equations, together with a simple treatment of fire-plume air entrainment. The results provide information on the growth of the ceiling layer and the smoke and CO concentration in the layer over time (Guillermo, et al., 2005). Fire growth is defined as alpha-t^2 fire. Radiation is not taken into account thus the HRR employed is the total HRR. The combustion products together with the air entrained accumulate in the hot layer and have uniform properties. The equations are shown in Appendix A.

Zone model

The zone model concept is stemmed from the assumption that a volume can be subdivided into zones, in which the properties homogeneous but vary over time. Similar to the analytical approach, it was also derived from mass, energy and species conservation equations. The momentum equation is not explicitly solved. The fire is represented as a source of energy and mass. The plume is accumulated in the upper layer of the enclosure and acting as a pump for the mass from the lower zone. Detail explanation of the mathematical expressions used can be consulted in Quintiere (2002).

Field model

The most advanced model is field models. In field models, fire enclosure is divided into a large number of control volumes within which the conservations equations are solved. They numerically solve the equation of continuity, the conservation of mass, momentum and energy as a system of partial differential equations. Turbulence phenomena, reaction kinetics, radiation transport and pyrolysis are considered in the modelling.

In recent years, there are three approach developed in fire field models. They are namely DNS (Direct Numerical Simulation), RANS (Reynolds-averaged Navier-Stokes) and LES (Large Eddy Simulation). In DNS, the direct numerical solution of the governing equation is solved. As it is extremely expensive in computational time, DNS is considered not practical for large-scale fire simulations. RANS models attempt to solve the conservation equations by averaging in time. However, they are unable to solve the scale-dependent dynamic behaviours, which are predominant during the pulsation cycle of buoyant fires. In LES, averaging is performed locally over space. Consequently, the turbulence phenomenon of fire is better captured. Due to this reason, LES has been most preferred to adopt in fire modelling.

4.2.3 Modelling software

A large number of modelling software to investigate smoke development and movement has been developed. In this Section, one example from zone model and field model, B-RISK and FDS6, is compared. Table 4.7 provides a brief description of the theory, boundary condition and also features for both models. Equations used in the modelling software are presented in Appendix A.

Table 4.7 Examples of smoke spread modelling software

Modelling software	Methodology	Limitations	Features
B-RISK (Wade, et al., 2013)	• Zone model • Options on plume entrainment model: McCaffrey, Heskestad or Zukowski correlation • Point source model of radiation • Combustion gas products are calculated using Global Equivalence Ratio and experimental data • Toxicity is calculated using Purser and ISO 3572 method	• Enclosure must be modelled as rectangular volumes • Not suitable for enclosure with (L/W > 5) and (H/min[L,W]>5) • Modelling of large opening in ceiling is not recommended	• Allow user to assign distribution as data input • Wind effects are considered • Low computational time consumption • Publicly available
FDS 6 (McGrattan, et al., 2014)	• Field model: LES • Single step and mixing-controlled chemical reaction as combustion model • Radiative heat transfer is calculated using Finite Volume Method • Geometry is defined in meshes that have to conform governing equation • All solid surfaces are assigned thermal boundary conditions • Heat and mass transfer to and from solid surfaces are evaluated with empirical correlations	• Wind effect is not considered • Amount of time required to set input data • Deep understanding of fire dynamics is required as user • Computationally extensive	• More precise treatment of gas species properties • Turbulence is well-captured • Publicly available

4.3 Fire safety system

Availability of fire safety system in building is mandatory by codes. Fire safety system usually consists of a detection system, suppressing system and smoke control management. Fire detection system is intended to provide early warning to occupants in case of fire hence they can immediately evacuate. Fire suppression and smoke management system are designed to maintain tenable condition in the building in case of fire thus people can evacuate without any harm or to maintain structural integrity from the effect of fire spread. To achieve the design objective, those systems must be able to effectively operate and perform as they are intended.

Table 4.8 Parameters to adjust in fire safety system sub-model

Output	Parameter	Values
Detection activation time	• Smoke obscuration • Volume of smoke	Calculated in Smoke Spread sub-model
Suppression (sprinkler) activation time	• HRR • Hot gas temperature • Ceiling height • Response Time Index • Activation temperature	• Calculated in Smoke Spread sub-model • Calculated in Smoke Spread sub-model • Defined • Defined by standard • Defined by standard
System effectiveness	• System probability of activation • System efficiency	Refer to Table 4.10

The sprinkler response time is calculated using Equation (4.4).

$$\frac{dT_d}{dt} = \left[\frac{u^{\frac{1}{2}}(T_{g,n} - T_{d,n-1})}{RTI}\right] \tag{4.4}$$

with

$$T_g - T_a = \frac{5.38(\frac{\dot{Q}}{r})^{2/3}}{H} \qquad \text{if } \frac{r}{H} > 0.18$$

$$T_g - T_a = \frac{16.9(\frac{\dot{Q}}{r})^{2/3}}{H^{5/3}} \qquad \text{if } \frac{r}{H} \leq 0.18$$

$$u = \frac{0.2\dot{Q}^{1/3}H^{1/2}}{r^{5/6}} \qquad \text{if } \frac{r}{H} > 0.15$$

$$u = 0.95\left(\frac{\dot{Q}}{H}\right)^{1/3} \qquad \text{if } \frac{r}{H} \leq 0.15$$

where T_g is the maximum, near ceiling, fire-gas temperature (°C), T_a is the ambient temperature (°C), $\dot{Q}$ is the total heat release rate of the fire (kW), r is the radial distance from the axis of the fire plume (m), H is the height above the origin of the fire (m), u is the maximum, near ceiling, fire-gas velocity (m), T_d is the temperature of the link (°C), RTI is the Response Time Index for the sprinkler ($m^{1/2} s^{1/2}$).

Effective fire safety system is shown to have a positive impact on safety level in buildings in case of fire (Benichous, 2000). The effectiveness of fire protection system consists of three components (Marsh, 2008).

1. Availability – will it be available when called upon? For example: when the sprinkler system is being repaired when the fire happened, it may be considered to have zero availability at that moment.
2. Reliability – will it operate when called upon?
3. Efficacy – will it successfully perform its intended function?

The availability and reliability of the system are grouped together as the probability of activation. In the current model, the effectiveness of individual fire safety system is used as input in pre-defined events in QRA to determine the risk of a specific scenario. The effectiveness of the system is measured using Equation (4.5). Information on the activation and efficacy of each type of fire safety system is summarized in Table 4.9.

$$\textit{Effectiveness} = (\textit{probability of activation}) \times \textit{efficacy} \tag{4.5}$$

Table 4.9 Fire safety system effectiveness data

System	Activation	Efficacy	Reference
Smoke detectors			(Marsh, 2008)
▪ Smouldering fire	70%		
▪ Flaming fire	80%		
▪ Post-flashover fire	85%		
Smoke detectors			(Bukowski, et al., 2002)
▪ Residential	75.1% - 80.6%		
▪ Institutional	82.3% - 84.6%		
▪ Commercial (office, storage, stores)	70.2% - 73.7%		
Sprinkler system			(John R. Hall, 2013)
▪ Residential	94%	97%	
▪ Educational	87%	97%	
▪ Health care (hospital, clinic, nursing home)	86%	98%	
▪ Offices or stores	90%	97%	
▪ Storages	79%	97%	
▪ Public assembly (eating or drinking establishment)	92%	95%	
Smoke control system	90%	N/A	(British Standards, 2003)

Particularly for the sprinkler system, there are two general approaches to estimate sprinkler effectiveness: component-based and system-based. Component-based is a bottom-up approach that require details of the component system failure rate per unit time. It uses fault tree to calculate the reliability of the system. This approach is limited to provide reliability information only due to difficulties in estimating individual component efficacy. The system-based approach utilises data from system operation in previous fire events from a population of buildings to estimate the measure of effectiveness. Due to the majority of sprinkler failures come from human error, Frank et. al. (2013) suggested not to apply component-based approach exclusively without system-based study data. They also emphasized on using a range of values with associated probabilities to appropriately represent the uncertainty in estimating sprinkler effectiveness. A uniform or triangular distribution shape might be the most suitable to use with a peak between 90% and 95%.

4.4 Fire department intervention

Fire department intervention sub-model contributes to life safety by rescuing trapped occupants in the building in case of fire. Despite best effort from the author, there are difficulties in finding previous research on how to quantify fire department intervention. The model explained below is the one used in FiRECAM^{TM}. The outputs of fire department intervention sub-model are intervention time, extinguishing and rescue effectiveness. Parameters related to fire department intervention sub-model are summarized in Table 4.10. The sequential events of fire department response is displayed in Figure 4.2.

Table 4.10 Parameters to adjust in fire department intervention sub-model

Output	Parameter	Related input	Value
Intervention time	Notification time	• Automatic alarm notification system • People action to call	• Calculated from Smoke Spread sub-model • Defined in Occupant Response sub-model
	Dispatch time	• Crew skill or experience level • Availability of staffs or resources in fire station	Fire statistic: 30 – 60 s (Bénichou, et al., 2002)
	Preparation time	Crew skill or experience level (professionals or volunteer)	Fire statistic: 30 – 105 s (Bénichou, et al., 2002)
	Travel time	• Distance between building & fire station location • Speed of vehicle on the road	Defined
	Setup time	• Building heights • Water system tools availability (connection, hose, etc) • Crew skill	Defined or 60 s (Bénichou, et al., 2002)
Extinguishment time and effectiveness	• Fire severity • Water resource • Crew size	• Fire growth • Sprinkler effectiveness • HRR • water availability	Calculated from Fire Growth sub-model Defined
Rescue time and effectiveness	• Intervention time • Number of trapped occupants • Smoke properties • Crew size	• Building plan layout • Factors in intervention time • Occupant decision-making • Toxicity • Visibility	• Defined • Calculated • Calculated in Occupant Response sub-model • Calculated from Smoke Spread sub-model • Calculated from Smoke Spread sub-model • Defined

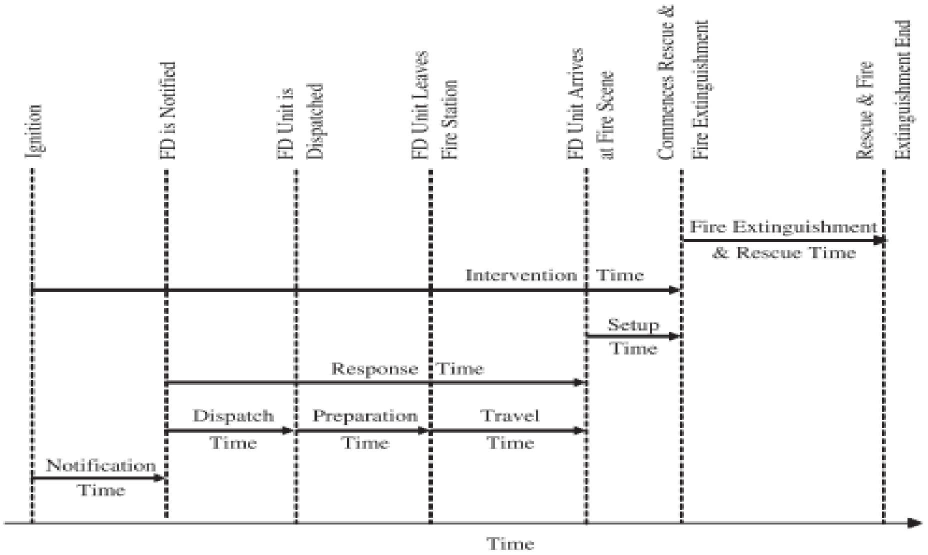


Figure 4.2 Sequential events of fire department intervention *(Yung, 2008)*

Tilander (2004) has made an attempt to curve-fitting the fire department intervention time distributions using fire statistic data in Finland from years 1994 – 1997. She stated that the turnout time, response time and the operation time can be presented as gamma distribution. The turnout time is the duration from the moment the unit is notified until it leaves the fire station. The response time is duration from the moment the unit is notified until it arrives at the fire scene. The operating time is the duration from the moment the unit is notified until it returns to the fire station. The estimated parameters of the distribution are shown in Table 4.11.

Table 4.11 Estimated parameter of the gamma distributions *(Tilander, 2004)*

Parameter	**a**	**α_1**	**β_1**	**α_2**	**β_2**
Turnout time (min)	0.87	1.7	2.1	1.2	10
Response time (min)	0.35	6.6	1.1	2.5	6.1
Operating time (min)	0.5	2.9	17	1.9	76

Based on developed sub-models, there is no direct usage of the intervention time to occupant evacuation. This sub-model interacts with occupant life safety by comparing the intervention time to the time when untenable conditions reached. If the intervention time is less than time to untenable condition, number of people rescued can be calculated thus reducing the total number of fatalities. For fire department rescue effectiveness, Bénichou et. al. (1999) calculated it by considering the number of trapped occupants, firefighter crew size, the status of fire and smoke concentration. They derived a curve of the effectiveness probability versus number of trapped occupants as shown in Figure 4.3. The effectiveness value is then applied to the event tree analysis under the rescue effectiveness events.

Proulx et. al. (1997) mentioned that real evacuation time required in 7-storeys office buildings might range from 4 – 5 minutes. While the time needed for the fire brigade to commence rescue based on the Canadian study is in the range of 7 – 16.8 minutes (Yung, 2008). Assuming that there are no trapped occupants, it is shorter than the time needed by the fire brigade to start the rescuing process. In his study, Gunnesjö (2014) suggested that building safety performance should be independent of location, near to fire station or not. Fire service intervention should be treated as redundancy for life safety purposes

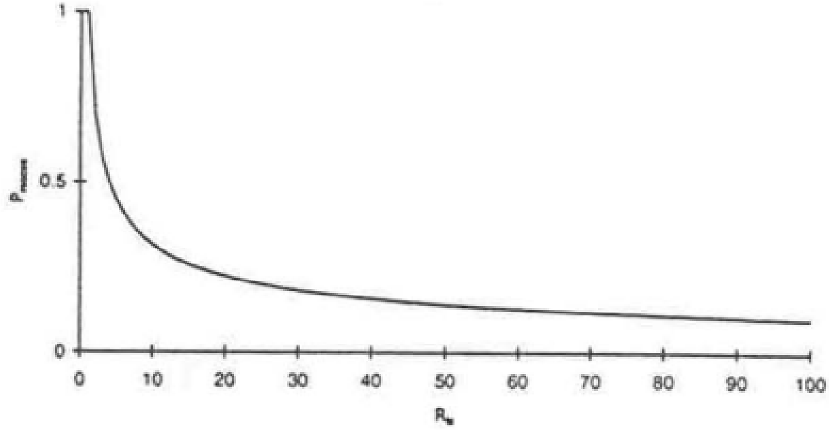


Figure 4.3 Curve of the probability of rescue effectiveness of fire department versus the ratio of number of trapped occupants to the firefighters’ crew size *(Bénichou, et al., 1999)*

4.5 Occupant response and evacuation

Parameters related to occupant response and evacuation sub-model is explained in Section 4.5.1. Existing different methods on modelling occupant behaviours and evacuation is described in Section 4.5.2.

4.5.1 Parameters of interest

Table 4.12 summarizes the parameters to adjust in occupant response and evacuation sub-model. The explanations for each parameter is explained below.

Table 4.12 Parameters to adjust in occupant response and evacuation sub-model

Output	Parameter	Input
Occupant behaviour	Compartment geometry (obstacles, exits, evacuation route)	Defined
Occupant response behaviour	• Occupant characteristic (gender, age, knowledge, affiliation) • Occupant distribution location • Hazard exposure (heat, smoke, toxicity)	• Defined • Defined • Calculated in Smoke Spread sub-model
Detection & alarm time	-	Calculated in Smoke Spread sub-model
Pre-movement time	-	Statistical data
Travel time	• Distance to exit • Walking speed • Occupant behaviour	• Defined • Statistical data • Defined

The time available for a safe escape of the occupants in the event of a fire is limited to the time when untenable conditions occur along the evacuation route. The sequence is illustrated in Figure 4.4. The required escape time is divided into three main categories: detection & alarm time, pre-movement time and travel time.

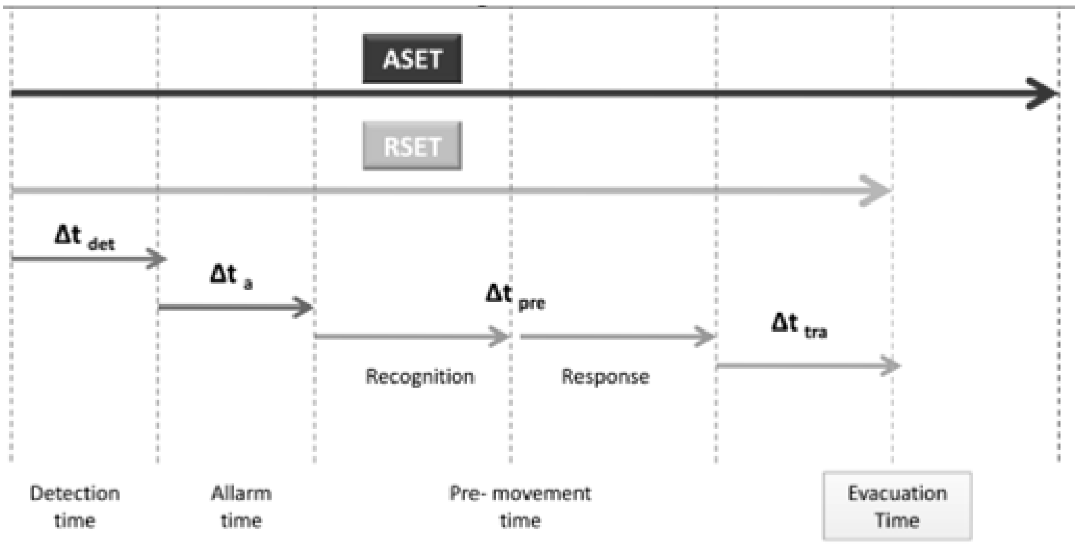


Figure 4.4 Sequence of total evacuation time *(CFPA Europe, 2009)*

The detection and alarm time is the time from the beginning of ignition to it is detected (either by an automatic system or people) and trigger the activation of the alarm. In some cases, detection and alarm activation are almost simultaneous. This depends on fire characteristics, occupant characteristics and fire protection system. Detection times for automatic system can be calculated, but estimating detection time by people is difficult. Studies from Charters et. al. (2002) shows that the detection time for shops and commercial premises is 1 minute with a probability of 35%.

Pre-movement time encompasses the recognition and response time. It represents the time from occupants become aware and start to move. It gives a great effect to the total escape time. Up to date, the way to measure pre-movement time is by utilising fire drill statistics or engineering judgment. In their studies, Lord et. al. (2005) estimated the average pre-movement time for office building (n=141) and apartments (n=341) based on existing research to be 71 s and 347 s, respectively. Using the data from actual fire drill, they investigated three different approaches to input the pre-movement time into simulation model: use the average pre-movement time throughout the entire building, use different pre-movement time per floor, use the average pre-movement time but assign it individually to the occupants. Their results show that applying different pre-movement time per floor gives the closest total escape time to experiment. However, the availability of fire drill evacuation data is highly required. In another study, Proulx (1997) found that 89% of the occupants start to move within 1 minute from evacuation drill in 7-stories office building in London. Charters et. al. (2002) calculated the pre-movement time for occupants in all locations in shops and commercial premises to be under 2 minutes.

Travel time is the time occupants start to move from their original location to a safer place. It is mainly influenced by the occupants' characteristics, the travel distance and the conditions along the evacuation route. It can be calculated manually or using software model. A model that can adequately simulate the human behaviour response and its interaction to fire, e.g. visibility effect, is advantageous to use.

4.5.2 Modelling method

Putting life safety as a priority in quantifying building fire design instigates the need to perform occupant response and evacuation modelling. Research in this field has been actively developing for at least 30 years (Gwynne, et al., 1999). A number of modelling methodologies are available with various principle to represent the enclosure representation, population behaviour and perspective. The methods can be adopted separately or in combination to give more realistic simulation. Overview of most widely used computation models is presented as concluding remarks.

Cellular Automata

Cellular automata (CA) model was first introduced by Von Neumann (Xiaoping, et al., 2009). It is a rule-based dynamic model consisting of a uniform grid of cells. Rule-based model means that the occupant make decisions based on their current situation. It emphasizes the intrinsic properties of the occupant. The discreteness means that the position of the agents is updated in well-defined steps. In the computer simulation, the persons all move at the same time (Schadschneider, et al., 2008). The uniform grid and the possible direction used in CA are displayed in Figure 4.5. Each cell in CA can only be occupied by one person. A person can move to the neighbouring cells depending on three factors: desired direction of motion to find shortest connection, interactions with other occupants and interaction with obstacles such as walls and doors.

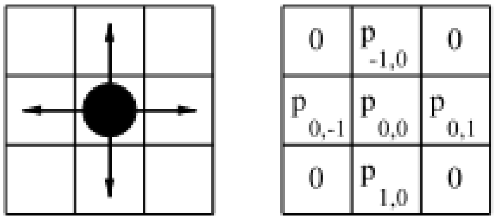


Figure 4.5 Von Neumann neighbouring cell that indicates the possible agent movement *(Schadschneider, et al., 2008)*

CA model is ideally suited for large-scale computer simulations as it employs discreteness in space, time and state variables. Due to its rule-based model, CA works well for low-density condition or where waiting in a lane formation occurs. It is also simple and cheap in computational time (Xiaoping, et al., 2009). The limitations of CA model is listed below.

- Limited possible movement due to limited grid size
- Limit the possibility of simulating heterogeneous crowd since it will not allow to have bigger or smaller person than the cell size
- The maximum flow rates are fixed throughout the simulation. It contradicts the principle where the flow rate should increase as the density increase until it reaches a maximum and from then the density increase makes the flow rate decrease
- During simulation, the occupant does not have ability to re-planning the route when changes occur in the environment

Flow-based

Crowd dynamics has some similarities with fluid flow. The flow-based model uses partial differential equations to describe how density and velocity change over time. Hughes (2000) has performed extensive studies in developing continuum model to understand the choice of path and crowd in motion. The governing equations are derived based on three hypothesis:

1. The speed of occupant movement is determined by the crowd density only
2. Occupants have common sense of the task
3. Occupants seek to minimise estimated travel time while avoiding areas with extreme crowd densities

Flow-based is categorized as a force-based model. It focusses on the extrinsic properties and their relevance for the motion of the occupants. In this model, the occupants ‘feel’ a force exerted by others and the surroundings. It is a physical approach based on the observation that the existence of others leads to deviation from its original motion. Since the occupant is considered to behave like fluid, the complexity of perception, decision process making or actions are not taken into account in this model (Schadschneider, et al., 2008). This model is best applied to simulate jamming situations where the crowd density is very high (Xiaoping, et al., 2009).

Social force

Helbing and Molnar (1995) have proposed the social force method to simulate human movement. It is believed as the most well-known model which can successfully simulate the most typical phenomena observed in occupant dynamics and achieve very realistic simulation results (Xiaoping, et al., 2009).

Based on their study, sensory stimulus causes behavioural reaction that depends on the personal objective and external forces. The conceptual of this model is defined as follow:

1. Occupant wants to reach a certain destination as comfort as possible. As a consequent, he intuitively takes shortest possible route. If his motion is disturbed, he will walk to the desired direction with a certain desired speed.
2. The motion of an occupant is influenced by external factors. An occupant typically feels uncomfortable if he gets too close to others or the boundaries, e.g. walls, thus he will keep a certain distance. This phenomenon is described as repulsive effects.
3. Occupant is sometimes attracted by other occupant or objects. For instance is when occupants tend to move in a group. This phenomenon is called attractive effects.

The mathematical expression for the occupant’s change of velocity over time is displayed in Equation 4.6.

$$\frac{d\boldsymbol{v}_j}{dt} = \frac{\boldsymbol{v}_j^{(0)} - \boldsymbol{v}_j}{\tau_j} + \boldsymbol{f}_j^{(soc)} + \boldsymbol{f}_j^{(phys)} \tag{4.6}$$

where v_j is the actual velocity of the occupant (m/s), $v^{(o)}{}_j$ is the preferred velocity of the occupant (m/s)

t is time (s), τ_t is the acceleration time (s), $f_j^{(soc)}$ is the total force due to other occupant and boundaries (N), $f_j^{(phys)}$ is the physical force due to high density situation (N).

The social force model works well in capturing the highly dense of occupant behaviour such as faster-is-slower effect (i.e. certain processes take more time if performed at high speed. In other words, waiting can often help to coordinate the activities of several competing units and to speed up the average progress), arching and clogging. On the contrary, the social force model does not consider the occupant ability to make local decisions based on personal strategies (Xiaoping, et al., 2009).

Agent-based

An agent-based model is a computational model that use bottom-up approach in which system control is decentralized and governed only by the behaviour of agents (Wagner & Agrawal, 2014). It consists of three elements (Macal & North, 2011):

1. Agents with their attributes and behaviours
2. Agents relationships and methods of interaction
3. Agents' environment

In this model, one occupant is defined as agent who is autonomous and heterogeneous, allowing him to function independently and distinguished in a population. An agent is also adaptive and goal-directed. Those characteristics make an agent able to compare evacuation routes choices to minimise the evacuation time needed. An agent is also embedded with social nature force to interact with others and the environment. In recent years, the agent-based model has been the most preferred method to simulate crowd movement (Wagner & Agrawal, 2014). It is considered to give a more realistic result by taking into account the heterogeneity and social knowledge factor. It captures emergent phenomena well. It also permits the user to modify the agent characteristic depending on the case. The major limitation of the agent-based model is the amount of computing power required.

4.5.3 Enclosure representation

There are three methods to represent the enclosure for evacuation modelling based on the level of space resolution (Kuligowski, et al., 2010). The illustration on how the three models defining the space is depicted in Figure 4.6. The overview of the principle is described as follow.

1. Coarse network

In a coarse network model, the space is illustrated as a network of arcs and nodes, representing different parts of the infrastructure. Each node may represent room a room or corridor irrespective to its physical size. Nodes are linked by the arcs representing connectivity within the actual enclosure. An occupant can move from one section of the building to another section without knowing the movement within the section itself. The speed of movement is calculated by a mathematical flow equation derived from real-life observations of crowd movement (Castle, 2007). As a result, occupant movement cannot be exactly modelled. Individual perspective cannot be simulated thus no behavioural aspect, e.g. keeping a comfortable distance from obstacles, is observed.

Being the simplest technique, the coarse network model is computationally cheap. It is useful as a first approximation of a building's maximum and minimum total evacuation time. However, this model is not suitable when complex enclosure structure and occupant behaviour are expected during evacuation. Based on a recent survey, the coarse network model is no longer in the interest of evacuation model developer and user (Ronchi & Nilsson, 2012).

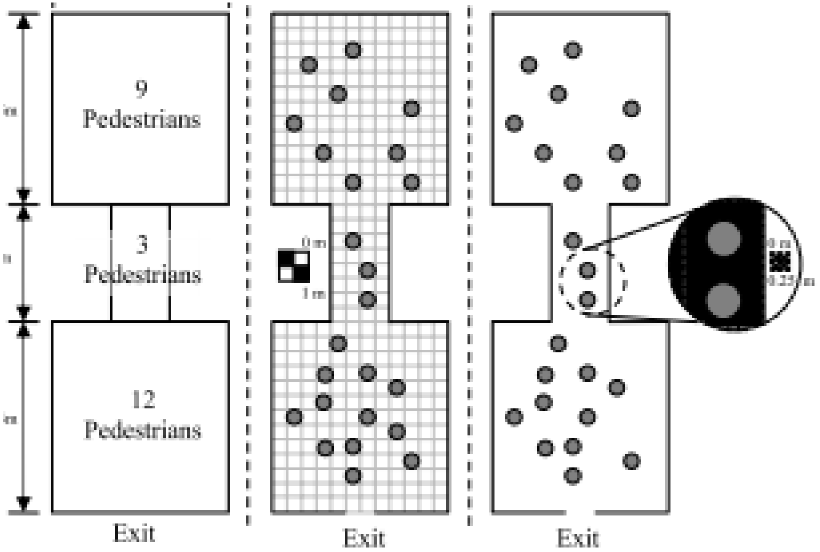


Figure 4.6 Enclosure representation in each network model *(Castle, 2007)*

2. Fine network

Fine network model divides the space into a number of small grid cells on which the occupant can move to and from. One grid cell only allows to be occupied by one occupant. The size, shape and connectivity of the cell can be varied from one modelling software to another. A large geometry that consists of many compartments can be constructed by thousands of nodes. It gives better representation of the actual geometry and precise location of each individual at any time during the evacuation (Gwynne, et al., 1999). Due to finer space description, each occupant is allowed to have different movement and interaction between them or the surroundings. In recent years, this model has been widely used to perform occupant evacuation modelling in various types of buildings (Ronchi & Nilsson, 2012).

3. Continuous network

Continuous network models simulate occupant movement through a coordinate system within the enclosure. The occupant location is not tied to a specific cell, but there are rules that limit the minimum distance between occupants (Kuligowski, et al., 2010). As seen in Figure 4.6, this model is a refined version of the fine network approach. It accurately illustrates the actual geometry thus enable to simulate occupant behaviours that may be sensitive to occupant location, orientation and distance to others.

Continuous network model recalculates the coordinates of the occupants at every time-step. As a compensation for its complexity, the computational time required is extremely expensive. Due to this limitation, very few applications have adopted the continuous approach to date. The other disadvantage is the difficulties in simulating movement of several thousand occupants with a rich set of behavioural and decision-making characteristics. Applications that have adopted this approach tend to set a limited number of behavioural characteristics (Castle, 2007).

4.5.4 Modelling software

There has been a total of 26 computer models that focus on simulating building evacuation up to date (Kuligowski, et al., 2010). In this Section, only top 5 most widely known evacuation modelling software will be described. The models are chosen based on a recent survey conducted by Ronchi and Kinsey (2011). The selection was based on models of which users mostly aware.

1. buildingEXODUS (Galea, et al., 2014)

It was developed by FSEG Group in University of Greenwich, UK. It was designed for applications in the built environment and is suitable for application to a supermarket, public buildings, high-rise buildings, school, etc. The computer programme buildingEXODUS proves to be a very effective tool for analysing the evacuation behaviour of the complicated structures. However, it requires an elaborate set of data regarding widespread specialist fields.

2. FDS+Evac (Korhonen & Hostikka, 2009)

FDS+Evac is the evacuation model of FDS (Fire Dynamic Simulator). It was mainly developed by the VTT Technical Research Centre of Finland. FDS+Evac computes the position, the velocity, and the dose of toxic gases of each agent inside the computational domain at each discrete time step.

3. Simulex (Thompson & Marchant, 1995)

Simulex was originally developed by Thompson. Up to date, it is applied for the escape movement of large numbers of individuals in single level or multi-level buildings. It has been applied to simulate evacuation in schools, industrial premises, hotels and terminal.

4. STEPS (Waterson & Pellissier, 2010)

STEPS (Simulation of Transient and Pedestrian movementS) was developed by Mott MacDonald as a microscopic prediction tool of pedestrian movement under both normal and emergency conditions. It has been widely used in occupant evacuation modelling of public buildings such as a stadium, terminal, and office buildings.

5. Pathfinder (Thunderhead Engineering, 2014)

Pathfinder was developed by Thunderhead Engineering. It is an agent-based egress model that uses steering behaviour to simulate the occupant movement.

Table 4.13 summarizes basic information of the software mention above. It includes the simulation method and enclosure representation used. The boundary conditions that limit the application of the software and the basis on how each model evaluates the evacuation time are also provided.

The ability to demonstrate building occupant evacuation process as close as possible to reality has always been appealing. The reality itself is represented by how well the structure, fire and human behaviour are defined. Consequently, the trend of evacuation modelling development is pushed towards models that can comprise the mentioned aspects (Gwynne, et al., 1999). Consulting the described modelling methodology, agent-based model with fine network geometry are deemed to be the most promising combination. Those models can accurately reproduce sophisticated behaviour events during building evacuation. However, it is important to note that this deduction does not mean to depreciate other models value. The other developed models are still beneficial to adopt for evacuation simulation depending on the defined level of detail and resource availability.

Table 4.13 Examples of building occupant evacuation modelling software

Modelling software	Methodology	Limitations	Features
building-EXODUS	• Fine network model (0.5m x 0.5m) • Reduced walking speed derived from Jin and Yamada • Pre-movement time is defined from 0-1000 second. Data are collected from various experiments and fire drills. • Potential map as guide for movement towards exit	• Data sources are mainly from statistic in UK and USA	• Comprehensive consideration of behavioural actions • Integration to smoke spread sub-model. User-defined or imported from CFAST or SMARTFIRE.
FDS+Evac	• Combination of social-force and agent-based model • Continuous network model (0.25m x 0.25m) • The smoke concentration influencing occupant walking speeds use the results of the experiment by Frantzich and Nilsson • The pre-movement time is decided by the user input by giving distributions for the detection and reaction times • The exit selection is modelled as an optimisation problem, where each evacuee tries to select the exit that minimises the evacuation time.	• Limited to buildings whose floors are mostly horizontal. Inclined geometry application has not been validated. • No use of elevator during evacuation. • No merging flows allowed in the staircase model. • Exit path should be at least 0.7 m width. • Maximum agents allowed on the evacuation mesh are 10,000 • Herding behaviour is not simulated • Considerably high time required for the input set-up • Repetitive simulation needs to perform due to stochastic approach of agent initial position • High computational time required to simulate • Not yet fully validated	• Integration to smoke spread sub-model. User-defined or imported from FDS.

Modelling software	Methodology	Limitations	Features
Simulex	• Agent-based model • Continuous network model (0.2m x 0.2m) • Distance map approach as movement towards exit • Pre-movement time can be defined in three distribution form: normal, triangular and uniform	• Maximum population is 15,000 • No smoke impact is at all considered • High computational time required to simulate • Max. people density is 2 ppl/m^2	• Overtaking and impeded walking speed are considered
STEPS	• Combination of cellular automata and agent-based model • Fine network model (0.5m x 0.5m) • Potential map as guide for movement towards exit • Reduced walking speed derived from Jin and Yamada experiment	• No smoke impact on exit choice is considered • No smoke impact of emergency exit design on exit choice is considered	• Patience level and exit familiarity are attributed to agents • Fully verified and validated • Integration to smoke spread sub-model. User-defined or imported from FDS or CFAST
Pathfinder	• Continuous network model (irregular triangular mesh) • Combination of agent-based and flow-based model • Movement towards exit defined as locally quickest technique, i.e. 1) locate target, 2) local and global knowledge, 3) path generation	• Does not consider influence of fire to evacuation process • Different result of total evacuation time depends on the simulation method chosen	N/A

4.6 Sub-model method grade based on defined criteria

Selecting appropriate modelling method to implement in fire risk assessment sub-model is not an easy task. Each modelling method has different capabilities and limitations. The application can differ from one case to another depends on the problem characteristic and resource availability. Choosing the most sophisticated method is not always the best way to quantify risk and vice versa. The phase within which risk assessment conducted can be one of consideration. When it is in the early design phase of a building, rough information on the life safety level might be sufficient. Therefore, risk assessment with a less time-consuming method that is better.

Modelling software with different methods for each sub-model has been studied in previous Sections. In this Section, an attempt to objectively choose the appropriate tool has been made by defining four criteria. They are accuracy, uncertainty, complexity and impact. Later, these criteria will be used to grade the reviewed modelling software. Sub-parameters that proportionally weighed are derived for each criterion. The complete criteria weighing grade can be found in Appendix B. The grade is described as avvalue from 0 to 5 which 0 shows the lowest worth of the criteria. The author would like to emphasize that the grade assigned is not intended to denote the superiority of one modelling software to the others. It is proposed as selection guideline for this thesis purpose only. Therefore, the grading result should not be seen as an utter conclusion. The sub-model method grade is displayed in Table 4.14. For corresponding modelling software, these information are found in (Galea, et al., 2014) (Galea, et al., 2014) (McGrattan, et al., 2014) (McGrattan, et al., 2014) (Thomas, `2008) (Thunderhead Engineering, 2012) (Kuligowski, et al., 2010)

Accuracy

In our world, there is no perfect model. Consequently, there will be no perfect results obtained from the model used. Model performance is measured by checking how accurate it is in solving the real problem by solving the right mathematical expression. Thus accuracy cannot be separated from the process of verification and validation. Referring to definition in ASTM E 1355 (McGrattan, et al., 2014),

“Verification is the process of determining that the implementation of a calculation method accurately represents the developer’s conceptual description of the calculation method and the solution to the calculation method.”

while

“Validation is the process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method.”

The modelling software is verified by checking on the assumptions and limitations of the theory used to see afterwards if it is applicable to the study performed. For instance is one-zone model. Noting the assumption of uniform properties at every point inside the plume, it might not be appropriate to use the one-zone model approach in estimating temperature distribution in the hot layer. Validation is checked by investigating if the results of modelling software had been compared with experimental measurement.

Uncertainty

As explained in Section 2.7, there are two types of uncertainty. Knowledge uncertainties arise from the imperfection of models. Advancing knowledge of the process can reduce this type of uncertainty. This can be related to the assumptions and limitations applied in the model. Thus selecting models with higher ‘verification level’ is considered as one way to reduce uncertainty. The other uncertainty type is caused by the randomness in nature and can be found in the variables. Due to complexity in quantifying uncertainty, in this thesis this criteria is limited to input data variable. The grade is related to the six level defined by Pate-Cornéll (1996). The modelling software that allows the user to define the input as function of probability distribution will be given 5 as the grade.

Complexity

In computational theory, complexity is simply described as how much computational resources are required to perform a given computational task. The terms of computational resource include the physical capacity of computation system, the efficiency of the algorithm and the computational time.

Another definition of complexity is how the model considers the interaction of various elements within. Complexity is not the same with complicated. The more complex the model is, the more interactions are simulated thus decreasing the level of independent from each variable. On the other hand, complicated model means that the model is not simple to solve. For example is the complexity of human behaviour. An agent-based model is deemed to be more complex than a flow-based model because it captures the interactions occur between human and the surroundings.

Combining the two definitions of complexity, it is considered in general that the more interactions modelled, the more expensive the computational time will be. This definition should be treated with care because it may be seen as a contradiction to each other. Higher complexity represents more interactions taken into account that should lead to more realistic simulation result. On the contrary, higher complexity may rise the amount of time needed.

Impact

Impact is defined as to what extent the outcome will be influenced if the input of the model is changed.

Table 4.14 The sub-model method grade

Sub-model	Modelling method or software	Accuracy	Uncertainty	Complexity	Impact
Fire growth	Deterministic approach	1	0	3	4
	Representative fuel	4	2	3	3
	Statistical approach	4	5	3	1
Smoke spread	B-RISK	3	4	5	1
	FDS	4	2	4	1
Occupant response and evacuation	buildingEXODUS	4	4	4	0
	FDS+Evac	3	4	4	1
	Simulex	4	4	4	1
	STEPS	4	4	3	1
	Pathfinder	3	4	3	1

5. Application of Risk Assessment Framework to Case Study

A general fire risk assessment framework has been proposed. A case study was performed to demonstrate the application of the framework to quantify life safety in building in case of fire. The outcome of the case study is presented in risk level for the occupants.

5.1 Methodology

The methodology carried out in this case study was based on the framework shown in Figure 3.1. The quantitative risk assessment was performed through the following steps.

1. A typical open office building was selected. Required inputs such as building and occupant characteristics were gathered.
2. Fire scenarios were developed using event tree analysis. The events were determined based on the fire ignition characteristic and safety measures available in the building. The frequency of each scenario was calculated based on literature.
3. The expected number of fatalities per scenario were calculated by monitoring occupant toxic dosage during evacuation. The sub-models evaluated are described as follows. The modelling method chosen was based on grade criteria in Table 4.13 and software availability.
    - Fire growth, calculated using statistical approach.
    - Smoke spread, calculated using FDS 6.
    - Occupant response and evacuation, calculated using STEPS 5.3.
4. The risk level was estimated by multiplying the frequency of each fire scenario with its corresponding fatalities. The risk outcome is presented as an F-N curve.

5.2 System definition

One section of an office building has been chosen as the system to be assessed. The boundary of the system is marked with red lines as illustrated in Figure 5.1. Any spaces beyond the red lines are therefore outside the scope of the system and will not be considered.

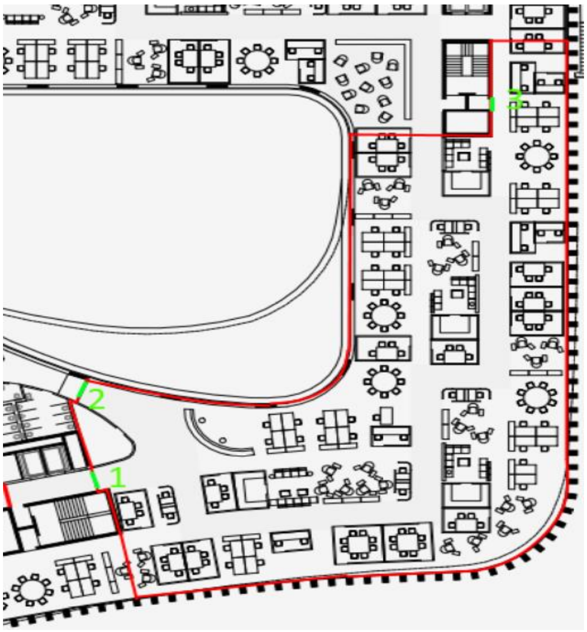


Figure 5.1 System boundary condition

The system compartment has an open office concept with several small rooms spread out in some locations. Room types and the share percentage in the compartment are described in Table 5.1. The compartment and occupants characteristics are summarized in Table 5.2. Compartmentation inside the system was not considered since the total surface area is still within the allowable limit, 2500 m^2, set by Belgium's legislation (2010).

Table 5.1 Type of room and area percentage

No.	Room type	Surface area (m^2)	Percentage (%)
1	Meeting room (SCR)	30	2.4
2	Kitchen	20	1.6
3	Lounge	32	2.5
4	Reception desk	10	0.8
5	IT room	13	1.1
6	Storage	8	0.5
7	Closed office area	80	6.4
8	Open office area	1057	84.6
Total		1250	100

Table 5.2 Compartment characteristic

Parameter	Value
Total surface area	1250 m^2
Height	3.5 m
Exit width (1/2/3)	0.8 / 1.8 / 0.8 m
Wall	Glass
Fire safety measure	Smoke detectors
Number of occupants	125
Occupants age range	18 – 50 yo

5.3 Scope and assumptions

To be aligned with the thesis scope, this case study is limited to a simplified risk assessment with multi-scenario event tree. No iterative simulation of the scenarios is considered.

The following main assumptions were made during the development of the case study.

- Fire department intervention is not taken into account. It is assumed that the time needed for the fire brigade to commence rescue is much longer than the total evacuation time.
- The fire is assumed to be confined to the fire compartment origin. Fire will not spread to adjacent rooms giving therefore no influence to occupant life safety. It is encouraged by fire statistics in (Department for Communities and Local Government, 2012) where in 75.4% of the cases fire did not extend beyond the room of origin.
- Heat release rate is considered to be the only sensitive parameter that affect the risk outcome hence its value is varied. The other parameter value is taken as an average value.
- Fire events occur during the day.

5.4 Tenability criteria

Toxicity was chosen as the tenability criteria in this case study. The toxicity is expressed as Fractional Incapacitation Dose (FID). The FID model relates the toxic dose inhaled by an individual to the dose where incapacitation happens. Incapacitation caused by asphyxiant gases. The two major asphyxiant gases in fires are: CO and HCN. In the case study, the threshold value for FID causing fatalities is 1. It means that occupant is always able to evacuate as long as the FID is lower than 1. The FID is calculated using method developed by Purser (2002) as expressed in Equations (5.1).

$$FID = FID_{CO} + FID_{O2} + FID_{HCN} + FID_{heat} \tag{5.1}$$

with

$$FID_{CO} = 3.317x10^{-5}\frac{RMVo}{COHb}\int_{o}^{t} V_{CO2}\, x\, [CO]^{1.036} dt$$

$$FID_{CO2} = \int_{o}^{t} \frac{1}{\exp(6.1623 - 0.5189\, x\, \%CO_2)} dt$$

$$FID_{O2} = \int_{o}^{t} \frac{1}{\exp(8.13 - 0.54(20.9\% - \%O_2))} dt$$

$$FID_{HCN} = \int_{o}^{t} \frac{V_{CO2}}{\exp(5.396 - 0.023[HCN])} dt$$

$$FID_{heat} = \int_{o}^{t} \left(\frac{1}{\mathrm{t}_{lrad}} + \frac{1}{\mathrm{t}_{lconv}}\right) dt$$

$$V_{CO2} = exp\left(\frac{[CO_2]}{5}\right)$$

$$\mathrm{t}_{lrad} = \frac{16.67}{q^{1.33}}$$

$$\mathrm{t}_{lconv} = 5.10^{7}\, x\, T^{-3.4}$$

where *RMVo* is volume of air breathed (L/min), *COHb* is concentration of CO in haemoglobin at incapacitation (30% for light activity) (ppm), *t* is time exposure (min), *[CO]* is CO concentration, *[HCN]* is HCN concentration, V_{CO2} is multiplication factor, t_{lrad} is time to incapacitation due to radiant heat (min), t_{lconv} is time to incapacitation due to convective heat (min), *q* is radiant heat flux (kW/m^2).

5.5 Fire hazard identification

The hazard identification was carried out by investigating on items that can be ignited based on the type of rooms. The potential equipment involved in ignition is displayed in Table 5.3 based on fire statistics.

Table 5.3 Potential equipment involved in ignition *(J.R. Hall, 2013)*

No.	Equipment involved in ignition	Case (per year)	Percentage (%)
1	Fixed wiring and related equipment	5201	32.1
2	Microwave/Oven	3941	24.3
3	Lamp, bulb or lighting	2763	17.0
4	Water heater	1318	8.1
5	Refrigerator with freezer	791	4.9
6	Cord or plug	727	4.5
7	Computer and related items	374	2.3
8	Entertainment (TV, stereo equipment, audio speakers, overhead projector)	253	1.6
9	Other office equipment (printer/copier/fax/paper shredder/cash register/unclassified)	234	1.4
10	Coffee maker / teapot	232	1.4
11	Dishwasher	182	1.1
12	Floor care equipment	93	0.6
13	Control and detection equipment	86	0.5
14	Telephone or answering machine	25	0.2
Total		**16220**	**100**

5.6 Fire scenarios

To give a good representation of the smoke spread in reality, there were 3 fire locations selected for the case study. They are shown in Figure 5.2. The room types were divided into 2 main categories named open office and small room. The small room includes any closed room such as, IT room, storage, kitchen, meeting room and closed office room.

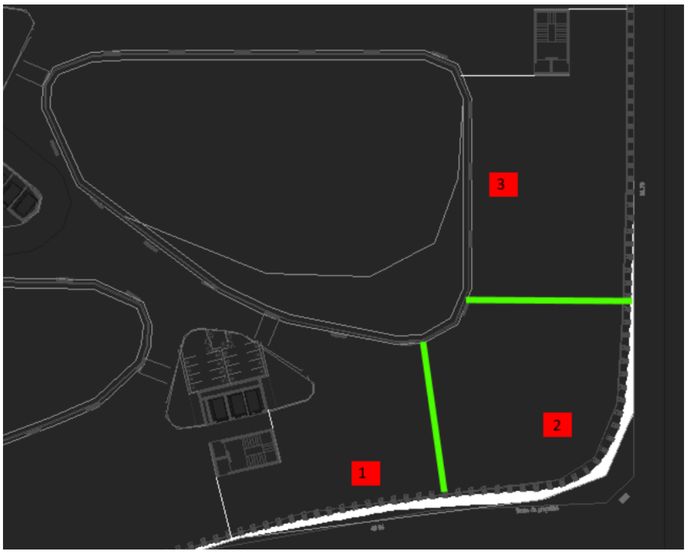


Figure 5.2 Selected fire locations

An event tree was constructed to develop credible fire scenarios. The events were distinguished based on fire location, fire origin type of room, smoke detector activation and fire growth rate value. The event tree developed is displayed in Figure 5.3.

5.7 Input data

This section summarizes the input data used during the development of the case study.

- **Fire growth rate (α)**

Fire growth rate values can be represented well with log-normal distribution. The estimated log-normal distribution parameters of fire growth rate parameter for several building occupancies based on literature is summarized in Table 5.4.

Table 5.4 Log-normal distribution parameters of fire growth rate

Building type	**μ_α**	**σ_α**	**E(α) (kW/s^2)**
Office	-7.1	1.8	0.016
Retail	-5.4	1.9	0.027
All building types	-6.5	2	0.012

As the main intention of the case study is to demonstrate the risk assessment framework application and not to assess the real design of the building, the most conservative fire growth rate value was applied. It is shown in Table 5.4 that the expected fire growth rate for office is much lower than retail. For this thesis purpose, the fire growth rate value used was therefore based on retail building.

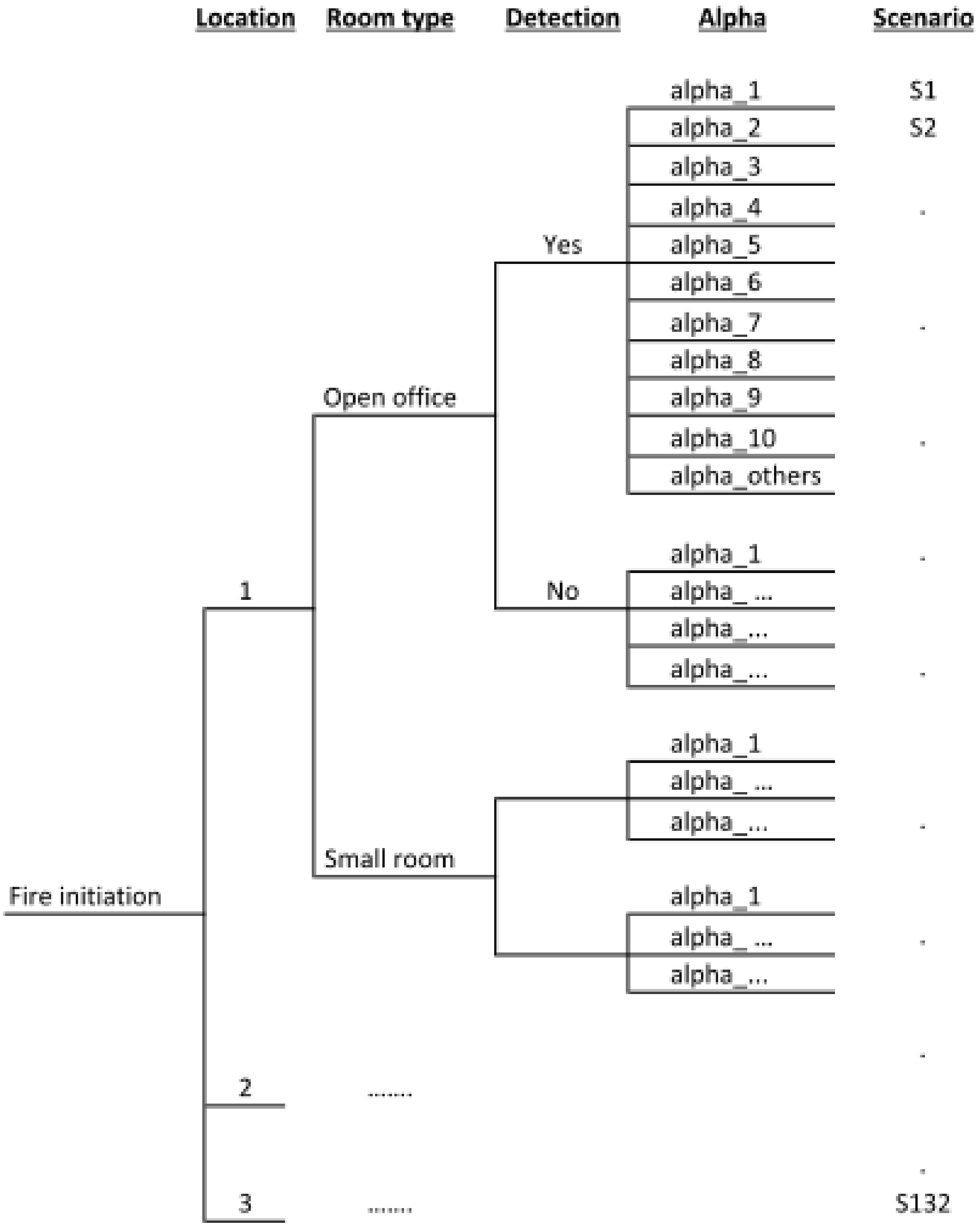


Figure 5.3 Schematic picture of the used event tree

Choosing the most representative value from a distribution is not an easy exercise. The probability density function of fire growth rate log-normal distribution was plotted to know at which range the fire growth rate result in fatalities. This was done by dividing the area under the curve into 10 sections with equal surface area. Each range has a probability of 0.1. Knowing that HRR is the most sensitive parameter in fire development, the area under the curve in the last range was divided further by 10. The probability for this latter division is 0.01. The middle value in each section was then selected as the representative fire growth rate for different scenarios. The fire growth rate sections division is shown in Figure 5.4. The mid-value used is indicated by red line. The estimated range of fire growth rate and its mid-value are summarized in Table 5.5.

The fire growth rate was determined based on a distribution which already taken into account smouldering fire. As a result, the type of fire was not anymore considered as one of the events in the event tree development.

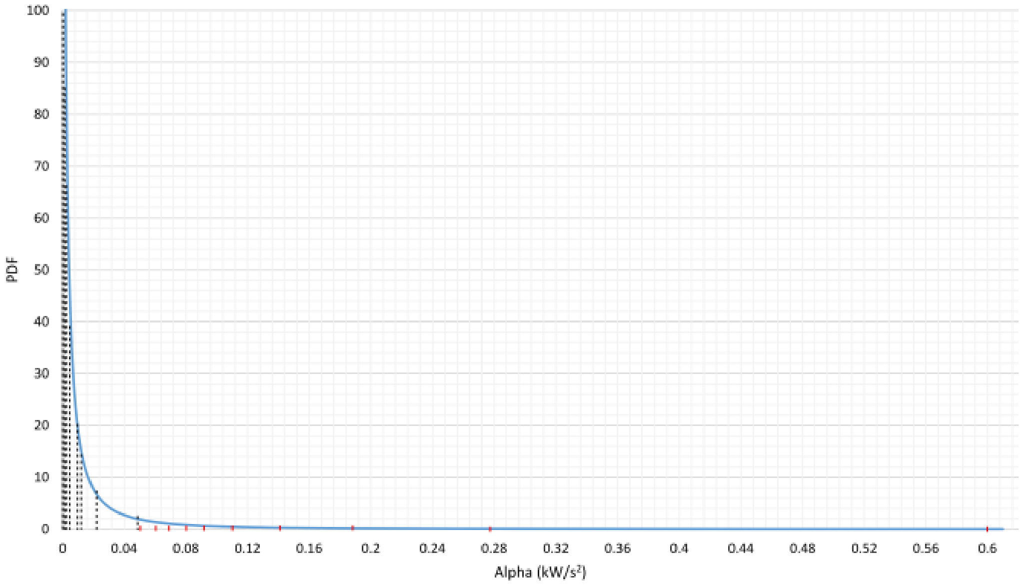


Figure 5.4 Estimated log-normal distribution of the fire growth rate value

Table 5.5 Estimated fire growth rate value for different scenarios

Interval	Range of alpha (kW/s^2)	Mid-value alpha (kW/s^2)	Remarks
0.90 - 0.91	0.0516 - 0.0577	0.0545	Alpha_10
0.91 - 0.92	0.0577 - 0.0652	0.0612	Alpha_9
0.92 - 0.93	0.0652 - 0.0746	0.0696	Alpha_8
0.93 - 0.94	0.0746 - 0.0866	0.0802	Alpha_7
0.94 - 0.95	0.0866 - 0.1028	0.0941	Alpha_6
0.95 - 0.96	0.1028 - 0.1257	0.1132	Alpha_5
0.96 - 0.97	0.1257 - 0.1610	0.1412	Alpha_4
0.97 - 0.98	0.1610 - 0.2236	0.1871	Alpha_3
0.98 - 0.99	0.2236 - 0.3753	0.2789	Alpha_2
0.99 - 0.999	0.3753 - 1.6023	0.6029	Alpha_1

- **Frequency of fire**

The frequency of fire occurrence is one of the key parameters of most probabilistic risk assessments. It is usually the initiating event in event trees. Existing research states that fire frequency strongly depends on the floor size of the building. In (British Standards, 2003), the frequency of fire starting is approximated using Equation (5.2).

$$F_i = aA_b^b \qquad (5.2)$$

where F_i is the frequency of fire (fires/year)

a and *b* are constants for particular type of building related to occupancy

A_b is the floor area of the building (m^2)

The value of *a* and *b* for office extracted from (British Standards, 2003) are 0.000059 and 0.9. These are based on statistical studies in the UK from year 1970 – 1980. It should be noted that this estimation may bias the result due to different condition and building characteristics from countries to countries. The fire initiation frequency of this case study is expressed below.

$$F_i = 0.000059\ (1250)^{0.9} = 0.0361\ fires/year$$

- **Fire location**

As described earlier, the fire location was divided into 3 places. It was assumed that the probability of fire happening at each location to be equal to 33.3%.

- **Room type**

The probability of fire happening for different room types were derived based on the surface area (refer to Table 5.1). It was calculated as follow.

$$P_{open\ fire} = \frac{Total\ area\ of\ open\ spaces}{Total\ surface\ area} = \frac{1100}{1250} = 0.88$$
$$P_{small\ room} = 1 - P_{open\ fire} = 1 - \ 0.88 = 0.12$$

- **Smoke detector effectiveness**

The probability of smoke detector effectively detected fire in office buildings was determined based on range of data from Bukowski et. al. (2002). The lower value, 0.7, was taken to give conservative result.

- **Occupant location distribution**

The number of occupants in the building was estimated to be 125. There will be no use of the building during the weekends hence no occupant load. The author was not able to find appropriate reference on the occupant location distribution therefore it was assumed. The occupant location distribution was assigned based on the room type percentage. Therefore, 88% of the total occupants, 110 people, will occupy the open office area. It was also assumed that not all small rooms will be used at the same time. Therefore 15 occupants will be assigned in 2 random small rooms in each fire location. Table 5.6 presents the assumed occupant location distribution.

Table 5.6 Assumed occupant location distribution

Location	Fraction	No. of people
Open office	0.88	110
• Zone 1		30
• Zone 2		30
• Zone 3		40
• Zone 4		10
Small room	0.12	15
• Room 1		8
• Room 2		7

- **Area of fire and HRRPUA**

The area of fire was investigated by Holborn et. al. (Holborn, et al., 2004). The study showed that the area of fire can be described by log-normal distribution. The maximum heat release rate that can be achieved was expressed as normal distribution with mean 500 kW/m^2. However, this value is appropriate for storage or warehouse. For other buildings, he suggested using a mean value of 250 kW/m^2. The values of fire area and heat release rate per unit area based on literature are displayed in Table 5.7.

Table 5.7 Distribution parameters of fire area and heat release rate per unit area

Parameter	Unit	Distribution	μ	σ	Average
HRRPUA	(kW/m^2)	Normal	500	100	250
Area of fire	(m^2)	Lognormal	0.83	2.14	18

- **Heat of combustion**

The heat of combustion depends on the properties of material burning. In Hede (2011), the range of heat combustion in an office building based on the relevant fuel properties is 17 – 44 kJ/g. The heat of combustion of 25 kJ/g was chosen as the representative value.

- **Products yield**

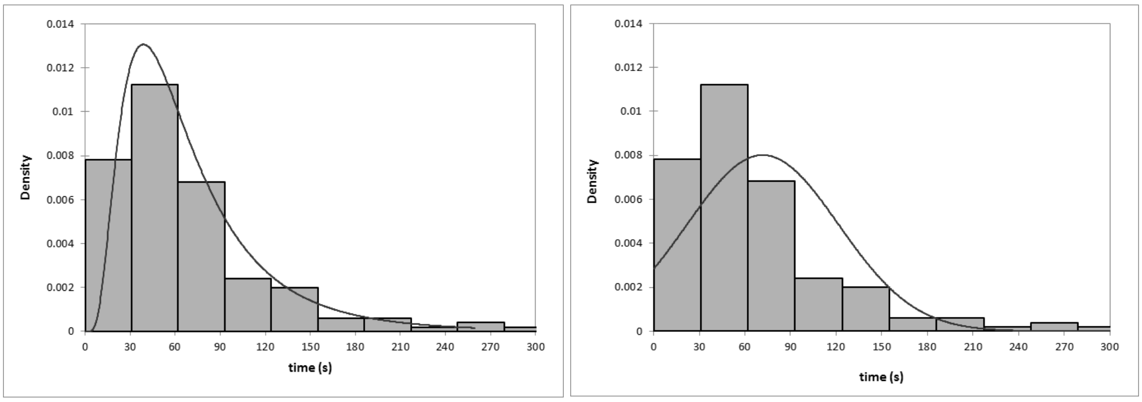
The yield of CO, CO_2 and HCN are used to calculate the toxicity level while the soot yield is used in the visibility threshold assessments. The yields are dependent on the burning material, and no stochastic models could be found in the literature. Normal distributions proposed by Albrecht (2014) were chosen for the case study. It was shown in Table 5.8. The average value of each parameter was used in the fire modelling.

Table 5.8 Distribution parameters of products yield

Parameter	Unit	Distribution	μ	σ
Soot yield	(g/g)	Normal	0.12	0.04
CO yield	(g/g)	Normal	0.09	0.03
HCN yield	(g/g)	Normal	0.006	0.002

- **Pre-movement time**

Pre-movement time can greatly affect the evacuation time of a building. It varies from person to person because of the random nature of human hence the pre-movement time is best estimated by use of statistical data and probability functions. The pre-movement time was extracted from study by Proulx et. al. (1997). Log-normal and normal distribution have been fitted to the observed data. The fitting was done using xlstat. The results are shown in Figure 5.5. As can be seen, the log-normal distribution seems to be the closest fit and therefore chosen to represent the pre-movement time distribution. The estimated distribution parameters are summarized in Table 5.9.



(a) (b)

Figure 5.5 Distribution of pre-movement time for office buildings fitted with (a) log-normal and (b) normal distribution

Table 5.9 Estimated distribution parameters of pre-movement time for office buildings

Parameter	Unit	Distribution	μ	σ	Average
Pre-movement time	(s)	Log-normal	4.07	0.64	71

- **Walking speed**

Walking speed depends on people characteristics (age, sex, mobility status, etc.) and the surroundings (smoke density, horizontal or inclined path, etc.). Therefore, it is best estimated using distributions. Only horizontal walking speed was considered due to no stairs encounter during the evacuation in the building. The horizontal walking speeds for different occupant group in office buildings are summarized from several different sources in (Lord, et al., 2005) as displayed in Table 5.10.

Table 5.10 Summary of horizontal walking speed in office buildings based on occupant group

Walking speed	**18 – 29 yo**	**30 – 50 yo**
Distribution	Normal	Normal
Data points	1695	1683
Mean (m/s)	1.12	1.12
Std. deviation (m/s)	0.25	0.25
Minimum (m/s)	0.25	0.25
Maximum (m/s)	1.9	1.9

6. Results

The risk assessment framework model used to quantify life safety in building was outlined in Chapter 3. The framework was applied to the case study office building described in Chapter 5. In this Chapter, the results obtained for the case study is presented.

6.1 Fire development

Based on the scenarios developed in the event tree, there were 10 fire growth rate values to calculate. The fire development was modelled in FDS 6 for 600 s. The maximum heat release rate that can be achieved was 4.5 MW. The fire growth curve for each value is depicted in Figure 6.1. The snapshots displaying smoke, temperature and gas products combustion profile are presented in Appendix B.

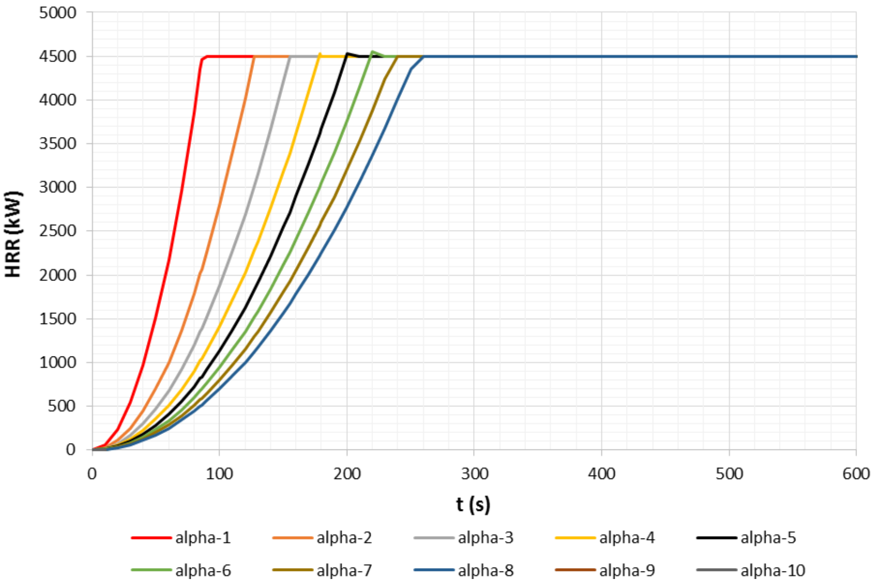


Figure 6.1 Fire growth curve for all alpha values

6.2 Total evacuation time

The total evacuation time was calculated using STEPS 5.3. The smoke extinction coefficient obtained from smoke spread sub-model was incorporated to give a more realistic result by having reduced walking speed of the occupants. The gas combustion products concentration was also used to get the individual exposure dose over time. The individual location of the occupants was set randomly within the specified area. Therefore, the simulation for each scenario was repeated 3 times to get representative result. It was shown that the total evacuation time does not vary much (less than 10%). For all scenarios, the calculated total evacuation time falls within 5 to 6 minutes. The example of total evacuation time for scenario using alpha_1 value is displayed in Table 6.1.

Table 6.1 Calculated total evacuation time for scenario using alpha_1

Room type	Location	Total Evacuation time
Open office	1	5 min 19 sec
	2	5 min 38 sec
	3	5 min 34 sec
Small room	1	5 min 26 sec
	2	5 min 30 sec
	3	5 min 28 sec

6.3 Expected fatalities

The expected fatalities were determined based on individual FID value. If the FID value is equal or higher than 1, the individual is not able to evacuate resulting in fatality. From total of 132 scenarios, there were only 60 calculations of fatalities. It was due to the similar smoke detection activation event. Therefore, the fatalities calculation only depend on room type, fire location and fire growth rate value. The case in which fatalities are found is summarized in Table 6.2.

Table 6.2 Expected number of fatalities for different scenarios

Room type	Location	Alpha	Expected fatalities
Open office	1	1	10
		2	5
		3	4
		4	2
		5	1
	2	1	4
		2	2
	3	1	12
		2	4
		3	3
		4	1
		5	1
Small room	3	1	3
		2	2
		3	1

As can be seen in Table 6.2, there are only 15 out of 60 cases resulting in fatalities. It is due to the fire growth rate value used. The trend shows that the lower the fire growth rate value, the lower the number of fatalities expected. The results show that the lowest fire growth rate value cause fatalities in the office building is alpha_5 (0.113 kW/m^2).

Table 6.2 also shows that different room type influence the number of expected fatalities. Another influencing factor is fire location. For the same room type and fire growth rate value, fire location 2 (i.e. fire is located in the middle of the office building) has the lowest fatalities number.

6.4 Estimated risk outcome

In the event tree analysis, the frequency of each scenario was calculated by multiplying the probability of occurrence of every pre-defined events. The frequency of each scenario was then multiplied with expected fatalities obtained from the consequence analysis to give expected fatalities per year per scenario. By summarising the calculating expected fatalities per year from all scenarios, the risk outcome for the office building was obtained. Table 6.3 displays the expected fatalities for scenarios causing fatalities. Full details of the frequency assessment are presented in Appendix D.

The cumulative frequency of fire is plotted against fatalities as an F-N curve in Figure 6.3. The result was computed using Equation (6.1).

$$Risk\ outcome = \sum_i p_i . c_i = 0.0052\ fatalities\ per\ year \tag{6.1}$$

where p_i is the frequency of fire scenario (per year) and c_i is the estimated consequence.

Table 6.3 The expected fatalities for scenarios causing fatalities

Scenario	**Expected fatalities per scenario (per year)**	**Expected fatalities (per year)**
S1	7.33841E-05	0.00073
S2	7.33841E-05	0.00037
S3	7.33841E-05	0.00029
S4	7.33841E-05	0.00015
S5	7.33841E-05	0.00007
S11	3.14503E-05	0.00031
S12	3.14503E-05	0.00016
S13	3.14503E-05	0.00013
S14	3.14503E-05	0.00006
S15	3.14503E-05	0.00003
S41	7.33841E-05	0.00029
S42	7.33841E-05	0.00015
S51	3.14503E-05	0.00013
S52	3.14503E-05	0.00006
S81	7.33841E-05	0.00088
S82	7.33841E-05	0.00029
S83	7.33841E-05	0.00022
S84	7.33841E-05	0.00007
S85	7.33841E-05	0.00007
S91	3.14503E-05	0.00038
S92	3.14503E-05	0.00013
S93	3.14503E-05	0.00009
S94	3.14503E-05	0.00003
S95	3.14503E-05	0.00003
S101	1.00069E-05	0.00003
S102	1.00069E-05	0.00002
S103	1.00069E-05	0.00001
S111	4.28868E-06	0.00001
S112	4.28868E-06	0.00001
S113	4.28868E-06	0.000004

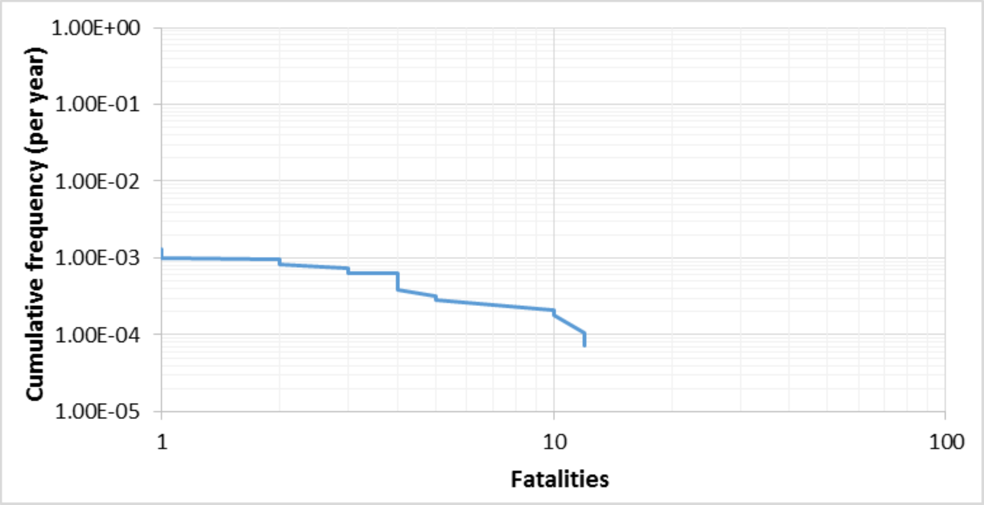


Figure 6.2 F-N curve for the office building

7. Discussions

The discussions in this chapter are divided into 2 parts, discussion on the fire risk assessment model framework adopted and discussion on the case study.

7.1 Discussion on the framework model

The idea of this thesis is to study the risk assessment model framework to quantify life safety in buildings in case of fire. Intensive literature review on previously developed risk assessment frameworks has been performed. It was found that an integrated framework such as FiRECAM^{TM}, CESARE-RISK, and CRISP is convenient to adopt. The integration benefits the user due to its ability to capture the interactions of all the sub-models. On the other hand, the fixed integration limits the users' flexibility. For instance is the limited options on which sub-models or modelling methods they require for the risk assessment. Another limiting point is the availability of the integrated framework model to public. Therefore, the author has proposed a general fire risk assessment model framework based on the gathered knowledge. Suggestions that can improve the validity of the existing frameworks were added in Chapter 3. It is anticipated that the 'general' term might lead to a question of 'what added value can be achieved by applying the general model instead of the integrated one?'. By applying general frameworks, it is possible for users to select the most effective combinations of evaluating the sub-models based on their needs.

One of the benefit from applying general risk assessment is flexibility. Consequently, users can choose the complexity level of modelling method in each sub-models. This issue was mainly pointed out in previous studies in occupant response and evacuation sub-model. The need to account for the interaction of various elements within human behaviour is believed to have huge impact on the level of risk outcome. However it is important to remember that the user must not rely the final risk analysis based on simulation results only. The computational software shall be regarded as a tool which gives output regardless what kind of input is provided. It is the user responsibility to distinguish which input is appropriate or which one is not to obtain realistic result.

In Chapter 2, it was explained that a holistic quantitative risk assessment consists of frequency assessment and consequence analysis. The consequence analysis was initially performed by selecting a single input for a certain sub-model. It was found that for all sub models, the trend of determining input has shifted to a more probabilistic way. Statistic data source that presented as a probability of distribution has been widely utilised. When selecting input value from a distribution for a parameter, it shall be noted that the average value might not be the best to choose. When the average value is chosen it means that there are 50% of the cases which are not considered. Therefore, the estimated risk might be underestimated. It is strongly suggested that the input value for each parameter should be a specified number of standard deviation above the mean value (Holborn, et al., 2004). Main limitation on this approach is the limited well-recorded information about fire statistic. When there is only a very small number of data, the results obtained shall not be treated as an absolute value. The results shall be seen as an indication on which magnitude the real condition can fall. However, this limitation can be resolved in further time if the fire statistics data become more available

7.2 Discussion on the case study

During the study, the author acknowledged that accurately evaluating life safety in a building is not an easy task. The difficulties arose as the uncertainties from a number of factors cannot be fully eliminated. The factors include the input data selected, the assumptions taken, modelling method limitations and others. The difficulties also come from the complexity of probable fire scenarios.

The case study was carried out using the steps described in the general framework proposed. There were 3 sub-models evaluated: fire growth, smoke spread and occupant evacuation. The modelling method selected for each sub-model was determined based on the criteria explained in Section 4.6. The estimated risk outcome shows that the combination of selected method works well and give reasonable result (refer to Section 6.4). It is indisputable that the combination method can differ depending on the risk assessor need and resources availability. The combination method can also differ from one case to another, e.g. less complex smoke spread modelling for a small compartment. Nevertheless, the final risk result shall be in the same order of magnitude despite different methods adopted.

In Section 5.3, it was stated that the input of parameter was taken at its average distribution value except for fire growth rate. This was intended to have a representative value from each parameter. However, this consideration must be treated with care. When an average value of one parameter is combined with another parameter, there are possibilities that the combination resulting in fatalities. When the average value is used, it shall be mentioned in advanced thus the results obtained must not be treated as an absolute value. Specifically for the case study, the average value usage was considered as simplification due to time constraint.

The expected fatalities per fire scenario were estimated by monitoring the FID value for each individual. This approach is considered to be more realistic than only by comparing required escape time to available escape time. This approach integrates individual condition with the fire condition at his evacuation location over time. One limitation is that since the distribution of occupant location in the building was semi-randomly determined, the total FID can differ for each calculation step. The uncertainty arose can be reduced by repeating the calculation more than once. Another limitation is that it requires the appropriate integration between the smoke spread an occupant response & evacuation sub-model. Consequently, the options of modelling methods can be used are limited.

As anticipated, Table 6.2 shows that the room type influences the number of fatalities expected. The open office gives fatalities for every fire location while small room only gives fatalities for fire location 3. When the fire is located in an open area, the smoke, heat and gas products toxicities can be immediately subjected to the occupants. On the contrary, the impacts of small room fire will not be experienced by the occupants until it comes out of the fire room origin. However, it should be remembered that this condition will only apply when there is no individual in the fire room origin, as what the condition is in the case study. In other case where there might be people inside the fire room origin, the opposite results are expected.

Based on Table 6.2, it is observed that fire location gives impact on the number of expected fatalities. For the same room type and fire growth rate value, fire location 2 (i.e. fire is located in the middle of the office building) has the lowest fatalities number. For fire location 1 and 3, the fire was located in the vicinity of exit making occupants who pass through the route to be exposed more of the smoke, heat and toxic gases. When the smoke layer has not been encountered directly by the occupant, it is possible to happen. However, once the smoke becomes too thick making a very low visibility level, it is very likely that the occupants change their exit options and turn around from the smoke. Consequently, the risk was overestimated.

It is also observed in Table 6.2 that there was an only slight difference in the total evacuation time for each scenario. In reality, if the effect of smoke encounter to exit choice is considered, the total evacuation time will be longer especially for the scenarios where the fire location is near the exits (i.e. fire location 1 or fire location 3). Because decision change on exit choice was not taken into account, the risk result was again overestimated.

Looking at the calculated total evacuation time, the factors that cause differences are different pre-movement time assigned to each occupant, different walking speed assigned to each occupant and variation of occupant location distribution.

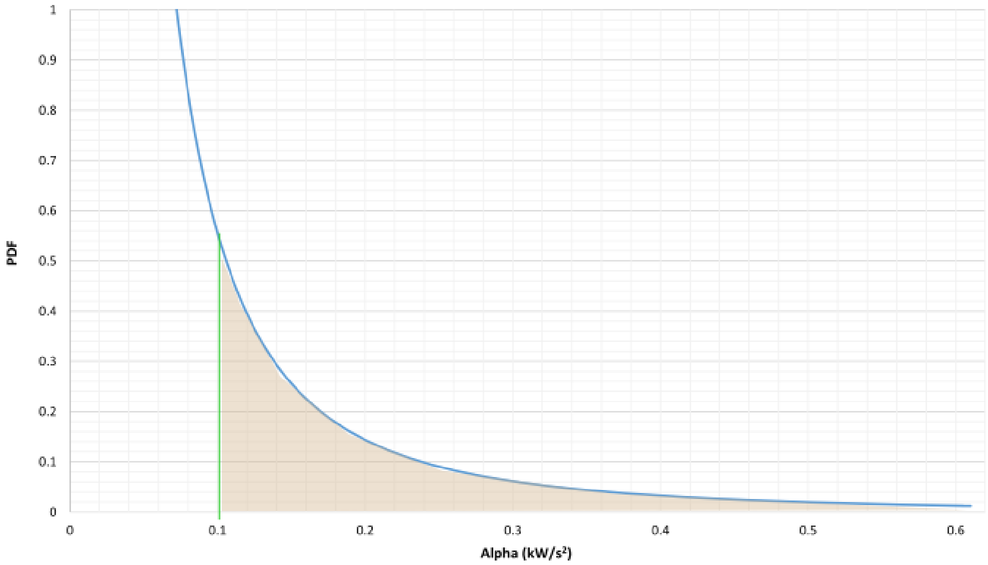


Figure 7.1 PDF plot of fire growth rate value which cause fatalities

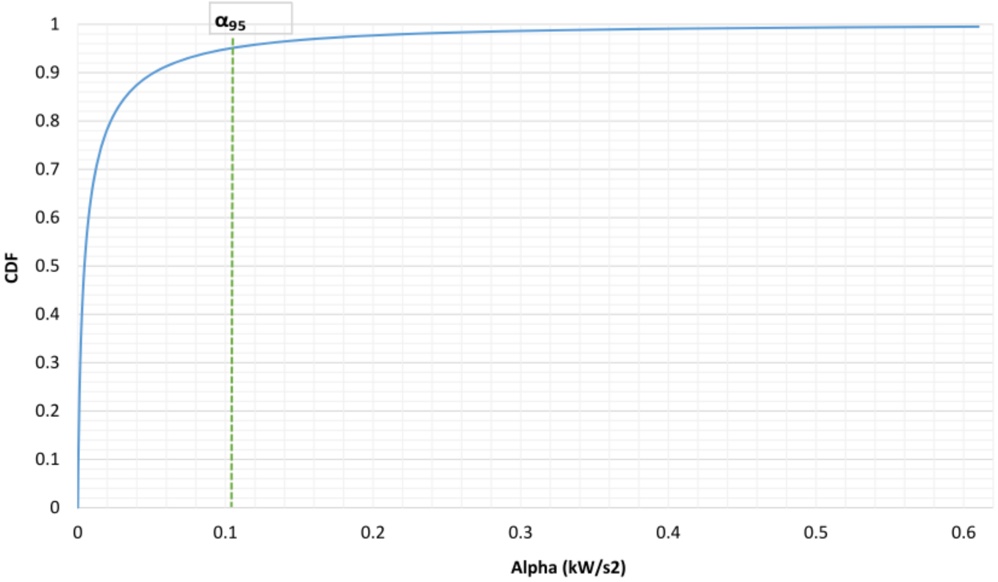


Figure 7.2 CDF plot of fire growth rate value which cause fatalities

The results show that the lowest fire growth rate value cause fatalities in the office building is alpha_5 (0.113 kW/m^2). From the fire growth rate value determination (refer to Section 5.7), alpha_5 is the mid-value of alpha interval 0.1028 – 0.1257 kW/m^2. Figure 7.1 depicts the plot of a probability density function of fire growth rate log-normal distribution. The shaded area under the curve represents the fire growth rate value where fatalities expected to occur. A cumulative distribution function against fire growth rate value is shown in Figure 7.2. The green line indicates the lower limit of alpha interval causing fatalities, 0.1028 kW/m^2. It is denoted as α_{95} as this value is the 95-th value of the distribution (refer to Table 5.5). From results in Figure 7.2, it is shown that the probability of not having fatalities when the fire growth rate value is below 0.1028 kW/m^2 is 0.95. Based on this result, the 95-th percentile value is representative and conservative enough to be used as input value. It can be concluded that the safety margin for the office building is 5%. However, this statement must be treated carefully. It is only valid for the condition where HRR is assumed to be the only sensitive parameter in the whole assessment process (refer to Assumptions in Section 5.3).

The estimated risk outcome for the office building is 0.0052 fatalities per year or 1 fatalities in every 192 year. Comparing to the fire initiation frequency, 0.036 fires/year, it gives approximately 14% of fire cases resulting in fatalities. Risk result can be evaluated by comparing to absolute criterion (ALARP, acceptable or unacceptable risk) or to acceptance criteria of similar building which in compliance with codes. As the intention of the case study is to demonstrate the general framework application, no specific comparative value has been defined. Nevertheless, as a rough comparison the risk result is compared to fire incidents in England (British Standards, 2003). There was an average of 0.2 fatalities per fire occur or an average of 0.001 fatalities per office building per year during 1995 – 1999. Although the risk result in the case study is 5 times higher, it is in the same order of magnitude (10^{-3}) to the fire incidents. The main factor that cause risk overestimation is the fire growth rate value which were stemmed from retail building data.

8. Conclusions and Suggestions for Future Research

This Chapter summarizes the conclusions made based on the study performed and the suggestions for future research.

8.1 Conclusions

Study on risk assessment model to quantify life safety in building in case of fire has been carried out. The developed fire risk assessment model frameworks have been investigated. The sub-models used have been evaluated in terms of its development status, important parameters and modelling methods. The interactions between the sub-models have also been highlighted.

During the study, a general risk assessment model framework was proposed. The general definition allows user to mix-and-match the available sub-models modelling method. As an additional aid to choose the appropriate methods, selection criteria have been defined. This way the most optimal combination of methods can be selected to measure the safety risk level. To address a broader risk-informed frameworks, a probabilistic distribution was introduced in the process of determining input parameter value. The distribution can be inferred from fire statistic data.

The proposed framework was applied to a simple case study of an office building. It was found that the 95-th value of the probability distribution is suitable to select as input parameter value. The risk outcome shows that the risk level of the building is 0.0052 fatalities per year. This value is not the absolute level of safety of the building thus should be regarded as indicative value. A comparison to a fire incidents data in England was made. It was shown that the estimated risk level is in the same order of magnitude, 10^{-3} fatalities per year, with the actual data. Based on the results and the way the case study performed, it is concluded that the model framework proposed works and able to be implemented in real life building risk assessment.

8.2 Suggestions

During the study, suggestions have been identified to improve the quality of future research in similar studies. They are summarized as follow.

- When assessing life safety in a building, the building and occupant characteristics are important because they determine which sub-models should be evaluated and which are less important. For instance is the need to include fire department intervention sub-model when assessing life safety in high rise building.
- The importance of accounting more of the human behaviour aspect, particularly in decision-making change due to fire hazard (such as smoke) during evacuation.
- The assumption on one parameter is the only sensitive parameter should be disregarded. In every sub-model, there should be at least one sensitive parameter to vary (or using value derived from distribution data) to increase the accuracy. For example: pre-movement time in occupant response and evacuation sub-model or HCN yield in toxicity level calculation.
- The importance to choose the most representative value from the probability function, e.g. the 95-th value, for every parameter. Not only as it is more realistic but it also improves the accuracy of the risk outcome. For this matter, the availability of statistical data is highly required.
- To obtain a more realistic result of the probability distributed outcome, a large number of simulations should be carried out.

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APPENDIX A – Sub-models modelling method

A.1 FiRECAM^{TM}

Fire types probability of occurrence

Table A.1 Fire types occurrence from fire statistics in Canada (1983 – 1990) and USA (1985 – 1989) (*Gaskin & Yung, 1993)*

Type of fire	Canada		USA	
	Sprinkler	Non-sprinkler	Sprinkler	Non-sprinkler
Apartments				
Flashover	5.1%	18.3%	6.3%	18.3%
Non flashover	76.7%	62.6%	72.3%	63%
Smouldering	18.2%	19.1%	21.4%	18.7%
Offices				
Flashover	-	-	5.1%	24.2%
Non flashover	-	-	65.4%	53.5%
Smouldering	-	-	29.5%	22.3%

Fire growth and smoke spread sub-model (Cooper & Yung, 1997)

Table A.2 Equations used in fire growth and smoke spread sub-model in FiRECAM^{TM}

Paramater	Equations
Mass loss rate • Flaming fire • Smouldering fire	$R_{ML} = \left(m_{ideal}\frac{Y_{O2i}}{0.23} + \frac{q_r}{\Delta H_v}\right)Av$ $R_{ML} = 1\,x\,10^{-8}(2.78t + 0.00856t^2)$ if $t < 3600s$ $R_{ML} = 1.21\,x\,10^{-3}$ if $t \geq 3600s$ where R_{ML} is mass loss rate (kg/s), m_{ideal} is pyrolysis rate of the fuel (kg/(m^2.s), Y_{O2i} is oxygen mass fraction before combustion, q_r is the external heat flux to the fuel (W/m^2), ΔH_v is heat of vaporization (J/kg), A_v is burn area at time (m^2) and t is elapsed time (s).
Fire spread	$Av = \pi\left[\left(\frac{A_{vo}}{\pi}\right)^{0.5} + \int V_f\,dt\right]^2$ With $V_f = \left(\frac{C^{-2}}{(q_{o,ig}-q_r)^2}\right)\left(\frac{Y_{O2,i}-0.11}{0.12}\right)^{0.5}$ for $Y_{O2,i} > 0.11$ $V_f = 0$ for $Y_{O2,i} < 0.11$ Where A_v is burn area at time t (m^2), A_{vo} is initial burn area (m^2), V_f is the actual flame speed as limited by the available oxygen (m/s), c is flame heat transfer modulus (m$^{3/2}$ s$^{1/2}$ W^{-1}), $q_{o,ig}$ is minimum external heat flux required to ignite the fuel (W/m^2), q_r is external heat flux to the fuel (W/m^2), Y_{O2i} is oxygen mass fraction before combustion.
Mass flow rate of gas	$m_a = \frac{2}{3}\sqrt{2gH_o}C_D r_{Go} A_o \left[\left(1-\frac{T_o}{T_G}\right)\left(\frac{T_o}{T_G}\right)\right]^{0.5}\left[1-\frac{n}{H_o}\right]^{1.5} F$ With C_D = 0.68 for inflow (dense air) C_D = 0.73 for outflow (hot gases)

Paramater	Equations
	$F = 1.19 - 1.77\frac{H_o}{2L} + 0.000625(T_G - 273)$ Where m_a is mass flow of gases leaving the compartment (m/s), *g* is gravity acceleration (m/s^2), H_o is height of opening, *T* is temperature (K), *F* is correction factor for the ventilation rate, C_D is orifice coefficient for compartment ventilation, *L* is compartment length (m).
Product gas concentration - Flaming fire - Smouldering fire	$Y_{PRO} = \frac{Y_{PRO}^{o}\rho_G V + (1 + 0.23\gamma)\mu R_{ML}\Delta\mathrm{t}}{\rho_G V + (m_a + R_{ML})\Delta\mathrm{t}}$ $Y_{CO} = Y_{PRO}\frac{28a}{28a + 44b + 18x}$ $Y_{CO2} = Y_{PRO}\frac{44b}{28a + 44b + 18x}$ $Y_{CO} = 0.05Y_{PRO}$ $Y_{CO2} = 0.56Y_{PRO}$ where R_{ML} is mass loss rate (kg/s), *Y* is mass fraction for each associated gas product, t is time (s), m_a is mass flow of gases leaving the compartment (m/s), ρ_g is gas density, V is volume.
Toxicity	$FID_{CO} = \int_o^t \frac{8.2925x10^{-4}\{ppm\ CO(t)\}^{1.036}}{30}dt$ $V_{CO2} = \frac{exp(0.2496\ \%CO_2 + 1.9086)}{6.8}$ $FID = FID_{CO}\ x\ V_{CO2}$ Where *FID* is fractional incapacitation dose, *t* is time to exposure (min), V_{CO2} is multiplication factor.

Occupant response and evacuation sub-model (Proulx, et al., 1997)

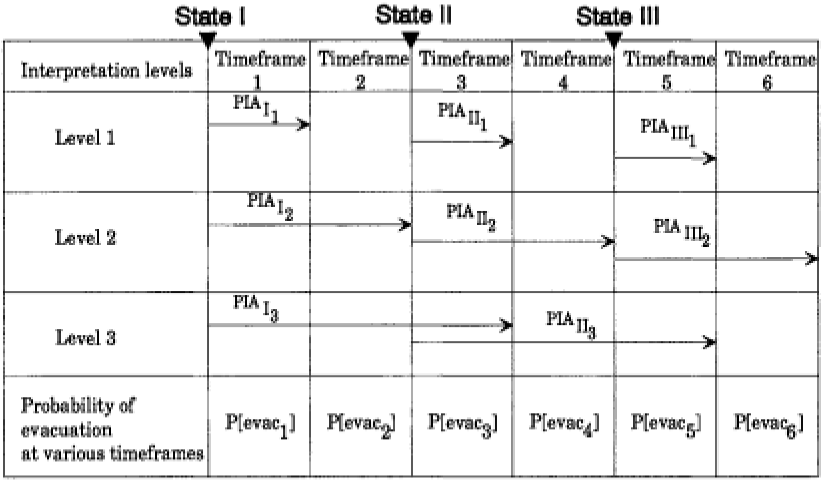


Figure A. 1 Timeframes and response delays according to interpretation levels

Table A.3 Probabilities of occupants starting to evacuate

Location	TF1	TF2	TF3	TF4	TF5	TF6	No Response
OCF (On compartment fire)	0.9001	0.0967	0.0029	0.0002	0.0001	0	0
OLF (On the level of OCF)	0.001	0.6872	0.1497	0.1250	0.0369	0.0003	10^{-6}
OOL (On other level)	0.001	0.5531	0.0892	0.2731	0.0669	0.0167	7.1×10^{-5}

Figure A.2 illustrates the network model used to describe occupants movement. The nodes specify compartment doors, doors, corridors, exits and occupants initial location. There are two types of nodes in the network namely destination node and source node. Destination node such as exits are weighed as positive value while source node are negative, The evacuation path are created according the value of the nodes, The higher the weighing of the destination node, the higher its attraction for occupants.

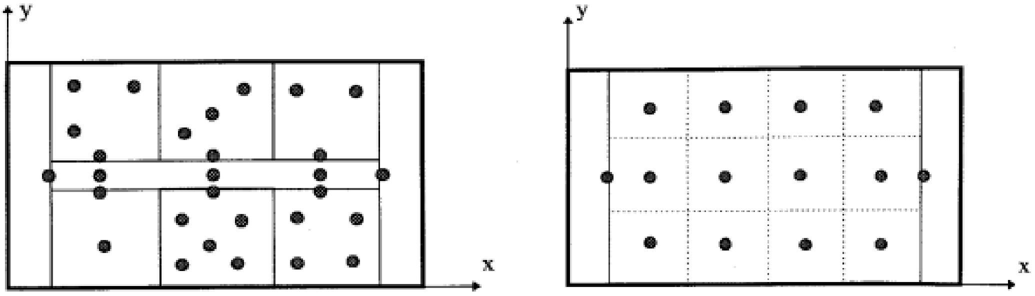


Figure A. 2 Network model for divided floor (left) and open space floor (right)

Fire department response model (Bénichou, et al., 2002)
The required information on time used in this sub-model is extracted from the fire statistics and engineering assumptions as summarized in Table A.4.

Table A.4 Fire department response model data input

Parameter	Time (s)
Dispatch time	30 – 60
Preparation time	30 – 105
Travel time (depends on the distance between fire station and building location and the vehicle speed)	180 - 240
Set-up time (small building)	60

A.2 Fire growth - analytical approach

Table A.5 Equations used in analytical approach *(Guillermo, et al., 2005)*

Parameter	Equations
Mass of fuel consumed	$\dot{m}_f = \frac{\dot{Q}_{hrr}}{\Delta H_c}$ Where $\dot{m}_f$ is mass of fuel consumed (kg/s), $\dot{Q}_{hrr}$ is heat release rate (kW), $\Delta H_c$is the effective heat of combustion per mass of fuel (kJ/kg)
Mass of gases transported to hot layer	$\dot{m}_h = \dot{m}_f + \beta(1+S)\dot{m}_f$ Where $\dot{m}_h$ is mass of gas transported to hot layer (kg/s), $\dot{m}_f$ is mass of fuel consumed (kg/s), β is a plume-entrainment constant parameter, S is the stoichiometry air to fuel mass ratio.
Temperature of hot layer	$T_h = \frac{\dot{Q}_{hrr}}{\dot{m}_{hl}C_p} + T_0$ Where T_h hot layer temperature (K), $\dot{m}_h$ is mass of gas transported to hot layer (kg/s), C_p is heat capacity (kJ/(kg. K)), T_0 is temperature ambient (K), $\dot{Q}_{hrr}$ is heat release rate (kW).
Concentration of smoke	$C_s = \frac{y_s \int_0^t \dot{m}_f d\tau}{V_h}$ Where C_s is soot concentration, y_s is soot yield, V_h is volume of hot layer (m^3), $\dot{m}_f$ is mass of fuel consumed (kg/s).
Concentration of CO	$C_{CO} = \frac{y_{CO} \int_0^t \dot{m}_f d\tau}{V_h}$ Where C_{CO} is CO concentration, y_{CO} is CO yield, V_h is volume of hot layer (m^3), $\dot{m}_f$ is mass of fuel consumed (kg/s).
Volume of hot layer	$V_h = \frac{\int_0^t \dot{m}_h d\tau}{\rho_g}$ Where V_h is volume of hot layer (m^3), $\dot{m}_h$ is mass of gas transported to hot layer (kg/s), ρ_g is the density of gases in hot layer (kg/m^3).

A.3 Smoke spread - B-RISK

Tabel A.6 Example of equations used in B-RISK *(Wade, et al., 2013)*

Paramater	Equations
Temperature - Upper layer (*u*) - Lower layer (*l*)	$\frac{dT_u}{dt} = \frac{1}{C_p \rho_u V_u}\left[\left(\dot{h}_u - C_p \dot{M}_u T_u\right) + V_u \frac{dP}{dt}\right]$ $\frac{dT_l}{dt} = \frac{1}{C_p \rho_l V_l}\left[\left(\dot{h}_l - C_p \dot{M}_l T_l\right) + V_l \frac{dP}{dt}\right]$ Where T is temperature of upper layer gases (K), t is time (s), C_p is heat capacity (kJ/(kg. K)), ρ is the density of gases in hot layer (kg/m^3), V is volume (m^3), P is pressure in the room at floor level relative to atmospheric (Pa).
Mass of plume (Heskestad)	$m_p = 0.071\dot{Q}_c^{\frac{1}{3}}(z - z_o)^{5/3}\left[1 + 0.026\dot{Q}_c^{\frac{2}{3}}(z - z_o)^{-5/3}\right]$ Where $\dot{m}_p$ is mass flow rate of air entrained (kg/s), $\dot{Q}_c$ is convective heat release rate (kW), z is height of the smoke layer from the base of fire (m), z_o is virtual origin (m).
Gas product concentration	$\phi_e = \frac{\Delta H_c \dot{m}_f}{\Delta H_{O2} m_p Y_{O2,l}}$ $Y_{CO2} = \frac{Y_{CO2,wv}}{\phi}$ $Y_{HO2} = \frac{Y_{HO2,wv}}{\phi}$ Where ϕ is the global equivalence ratio, $\Delta H_c$is the effective heat of combustion per mass of fuel (kJ/kg), $\dot{m}_f$ is mass of fuel consumed (kg/s), $\dot{m}_p$ is mass flow rate of air entrained (kg/s), $Y$is mass fraction for each associated gas product.
Toxicity	$FED_{CO} = 3.317x10^{-5}\frac{RMVo}{COHb}\int_o^t V_{CO2}\ x\ [CO]^{1.036}dt$ $V_{CO2} = exp\left(\frac{(\%CO_2)}{5}\right)$ $FED_{O2} = \int_o^t \frac{1}{\exp(8.13 - 0.54(20.9\% - \%O_2))}dt$ $FED_{HCN} = \int_o^t \frac{V_{CO2}}{\exp(5.396 - 0.023[HCN])}dt$ $FED = FED_{CO} + FED_{O2} + FED_{HCN}$ Where *RMVo* is volume of air breathed (L/min), *COHb* is concentration of CO in haemoglobin at incapacitation (30% for light activity) (ppm), *t* is time exposure (min), *[CO]* is CO concentration, *[HCN]* is HCN concentration, V_{CO2} is multiplication factor.
Visibility	$v = \frac{3}{k_{avg}}$ (reflective signs) ; $v = \frac{8}{k_{avg}}$ (illuminated signs) ; $k_{avg} = \frac{Y_{soot}}{\rho_u} k_m$ Where v is visibility (m), k_{avg} is average extinction coefficient (m^{-1}), Y_{soot} is soot yield, ρ_u is the density of gases in hot layer (kg/m^3), k_m is particle extinction cross-section (m^2/kg-soot)

APPENDIX B - Details of sub-models grade

Different sub-criteria are defined for each sub-models. The summation of sub-criteria grade represents the method grade in the corresponding criteria. 0 represents minimum grade whereas 5 is the maximum grade. The final calculated grade is always rounded up for simplification.

Table B.1 Fire growth sub-model grade

Criteria	Weight	Grade		
		Det.	Rep.	Stat.
Accuracy		**1**	**4**	**4**
Verification	0.5	1	4	3
Validation	0.5	1	2	4
Uncertainty		**0**	**2**	**5**
Complexity		**3**	**3**	**3**
Item ignited	0.5	0	3	4
Occupancy type		1	4	4
Other		1	1	2
Computational time	0.5	5	3	2
Impact		**4**	**3**	**1**
Model input	1	4	3	1

Table B.2 Smoke spread sub-model grade

Criteria	Weight	Grade	
		FDS6	B-RISK
Accuracy		**4**	**3**
Verification[1]	0.5	3.4	2.8
Validation[2]	0.5	2.4	1.7
Uncertainty		**2**	**4**
Complexity		**4**	**5**
Combustion model	0.5	4	4
Entrainment model		4	4
Radiation model		4	4
Smoke detection		4	4
Sprinkler system		4	4
Gas production		4	4
Smoke control system		4	4
Other		2	2
Computational time	0.5	2	3
Impact		**1**	**1**
Model technique[3]	0.5	1	1
Model input[4]	0.5	1	1

[1] Verification consists of:

- Fire model: one-zone model (1), two-zone model (3), field model (4)
- Radiation model: point source (2), finite volume model (4)
- Combustion model: GER (3), mixing controlled (3)

[2] Percentage difference with experimental result: 0 – 10 (5), 11 – 20 (4), 21 – 30 (3), 31 – 50 (2), 51 – 70 (1), 71 – 100 (0).

[3] Only grid size is considered.

[4] Percentage difference of result if input change: 0 – 10 (0), 11 – 20 (1), 21 – 30 (2), 31 – 50 (3), 51 – 70 (4), 71 – 100 (5).

Table B.3 Occupant response and evacuation sub-model grade

Criteria	Weight	Grade				
		building EXODUS	FDS+evac	Simulex	STEPS	Pathfinder
Accuracy		**4**	**3**	**4**	**4**	**3**
Verification	0.5	4	2	4	4	4
Validation[1]	0.5	4	3	4	4	2
Uncertainty		**4**	**4**	**4**	**4**	**4**
Complexity		**4**	**4**	**4**	**3**	**4**
Individual behaviour	0.5	5	4	4	4	4
Human-human interaction		5	4	4	4	4
Human-surrounding interaction		5	3	3	4	4
Other		4	2	1	2	1
Computational time	0.5	3	4	4	3	3
Impact		**0**	**1**	**1**	**1**	**0**
Model input	1	0	1	1	1	1

[1] Percentage difference with experimental result: 0 – 10 (5), 11 – 20 (4), 21 – 30 (3), 31 – 50 (2), 51 – 70 (1), 71 – 100 (0).

[4] Percentage difference of result if input change: 0 – 10 (0), 11 – 20 (1), 21 – 30 (2), 31 – 50 (3), 51 – 70 (4), 71 – 100 (5).

APPENDIX C – Snapshots of FDS modelling results

C.1 Geometry set-up

Figure C.1 Example of system geometry set-up in FDS 6 (open office - fire location 2)

C.2 SMV snapshots

The following figures are examples of snapshots from the FDS modelling results. Due to the similar trend shown in each scenario, only snapshots from scenario of fire location 3 and alpha_1 are presented. All slice files were taken at 2 m height.

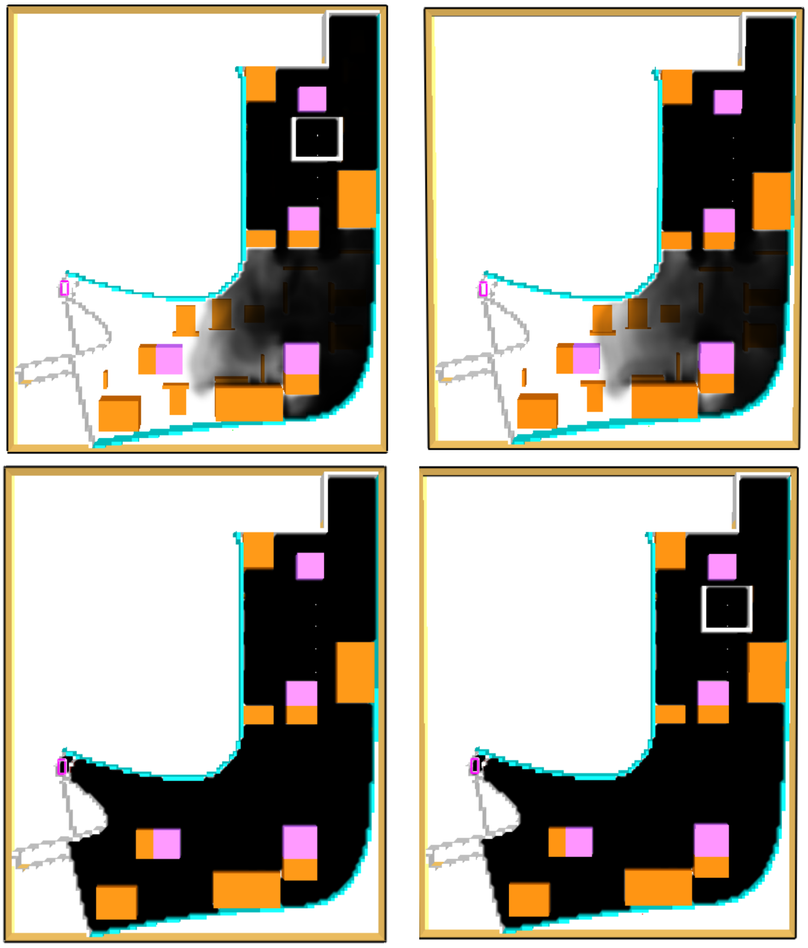


Figure C.2 Smoke spread for open office fire (left) and small room fire (right)
at t = 90 s (above) and t = 360 s (below)

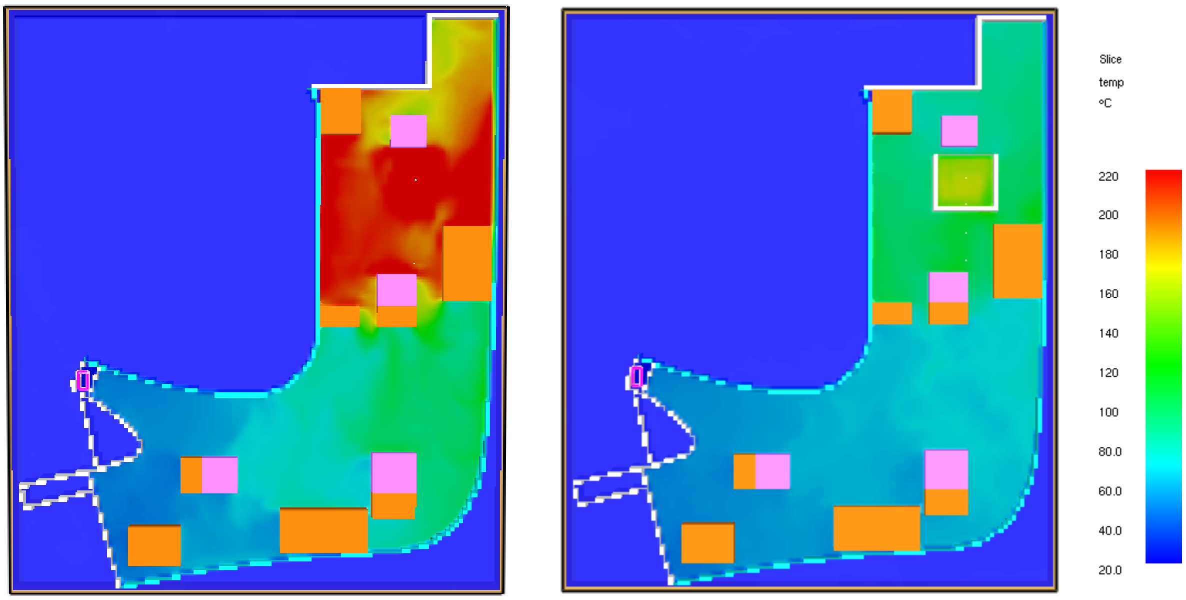


Figure C.3 Averaged temperature slice for open office fire (left) and small room fire (right) at 360 s

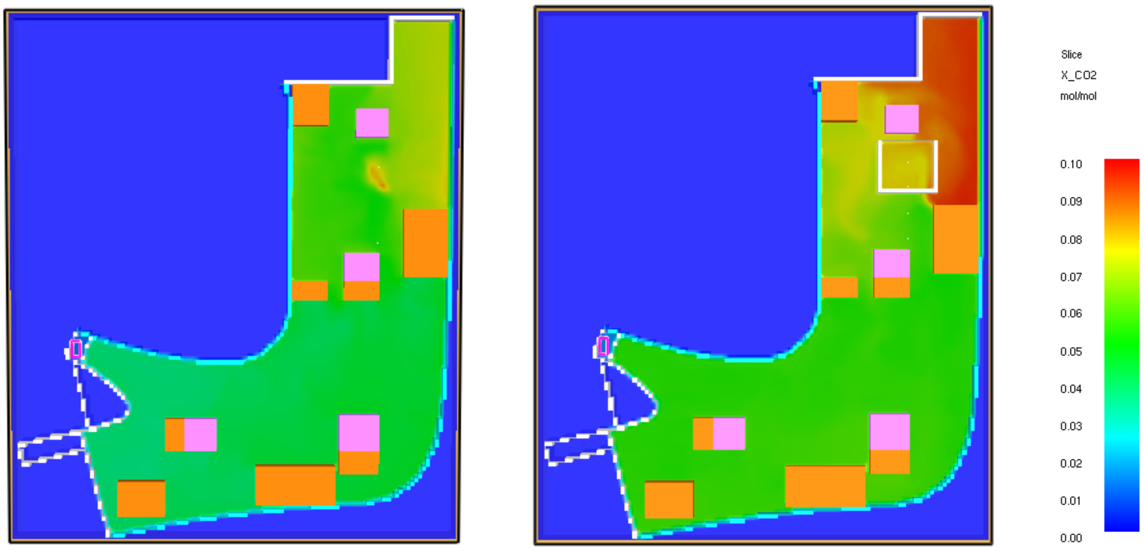


Figure C.4 CO_2 concentration for open office fire (left) and small room fire (right) at 360 s

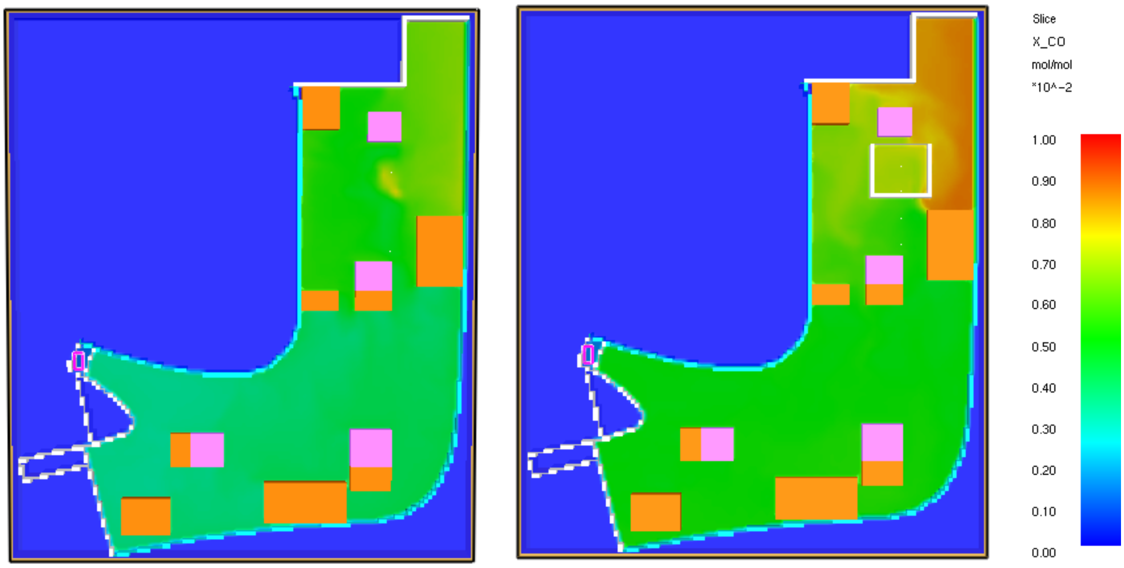


Figure C.5 CO concentration for open office fire (left) and small room fire (right) at 360 s

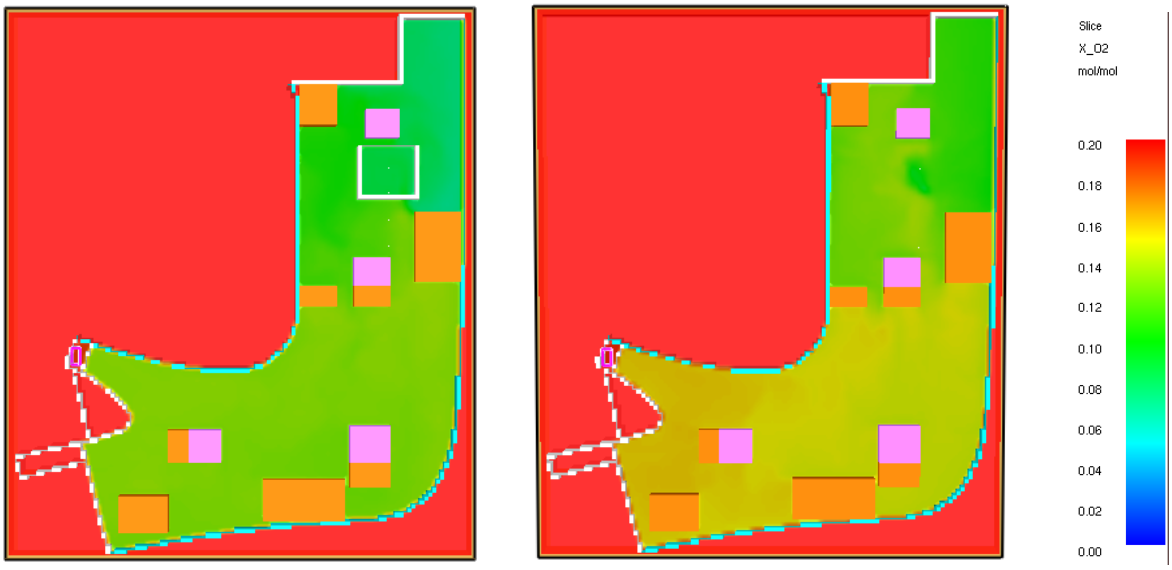
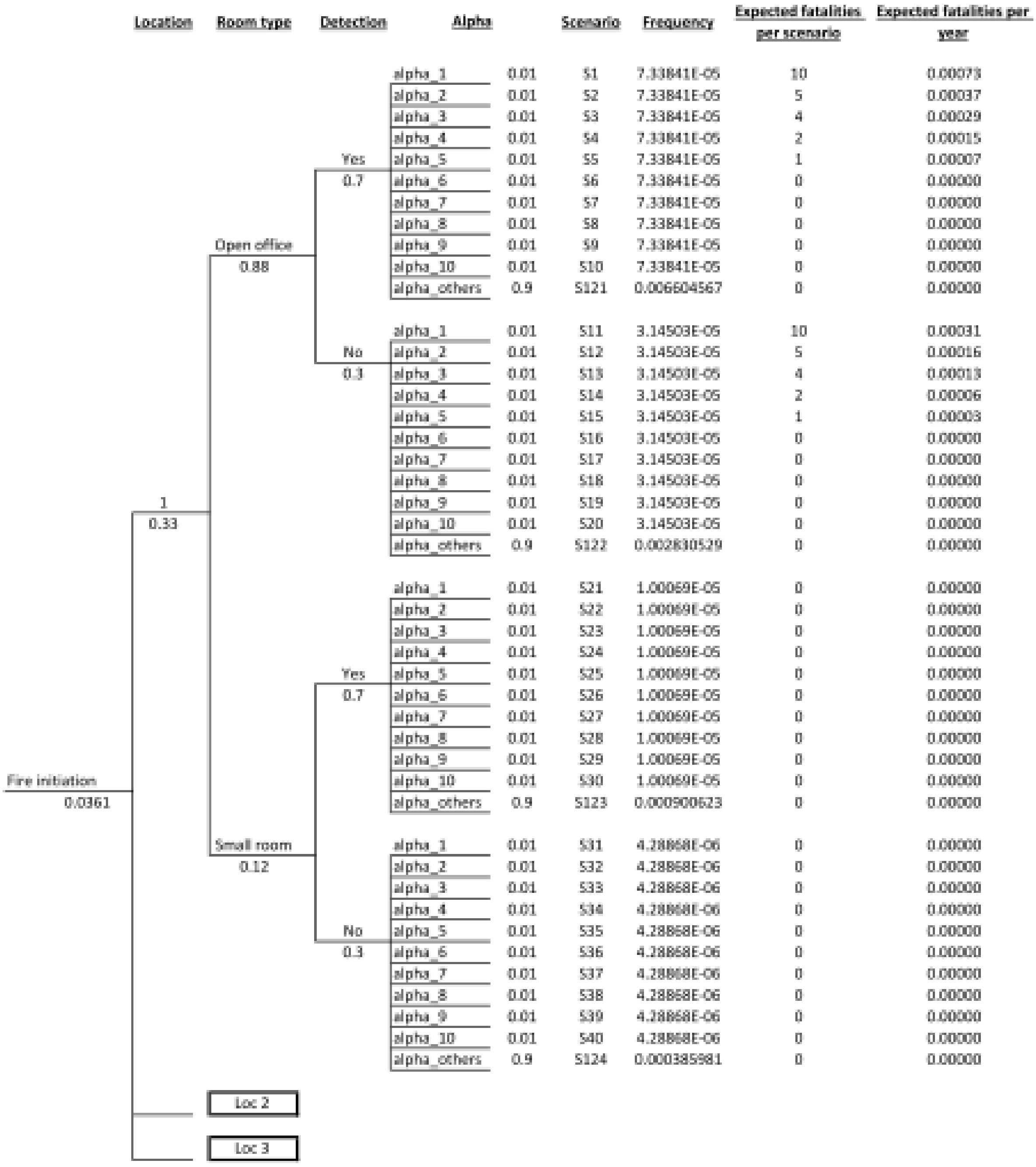


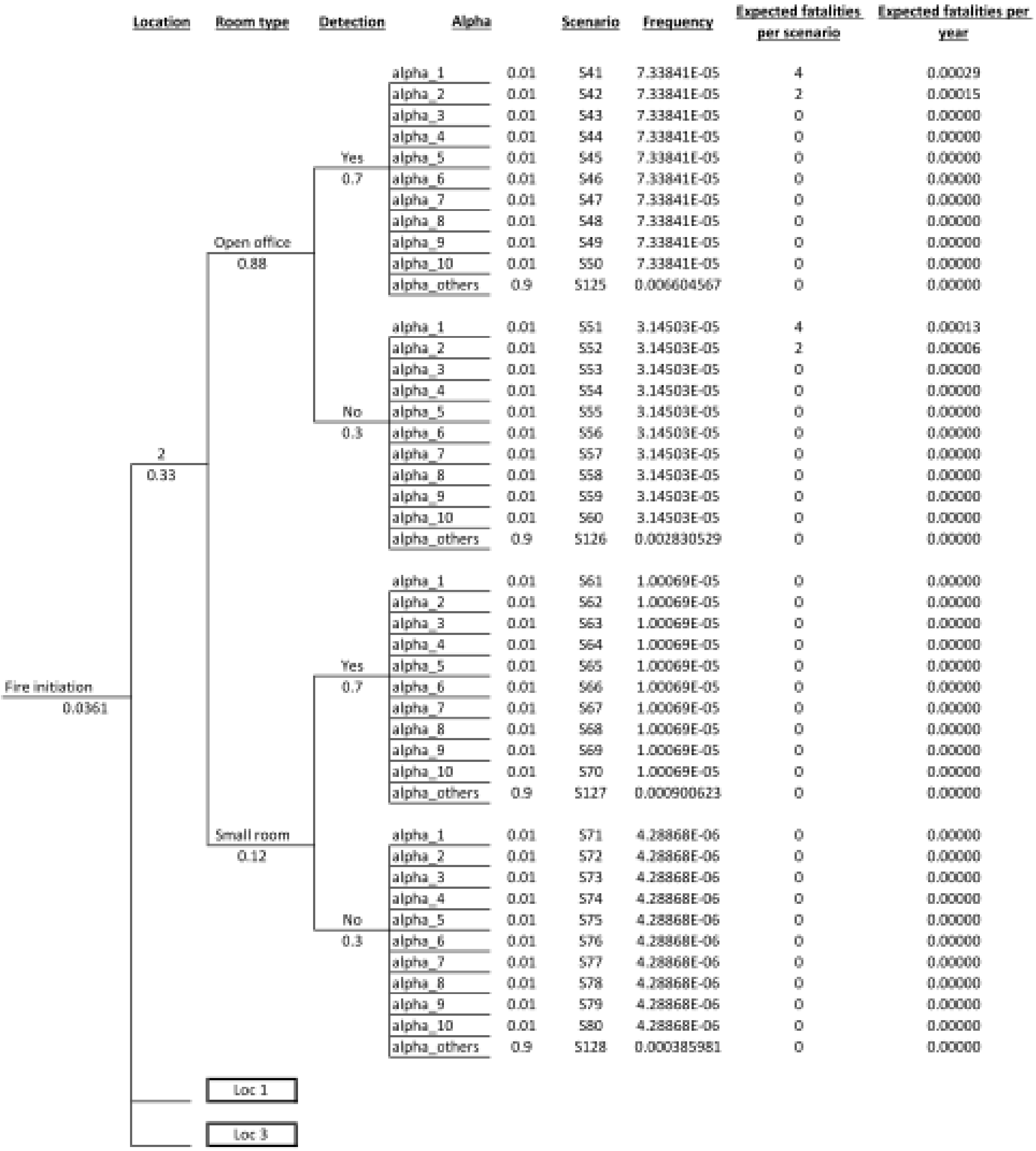
Figure C.6 O_2 concentration for open office fire (left) and small room fire (right) at 360 s

APPENDIX D – Full event tree analysis



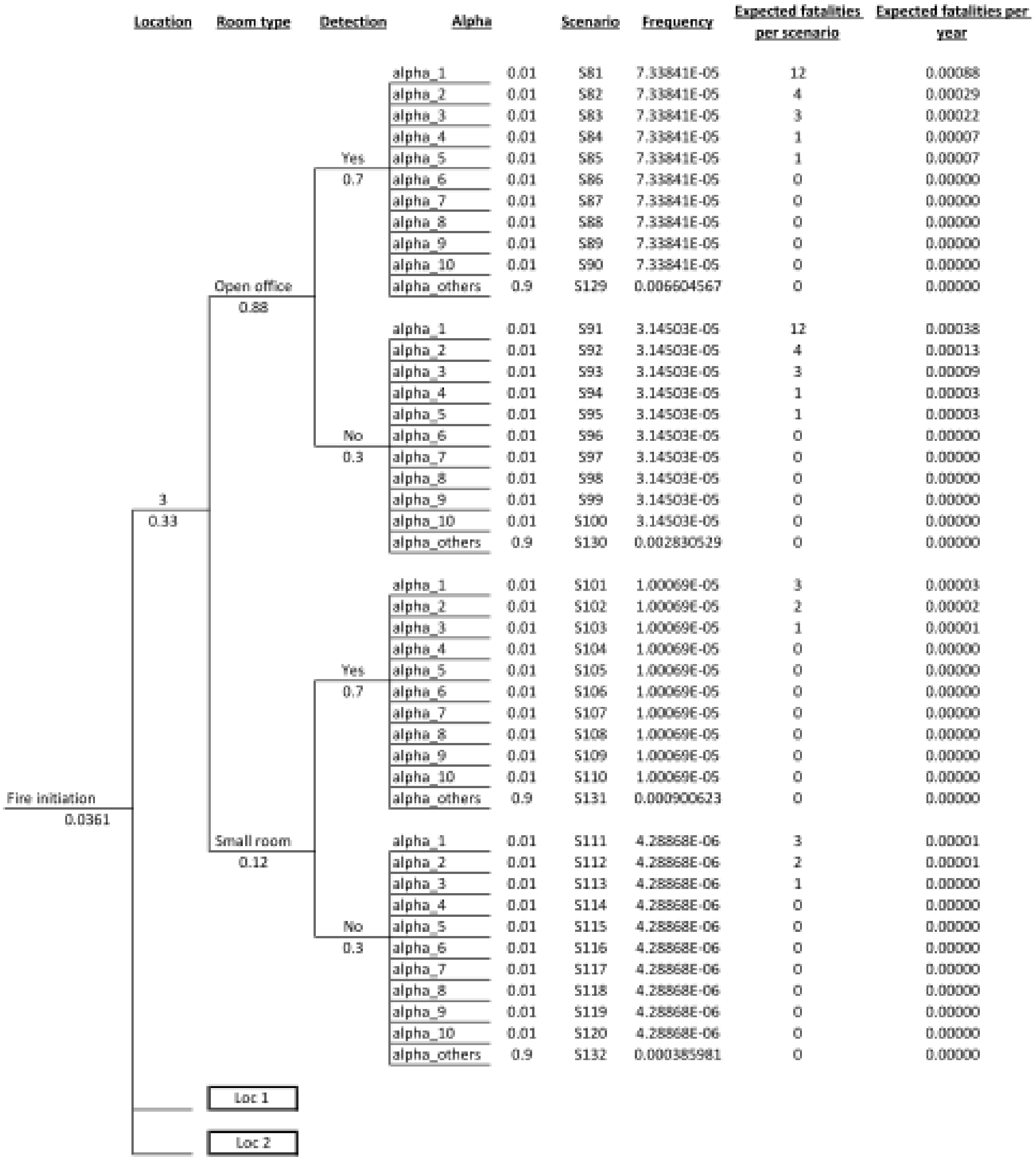
Location	Room type	Detection	Alpha		Scenario	Frequency	Expected fatalities per scenario	Expected fatalities per year
1 0.33	Open office 0.88	Yes 0.7	alpha_1	0.01	S1	7.33841E-05	10	0.00073
			alpha_2	0.01	S2	7.33841E-05	5	0.00037
			alpha_3	0.01	S3	7.33841E-05	4	0.00029
			alpha_4	0.01	S4	7.33841E-05	2	0.00015
			alpha_5	0.01	S5	7.33841E-05	1	0.00007
			alpha_6	0.01	S6	7.33841E-05	0	0.00000
			alpha_7	0.01	S7	7.33841E-05	0	0.00000
			alpha_8	0.01	S8	7.33841E-05	0	0.00000
			alpha_9	0.01	S9	7.33841E-05	0	0.00000
			alpha_10	0.01	S10	7.33841E-05	0	0.00000
			alpha_others	0.9	S121	0.006604567	0	0.00000
		No 0.3	alpha_1	0.01	S11	3.14503E-05	10	0.00031
			alpha_2	0.01	S12	3.14503E-05	5	0.00016
			alpha_3	0.01	S13	3.14503E-05	4	0.00013
			alpha_4	0.01	S14	3.14503E-05	2	0.00006
			alpha_5	0.01	S15	3.14503E-05	1	0.00003
			alpha_6	0.01	S16	3.14503E-05	0	0.00000
			alpha_7	0.01	S17	3.14503E-05	0	0.00000
			alpha_8	0.01	S18	3.14503E-05	0	0.00000
			alpha_9	0.01	S19	3.14503E-05	0	0.00000
			alpha_10	0.01	S20	3.14503E-05	0	0.00000
			alpha_others	0.9	S122	0.002830529	0	0.00000
	Small room 0.12	Yes 0.7	alpha_1	0.01	S21	1.00069E-05	0	0.00000
			alpha_2	0.01	S22	1.00069E-05	0	0.00000
			alpha_3	0.01	S23	1.00069E-05	0	0.00000
			alpha_4	0.01	S24	1.00069E-05	0	0.00000
			alpha_5	0.01	S25	1.00069E-05	0	0.00000
			alpha_6	0.01	S26	1.00069E-05	0	0.00000
			alpha_7	0.01	S27	1.00069E-05	0	0.00000
			alpha_8	0.01	S28	1.00069E-05	0	0.00000
			alpha_9	0.01	S29	1.00069E-05	0	0.00000
			alpha_10	0.01	S30	1.00069E-05	0	0.00000
			alpha_others	0.9	S123	0.000900623	0	0.00000
		No 0.3	alpha_1	0.01	S31	4.28868E-06	0	0.00000
			alpha_2	0.01	S32	4.28868E-06	0	0.00000
			alpha_3	0.01	S33	4.28868E-06	0	0.00000
			alpha_4	0.01	S34	4.28868E-06	0	0.00000
			alpha_5	0.01	S35	4.28868E-06	0	0.00000
			alpha_6	0.01	S36	4.28868E-06	0	0.00000
			alpha_7	0.01	S37	4.28868E-06	0	0.00000
			alpha_8	0.01	S38	4.28868E-06	0	0.00000
			alpha_9	0.01	S39	4.28868E-06	0	0.00000
			alpha_10	0.01	S40	4.28868E-06	0	0.00000
			alpha_others	0.9	S124	0.000385981	0	0.00000

Figure D.1 Event tree – fire location 1



Location	Room type	Detection	Alpha		Scenario	Frequency	Expected fatalities per scenario	Expected fatalities per year
2 0.33	Open office 0.88	Yes 0.7	alpha_1	0.01	S41	7.33841E-05	4	0.00029
			alpha_2	0.01	S42	7.33841E-05	2	0.00015
			alpha_3	0.01	S43	7.33841E-05	0	0.00000
			alpha_4	0.01	S44	7.33841E-05	0	0.00000
			alpha_5	0.01	S45	7.33841E-05	0	0.00000
			alpha_6	0.01	S46	7.33841E-05	0	0.00000
			alpha_7	0.01	S47	7.33841E-05	0	0.00000
			alpha_8	0.01	S48	7.33841E-05	0	0.00000
			alpha_9	0.01	S49	7.33841E-05	0	0.00000
			alpha_10	0.01	S50	7.33841E-05	0	0.00000
			alpha_others	0.9	S125	0.006604567	0	0.00000
		No 0.3	alpha_1	0.01	S51	3.14503E-05	4	0.00013
			alpha_2	0.01	S52	3.14503E-05	2	0.00006
			alpha_3	0.01	S53	3.14503E-05	0	0.00000
			alpha_4	0.01	S54	3.14503E-05	0	0.00000
			alpha_5	0.01	S55	3.14503E-05	0	0.00000
			alpha_6	0.01	S56	3.14503E-05	0	0.00000
			alpha_7	0.01	S57	3.14503E-05	0	0.00000
			alpha_8	0.01	S58	3.14503E-05	0	0.00000
			alpha_9	0.01	S59	3.14503E-05	0	0.00000
			alpha_10	0.01	S60	3.14503E-05	0	0.00000
			alpha_others	0.9	S126	0.002830529	0	0.00000
	Small room 0.12	Yes 0.7	alpha_1	0.01	S61	1.00069E-05	0	0.00000
			alpha_2	0.01	S62	1.00069E-05	0	0.00000
			alpha_3	0.01	S63	1.00069E-05	0	0.00000
			alpha_4	0.01	S64	1.00069E-05	0	0.00000
			alpha_5	0.01	S65	1.00069E-05	0	0.00000
			alpha_6	0.01	S66	1.00069E-05	0	0.00000
			alpha_7	0.01	S67	1.00069E-05	0	0.00000
			alpha_8	0.01	S68	1.00069E-05	0	0.00000
			alpha_9	0.01	S69	1.00069E-05	0	0.00000
			alpha_10	0.01	S70	1.00069E-05	0	0.00000
			alpha_others	0.9	S127	0.000900623	0	0.00000
		No 0.3	alpha_1	0.01	S71	4.28868E-06	0	0.00000
			alpha_2	0.01	S72	4.28868E-06	0	0.00000
			alpha_3	0.01	S73	4.28868E-06	0	0.00000
			alpha_4	0.01	S74	4.28868E-06	0	0.00000
			alpha_5	0.01	S75	4.28868E-06	0	0.00000
			alpha_6	0.01	S76	4.28868E-06	0	0.00000
			alpha_7	0.01	S77	4.28868E-06	0	0.00000
			alpha_8	0.01	S78	4.28868E-06	0	0.00000
			alpha_9	0.01	S79	4.28868E-06	0	0.00000
			alpha_10	0.01	S80	4.28868E-06	0	0.00000
			alpha_others	0.9	S128	0.000385981	0	0.00000

Figure D.2 Event tree – fire location 2



	Location	Room type	Detection	Alpha		Scenario	Frequency	Expected fatalities per scenario	Expected fatalities per year
Fire initiation 0.0361	3 0.33	Open office 0.88	Yes 0.7	alpha_1	0.01	S81	7.33841E-05	12	0.00088
				alpha_2	0.01	S82	7.33841E-05	4	0.00029
				alpha_3	0.01	S83	7.33841E-05	3	0.00022
				alpha_4	0.01	S84	7.33841E-05	1	0.00007
				alpha_5	0.01	S85	7.33841E-05	1	0.00007
				alpha_6	0.01	S86	7.33841E-05	0	0.00000
				alpha_7	0.01	S87	7.33841E-05	0	0.00000
				alpha_8	0.01	S88	7.33841E-05	0	0.00000
				alpha_9	0.01	S89	7.33841E-05	0	0.00000
				alpha_10	0.01	S90	7.33841E-05	0	0.00000
				alpha_others	0.9	S129	0.006604567	0	0.00000
			No 0.3	alpha_1	0.01	S91	3.14503E-05	12	0.00038
				alpha_2	0.01	S92	3.14503E-05	4	0.00013
				alpha_3	0.01	S93	3.14503E-05	3	0.00009
				alpha_4	0.01	S94	3.14503E-05	1	0.00003
				alpha_5	0.01	S95	3.14503E-05	1	0.00003
				alpha_6	0.01	S96	3.14503E-05	0	0.00000
				alpha_7	0.01	S97	3.14503E-05	0	0.00000
				alpha_8	0.01	S98	3.14503E-05	0	0.00000
				alpha_9	0.01	S99	3.14503E-05	0	0.00000
				alpha_10	0.01	S100	3.14503E-05	0	0.00000
				alpha_others	0.9	S130	0.002830529	0	0.00000
		Small room 0.12	Yes 0.7	alpha_1	0.01	S101	1.00069E-05	3	0.00003
				alpha_2	0.01	S102	1.00069E-05	2	0.00002
				alpha_3	0.01	S103	1.00069E-05	1	0.00001
				alpha_4	0.01	S104	1.00069E-05	0	0.00000
				alpha_5	0.01	S105	1.00069E-05	0	0.00000
				alpha_6	0.01	S106	1.00069E-05	0	0.00000
				alpha_7	0.01	S107	1.00069E-05	0	0.00000
				alpha_8	0.01	S108	1.00069E-05	0	0.00000
				alpha_9	0.01	S109	1.00069E-05	0	0.00000
				alpha_10	0.01	S110	1.00069E-05	0	0.00000
				alpha_others	0.9	S131	0.000900623	0	0.00000
			No 0.3	alpha_1	0.01	S111	4.28868E-06	3	0.00001
				alpha_2	0.01	S112	4.28868E-06	2	0.00001
				alpha_3	0.01	S113	4.28868E-06	1	0.00000
				alpha_4	0.01	S114	4.28868E-06	0	0.00000
				alpha_5	0.01	S115	4.28868E-06	0	0.00000
				alpha_6	0.01	S116	4.28868E-06	0	0.00000
				alpha_7	0.01	S117	4.28868E-06	0	0.00000
				alpha_8	0.01	S118	4.28868E-06	0	0.00000
				alpha_9	0.01	S119	4.28868E-06	0	0.00000
				alpha_10	0.01	S120	4.28868E-06	0	0.00000
				alpha_others	0.9	S132	0.000385981	0	0.00000
	Loc 1								
	Loc 2								

Figure D.3 Event tree – fire location 3