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# Risk Acceptance in Fire Safety Engineering: Development of Reference Case Studies

Ayyappa Thejus Mohan

Promoters: Prof. dr. ir. Robby Caspeele, Prof. dr. ir. Ruben Van Coile

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**International Master of Science in Fire Safety Engineering**

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# Abstract

Traditional deterministic fire engineering builds on the collective experience of the fire safety profession, obtained through a continuous process of trial and error. For uncommon fire safety designs, probabilistic risk assessment (PRA) is a necessary methodology to demonstrate adequate safety. Guidance on the application of probabilistic methods to fire engineering can be found in the UK PD 7974-7:2019. But there are no reference case studies demonstrating a structured application of the probabilistic methods to fire engineering design. At the same time, there is no guidance on defining the risk tolerability limits for a building project through stakeholder communications in PD 7974-7:2019.

Aiming to clarify these aspects, PD 7974-7:2019 is explored and a literature review of risk acceptance in fire safety engineering is performed. In the context of fire safety engineering, the literature review indicates that there are no established risk tolerability criteria in the building sector when compared to the industrial and transportation sectors. Through literature review and carefully analysing public reaction on past fire incidents, the important risk perception factors that need to be considered in fire safety engineering specific to the built environment are identified. Acknowledging that what need to be considered in setting risk tolerability criteria for a specific project in the built environment, a risk tolerability framework is proposed. Also, a methodology is developed to demonstrate structured application of the probabilistic methods to fire engineering design. This methodology together with the proposed risk tolerability framework, incorporating the feedback of fire safety professionals, is demonstrated through three case studies. These case studies can serve as a reference to practicing fire safety engineers. Moreover, the risk tolerability framework provides a clear guidance to fire safety engineers and authorities to establish a risk tolerability criterion for a specific project in the built environment acknowledging the public risk perception.

# സംഗ്രഹം

പരമ്പരാഗതമായ ഫയർ എൻജിനീയറിങ് അഗ്നിശമന സുരക്ഷാ വിഭാഗത്തിന്റെ മുൻകാല അനുഭവത്തെ അടിസ്ഥാനമാക്കിയാണ് രൂപകല്പന ചൈതിട്ടുള്ളത്. അസാധാരണമായ അഗ്നിസുരക്ഷാ സംവിധാനങ്ങൾക്കായി, മതിയായ സുരക്ഷ തെളിയിക്കുന്നതിനുള്ള ഒരു രീതിയാണ് പ്രോബബിലിറ്റി റിസ്ക് വിലയിരുത്തൽ (പിആർഎ). ഈ രീതികൾ പ്രയോഗിക്കുന്നതിനുള്ള മാർഗനിർദേശം ബ്രിട്ടീഷ് പി.ഡി. 7974-7: 2019 ൽ പ്രതിപാദിച്ചിട്ടുണ്ട്. എന്നാൽ ഇതിന്റെ ഘടനാപരമായ പ്രയോഗത്തെ പറ്റി പഠനങ്ങൾ ഒന്നുംതന്നെ പൂർവ വൈഞ്ജാനിക അവലോകനത്തിൽ കാണുവാൻ സാധിക്കുന്നില്ല. അതേ സമയം, PD 7974-7: 2019ൽ കെട്ടിട ഉടമകളുടെ ആശയവിനിമയത്തിലൂടെ ഒരു കെട്ടിടനിർമ്മാണത്തിന്റെ പരിമിതമായ പരിമിതി നിർണയിക്കുന്നതിൽ മാർഗനിർദേശമില്ല.

ഈ വശങ്ങൾ പൂർണ്ണമായും വ്യക്തമാക്കുവാൻ സാധിക്കുന്ന വിധത്തിൽ, PD 7974-7: 2019 പര്യവേക്ഷണവും ഫയർ സുരക്ഷാ എൻജിനീയറിങ്ങിൽ അപകടസാദ്ധ്യതയുള്ള ഒരു പൂർവ വൈഞ്ജാനിക അവലോകനം നടത്തി ഒരു പുതിയ രീതി ആവിഷ്കരിക്കുവാൻ ഉദ്ദേശിച്ചാണ് ഈ സംരംഭം. വ്യവസായ മേഖല ആയും ഗതാഗത മേഖല ആയും താരതമ്യപ്പെടുത്തുമ്പോൾ, കെട്ടിട നിർമ്മാണ മേഖലയിൽ നിർണായകമായ അപകടസാധ്യതയുള്ള മാനദണ്ഡങ്ങൾ വിരളം. പൂർവ വൈഞ്ജാനിക അവലോകനത്തിൽ നിന്നും മുൻകാല തീപിടുത്ത സംഭവങ്ങളെക്കുറിച്ചുള്ള വിദ്ഗ്ധരുടെ പ്രതികരണത്തിൽ നിന്നും അഗ്നിസുരക്ഷാ സംവിധാന മാനദണ്ഡങ്ങൾ തിരിച്ചറിഞ്ഞിട്ടുണ്ട്. അപ്രകാരം നിർമാണ മേഖലയിൽ റിസ്ക് ടോളറബിലിറ്റി ഇതിനോടൊപ്പം നിർദേശിക്കുന്നു. ഫയർ എൻജിനീയറിങ്ങ് ഡിസൈൻ നേരിടുന്ന പ്രോബബിലിസ്റ്റിക് രീതികളുടെ ഘടനാപരമായ ഒരു രീതിശാസ്ത്രം വികസിപ്പിച്ചെടുത്ത് മൂന്ന് പ്രയോഗിക പഠനത്തിലൂടെ ഇതിന്റെ നിജസ്ഥിതി ഈ പ്രബന്ധത്തിൽ ഉറപ്പുവരുത്തുന്നു. ഈ റിസ്ക് ടോളറലിറ്റി ഫ്രെയിംവർക്ക് പൊതു അപകടസാധ്യതയുള്ള നിർദ്ദിഷ്ട പദ്ധതിക്ക് അപകടസാദ്ധ്യത ഉറപ്പാക്കാനുള്ള മാനദണ്ഡം ഉറപ്പാക്കാൻ സുരക്ഷാ എഞ്ചിനീയർമാരെയും അധികാരികളെയും വ്യക്തമായ മാർഗനിർദ്ദേശം നൽകുന്നു.

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# 1 Introduction

This chapter provides an introduction by highlighting the background of the probabilistic risk assessment (PRA) to fire safety engineering in buildings. This chapter also provides a description of research focus revealing the problems that need to be addressed in PRA in the context of fire safety engineering, the aims and objectives of the dissertation, the methods used to achieve the aims and objectives, and the structure of the dissertation.

## 1.1 Background

A look into the history of fire safety clearly reveals that lessons learnt from past fire incidents played a major role in the development of fire safety engineering [1,2]. In the United Kingdom (UK), even though, for example, attempts were made in 12th century to legislate for fire safety in London, The Great Fire of London in 1666 resulted in the adoption of The Rebuilding of London Act 1666 [3]. With the advent of new technologies, humans improved the standard of living which introduced more hazards. In order to deal with these hazards and enforce minimum standards of construction, safety and performance of buildings, approved documents and guides were implemented under the Building Act 1984. Accordingly, different fire safety design approaches were developed to limit the fire risk in buildings and to ensure safety of people, property and environment. The traditional fire safety design approach involves the use of prescriptive guidelines which is widely applicable to common buildings [3–5].

However, with the increasing complexities of the project, the ‘adequate level of safety’ when applying prescriptive rules becomes questionable since the buildings falls outside the relevant field of application of the prescriptive guidance [5]. Furthermore, the prescriptive guidance is developed in a reactive manner and hence does not necessarily take into account the rare events which can occur in the future [5]. In addition to these, the advances in computational fluid dynamics and new construction products into the built environment enhanced the move towards the Performance Based Design (PBD). It is important to note that the traditional PBD approach is deterministic and the treatment of risk is qualitative. Therefore, one of the common characteristics of the prescriptive and performance based design is that the probability that the design does not meet the fire safety objective(s) is not explicitly evaluated [5]. Furthermore, the attainment of an ‘adequate level of safety’ is based on collective experience of the profession. The necessity to demonstrate the attainment of ‘adequate level of safety’ led to the application of probabilistic methods in fire safety engineering, which is commonly accepted as a tool for PBD [5]. Even though, this method was considered in nuclear industries and other process industries earlier, the King Cross underground station fire at London in 1987 raised questions on dealing with the stochastic nature of fire [1] which emphasized the call for probabilistic risk assessment in the built environment. The need to understand the realistic responses of buildings in fire led to the development of the UK Published Document series PD 7974, of which Part 7 (PD 7974-7:2003 Application of fire safety engineering principles to the design of buildings – Part 7: Probabilistic risk assessment [6]) provides guidance on the application of Probabilistic Risk Assessment (PRA) for fire safety engineering in buildings [6,7].

## 1.2 Research Focus

The interest created amongst the fire safety professionals and research community on demonstrating ‘adequate level of safety’ for unique building designs with the use of PRA promoted in-depth study on this topic. Nevertheless the position of PRA in the design process, the relationship between different acceptance concepts and the responsibilities of the designer remained unclear in PD 7974-7:2003 [5]. Similarly, recent studies indicates that the limited application of PRA in fire safety engineering is due to the lack of data related to real structures subjected to real fires [7]. Also, the data to perform PRA in the 2003 version of the published document is between the period 1966 and 1987. Although PD 7974-7:2003 [6] is revised recently, only the unclear aspects mentioned above are addressed in detail and the data to perform PRA has only been partially updated. At the same time, the PD 7974-7:2019 [8] focusses on high level principles and does not include reference examples demonstrating application of the principles to practicing fire safety engineers.

PD 7974-7:2019 [8] puts a lot of emphasis on acceptability and tolerability of risk in built environment. Still the question on setting risk acceptability and tolerability criteria for a project in built environment is unexplored. On the other hand, in the industrial sector (nuclear and process industries) countries like the United Kingdom and the Netherlands have taken large efforts to address risk criteria [9,10]. However, the importance of research in the topic of tolerable and acceptable criteria for fire risk in buildings becomes more visible when other researchers highlight the need to focus on this topic. Olsson [11] points out that the lack of established acceptable fire risk criteria makes it difficult for the designer to determine whether his building is safe or not. Similarly Meacham [12] mentions that the regulatory and design communities are struggling with the concept of “acceptable risk”. Besides Hopkin et al. [5,13] feels that foundations upon which the adequacy of design is accepted is crudest.

These problems could be addressed by concentrating more into the risk acceptability and tolerability in fire safety engineering. Therefore, a major focus of this research will centralize on the topic of tolerable and acceptable risks for fire risk in buildings which is explicitly discussed in chapter 3. There are few questions to be raised to delve into these topics. What is risk and how to measure it? What is ‘adequate safety’? Is there a difference between tolerable and acceptable risks? How are the risk acceptance criteria in industrial sector set up in different countries over the world? What are the difficulties involved in the current methods of setting up the risk acceptance criteria? Is risk perception a significant topic to be considered as far as risk acceptability and tolerability is concerned? Will the tolerable risk be the same for a hospital and an office building? Finding answers to these questions by critical evaluation of the relevant literature is vital to develop a risk tolerability framework. However, a framework developed for risk tolerability is incomplete without demonstrating their applicability through reference examples.

## 1.3 Aims and Objectives

The overall aim of this dissertation is to develop peer-reviewed and documented case studies applying probabilistic methods to fire engineering design as per the PD 7974-7:2019 [8]. The following objectives have been identified of paramount importance in helping to achieve the aforementioned aim:

1. Study of PD 7974-7:2019 and literature review of risk acceptance in fire safety engineering.
2. Development of a framework for setting risk tolerability and broadly acceptable limit for projects in the built environment.
3. Development of case studies by structured application of probabilistic methods in accordance with the PD 7974-7:2019 and the developed risk tolerability criteria.
4. Presentation and discussion of developed risk tolerability framework and case studies to stakeholders.
5. Updating methodology, cases and report in function of stakeholder feedback. Identification of caveats in the methodology.

In order to understand the concepts of probabilistic methods in fire safety engineering and also answer the different questions that were raised previously, objective 1 focuses on studying PD 7974-7:2019 and performing a critical literature review on risk acceptance in fire safety engineering. The knowledge gained on the topic is then utilized to achieve the second objective of developing a framework for setting broadly acceptable and maximum tolerable risk criteria for projects in the built environment. The suggested framework is subsequently employed to accomplish the third objective of developing case studies. Finally, objectives 4 and 5 will be achieved by presenting and discussing the developed case studies with the fire safety professionals for their feedback as well as to identify the caveats in the methodologies adopted.

## 1.4 Methodology

In order to accomplish the aims and objectives of the dissertation, the methodology as depicted in Figure 1.1 is followed.

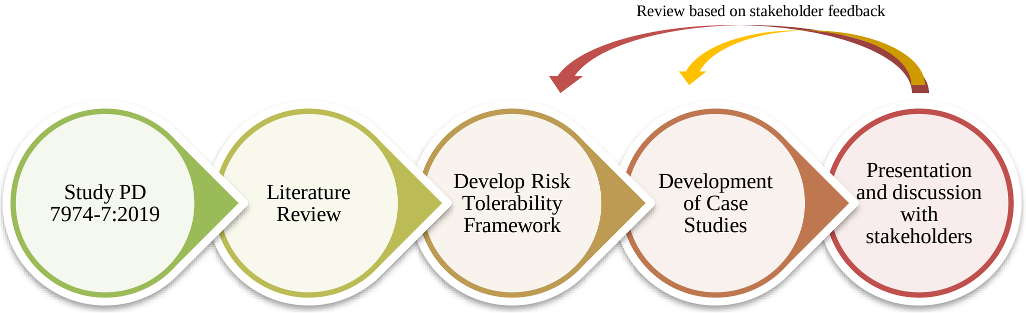


Figure 1.1: Flow chart describing methodology for the dissertation

In order to obtain an idea of PRA in fire safety engineering, the PD 7974-7:2019 is explored. With the background knowledge gained from PD 7974-7:2019, a literature review is carried out focusing on understanding the risk acceptance criteria in fire safety engineering. For this, different text books, journal papers, conference proceedings, course presentations on various topics relevant to the risk acceptance are explored. Such a critical analysis helps to understand the different aspects to be considered while setting risk acceptance criteria and its associated problems. With these inputs, a risk tolerability criteria framework is developed specifically for the built environment. Incorporating the principles mentioned in the PD 7974-7:2019 and the developed risk tolerability criteria framework, three case studies of different occupancy types are developed. Data, for instance for evacuation, which are unavailable in PD 7974-7:2019 and PD 7974-7:2003 are taken from relevant literature. Also, the two-zone model B-RISK is used for the case studies. Similarly, for a case study evacuation simulation software Pathfinder is used. The developed case studies and proposed risk tolerability framework are discussed with the fire safety professionals for their feedback. Also, the caveats in the methodologies are identified. According to their feedback, necessary changes are made in the case studies.

## 1.5 Structure of Dissertation

Development of peer-reviewed and documented case studies applying probabilistic methods to fire engineering design as per the revised PD 7974-7:2019 need a systematic approach involving a discussion of various topics through literature review. A flowchart describing the structure of this master thesis is given in Figure 1.2.

*Chapter 1 – Introduction*

*Chapter 2 – PD 7974-7:2019 and Concepts of Risk*

This chapter introduces the concepts of risk and emphasize the importance of probabilistic approach in fire safety engineering. The basis of PD 7974-7:2019 and the need for developing a risk tolerability framework for projects in the built environment are highlighted. Accordingly, risk perception and its importance in fire safety engineering are looked into. Moreover, the various risk perception factors that need to be considered from the perspective of society are discussed. Next, the focus moves on to risk aversion and how it is being considered currently in setting risk acceptability and tolerability criteria in general. Finally, the ethical aspects in fire risk assessment are discussed.

*Chapter 3 – Risk Tolerability Framework*

This chapter looks into the proposed framework for setting *de minimis* limit and tolerability limit for a project in the built environment. However, at first the acceptability and tolerability of risks are discussed. Challenges involved in setting up *de minimis* limits and tolerability limits of risk are then explored. Accordingly, different risk control approaches as well as risk models putting emphasis on the individual and societal risks are focused. Referring to all these discussions, a risk tolerability framework employing a step by step procedure in setting *de minimis* limit and tolerability limit for a project in the built environment is proposed. Finally, the feedback from the fire safety professionals on the developed risk tolerability framework are presented.

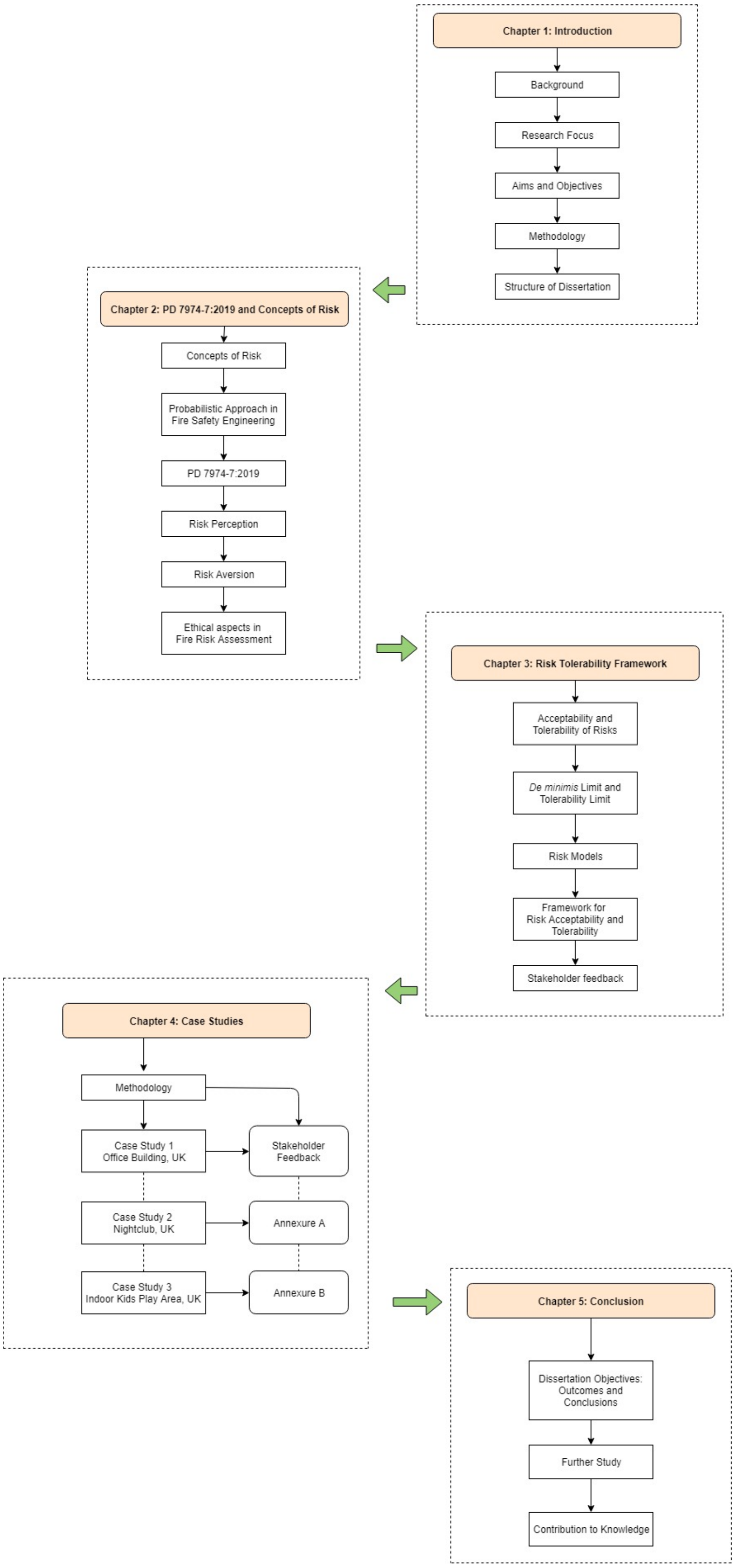


Figure 1.2: Flowchart describing the structure of the dissertation

*Chapter 4 – Case Studies*

This chapter is devoted for the case studies developed applying the principles of PD 7974-7:2019 and the proposed risk tolerability framework. As a starting point, a methodology is presented for the application of the principles of PD 7974-7:2019. This methodology is then followed in three different case studies – office building, night club (Annexure A) and indoor kids play area (Annexure B). Stakeholder feedbacks are also presented.

*Chapter 5 – Conclusion*

This section will revisit the dissertation objectives and summarize the important outcomes of this dissertation. Recommendation for future work are then discussed. Most importantly, the contribution of this work in the field of probabilistic risk assessment in fire safety engineering, specifically to the built environment are clarified.

# 2 PD 7974-7:2019 and Concepts of Risk

In order to reach a point to develop case studies applying the principles of PD 7974-7:2019, it is critical to study this published document and realize where further research is necessary and what are the important factors to be considered as far as the term ‘risk’ is concerned. This chapter aims to understand the term ‘risk’, the difference between probabilistic and deterministic approach, the core concepts of PD 7974-7:2019 and the topics which require further research, different factors which are relevant to risk tolerability: risk perception, risk aversion and the ethical aspects of fire risk assessment. Better understanding of these topics of PRA by a critical evaluation of the relevant literature helps to develop the building blocks of a risk tolerability framework.

Figure 2.1: Flow chart highlighting the structure of chapter 2

## 2.1 Concepts of Risk

So far, the term ‘risk’ is frequently used in the discussions. But, what does the term ‘risk’ really mean? How is it measured? All these are explored in this section.

The term ‘risk’ is defined in different ways and an universal definition of risk is absent [5,14,15]. The meaning of the term risk differs from person to person. This means a layman will define risk entirely in a different way when compared to a risk professional [16,17]. Also, the term differs according to the context of the risk problem that is being addressed [12]. In the context of fire safety engineering, the outcome of PRA will not be fruitful if the stakeholders involved in the project interpret the term ‘risk’ differently. Therefore, it is supreme to have a clear understanding of the term ‘risk’. As far as engineering applications are concerned, risk can be defined as a ‘*function of the probabilities and consequences of a set of undesired events*’ [5,18]. Moreover, this definition has the benefit of brevity. For more clarity, one should understand that hazard is a ‘source of danger’ [19] which can cause harm to people, property and environment. But, the likelihood of occurrence of hazard is uncertain i.e. whether it leads to negative consequences or not. This uncertainty is in principle quantified by probability.

From another point of view on defining ‘risk’, Meacham [12] suggests that other key factors relevant to risk, in the context of fire safety engineering, need to be considered and proposed the following definition for risk:

*‘‘the possibility of an unwanted outcome in an uncertain situation, where the possibility of the unwanted outcome is a function of three factors: loss or harm to something that is valued (consequence), the event or hazard that may occasion the loss or harm (scenario), and a judgement about the likelihood that the loss or harm will occur (probability).’’*

Although Meacham asserts that this definition of risk accommodates key factors like the differences in risk perception, social and cultural experience, uncertainty and variability along with the other common factors (scenario, consequence and probability), such factors are not reflected in the definition unless it is clearly specified. In short, it could be argued that if Meacham's definition and the definition of risk in engineering applications are presented to stakeholders without further explanation, it makes no difference between the former and latter definitions. In fact, the key factors mentioned by Meacham need to be highlighted while framing the risk tolerability and acceptability criteria for a project.

To apprehend how risk is measured, it is good to touch up on the definition of risk stated by Kaplan and Garrick [19]:

*"Risk is equal to the triplet (*$s_i$*,* $p_{i,}$*,* $c_i$*) where* $s_i$ *is the* $i^{th}$ *scenario,* $p_i$ *is the probability of that scenario, and* $c_i$ *is the consequence of the* $i^{th}$ *scenario,* $i = 1,2,\ldots N$*"*

In an extensive PRA, all possible scenarios, their probability of occurrences and consequences will be accounted. If each of these scenarios are arranged in the increasing severity of their consequences and plotted against the cumulative probabilities, a risk curve as illustrated in Figure 2.2 is obtained. In simple terms, risk curves deliver a graph depicting the measure of risk.

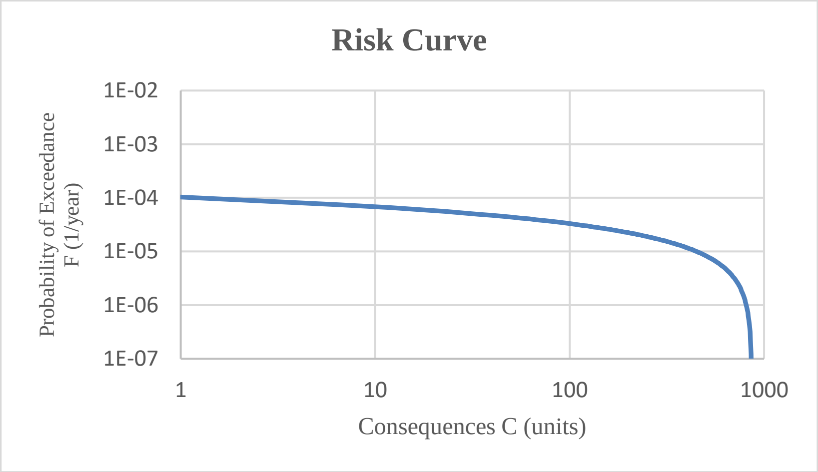


Figure 2.2: Illustration of Risk Curve

Generally, risk is mentioned in terms of frequency of occurrence of an event instead of the probability of an event. As shown in Figure 2.2 it is a common practice to visualize risk curves in log-log scale. The horizontal axis denotes the consequence severity while the vertical axis denotes the probability of exceedance. Since there could be occurrences of many rare events with widespread consequences (i.e. for instance low frequency of occurrence and large number of fatalities) in engineering systems, the only practical way to incorporate them in risk curves is by using logarithmic scales [20]. The risk curves benefit in evaluating the estimated risks, communicating them to stakeholders and for decision-making.

From these discussions it is clear that the two significant components of risk are probabilities and consequences of a set of undesired events. Therefore, definition of risk for the engineering applications is used in this study.

## 2.2 Probabilistic Approach in Fire Safety Engineering

Probabilistic risk assessment (PRA) is also known as Quantitative Risk Assessment (QRA) [14,21]. In general, PRA involves studies where objective is to generate a measure of risk [6]. Even though the basic methods of PRA originated in the aerospace program in 1960s, the first modern study of PRA is considered to be in the nuclear industry [21]. In building sectors, the need to shift towards a goal-oriented approach was realized so as to deal with the development of technologies, new materials of constructions and innovative building designs. This resulted in the adoption of performance-based design approach (PBD) which gave designers more flexibility and facilitated innovation in building designs without compromising safety. However, the traditional PBD approach is deterministic and the treatment of risk is qualitative [5].

Before going into further topics, a clear distinction between deterministic and probabilistic approaches in fire safety engineering is necessary. This difference is explained taking an example of an office building. Firstly, in deterministic fire safety engineering approach, a worst credible scenario is considered. For example, peak heat release rate (HRR) considered in small office rooms are found to be 5MW [22,23]. It is important to note that even small smoldering fires, which has low HRR, can be hazardous to the occupants of the building during evacuation. Thus, it seems that the worst credible scenario considered for a deterministic fire safety engineering approach need not be the worst-case scenario and other possible scenarios which can have high consequences are left out. Secondly, in deterministic approaches it is generally assumed that the smoke heat extraction system or sprinkler system installed in the building works without any failure. Thus, the reliability of the systems is not being accounted in deterministic approaches. Thirdly, it is considered that fire grows once the ignition of a combustible material occurs in the office. The possibility of an occupant trying to extinguish fire manually, at the initial stages of fire development, is not being considered. Fourthly, the uncertainties are not explicitly considered in deterministic approaches (safety factors are used). For instance, a safety factor of 2 is frequently used in egress analysis [24,25]. Finally, in deterministic approaches it is difficult to rank various design options. When there are two design options for the office building satisfying the performance criteria, say smoke heat control system and sprinkler system, then the preference between the two options will be determined by the factors like costs, aesthetics, ease of maintenance etc. [5].

On the other hand, probabilistic fire safety engineering approach considers all possible scenarios, their consequences and likelihood of occurrences. It makes use of the tools like fault tree analysis (FTA) and event tree analysis (ETA) which helps to analyze the cause of a failure and its consequences if a failure occurs. In short, FTA and ETA helps to analyze probabilities and risk. For example, in the office building, the scenarios involving fire in office building during day, night, weekend, weekdays etc. can be considered in one go. Where as in deterministic analysis, the scenario considered for analysis will be during the peak working hours where the office building has maximum number of occupants. Since risk is explicitly estimated and evaluated in probabilistic approaches, the failure of fire protection systems, the chances of manual extinguishment of fire at its initial stages, uncertainties (described through random variables by their probability distributions), ranking of design options and economies in designs are handled to an extent. Therefore, it is clear that in probabilistic fire safety engineering approach the probability that the design does not meet the fire safety objective(s) is explicitly evaluated [5]. Moreover, PRA can be applied to all aspects of fire safety engineering for all building types and designs [6].

## 2.3 PD 7974-7:2019

Guidance on the application of probabilistic methods to fire engineering can be found in the UK PD 7974-7:2003 [6]. But this published document lacked the clarity on the position of PRA in the design process, the relationship between different acceptance concepts and the responsibilities of the designer. Recently, this published document is revised placing special emphasis on these issues. The PD 7974-7:2019 focusses on high level principles and attempts to provide a clear guidance on PRA in built environment which is evident from the consolidated flow chart for a design through PRA (Figure 2.3).

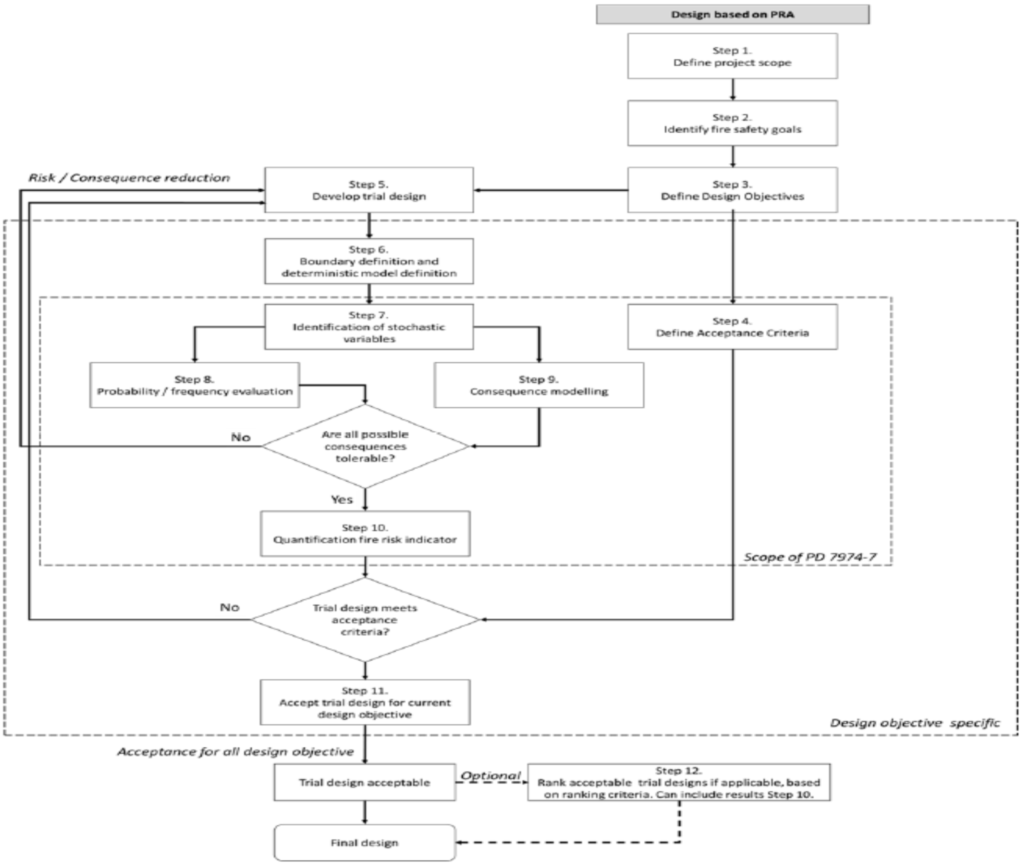


Figure 2.3: Consolidated flow chart for a design through PRA
(reproduced from PD 7974-7:2019 [8])

The hierarchy of risk acceptance concepts and the designer responsibility as a function of the applied acceptance concept is clearly explained in this published document.

Likewise, PD 7974-7:2019 provides a conceptual visualization of the broadly acceptable and tolerable limits which is depicted through a generalized frequency-consequence (FC) diagram (Figure 2.4), an example of a risk curve as discussed in the previous section. An explicit discussion on acceptable and tolerable risks is provided in chapter 3.

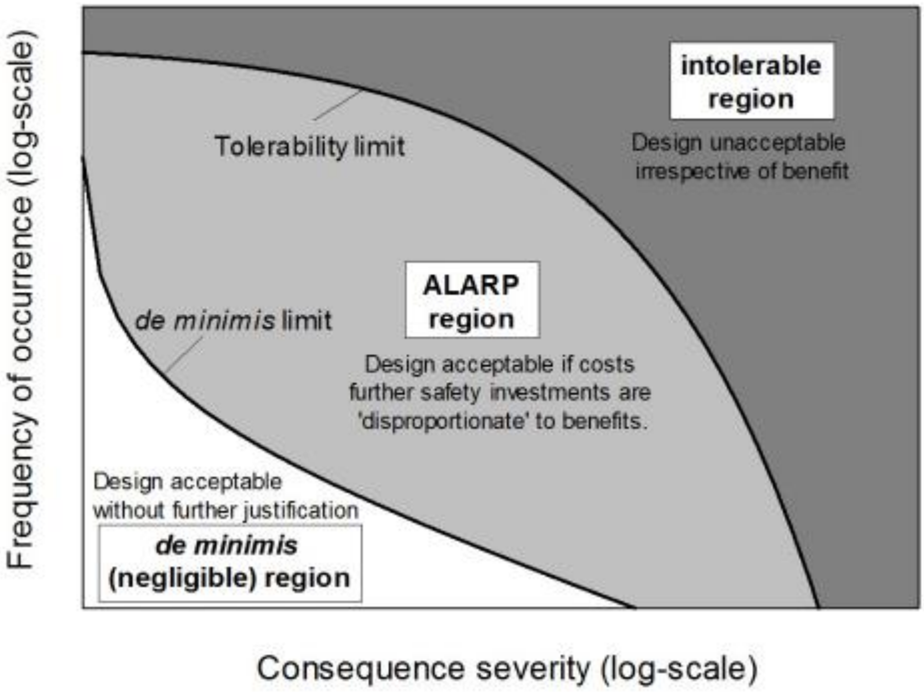


Figure 2.4: Generalized frequency- consequence (FC) diagram with indication of tolerability limit and de minimis limit (reproduced from PD 7974-7:2019 [8])

To understand the concept of the generalized FC diagram, it is essential to point out that zero fire risk is something unrealistic [5,26]. Therefore, final design adopted for a building project necessarily includes a residual risk [5,27]. In risk evaluation process, to know whether the residual risk is acceptable, tolerable or unacceptable, three different regions are demarcated as shown in Figure 2.4: *de minimis* region, As Low As Reasonably Practicable (ALARP) region and intolerable region. These regions are based on the concept of UK Health and Safety Executive (HSE) framework for the tolerability of risk [28]. If the estimated risk falls below the *de minimis* limit, a concept which was derived from a legal principle by risk professionals in early 1980s [26], design is considered acceptable without further justification. In UK HSE terminology, *de minimis* region is known as ‘broadly acceptable region’[28]. But defining acceptable residual risk is challenging due to the involvement of uncertainty and subjectivity [5,29]. At the same time, the decision to accept risk has a cost/benefit character [30]. PD 7974-7:2019 [8] defines tolerability limit as follows: *“the combinations of possible consequences and associated occurrence frequencies which are at the limit of societal acceptance.”* The region between tolerability limit and *de minimis* limit is known as ALARP where risk reduction measures need to be taken to reduce risks to As Low As Reasonably Practicable i.e. the residual risks are acceptable if further risk reduction is impractical or if its cost is grossly disproportionate to the improved gain. Figure 2.5 is just for an illustration purpose so as to communicate the general concept of gross disproportion and is not in agreement with PD 7974-7:2019.

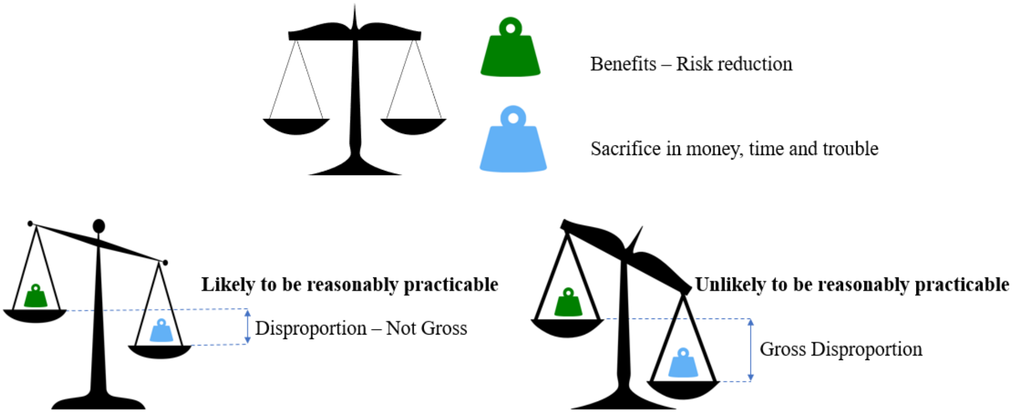


Figure 2.5: An illustration of the concept of Gross Disproportion in the view of ALARP (adapted from [31])

In addition, the risks falling in the intolerable region (also known as ‘unacceptable region’ as per UK HSE [28]) cannot be tolerated irrespective of the associated benefits [5]. Nevertheless, these limits are not explicitly mentioned in PD 7974-7:2019. For instance, PD 7974-7:2019 specifically mentions that risk acceptance criteria need to be defined through stakeholder consultations. Similar is the case with setting up the individual tolerability limit and societal tolerability limits when the fire safety goal is life safety. Thus there is a lack of guidance on defining the risk tolerability limits for a building project through stakeholder communications. On the other hand, acceptability and tolerability criteria specified in Annex A of PD 7974-7:2019 [8] is based on tolerability of risk from nuclear power stations [32]. So, the question is whether it is valid for a building project? This motivates to raise further questions on this context: What are the steps to be followed to set risk tolerability criteria for a building project? What are the different factors to be considered in that process? Why is the tolerability limit and the *de minimis* limit depicted in Figure 2.4 a curve, when the UK HSE limits are a line? Why not use the maximum tolerable limits and broadly acceptable limits specified for land use planning near industrial premises? To answer these questions, it is important to delve into relevant topics related to risk.

In short, a great significance is provided on risk tolerability and acceptability in PD 7974-7:2019. But it lacks an appropriate guidance on setting these limits for a project through stakeholder consultations. In addition, the revised document touches upon risk perception and psychological factors, but fails to explicitly mention which factors are relevant when defining risk tolerability criteria. Such omissions create confusion and mislead stakeholders while setting up risk tolerability limit for a project in the built environment. For instance, whether a hospital and an office building can have the same risk tolerability limit? Nevertheless, it is clear that the fire safety engineering practices develops from the lessons learned from past incidents. Accordingly, a lack of clarity in setting up the tolerability limits and broadly acceptable limits of risk for a project becomes a significant point of discussion when an incident occurs in future. Therefore, being proactive and developing a risk tolerability framework for a project in the built environment will benefit both the fire safety community as well as the society.

## 2.4 Risk Perception

Why is risk perception significant in fire safety engineering? In the context of fire safety engineering, for any building project, achieving an ‘adequate level of safety’ by fulfilling the public mandate is paramount. In order to accomplish this objective, social perceptions of risk need to be accounted [33]. Therefore, understanding risk and how it is perceived by the experts as well as the public is a crucial part of risk assessment and decision making. But it is interesting to note that the experts and the public perceive a risk differently [33–37]. For example, deadly nuclear power accidents occurred in different parts of the world have created fear in the minds of the people and they react vigorously against locating a nuclear power plant near a society despite the safety assurances of the experts. The anti-nuclear protest at the Kudankulam nuclear power plant in India is a perfect example of this [38]. Accordingly, measure of risk involves two components: first the calculation of risk based on the statistical data and experience of the experts and second rely on the perceptions of the experts assessing the risk. As a result, subjective judgement (experts or public) is an indispensable part of risk assessment. However, a decision made for managing a risk can be problematic if the judgements are faulty [37].

So, what is risk perception? According to Wachinger, G., et al. [39], risk perception denotes *‘the process of collecting, selecting and interpreting signals about uncertain impacts of events, activities or technologies’*. It is clear from this definition that risk perception involves subjective assessment of the probability of an undesired event and the magnitude of its consequences [36,40,41]. Thus, risk perception seems to have two dimensions: cognitive dimension and emotional dimension [41]. Cognitive dimension is related to the depth and understanding of an individual, a group or society about risk while emotional dimension is related to their feeling about risk [41].

Risk perception is an essential point for research and two approaches dominate them: psychological approach and sociological approach. Psychological approaches focuses on the unique and subjective qualities of risk perception [34,42] whereas sociological approaches focuses on the risk perception variables that emphasize on the social experiences and consequences of risk [43]. An important outcome of the sociological approach in risk perception is the cultural theory which highlighted risk perception has its origin in cultural factors [42]. In any case, studies concentrating on cultural theories has diminished amid the most recent years [42]. On the other hand, the vast majority of the speculations pursue the psychometric way to deal with risk perception, which focuses on the emotional dimension of risk perception [34,36,42]. From the perspective of fire safety engineering, it is vital to comprehend the manner in which individuals make judgements about risk. When lay people are asked to evaluate risks, since they do not have much statistical evidence, they usually rely on what they can imagine and recall about the risk in question from their past experiences [37].

Therefore, it is critical to address Heuristic-Systematic Model (HSM), a theory of information processing developed by Shelly Chaiken [44]. At the point when individuals are compelled to make decisions, they can process the data either heuristically or systematically. In heuristic information processing, individuals rely on general rules, stereotypes and shortcuts to make judgements [45] whereas in systematic information processing more effort will be put forward by individuals in understanding the information and making a judgement [36]. As a result, heuristics are valuable tools for decision-making if adequate data about probabilities or other resources are unavailable [36]. Few important types of heuristics related to risk perception in the outlook of fire safety engineering are presented in Table 2.1.

| Sl. No. | Type of Heuristics | Description | Examples highlighting its relevance in Fire Safety Engineering |
|---|---|---|---|
| 1 | Availability | Individuals see an occurrence of an event more likely if it is easy for them to recall or imagine [46]. | Aftermaths of Grenfell tower fire in London, UK in the year 2017: people living in similar high-rise buildings felt they are at more risk since such incidents are more likely to occur at their premises [47]. The media also focused a lot on the Grenfell tower fire and this induced people to imagine such incidents more often. |
| 2 | Representativeness | Individuals use this heuristic when a judgement needs to be made and uncertainty remains about the probability of occurrence of an event. This involves assessing similar objects [48]. | Individuals can judge all high-rise buildings are unsafe in London after the Grenfell Tower fire incident. |
| 3 | Proximity | 'Tendency to judge probabilities by monitoring the spatial, temporal, or conceptual distance to a target' [49]. | In the wake of Grenfell tower fire, few people raised questions about the occurrence of fire in their residential high-rise building and whether they will be able to evacuate safely through the single evacuation staircase [47]. Grenfell tower only had a single staircase for evacuation. The close proximity of similar situation in the buildings occupied by people makes them to raise such questions. |

Table 2.1: Few important types of heuristics related to risk perception in the outlook of fire safety engineering

All these heuristics types are focusing on the ‘likelihood of occurrence of events’ component of risk. Research also indicates that people are more concerned with the ‘consequence of event’ than the other component of risk [37]. For instance, there were many incidents of façade fires in high-rise buildings around the world. However, in most of these incidents, there were no fatalities. But large fatalities in Grenfell tower fire made it different.

In order to explore the qualitative characteristics of risk, psychometric methods were employed [34,37]. Similarly surveys and experiments have uncovered that risk perception is affected by a progression of properties of risk source or the risk situation [43]. In the context of building fire safety engineering, apart from the different type of heuristics mentioned in Table 2.1, the most important qualitative characteristics [12] and their direction of influence on risk perception are discussed below.

- *Service of the building under normal/emergency conditions and importance of building*

Importance of a building is critical since it has an influence in the direction of influence on risk perception. For instance, the devastating fire at Brazil’s National Museum in September 2018 resulted in an ‘incalculable loss’ and public expressed immense anger [50]. This indicates that more the importance of a building, less is the risk tolerance. Similar is the case with the buildings which are important to deal with emergencies. For example, Miryang hospital fire with 37 fatalities in South Korea in January 2018, swelled public anger and criticisms [51,52].

- *Occupancy - vulnerable groups*

As per National Fire Protection Association (NFPA), vulnerable groups or individuals includes children, the elderly or those with a disability [53]. However, a better description is given in official Norwegian documents: ‘*vulnerability is described as related to factors such as old age, reduced mobility or cognitive abilities, mental health problems, and substance abuse*’ [54]. For buildings which are specifically built for the vulnerable groups, the society tolerate less risks. This is clearly visible from the two fire incidents that occurred in March 2018: one which killed 25 drug rehabilitation patients in Baku, Azerbaijan [55] and the other which killed 64 people, mostly kids, in Russia Kemerovo fire [56]. But the interesting fact is that when a fire incident results in fatalities of people in different age groups, the society puts more focus on the total number of fatalities rather than the number of vulnerable groups who died in the incident. This is evident from the Grenfell Tower fire where society placed more importance on the number of fatalities irrespective of the age groups. Thus, in this case, the number of vulnerable groups who lost their lives became trivial.

- *Sleeping risk*

Studies indicate that sleep is a major risk factor for dying in a fire [57]. Sleeping risk is involved in residential buildings, hotels, accommodation buildings for students etc. Therefore, while designing such buildings, it is important to realize that the society tolerate less risks even if the occupants are familiar with the layout of the building. It is evident from the public reaction of Grenfell tower fire in June 2017, in London [58].

- *Potential for catastrophe (dread) and possibility to evacuate*

For instance, there have been catastrophic tunnel fires in the past. It is important to note that tunnels are difficult to access during rescue operations. Also, the enclosed nature of the tunnel structure enhances rapid increase in temperature in case of a fire. Moreover, evacuating tunnels during a fire occurrence is a difficult and time-consuming task [59,60]. It is true that public do not tolerate high risks in such premises which is evident from the public response after the Mont Blanc tunnel fire in 1999 [61]. Therefore, the risk tolerances in occupancies involving potential for catastrophe and difficulties in evacuation should be less. In developed countries, the aftermath of Grenfell Tower fire in London remains in the mind of society and hence high-rise buildings also need to be given a special care with this regard. Similarly, special attention needs to be given for buildings near industrial premises and other hazardous installations and warehouses.

- *Familiarity*

Familiar layout of a building makes it easier for the occupants to know the risks and evacuate in case of an emergency. This is true in the case of office buildings where the employees are aware of the layout of the building. However, there can be visitors in these premises who are unfamiliar with the building layout. Therefore, evacuation of an office in case of a fire also depends on the fire safety management as well as the safety culture of the organization. Similar is the case with residential buildings where people are familiar with the layout. However, the possibility of new occupants in a building and visitors cannot be ruled out. From the perspective of society, the occupants of these building are considered to be familiar with the layout. On the other hand, occupants of the public buildings such as shopping malls, auditoriums etc. are unfamiliar with the building layout. As such, society tolerate less risks in such premises.

- *Trust*

'Lack of trust' is a significant factor which has an influence on the societal risk perception. At the same time, it is easy to destroy the trust, while to re-build them it takes a longer time [34]. In risk assessment the direct consequences of fire incidents are mostly focused i.e. number of fatalities, property loss etc. However, there are many indirect consequences associated with a fire incident among which 'trust' is a highlighting one. Therefore, trust-destroying events includes the building fire incidents. Here, the society losses trust on the government, authorities of the country controlling and regulating the building projects and also on the building development groups (owners). This is evident especially from the outcome of Grenfell Tower Fire [58]. In such cases the society do not tolerate much risks. Even though studies have not carried out in the context of fire safety engineering in built environment to understand the relevance of trust on the perceived risk and acceptance, studies have been carried out in nuclear power industries. For example, a study conducted to analyze the impact of trust on the perceived risk and acceptance of nuclear power energy [62] developed a causal model of trust as shown in Figure 2.6. This study indicated that trust directly influenced the perceived risk and acceptance of nuclear power. Also, the study highlighted that the government should have a structured framework for regulation as a part of its risk management and communication endeavors. This is due to the fact that the trust in regulation is seen to be more critical to explain risk perception and risk acceptance than the trust in government.

Research also indicates that factors such as voluntariness and artificiality of risk influence the risk perception. But, in the context of fire safety engineering in a built environment, these factors are debatable topics. For instance, according to Starr [63] public seems to accept risks from voluntary activities more readily than from the involuntary activities. The distinction is as follows: in voluntary activities the individuals can use their own system to evaluate their experiences while in the involuntary activities the options and criteria for individuals are determined by a controlling body [63].

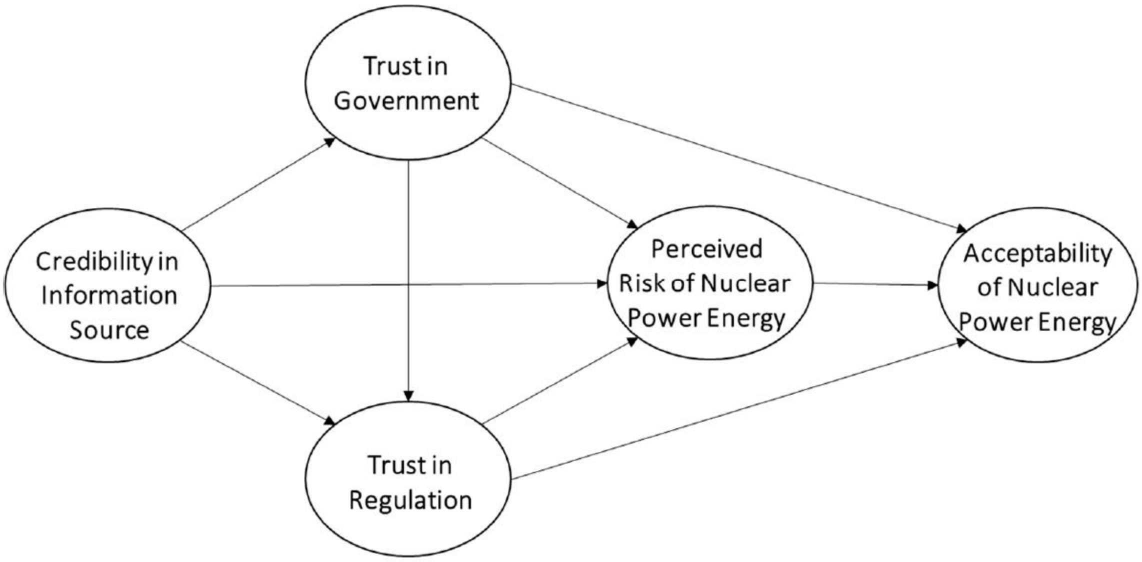


Figure 2.6: Causal model of trust (reproduced from [62])

In that case occupants in high-rise residential buildings, offices, hospitals, shopping mall etc. are considered to be involuntary activities because a controlling body such as a governmental authority comes into picture who frames the regulations for the building sector. On the other hand, from an individual’s perspective it can be voluntary. For example, a person who visits a crowded night club, a family who lives in a building with combustible external cladding (as monthly rent is less and the workplace is close to the building). At the same time, are kids visiting an indoor play area considered voluntary? Do they really use their own value system? If yes, the society can tolerate more risk as per the hypothesis of Starr. But in reality, will society accept the death of these kids in case of a fire in such premises? From this discussion it seems that the use of factor ‘voluntariness’ to express risk perception in the context of fire safety engineering in built environment is inappropriate.

Similarly, artificiality of risk is also a debatable factor. All the built environment is man-made. Research has indicated that man-made disasters are not accepted by the society while natural disasters are accepted since they are uncontrollable [43]. Hence, the fires that have occurred in different built environment are man-made indicating that society have less tolerance to such incidents. But the question is whether the risk perception of the society alter if a fire, leading to multiple fatalities, occurs in a building due to an earthquake?

Perception of risk is also influenced by the media [41,64]. The influence of media can be related to the availability heuristics. Again there are other factors [41] which influence the public risk perception: amount of media coverage, frames used for describing risk, tone of media coverage, media sources and their trustworthiness, the way risks are presented. One might argue that these factors keep the Grenfell tower fire alive among the minds of public. However, in developing countries similar incidents become distant memories a week later [65]. Furthermore, studies have indicated that an individual's judgement of risk have all the earmarks of being resistant to change from the media since individual experience is a more grounded factor [64].

Another interesting factor which can be correlated to the influence of culture and beliefs to risk perception of society is psychophysical numbing [65]. Psychophysical numbing implies '*inability to appreciate losses of life as they become more catastrophic*'[66]. In such situations where large numbers are presented (say for instance large number of fatalities) the emotional dimension of risk perception is not that significant. For example, in developing countries which are densely populated and occurrence of fire incidents are high, the frequent reporting of accidental deaths in media in a monotonous pattern diminishes the impact of fire risks among the public [65]. At the same time the culture and beliefs of the society imparts a new perspective to the risk. For instance, in India people believe in 'karma': get what you give. So, if people die in fire incidents, people might believe it is 'fate'. In such situations, society accepts accidental deaths [65].

In short, society always desire an adequate level of safety in the built environment - whether it be a shopping mall, airport, residential building, hospital, office, old age home, kids' day care or university. When individuals visit or occupy any building, they expect it to be safe. The optimism bias also comes into picture i.e. in simple terms individuals believe 'it won't happen to me'. However, it is important to know that risk perception varies from country to country, region to region and people to people [65].

In a nutshell, the most important risk perception factors that need to be considered for decision making from the perspective of fire safety engineering in the built environment are as follows:

- Service of the building under normal/emergency conditions and importance of building, occupancy – vulnerable groups, sleeping risk, potential for catastrophe (dread) and possibility to evacuate, familiarity and trust.
- Heuristics – availability, representativeness and proximity, focusing on the 'likelihood of occurrence of events' component of risk. However, these factors are closely related to 'trust' which have an influence on the occurrence of an incident.

On the other hand, there are other risk perception factors such as voluntariness and artificiality of risk, culture and beliefs which seems to be important in general but from the perspective of fire safety engineering in the built environment it can be considered as trivial. This is due to the fact that few of these factors are debatable (voluntariness and artificiality of risk) whereas the others cannot be ethically justified (culture and beliefs). At the same time, perception of risk is also influenced by the media and is closely associated with the heuristics. This is further associated with the risk perception factor ‘trust’ as mentioned earlier.

## 2.5 Risk Aversion

As a matter of first importance, it is critical to comprehend that at present there is no accepted definition on the concept of risk aversion in general [67]. In the traditional fire safety design approaches, risks associated with rare high-consequence events are not explicitly considered [5]. At the same time, it is difficult to estimate risk of rare high-consequence events and hence the degree of uncertainty for such events in risk assessment will be greater [68]. From the outlook of society, a building fire resulting in 100 fatalities is often less tolerated by society compared to 100 separate building fires resulting one fatality in each incident [5,6,67,69,70]. It is interesting to note that in both cases the expected value given by the product of the associated frequency and consequence (scalar risk indicator) is the same. Hence, risk aversion envelops the events with same scalar risk indicator valued unequally [5]. It is also common that following a rare high-fatality building fire incident, the regulators are forced to over-commit societal resources, affecting the optimal way of their usage, for reasons distinctive to serving the society [70].

In a decision-making process, the concept of risk aversion is often incorporated using risk aversion factors [70]. These factors are implicitly or explicitly used in setting up risk acceptance criteria. Faber et al. [70] points out the implicit use of risk aversion factors in the risk acceptability and tolerability criteria employed in FN diagrams. Here the tolerability limit and *de minimis* limit is modeled by a power law [70]:

$$F(N_{PE}) = mN_{PE}^{-b} \qquad \text{Equation 1}$$

where $F(N_{PE})$ denotes the maximum tolerable probability of occurrence in a defined time interval, $N_{PE}$ indicates number of fatalities, $m$ indicates maximum tolerated frequency for a single fatality and $b$ represents risk aversion for large fatalities whose value varies from 1 to 2.

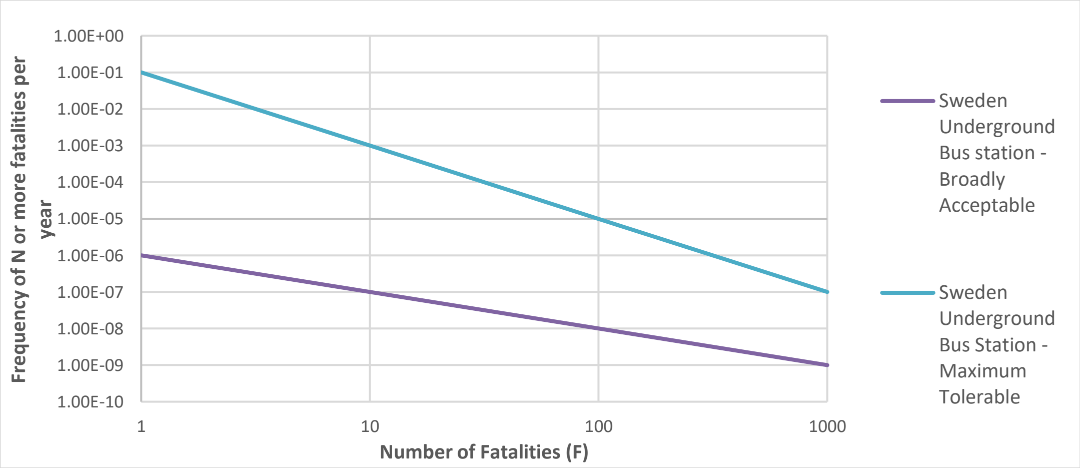


Figure 2.7: Suggested societal risk criterion in terms of upper and lower FN curves for an underground bus terminal in Sweden (adapted from [71])

For clarity, the factor $b$ represents the steepness of the broadly acceptable and tolerable limits as shown in Figure 2.7. In Figure 2.7, the maximum tolerable limit line has a steepness $b = 2$ (risk averse) while the broadly acceptable limit line has a steepness $b = 1$ (risk neutral). If no discrimination is made by the society between a risk of 1 fatality every year and a risk of 100 fatalities every 100 years, then the situation is described as risk neutral [72]. For example, the UK risk acceptance and tolerable limit line have a slope $b = 1$ which was justified based on historical data [73]. On the other hand, $b = 2$ indicates that higher fatalities are tolerated less frequently and thus it is termed as risk averse. For instance, Netherlands has adopted a slope $b = 2$ for tolerability bounds [9,21].

However, it is imperative to take note of Sunstein's [74] statement that real risk aversion does not exist since investments made on rare incidents with high consequences could be better utilized elsewhere, thus saving more lives. This is based on the fact that steeper the slope of the line, more stringent risk controls (more resources) are needed to reduce the risk. Therefore, even though a broadly acceptable limit line having a steepness $b = 1$ is called "risk neutral", but any qualitative distinction between events in function of their severity is a manifestation of "risk aversion". Only ALARP (without gross disproportion) is real "risk neutral". Similarly, Pate-Cornell [75] asserts that decision makers are commonly risk-averse and averse to epistemic uncertainties. Epistemic uncertainty highlights that little is known about the rare events with high consequences. Hence, spending more resources to reduce risks which are well known is more fruitful in the perspective of economic efficiency of public protection measures.

On the other hand, the explicit use of risk aversion factors is noticeable in the field of technical risk assessment [70]. Here the total risk R is calculated directly as follows:

$$R = \sum_{i=1}^{n} p_i \, N_{PE,i} \varphi\left(N_{PE,i}\right) \qquad \text{Equation 2}$$

where $p_i$ is the probability of occurrence of the event $i$ with number of potentially endangered people $N_{PE}$ and $\varphi$ is an aversion factor which is a function of $N_{PE}$.

However, the errors presented by the utilization of the risk aversion factors, either implicit or explicit, are obscure [70]. On the other hand, studies additionally suggests that the introduction of risk aversion factors distorts the link between the risk indicator and the consequence probability density function [5]. Moreover, studies reveals that for a decision-maker who does not have fully risk neutral position, in principle, only risk curves can transfer the required information [5].

In this regard recognizing both the benefit of scalar risk indicators in risk communication [76] and the ethical inclination for a risk neutral evaluation, a compromise is sought to allow the use of a risk neutral scalar risk-indicator [5]. It is important to note that the tolerability limit recognizes societal aversion to rare high-consequence events as well as to frequent low-consequences events. On the other hand, ALARP does not take into account any possible risk aversion. Therefore, following the existing risk engineering practices [9] the maximum tolerable limit and broadly acceptable limits of risk as shown in Figure 2.7 can be defined.

## 2.6 Ethical Aspects in Fire Risk Assessment

Ethics are concerned with distinguishing between what actions are “right” and “wrong” and what values are “good” and “bad” [77]. Similar is the case with the risk acceptance criteria which helps to distinguish between “right” and “wrong” [77].

In PRA, the probability of occurrence of a scenario and its consequences are considered. Thus, focusing the consequences of a fire incident, the ethical theory of consequentialism can be applied to the risk acceptance criteria. One form of consequentialism is utilitarianism which is based on the principle of utility [78]. Any actions which give greater happiness than pain are morally good for utilitarians [79]. In this regard ALARP principle can be considered as having a basis of utilitarianism [77]. On the other hand, deontology, another important ethical theory, focuses on moral duties [80] and risk acceptance criteria based on this ethics looks into the duty to protect e.g. the public and the environment to risk [77]. Vanem [77] highlights various principles for establishing risk acceptance criteria among which the combination of absolute probabilistic risk criteria (do not consider cost associated with mitigating the risk) together with ALARP principle (consider both risk levels and cost associated with mitigating the risk) is commonly used in PRA. Furthermore, Vanem [77] stresses that the principles employed for establishing risk acceptance criteria and the risk acceptance criteria themselves should be justifiable by ethical theories.

For clarity, the Grenfell Tower fire incident can be related to the ethical aspects. Madden [81] quoted *“increasingly it seems that the tower’s largely working-class residents had been living with a level of deadly risk that would never have been tolerated for their wealthier neighbours in the Royal Borough of Kensington and Chelsea.”* This statement clearly indicates an uneven and unequal urbanization today. The occupants of the buildings had even voiced their complaints on the fire safety issues to the authority which went unheard [82]. At the same time, the building renovation focused more on the aesthetics and cost reduction than ensuring safety of the occupants of the building. It is also unclear whether all residents were aware of combustible property of the external cladding after renovation. Therefore, one cannot argue that the occupants tolerated the risks. It is evident that both utilitarian or deontologist cannot accept this incident. The Grenfell Tower fire clearly emphasizes the significance of ethics and professionalism in the built environment.

In short, establishing risk acceptance criteria depends on the legal framework of the society and different legal framework might yield different criteria [83]. However, it is paramount to understand that establishing risk acceptance criteria should not be solely predicated on the scientific evidence. Considerations should be also given to social and ethical aspects while setting risk acceptance criteria. At the same time, a decision-making process should be transparent and also ought to be clear who are responsible when things turn out badly.

# 3 Risk Tolerability Framework

This chapter looks into the development of a framework for setting tolerability limit and broadly acceptable risk for a specific project in built environment.

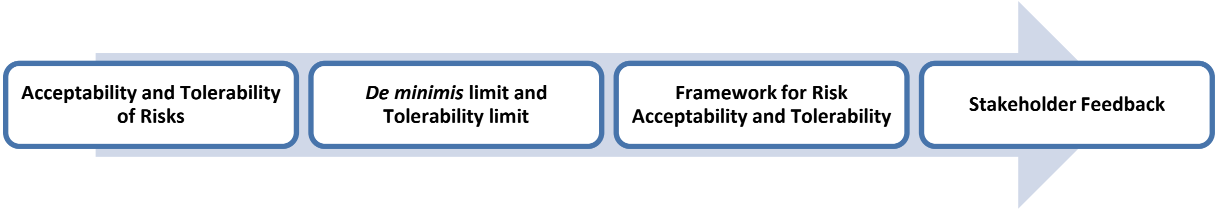


Figure 3.1: Flow chart highlighting the structure of chapter 3

The chapter begins with a discussion on the concept of risk acceptability and tolerability criteria in risk assessment. Later, the discussion touches up on different risk control approaches widely used in the European Union (EU). Then the two main risk measures for loss of life – individual risk and societal risk are explored. A small discussion is made on the current methods of setting risk acceptance criteria. Next, by identifying common aspects of risk criteria established in different countries and taking into account the different factors of risk discussed in chapter 2, a framework for setting *de minimis* limit and risk tolerability limit for a project in built environment is proposed. Finally, the feedback on the proposed framework from fire safety professionals is presented.

## 3.1 Acceptability and Tolerability of Risks

Zero risk is something unrealistic [5,26]. For example, if one feels driving a car involves huge risk and plans to walk, there are risks of getting injured from slips, trips and falls. Similarly, wearing a seat belt does not mean that one will not have fatal injuries in a car accident. However, it can reduce the consequences or harm to the person to an extent. Considering all these scenarios, there are plenty of cars being driven by people in the world. This implies that the residual risks are being tolerated by the people taking into account the benefits. This example, raises the question what are acceptable and tolerable risks?

‘Acceptability’ and ‘tolerability’ are two different terms [32]. Many attempts have been made by researchers to define acceptable risk, but none of these definitions are complete [84]. However, UK HSE [32] clarifies that for a risk to be ‘acceptable’ for purposes of life or work, people are prepared to accept it without any specific risk management options [29]. On the other hand tolerable risk define the level of risk society is prepared to live with so as to secure certain benefits provided that the risk is monitored and risk management options are taken to reduce it [29,32]. Some researchers argue that there is no such thing as acceptable risk [19,84]. This is because of its very nature risk should always be rejected and it is only the benefits that makes people to tolerate certain risks [85]. Again, few researchers emphasize that what is acceptable risk depends on who is accepting it, in which way and when [29,86]. Therefore, it is important to differentiate between various terms of acceptance highlighted by Bell et al. [29] which is given in Table 3.1. However, it is important to note that all these terms are not constant with time. As in the case of the risk perception, these terms of acceptance changes with time among the public.

| Sl. No: | Terms of Acceptance | Description |
|---|---|---|
| 1 | Individual acceptance | The acceptance of a specific person, investigated by non-aggregated quantitative or qualitative methods. |
| 2 | Aggregated-individual acceptance | The mean value of multiple individual acceptances. |
| 3 | System-internal acceptance | The communicated acceptance of a specific social system (e.g. stakeholders, scientists or relevant people). |
| 4 | Societal acceptance | The acceptance of society as a whole. |
| 5 | Expert acceptance | Experts define what an individual and society is willing to accept |

Table 3.1: Various terms of acceptance highlighted by Bell et al. [29]

But what is the significance of risk acceptance criteria in risk assessment? In the previous example of driving a car, if a driver does not know the speed limit on a highway, how can he evaluate whether he is exceeding the speed limits? Similarly, if there are no risk acceptance criteria, it is difficult to know whether the estimated risks in a risk assessment are high or whether it is required to reduce them by introducing sufficient measures. Thus, risk acceptance criteria help to translate numerical estimates (e.g. $10^{-4}$ per year) into value judgements (e.g. unacceptable risk) which can help in the decision-making process. Also, risk acceptance criteria helps to rank risks when two or more options are available to implement something (e.g. design options, fire protection systems to be provided etc.). In the absence of risk acceptance criteria, there is high chance that the worst-case scenarios with very low probability will be considered for decision making [87]. At the same time, in such case it often results in misapplication of resources on rare high-consequence scenarios than frequent low consequences scenarios. Figure 3.2 illustrates the significance of risk acceptability and tolerability criteria in decision making.

Figure 3.2: Significance of risk acceptability and tolerability criteria in decision making

The estimated risk in a risk assessment is compared with the risk acceptability and tolerability criteria which can be termed as risk evaluation criteria. This is done to determine whether the estimated risk is acceptable or tolerable. A cost-benefit analysis needs to be performed to demonstrate ALARP when the estimated risk falls in the tolerable region. Accordingly, a decision maker can make a decision.

According to PD 7974-7:2019 [8] the fundamental basis underlying the definition of acceptance criteria for fire safety is as follows:

*"The acceptance criteria aim to maximize societal welfare through a balancing of risks across domains, while acknowledging societal risk preferences. Applied to the fire safety objective of life safety, the acceptance criteria aim to maximize the number of lives saved across domains, under a constraint of societal tolerability."*

There are different PRA acceptance criteria to demonstrate adequate safety, illustrated in Figure 3.3, which is discussed in detail in PD 7974-7:2019 (also see [5]).

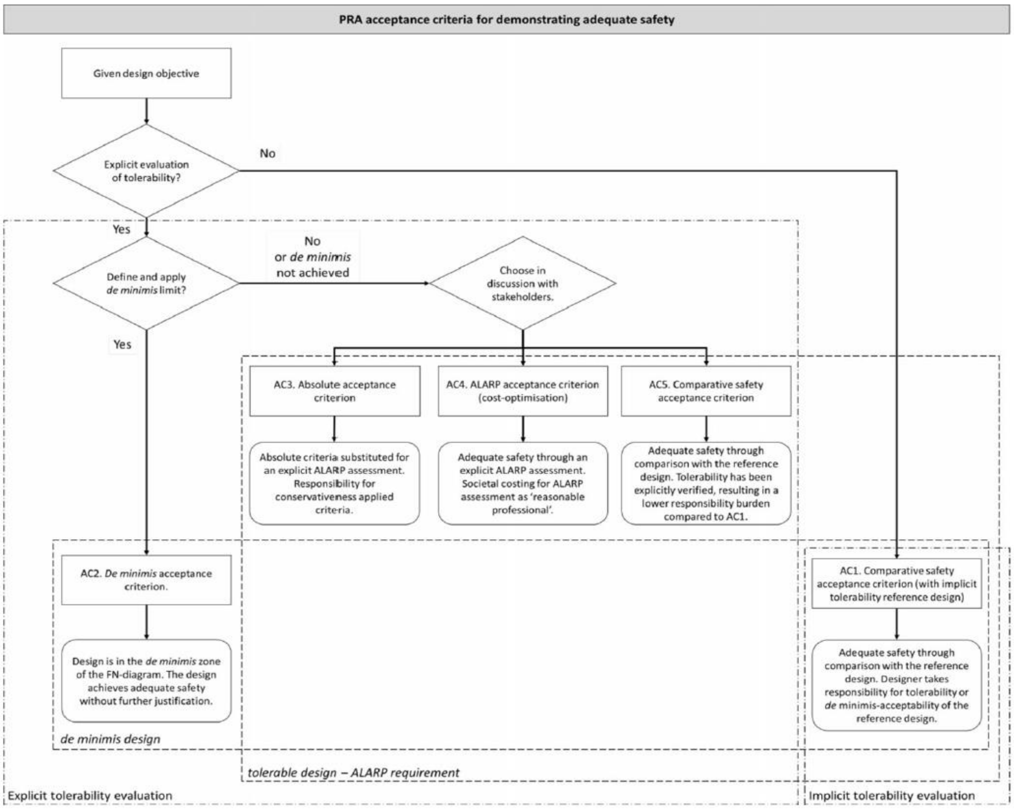


Figure 3.3: Flowchart to determine the applicable PRA acceptance criteria for demonstrating adequate safety (adapted from [8])

### 3.1.1 Challenges involved in setting up broadly acceptable limits and maximum tolerable limits of risk

In Figure 2.4, the idea of tolerability limit and acceptability limit is introduced using different regions in a generalized frequency-consequence (FC) diagram where the term *de minimis* is presented. The concept of '*de minimis risk*' is derived from this legal principle by risk professionals in early 1980s to consider trivial and non-trivial risks in risk assessment [26]. As mentioned before, if the estimated risk of a hazard exceeds the *de minimis* level, it requires further investigation and if it falls below *de minimis* level, it is excluded from further consideration. By doing so, more attention can be given to the non-trivial risks than trivial risks which also ensures better resource allocation. However, setting a *de minimis* level is not an easy task. Selecting a *de minimis* level need to consider societal concerns, risk perceptions, the nature of the risk, the applicable regulations, stakeholder consultations etc. which is clearly evident in the current *de minimis* criteria set by different countries of the world [9,26]. At the same time, there is no universally accepted *de minimis* level [88]. But is the perception and acceptance of the threatened population taken into account while setting a *de minimis* in risk assessment? Bell et al. [29] points out that it is not being considered at present. Similarly, studies also indicate that defining acceptable safe level involves uncertainty and subjectivity [5] since acceptable residual risk is not constant over time among stakeholders. Furthermore, M. Peterson [89] argues that negligible risk is vague implying that there is no sharp boundary between negligible and non-negligible risks. In risk assessments for process industries, building sectors etc. *de minimis* is considered under the specific-number view. i.e. a risk R can be considered *de minimis* if probability of R falls below a certain number N (example $10^{-6}$). Here the *de minimis* is identified by a specific number N and hence termed specific-number view. Again, questions can be raised why $10^{-6}$ and not $1.001 \times 10^{-6}$ which is hard to give an exact answer. Moreover, questions can be also raised in the perspective of fire risk assessment. For instance, if the probability of occurrence of a fire in a building annually leading to one death is $10^{-6}$ and the probability of occurrence of a fire in another building annually leading to 100 deaths is $10^{-8}$, are the risk same? Mathematically, risk is the same. This clearly indicates that when the fire incidents involve large fatalities, the *de minimis* becomes questionable.

On the other hand, Fischhoff et al. [88] asserts that acceptable risk problem can be viewed as a decision problem. Accordingly, they highlight five critical generic intricacies that exist for resolving acceptable risk problems which Meachem [12] have related to fire safety engineering (Figure 3.4).

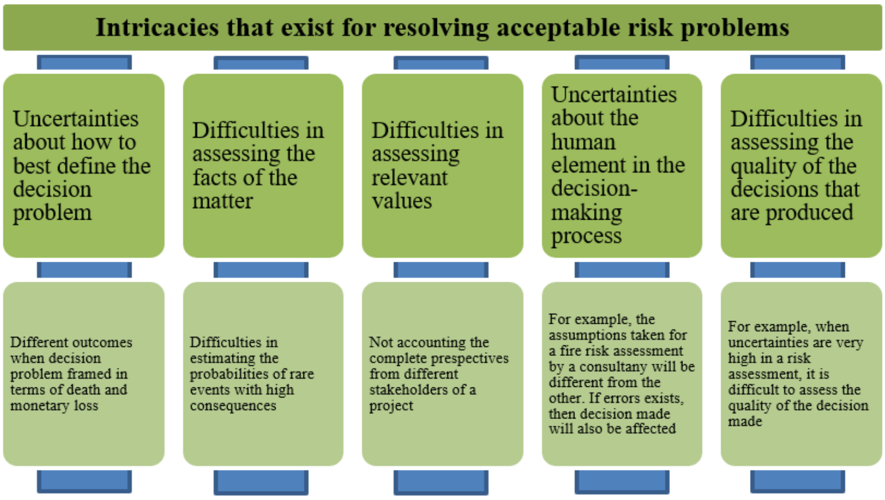


Figure 3.4: Intricacies that exist for resolving acceptable risk problems (adopted from [12])

## 3.2 *De minimis* limit and Tolerability limit

### 3.2.1 Risk Control Approaches

There are mainly three risk control approaches (Figure 3.5) widely used in the EU [68].

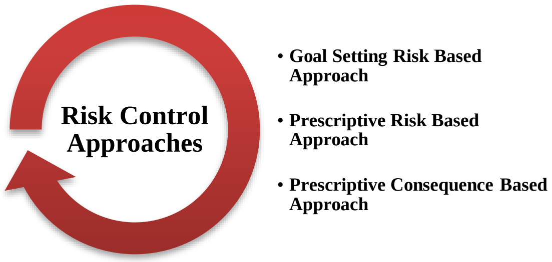


Figure 3.5: Three risk control approaches widely used in the EU [68]

In the goal-setting risk-based approach, the safety goal is specified and the means of accomplishing the goal is not stated. This approach is widely followed in the United Kingdom (UK) where the ALARP need to be demonstrated i.e. risk need to be reduced to as low as reasonably practicable. The main idea is that in the UK, tolerability limits are not used as a means to control the risk [68]. Thus, in the UK the risk criteria are the starting point of discussion between different stakeholders involved in a project [90]. Similar goal-setting risk-based approach is partially followed in the Netherlands where the risk in the tolerable region need to be reduced to a level As Low As Reasonably Achievable (ALARA). In the prescriptive risk based approach, which is followed in the Hungary and Czech Republic, a prescribed maximum level of risk is used for risk control [68]. Here some form of risk reduction is suggested but not necessarily enforced. Finally, in the prescriptive consequence-based approach the set level of consequence is used for risk control which is followed in the France. At the same time, Germany set no risk outside the facility boundary. Different risk control approach are existing since there are differences in the philosophy behind the legislative systems in different countries (for instance, the UK has "common law" system while the Netherlands has "Napoleonic law" system) as a result of which seemingly different or similar metrics can work out completely differently [90]. However, Trbojevic [68] suggests that the countries where safety regulators lack the know-how to impose goal-setting approach, could adopt the prescriptive approach.

### 3.2.2 Risk Models

Having defined risk and how it is being measured in the previous chapter, the question remains on how it is being used to indicate risks to people. Therefore, the outcomes of probabilistic risk assessment are expressed by means of individual risk and societal risk.

#### 3.2.2.1 Individual risk

Individual risk is defined as *the risk to a person in the vicinity of a hazard* [9]. The UK HSE [91] defines individual risk as follows: *"the likelihood that a particular person in some fixed relation to a hazard (e.g. at a particular location, level of vulnerability, protection and escape) might sustain a specified level of harm."* In other words, from fire safety engineering point of view in built environment, individual risk can be considered as the risk to an individual who may be at any point in the impact zone of a fire incident. For example, if a fire occurs in a particular floor of high-rise office building, individual risk can be considered as the risk to an individual at the remotest point of that office floor to evacuate to a safe location. In the same example, if a disabled person is present in that office floor, then the risk to that individual irrespective of his location on that floor will be considered since the level of vulnerability is high for that individual. Therefore, individual risk is independent of the population size of exposed to an incident i.e. in the example of the fire in an office building floor, individual risk is not influenced by the number of people present at that moment of fire. But it is important to note that likely overcrowding at the exits need to be taken into account for evacuation calculations. Hence, the significant aspect of the individual risk is that it is concerned of an identifiable person or a specific group (e.g. a named individual, a hypothetical (idealized) person, or a community residing in a particular geographical location [5]). Accordingly, the individual risk can be either location specific or person specific [8].

According to Frantzich [92] *if an occupant is inside a building, he or she will be subjected to risk in terms of the hazard frequency*. Therefore, the individual risk (IR) for each scenario can be determined using the following equation:

$$\text{IR} = \sum p_i \text{ for all } i \text{ in which } c_i > 0 \qquad \text{Equation 3}$$

where $p_i$ is the probability of sub scenario *i* occurring. Here $c_i > 0$, implies that if consequences $c_i = 0$, there is no risk.

The currently established individual risk criteria in the UK, the Netherlands, Czech Republic and Hungary is given in Table 3.2 (for more details refer [68]).

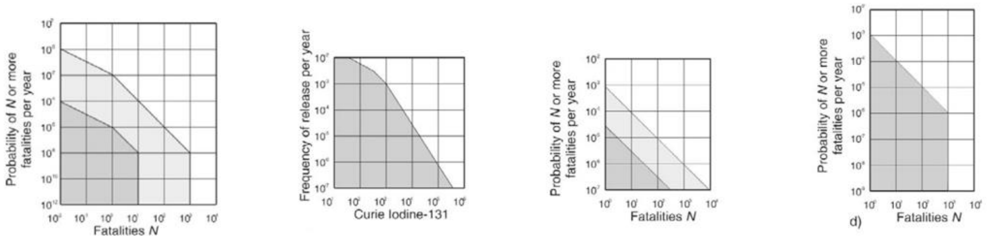
| Individual Risk per Annum | UK | Netherlands | Hungary | Czech Republic |
|---|---|---|---|---|
| $10^{-3}$ | Intolerable risk for workers | - | - | - |
| $10^{-4}$ | Intolerable risk for members of the public | - | - | - |
| $10^{-5}$ | Risk to be reduced to ALARP | Limit for existing installations, ALARA principle applies | Upper limit | Limit for existing installations |
| $10^{-6}$ | Broadly level of acceptable risk | Limit for new installations and general limit after 2010; ALARA applies | Lower limit | Limit for new installations |
| $10^{-7}$ | Negligible risk | - | - | - |
| $10^{-8}$ | - | Negligible risk | - | - |

Table 3.2: Currently established individual risk criteria in few European countries (reproduced from [68])

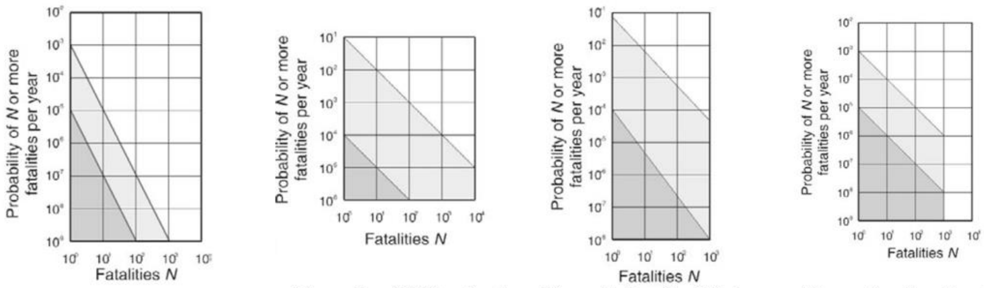
### 3.2.2.2 Societal Risk

Societal risk is defined as the *relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards* [93]. This indicates that societal risk is dependent on the population size exposed to an incident. Also, it is important to remember that society generally tends to be more concerned on incidents involving multiple fatalities. Such rare high fatality incidents might represent a small risk to an individual but still it will be considered as unacceptable [94].

In general, for risk assessment, societal risk is *expressed as the probability of exceedance (in one year) of a certain number of fatalities due to one event in a given population* [18]. Thus, risk curves which was illustrated in Figure 2.2 can be used to depict the societal risk. In such case, the risk curve can be termed as FN curve (graphical representation of societal risk) since it shows the probability of exceedance of a certain number of fatalities on a log-log scale. Societal risk can be also represented numerically in the form of risk integral [91]. Since PD 7974-7:2019 focuses on FN curves, which are widely used in risk assessment, the discussions in this study will focuses only on it. To delve more into FN curves, the risk acceptability limit of different countries (mentioned as ‘proof lines’ by Proske [95]) around the world illustrated in the book of Proske [95] is utilized and is shown in Figure 3.6. Here, the dray grey colored area indicates the acceptable region, light grey colored area indicates tolerable region and the white colored area indicates the unacceptable region of risk. Analyzing these proof lines highlight that they follow power-law (Equation 1) [70,95], risk aversion factors are considered (section 2.5) and minimum and maximum probability of exceedance of certain number of fatalities are proposed. So, the question is how are the risk acceptance criteria currently established?



**a) The Groningen curve (1978)** **b) The Farmer curve (1967)** **c) Revised Kinchin curve (1982)** **d) A curve from Hong Kong (1988)**



**e) A curve from Netherlands (1980s)** **f) A curve from ACDS from Great Britain (1991)** **g) A curve for the safety of off-shore installations in the UK (1991)** **h) A curve from Hong Kong (1993)**

Figure 3.6: Proof line for FN diagrams (reproduced from [95], based on [96])

Three fundamental principles are used to set risk acceptance criteria [97] which are illustrated in Figure 3.7. However, all these principles are used currently to set risk acceptance criteria. This ensures to an extent public participation in decision making process. For instance, a combination of these principles are used to derive target reliability values specified in Annex B of Eurocode 0 [97].

Figure 3.7: Three fundamental principles used to set risk acceptance criteria [97]

To construct proof lines given in Figure 3.6, one of the two approaches can be followed [95]. The first approach involves choosing an anchor point i.e. frequency of a certain incident. Selection of this single point can be based on expert judgement or stakeholder consultation. For example, an anchor point selected as per UK HSE R2P2 [28] is $\left(50, \frac{1}{5000}\right)$. This implies incidents resulting about at least 50 fatalities should not occur on average more than once every 5000 years. Once this point is selected, the risk aversion factor needs to be decided i.e. the slope of the line as discussed in section 2.5. With these inputs, proof lines can be constructed after which the area of the diagram can be divided into several regions – unacceptable, tolerable and acceptable. In the second approach, two anchor points can be selected and a proof line can be constructed. The anchor points for proof lines in different countries are shown in Figure 3.8.

| Country | Slope | Intercept |
|---|---|---|
| UK | -1 | 1.00E-02 |
| Hong Kong | -1 | 1.00E-03 |
| Netherlands | -2 | 1.00E-03 |
| Denmark | -2 | 1.00E-02 |
| Czech Republic | -2 | 1.00E-04 |
| France | 0 | 1.00E-07 |

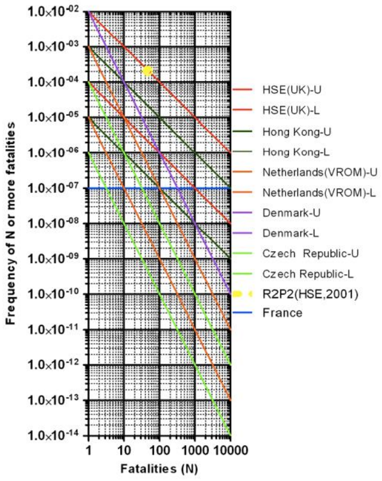


Figure 3.8: Anchor points for proof lines in different countries (reproduced from [98])

Nevertheless, PD 7974-7:2019 highlights that both individual risk and societal risk need to be considered applicable all the times. However, when the total number of occupants is low, then individual risk is expected to govern since actual calculations will indicate that generally in such cases societal risk is automatically fulfilled.

The discussion on societal risks will be incomplete without highlighting the issues associated with the use of FN curves in risk assessment. Few studies point out the limitations of traditional approaches to risk determination and evaluation in engineering. Firstly, Murphy and Gardoni [99] highlights that FN curves normally considers only the focal consequences (consequences which are immediately visible) of hazard. This is true in the case of the fire risk assessments. Considering the case of the Grenfell tower fire, London the focal consequences were fatalities, property loss and the economic losses. This implies many of the auxiliary consequences are not considered in risk assessment. Again, auxiliary consequences can be classified as type I and type II [99]. Type I auxiliary consequences are the additional immediate impacts on individuals or systems whereas type II auxiliary consequences indicate broader indirect effects of such scenarios on the society. In the example of Grenfell tower fire, type I auxiliary consequences are the post-traumatic stress disorder (PTSD) of the two-third of the adult survivors [100]. On the other hand, an example for the type II auxiliary consequences in this case are the hundreds of people who had to move out from the adjacent buildings of Grenfell tower [101]. Such auxiliary consequences are rarely considered in a risk assessment. Secondly, the cost benefit analysis (CBA) that is normally performed in a risk assessment do not distinguish between the economically weaker sections and wealthy people of the society. The individuals with less income try to pay only less for avoiding a risk. Generalizing the concept of the willingness to pay based on the GDP do not account these aspects. Shildrick [58] clearly points out from the perspective of Grenfell Tower fire that the limited and sometimes unsafe housing conditions available to those with limited financial resources have been, at times, laid uncomfortably bare. Studies also indicate that in CBA the public opinion or participation is rarely taken into account and the analysis is being carried out by the experts [102]. Thirdly, when FN curves are used to evaluate estimated risk and communicate to the stakeholders, the horizontal axis of FN curves reads N which is the ‘number of fatalities’. For example, the ALARP principle was originally prepared by the UK HSE for nuclear industry where the number of fatalities in a nuclear disaster is most likely [85]. But in the building fire risk assessment, is it really the number of fatalities or the number of people who are exposed to untenable conditions in case of a fire in the building? An apt usage for better understanding will be the expected number of people who are exposed to untenable conditions in case of a fire in the building among the total occupants. Fourthly, the annual frequencies of different scenarios are considered in FN curves. Even though it is a preferred unit in FN curves to communicate with the stakeholders, in terms of the ‘life safety’ goal in fire safety engineering, it is more meaningful if the frequencies are measured in terms of the ‘hours of occupancy used.’ This is due to the fact that the probability of an accidental fire starting in a building also depends on the presence or absence of human sources (e.g. smoking) apart from the non-human sources (e.g. faulty electrical equipment) [1].

## 3.3 Framework for Risk Acceptability and Tolerability

Aven and Vinnem [103] attempts to present and discuss a risk analysis regime without the use of risk acceptance criteria from the perspective of offshore oil and gas industry. These authors point out that the introduction of a pre-determined acceptance risk criteria makes stakeholders focus more on meeting these criteria rather than obtaining good cost-effective solutions and measures. At the same time, the risk analysis tools to evaluate risk in general do not have a sufficient precision level for such a mechanical use of criteria. This approach might be practical in oil and gas industry since the technologies as well as designs used are similar. Moreover, there are well defined prescriptive codes (e.g. API, ASTM etc.), standard operating procedures, safety training to employees and visitors entering the premises of these industries. However, such a risk analysis regime suggested by Aven and Vinnem cannot be generalized and adopted to the built environment since each building differs in design, material of construction, type of occupancy etc. Since PRA is a growing field in the built environment, the use of risk acceptance criteria and a framework to establish them is essential to utilize the full potential of performance-based fire safety design [104].

Based on the discussions presented in Chapter 2, it is clear that a framework for setting the *de minimis* limit and the tolerability limit for a specific project in the built environment should consider different risk perception factors relevant to fire safety engineering, risk aversion in terms of the steepness of proof lines and ethical aspects in fire risk assessment. At the same time, it is essential to understand the tolerability limit and *de minimis* limit established for different sectors in different countries for both individual risk and societal risk. This together with the knowledge on constructing the proof lines helps to develop a framework for setting and establishing *de minimis* limit and the tolerability limit for a specific project in the built environment. As such, a framework is suggested and illustrated in Figure 3.9.

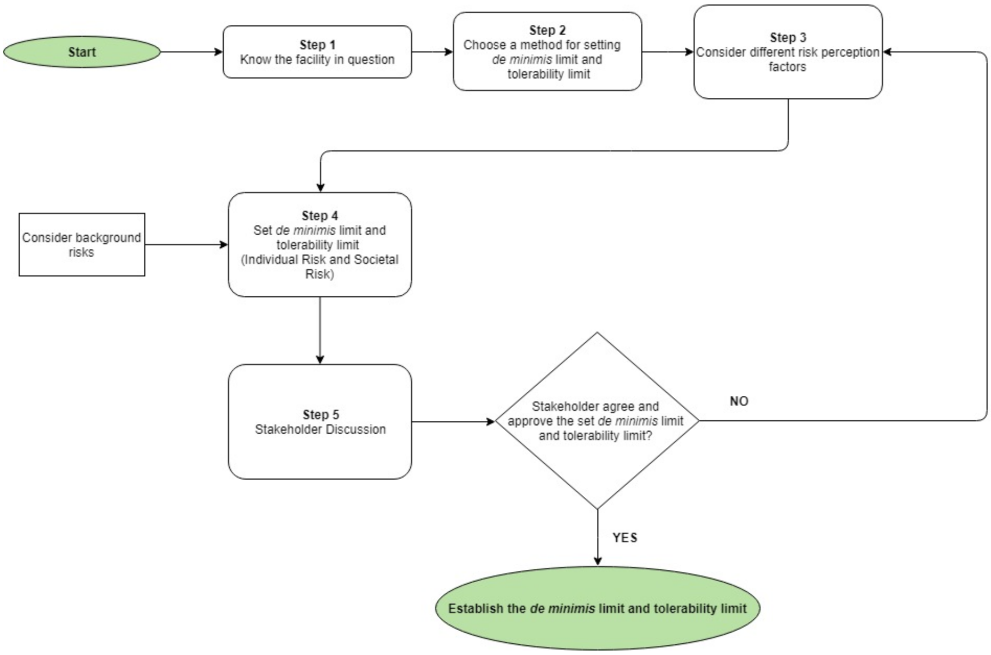


Figure 3.9: A suggested framework for setting *de minimis* limit and tolerability limit for a project in built environment

## Step 1: Know the facility in question

The first step is to understand the facility for which the PRA need to be carried out. Therefore, a building can be considered as a system with different components as indicated in Figure 3.10.

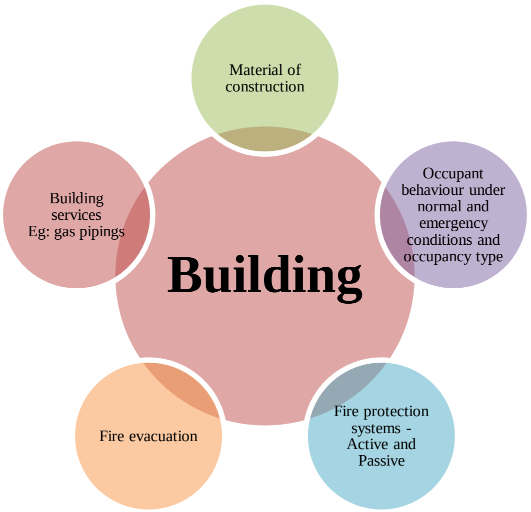
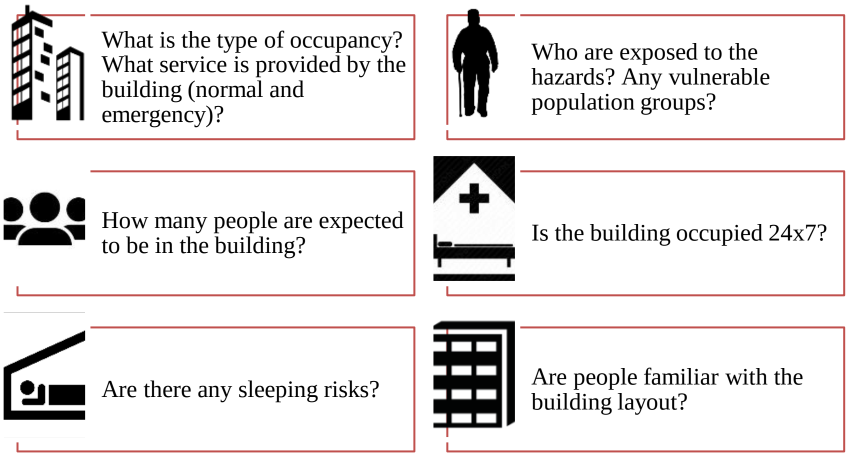


Figure 3.10: Different components of a building that requires a clear understanding for probabilistic fire risk assessment

Any issues or problems with any of these components of a building may lead to different kinds of consequences. For example, if fire detection system is not properly designed or fails to activate alarm and notify the occupants of a building in case of a fire, it can delay evacuation which can lead to number of fatalities or injuries. Therefore, understanding each of these components of a building helps to frame an entire spectrum of consequences which further aids to think about dealing with social aversion to high consequences events. This information needs to be captured in the risk curve. However, to start with, six important questions (given in Figure 3.11) are developed based on the discussions presented in section 2.4, 2.5 and 2.6 of chapter 2. These questions need to be answered since they are critical in setting *de minimis* limit and tolerability limit for a project in built environment.



What is the type of occupancy? What service is provided by the building (normal and emergency)?

Who are exposed to the hazards? Any vulnerable population groups?

How many people are expected to be in the building?

Is the building occupied 24x7?

Are there any sleeping risks?

Are people familiar with the building layout?

Figure 3.11: Six important questions to answer for understanding the facility in question

**Step 2: Choose a method for setting *de minimis* limit and tolerability limit**

This step is incorporated in the framework foreseeing the future of PRA in fire safety engineering. Therefore, one of the four methods illustrated in Figure 3.12 can be utilized for setting *de minimis* limit and tolerability limit of risk for a project in the built environment.

Figure 3.12: Different methods for setting risk acceptability and tolerability criterion

At first, it can be checked if any international best practices are available for setting up the risk acceptability and tolerability criteria for fire safety. If yes, it can be adopted with caution. For example, the risk tolerability criteria developed in Japan should not be directly applied in the UK without understanding the assumptions and limitations. Therefore, in such case, the international best practice can be considered as a guidance and accordingly necessary modifications or similar methodologies can be adopted to frame risk tolerability criteria.

In the absence of international best practices, the fire incident statistics can be utilized. This approach is followed by Wang et al. [105] to establish a fire societal risk criterion. However, availability of sufficient reliable data is a major issue. For example, Lundin [71] was unable to find sufficient comprehensive accident statistics for compressed natural gas (CNG) vehicles in an underground facility in order to quantify a safety target for an underground commuter bus terminal in Sweden. Moreover, use of statistical data can raise some issues. For instance, the results depend on the availability of fire incident statistics and the time period of data considered for the analysis [12]. To be clear on this, the data considered for the years 2015 to 2018 will give a different answer than the data considered for the years 2000 to 2018. Similarly, the reliability of the data also influences the results. Moreover, if different stakeholders are involved in the risk decision making process, there can be differences in opinion on selecting the consequences to be considered for the analysis (e.g. fatalities, injuries, monetary terms of damages or environmental impacts). There can be also questions raised on whether to consider the building fires fatalities due to terrorist attack as in the case of World Trade Centre, USA in 2001. Similar questions can be raised when choosing statistical data containing the Grenfell

Tower fire, UK. So, it is important to think whether it is really necessary to consider these statistical data when setting risk acceptability and tolerability criterion. It is clear from the public reaction that such incidents are not acceptable or tolerable. Therefore, making a distinction between ‘accepted’ and ‘unaccepted’ or ‘tolerable’ events in the fire incident statistics, especially from the perspective of the society, before utilizing the statistical data for setting risk tolerability limit is crucial.

The next method is to utilize the risk acceptance criteria established for other facilities in other sectors. For example, to develop a quantitative acceptance criteria for underground bus terminal in Sweden, Lundin [71] considered a risk assessment for a Swedish modern road tunnel and another example related to the land-use planning and development adjacent to dangerous goods routes in Sweden. Then important factors affecting tolerated risk in society were compared between the bus terminal and the other two cases. But it is important to note that the fire dynamics, human behavior in fire and the potential for catastrophe affecting risk perception of people differs between the cases considered.

The final method is developing a risk tolerability criterion directly through stakeholder consultation. This method is followed in the case studies demonstrated in this dissertation.

### Step 3: Consider different risk perception factors

Different risk perception factors discussed in section 2.4 need to be considered in this step. Society does not tolerate high risks in occupancies where vulnerable population group reside. As a result, if a fire occurs in a hospital and results in 50 fatalities, society might raise a question why more fire safety measures were not implemented in such an occupancy. Hence, according to the type of occupancy considered, risk tolerance needs to be made stringent. Thus, the important risk perception factors to be considered and few examples of premises where stringent risk tolerance need to be considered are shown in Figure 3.13.

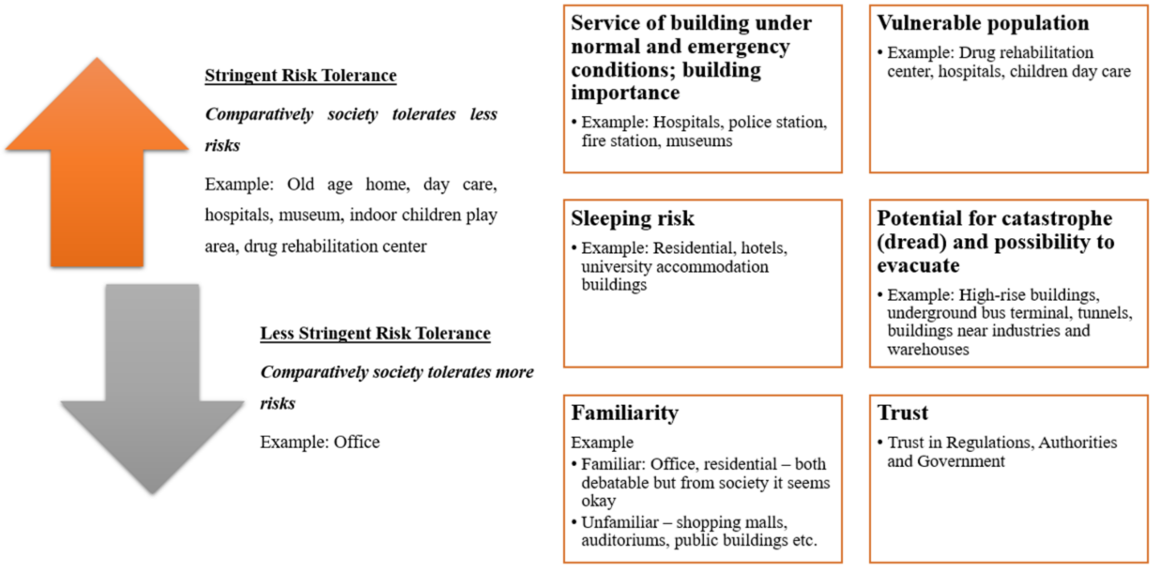
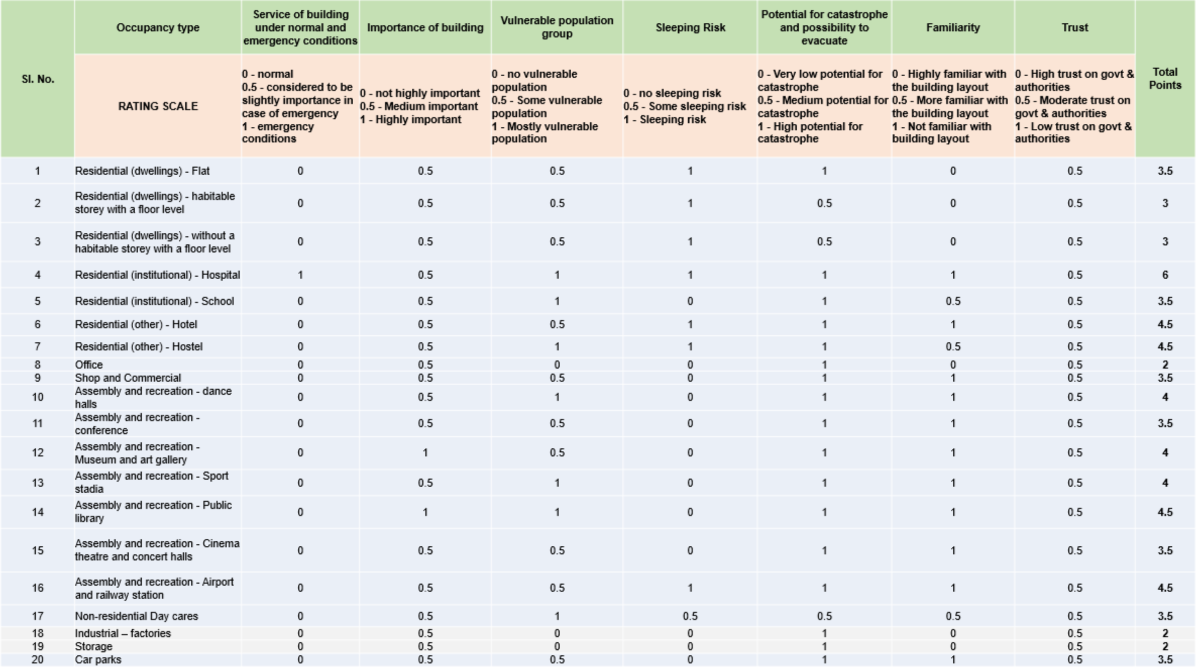


Figure 3.13: Important risk perception factors and examples of premises where stringent risk tolerance needs to be considered

It is clear from Figure 3.13 that the risk tolerance for hospital buildings and office buildings differs. But the question is how do we consider these factors in setting the *de minimis* limit and tolerability limit? This can be done by introducing a point-based system which aids to select a risk aversion factor representing the steepness of proof lines. One should be cautious while selecting the steepness of proof lines. For example, the intolerable limit in the UK is $10^{-4}$ and when ALARP is strictly imposed, in reality the risk is well below the limit [68]. Therefore, selecting a steepness of 2 and imposing ALARP strictly will be challenging and at the same time it can result in ineffective utilization of the resources. Therefore, considering the ethical aspects of risk assessment, a steepness of 1 and 1.5 are suggested in this risk tolerability framework. Steepness of 1 corresponds to that of the UK HSE criterion whereas 1.5 corresponds to the steepness set by Farmer [106] when the concept of proof lines were first introduced in risk assessment. Hence, for stringent risk tolerable criteria, it is suggested to use 1.5 and for less stringent criteria a slope of 1 is suggested. Moreover, the equation used to construct proof lines considers negative slope. As a result, for stakeholder discussion it is necessary to select between 1 and 1.5 for the building under consideration.

The point-based system as given in Table 3.3 considers different risk perception factors and a rating scale in which points vary from 0 to 1. For different occupancy types specified in table D1 of UK Approved Document B [107], the total points were evaluated. Accordingly, the minimum points obtained for residential buildings were found to be 3. Since the risk tolerance of residential buildings and office buildings are different, a total point of 3 is chosen as the baseline for the selection of risk aversion factor. Therefore, if the total points obtained during the evaluation is less than 3, a risk aversion factor of 1 is suggested. On the other hand, if total points obtained is equal to or greater than 3, a risk aversion factor of 1.5 is suggested.



| Sl. No. | Occupancy type | Service of building under normal and emergency conditions | Importance of building | Vulnerable population group | Sleeping Risk | Potential for catastrophe and possibility to evacuate | Familiarity | Trust | Total Points |
|---|---|---|---|---|---|---|---|---|---|
| | RATING SCALE | 0 - normal<br>0.5 - considered to be slightly importance in case of emergency<br>1 - emergency conditions | 0 - not highly important<br>0.5 - Medium important<br>1 - Highly important | 0 - no vulnerable population<br>0.5 - Some vulnerable population<br>1 - Mostly vulnerable population | 0 - no sleeping risk<br>0.5 - Some sleeping risk<br>1 - Sleeping risk | 0 - Very low potential for catastrophe<br>0.5 - Medium potential for catastrophe<br>1 - High potential for catastrophe | 0 - Highly familiar with the building layout<br>0.5 - More familiar with the building layout<br>1 - Not familiar with building layout | 0 - High trust on govt & authorities<br>0.5 - Moderate trust on govt & authorities<br>1 - Low trust on govt & authorities | |
| 1 | Residential (dwellings) - Flat | 0 | 0.5 | 0.5 | 1 | 1 | 0 | 0.5 | **3.5** |
| 2 | Residential (dwellings) - habitable storey with a floor level | 0 | 0.5 | 0.5 | 1 | 0.5 | 0 | 0.5 | **3** |
| 3 | Residential (dwellings) - without a habitable storey with a floor level | 0 | 0.5 | 0.5 | 1 | 0.5 | 0 | 0.5 | **3** |
| 4 | Residential (institutional) - Hospital | 1 | 0.5 | 1 | 1 | 1 | 1 | 0.5 | **6** |
| 5 | Residential (institutional) - School | 0 | 0.5 | 1 | 0 | 1 | 0.5 | 0.5 | **3.5** |
| 6 | Residential (other) - Hotel | 0 | 0.5 | 0.5 | 1 | 1 | 1 | 0.5 | **4.5** |
| 7 | Residential (other) - Hostel | 0 | 0.5 | 1 | 1 | 1 | 0.5 | 0.5 | **4.5** |
| 8 | Office | 0 | 0.5 | 0 | 0 | 1 | 0 | 0.5 | **2** |
| 9 | Shop and Commercial | 0 | 0.5 | 0.5 | 0 | 1 | 1 | 0.5 | **3.5** |
| 10 | Assembly and recreation - dance halls | 0 | 0.5 | 1 | 0 | 1 | 1 | 0.5 | **4** |
| 11 | Assembly and recreation - conference | 0 | 0.5 | 0.5 | 0 | 1 | 1 | 0.5 | **3.5** |
| 12 | Assembly and recreation - Museum and art gallery | 0 | 1 | 0.5 | 0 | 1 | 1 | 0.5 | **4** |
| 13 | Assembly and recreation - Sport stadia | 0 | 0.5 | 1 | 0 | 1 | 1 | 0.5 | **4** |
| 14 | Assembly and recreation - Public library | 0 | 1 | 1 | 0 | 1 | 1 | 0.5 | **4.5** |
| 15 | Assembly and recreation - Cinema theatre and concert halls | 0 | 0.5 | 0.5 | 0 | 1 | 1 | 0.5 | **3.5** |
| 16 | Assembly and recreation - Airport and railway station | 0 | 0.5 | 0.5 | 1 | 1 | 1 | 0.5 | **4.5** |
| 17 | Non-residential Day cares | 0 | 0.5 | 1 | 0.5 | 0.5 | 0.5 | 0.5 | **3.5** |
| 18 | Industrial – factories | 0 | 0.5 | 0 | 0 | 1 | 0 | 0.5 | **2** |
| 19 | Storage | 0 | 0.5 | 0 | 0 | 1 | 0 | 0.5 | **2** |
| 20 | Car parks | 0 | 0.5 | 0.5 | 0 | 1 | 1 | 0.5 | **3.5** |

Table 3.3: Point-system to select risk aversion factor (steepness of proof lines) for a specific building

Studies indicate that wider tolerable region, where ALARP need to be demonstrated by CBA, maximize societal welfare [5] and thus can be applied to achieve different fire safety goals in fire safety engineering. But there are no defined procedures to mathematically represent the curve in log-log graph and construct the proof lines. An attempt made to mathematically represent the curve in log-log graph was not successful. On the other hand, if a decision is made to join two anchor points with a curve instead of a line, the width of the tolerable region will be affected by the subjectivity of the stakeholders. Hence, the traditional method of connecting the anchor points with a straight line is proposed.

### Step 4: Set *de minimis* limit and tolerability limit (Individual risk and Societal risk)

This step can be done with or without the involvement of stakeholders. If the stakeholders are not involved, the engineering judgement and past experience of the designer can be used to set a criterion initially which can be discussed with the stakeholder for their acceptance in the later stage. However, it is highly recommended to involve stakeholders while setting up the criteria. The following four questions need to be answered before proceeding ahead.

1. What are the maximum tolerable limits established in other sectors (transportation, industries etc.)?
2. Should the unit of frequency of occurrence in FN curves defined in ‘per year’ or ‘hours occupancy used’?
3. What is the risk aversion factor that need to be selected (steepness of proof lines)?
4. In any case do you set a maximum number of people who can be exposed to untenable fire conditions considering risk aversion?

The maximum tolerable limits (tolerability limit) and broadly acceptable limits (*de minimis* limit) established in other sectors (Figure 3.14 and Figure 3.15) can be used as a reference to select an anchor point. In the case of setting unit of frequency of occurrence in FN curves, either of the two, as mentioned in point 2 above, can be selected based on the stakeholder consultation. However, for clarity and stakeholder discussion, it is highly recommended to use the unit of frequency in FN curves as ‘per year’.

### Individual Risk

The currently established individual risk criteria set by UK HSE for the members of the public (Table 3.2) is suggested for use. The same is also recommended in Table A.1 – Individual risk limits of PD 7974-7:2019 [8]. This is due to the fact that these limits were established taking into account the most difficult activities that can be controlled and also reflects the agreements reached at international level [28]. This is also evident from appendix 4 of UK HSE R2P2 document [28]. Moreover, Focaracci [108] points out that from literature data for voluntary risks, statistical data record an annual individual risk between $10^{-4}$ and $10^{-5}$ whereas for involuntary risks it is between $10^{-6}$ and $10^{-8}$ annually.

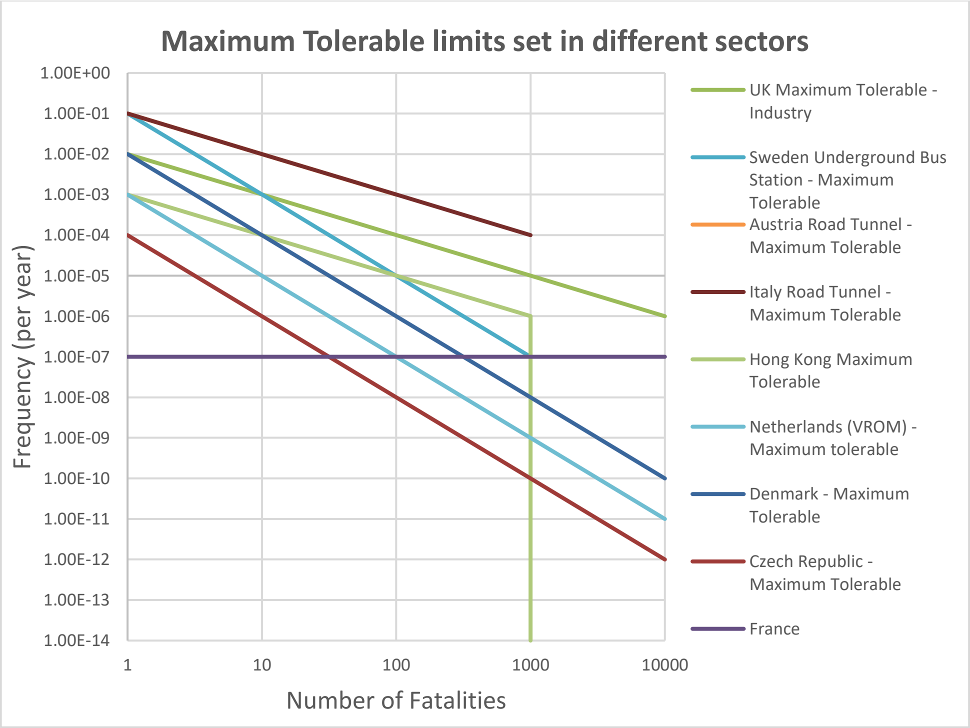


Figure 3.14: Maximum tolerable limits (or tolerability limit) set in different sectors

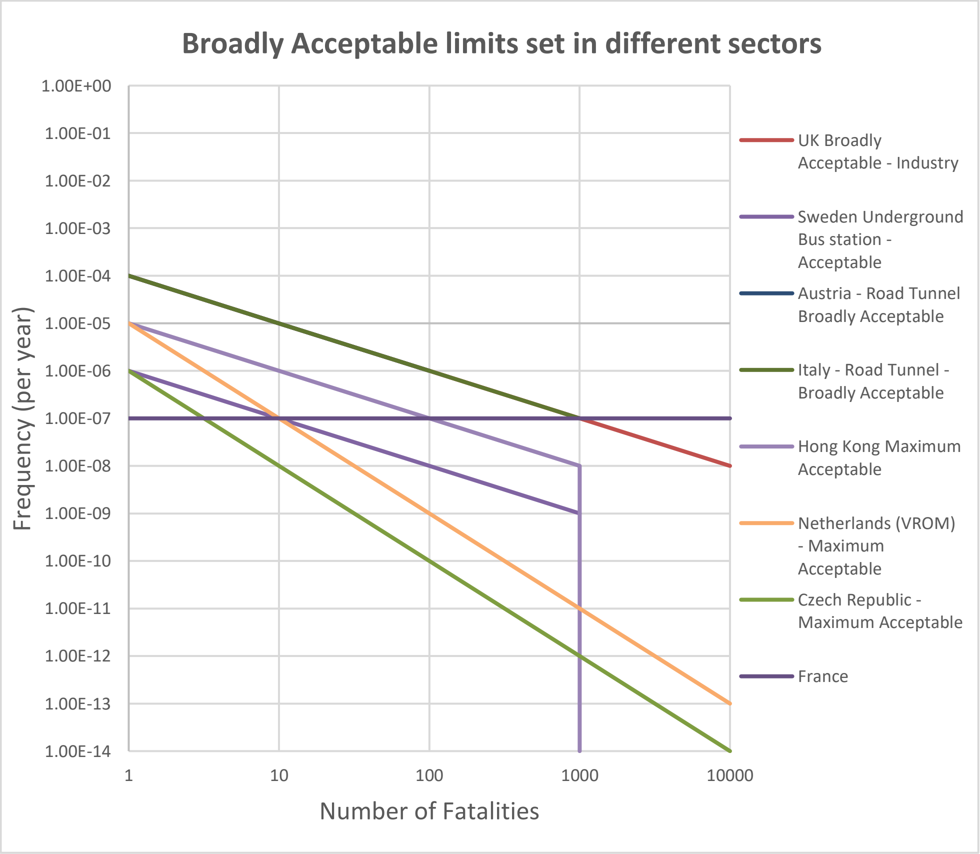


Figure 3.15: Broadly acceptable limits (or *de minimis* limit) set in different sectors

## Societal Risk

A flowchart illustrating the steps for setting up a societal risk criterion is shown in Figure 3.16. At first, through stakeholder consultation and considering the broadly acceptable limits established in other sectors, for 10 persons an acceptable frequency of exposure to untenable conditions is determined ($F_1$). Thus, anchor point 1 is set.

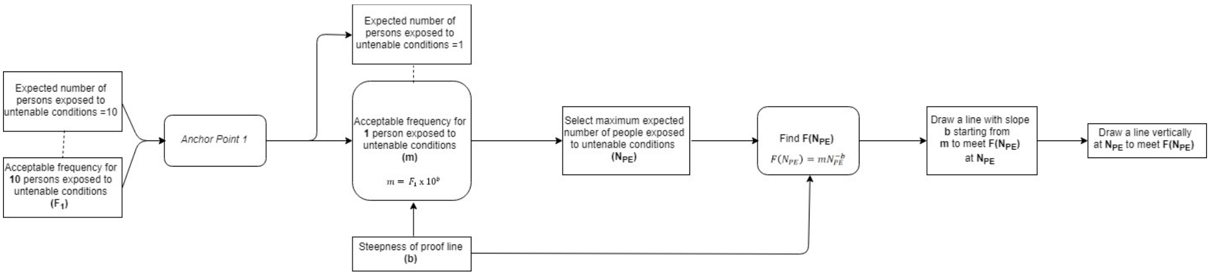


Figure 3.16: Flowchart illustrating the steps for setting up a societal risk criterion

Using anchor point 1 and the selected risk aversion factor in step 3, the acceptable frequency for 1 person exposed to untenable conditions (m) can be determined using the following equation:

$$m = F_1 \text{ x } 10^b \qquad \text{Equation 4}$$

Next, the maximum expected number of people exposed to untenable conditions ($N_{PE}$) can be set. This can be based on stakeholder discussions as well as from the statistics of maximum floor space factor seen in the occupancy under consideration. Thus, the accepted probability of occurrence in a defined time interval $F(N_{PE})$ can be determined using Equation 1. Thus, a line can be drawn from the point (1, m) passing through (10, $F_1$) and connecting point ($N_{PE}$, F($N_{PE}$)). Next, a line is drawn vertically down from the point ($N_{PE}$, F($N_{PE}$)) so as to meet the horizontal axis. This procedure is applicable for setting broadly acceptable limit as well as maximum tolerable limit. Thus, first maximum tolerable limit line can be constructed and then broadly acceptable limit line or vice-versa. As a result, different risk regions (acceptable, tolerable and unacceptable) can be created.

### Step 5: Stakeholder discussion

Even if stakeholders are involved in the previous steps, it is very important to finally get their acceptance or confirmation on the set maximum tolerable and broadly acceptable limits for the building under consideration. This is due to the fact that there are differences in the perception of risk between experts and public. In order to ensure that all aspects are considered in setting the risk tolerability criteria and further to ensure that there is no disagreement on the set risk criteria, a stakeholder discussion is mandatory. In case of any disagreement, the risk perception factor needs to be discussed (step 3) and all subsequent steps need to be followed. Finally, the set broadly acceptable risk and maximum tolerable risk criteria can be established for the specific project when the stakeholders agree and approve.

However, it is important to take note of few issues when stakeholders are involved in setting *de minimis* limit and tolerability limit for a project in the built environment. When a risk tolerability is defined through stakeholder consultation specific to a project, even in the case where two exact buildings are designed by two different consultants, the risk tolerability criterion established by each team might vary. Also, if the stakeholders involved in establishing risk tolerability limit are not serious and just adopt risk tolerability limit for a similar building blindly, the output of PRA need not be fruitful. Hence, it is recommended that the designer ensures that the stakeholders involved in the discussions are aware of the importance of different risk perception factors.

## 3.4 Stakeholder Feedback

The framework proposed for setting up the *de minimis* limit and tolerability limit of risk for a project in the built environment is mainly based on the literature review. Therefore, it is important to know whether the proposed framework can be practically implemented in an engineering project. Hence, as a part of stakeholder feedback, a recording of the presentation on this framework and its demonstration through a case study (office building) has been shared with fire safety professionals around the world. Moreover, it has been presented and discussed in person with few fire safety professionals [109,110]. The stakeholder feedback [109–115] helped to understand the limitations of the proposed framework from the practical point of view.

Mostly all the fire safety professionals who provided a feedback on the proposed risk tolerability framework mentioned that getting a quantitative target values from ‘stakeholder consultation’ is very difficult. This is due to the fact that many stakeholders do not understand risk well enough to contribute in a meaningful way. For example, one of the fire safety professionals mentioned that if a question is asked to a stakeholder regarding the probability of one person dying in a given building a year, the answer is often zero. Accordingly, to get a non-risk-expert to agree to quantitative target values is essentially impossible in today’s landscape. Therefore, in reality, fire engineers end up defining the risk by themselves and justify why that is appropriate. On the other hand, another fire safety professional is of the opinion that if the proposed risk tolerability framework is established in real projects in a country, then every building will have different interpretation of acceptable societal risk.

The fire safety professionals were also asked who are the ‘stakeholders’ that need to be involved in setting up the *de minimis* limit and risk tolerability limit according to the proposed risk tolerability framework. Accordingly, the following need to be considered as the stakeholders:

- The local authority
- Owners
- Operators
- Insurers
- Occupants or users of the building
- Fire Brigade

- Occupants of the adjacent properties who can be affected by a fire in the building under consideration

However, in reality, the feedback also stressed that for some buildings such as offices, residential, commercial, retail and industrial buildings, when the design is developed, none of the occupants are involved or even known. Moreover, people with financial, professional and moral responsibility for the building, its design or the area within a building would be the ones highly involved and willing to decide what limits are acceptable to them.

# 4 Case Studies

This chapter demonstrates a case study (other case studies are presented in Annexure A and Annexure B respectively) by structured application of probabilistic methods in accordance with the PD 7974-7:2019 and the proposed risk tolerability framework. A methodology is also developed for structured application of probabilistic methods.

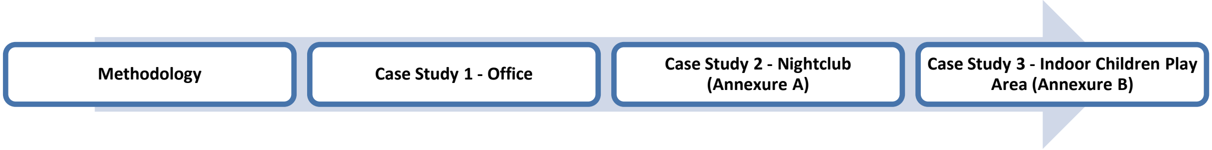


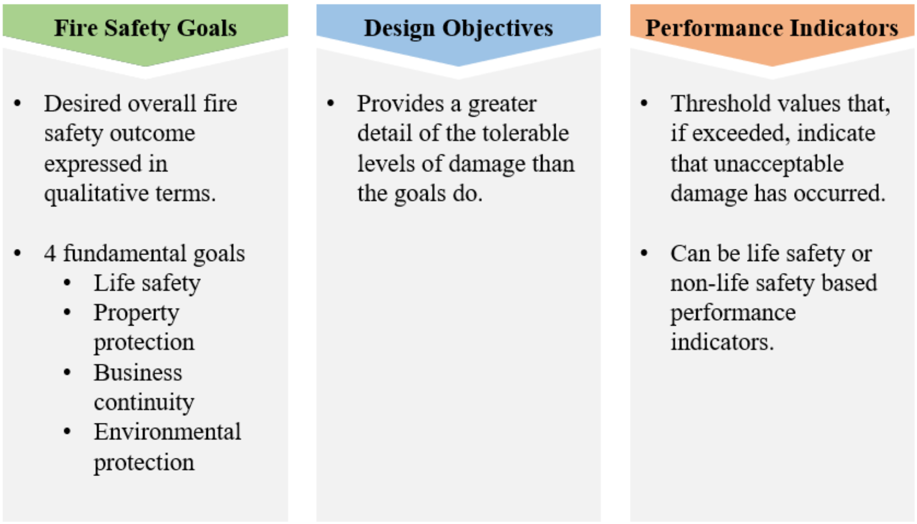
Figure 4.1: Flow chart highlighting the structure of chapter 4

## 4.1 Methodology

In order to have a structured application of probabilistic methods in fire safety engineering, developing a methodology which enables fire safety community to approach any project in the built environment is crucial. Based on a review of UK published document (PD 7974-7:2003 [6] and PD 7974-7:2019 [8]) and further discussions with a fire safety professional [116], a well-structured novel methodology is developed and is illustrated in Figure 4.3.

### Step 1: Set fire safety goals, design objectives and performance indicators

Once the project scope is clear, the first step is to set fire safety goals, design objectives and performance indicators through stakeholder consultation. It is important to understand the building characteristics before setting them. A description of these terms is given in Figure 4.2.



**Fire Safety Goals**

- Desired overall fire safety outcome expressed in qualitative terms.
- 4 fundamental goals
  - Life safety
  - Property protection
  - Business continuity
  - Environmental protection

**Design Objectives**

- Provides a greater detail of the tolerable levels of damage than the goals do.

**Performance Indicators**

- Threshold values that, if exceeded, indicate that unacceptable damage has occurred.
- Can be life safety or non-life safety based performance indicators.

Figure 4.2: Description on Fire Safety Goals, Design Objectives and Performance Indicators (based on [25,117])

However, this methodology is developed specifically for 'life safety' goal. Accordingly, necessary modifications need to be made in the proposed methodology to account for other fire safety goals.

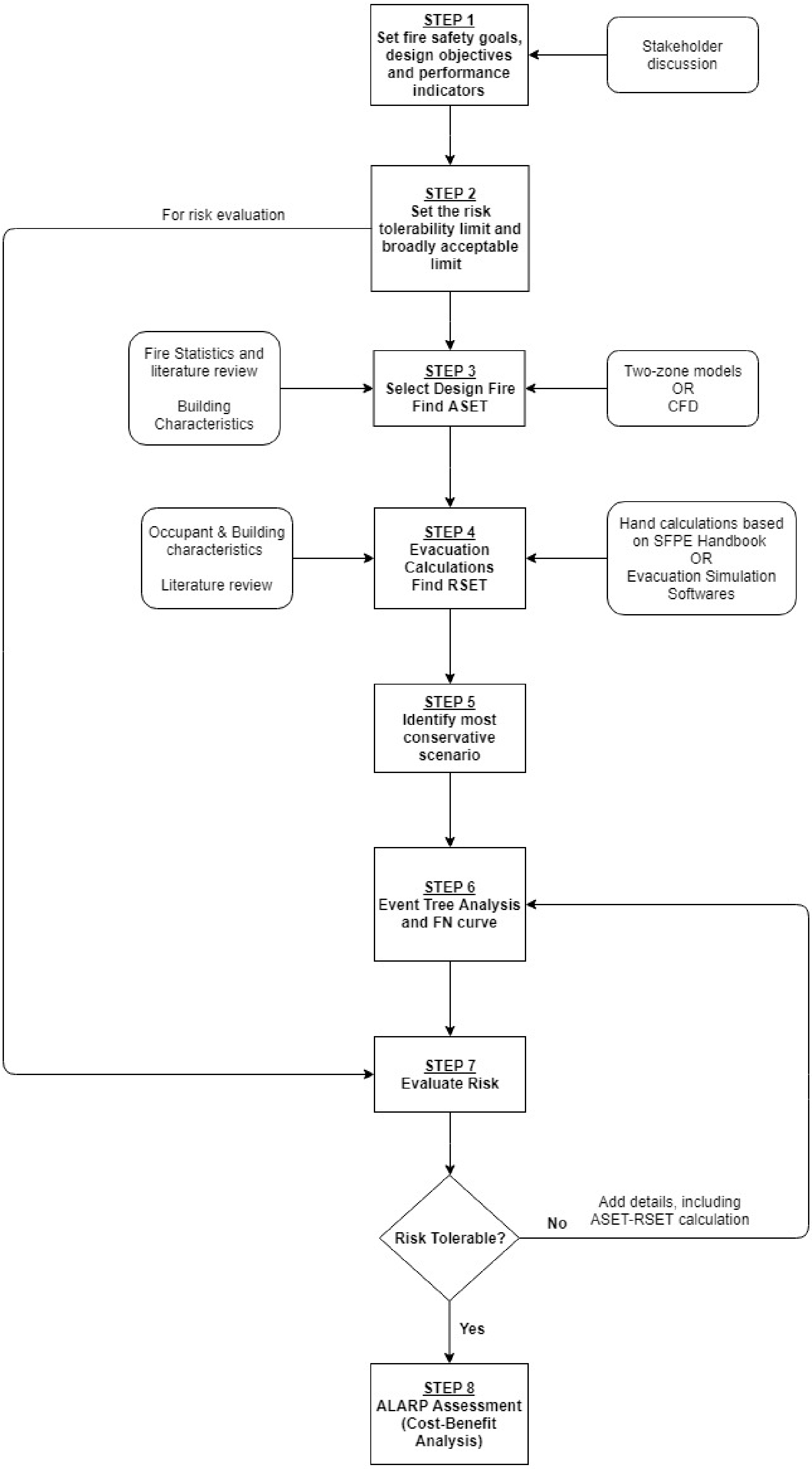


Figure 4.3: Flowchart illustrating a methodology for structured application of probabilistic methods in fire safety engineering

**Step 2: Set the risk tolerability limit and broadly acceptable limit (*de minimis* limit)**

The framework developed for setting risk tolerability limit and broadly acceptable limit for a specific project in the built environment as discussed in section 3.3 is adopted.

**Step 3: Select Design Fire - find ASET**

Next, the task is to determine Available Safe Egress Time (ASET) which is defined as *'calculated time available between ignition of a fire and the time at which tenability criteria are exceeded in a specific space in a building'* [118]. Data presented in Annex B (informative) of PD 7974-7:2019 [8] can be utilized as a starting point for ASET calculations. In addition, it is important to collect data through relevant literature specific to the type of occupancy being considered. For instance, statistical data on area of fire damage, fire growth rates, heat release rate per unit area (HRRPUA) etc. need to be collected for this purpose. Special care needs to be taken while selecting HRRPUA and hence it is recommended to refer [119]. These inputs help to select design fires. Accordingly, using a two-zone model or computational fluid dynamics (CFD) package, ASET can be determined.

**Step 4: Evacuation calculations – find RSET**

Required Safe Egress Time (RSET) is defined as *'calculated time available between ignition of a fire and the time at which occupants in a specified space in a building are able to reach a place of safety'* [118]. To determine RSET, designer might require to delve into literature to collect details of occupant density distribution, movement speed of occupants, pre-movement time of occupants, alarm time as well as detection time specific to the type of occupancy considered. Moreover, the designer should have a clear idea of the floor plan of the building, evacuation routes, the width of the exits etc. The total evacuation time can be calculated either by hand calculation based on SFPE handbook guidelines [120] or using evacuation simulation software.

**Step 5: Identify the most conservative scenario**

In performance-based design, from a life safety point of view for a typical design to be considered acceptable, ASET ≥ RSET [25]. If this condition is not satisfied, the number of people who will be exposed to untenable conditions can be determined. The untenable condition is based on the set performance indicator. A scenario in which the maximum number of people who will be exposed to untenable conditions (considering the highest occupant density, alarm time, pre-movement time etc.) will be considered as the most conservative.

**Step 6: Event tree analysis (ETA) and FN curve**

Depending on the type of occupancy, PD 7974-7:2019 provides data on ignition frequency or information to calculate them. This can be used as a starting point of the event tree analysis and all the relevant possible events need to be accounted in an event tree. Accordingly, for the most conservative scenario, an event tree analysis can be performed. Figure 4.4 provides a general example of an event tree illustrating a range of outcomes resulting from an initiating event. Sometimes it is necessary to perform fault tree analysis (FTA) to determine the probability of success or failure of a fire safety measure. In such cases, identifying the basic events and estimating the probabilities of basic events from statistical data or engineering judgement can help to determine the probability of success or failure of a fire safety measure, which is the top event. Figure 4.5 shows a fault tree created for determining the probability of failure of a fire protection system.

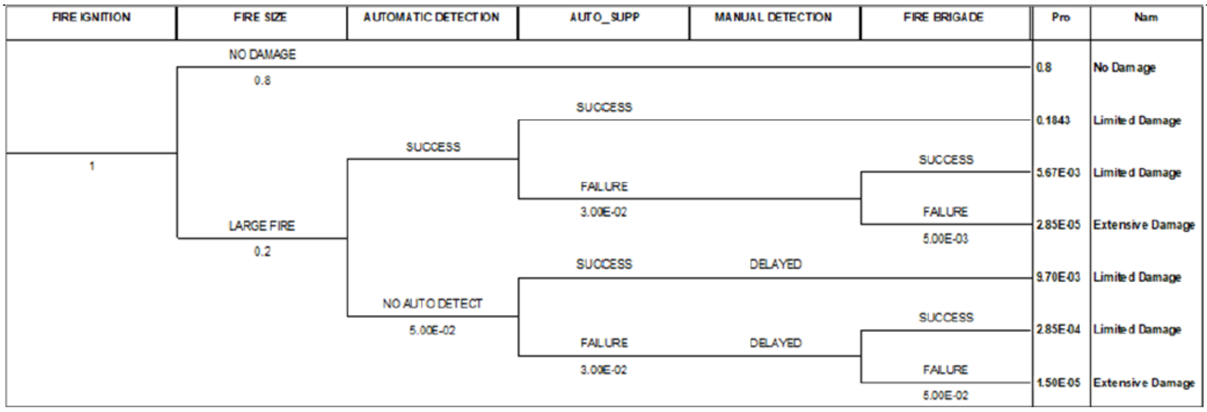


Figure 4.4: Event tree analysis (reproduced from PD 7974:7-2019 [8])

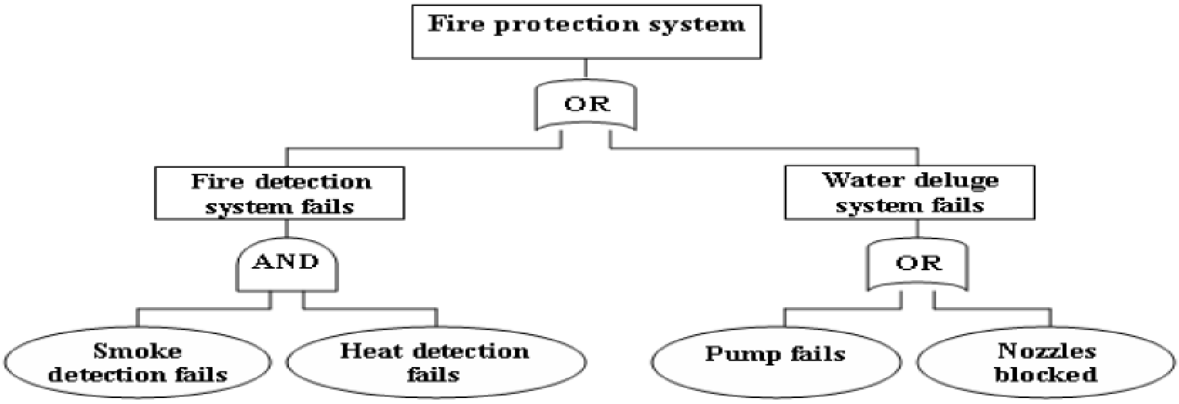


Figure 4.5: Fault tree analysis of a failure of fire protection system (reproduced from [121])

Therefore, for different possible scenarios the frequency of occurrence of each scenario (f) and the number of occupants exposed to untenable conditions can be determined (N). Thus, by taking cumulative frequencies (F), a FN curve can be produced.

### Step 7: Evaluate the risk

The established risk acceptability and tolerability criteria as per the proposed framework can be incorporated into the FN curves to evaluate the risk. Referring to Figure 3.3, if the estimated risk is found to be tolerable, an ALARP assessment need to be carried out. On the other hand, if the estimated risk is still unacceptable more details need to be incorporated in the event tree (step 5) and perform ASET-RSET analysis. For example, based on the results of one-way sensitivity analysis of RSET calculations, the most influencing parameter that have an effect on the expected number of people exposed to smoke (or defined performance indicator) can be included in the event tree analysis. This is a cyclic process which need to be performed until the estimated risk (FN curve) falls in the tolerable region where ALARP assessment need to be performed (tolerable region) or estimated risk (FN curve) falls in *de minimis* region (Figure 3.3). At this point, the individual risk can also be determined (Equation 3) and evaluated.

**Step 8: ALARP assessment**

As per PD 7974-7:2019 demonstrating ALARP through PRA in fire safety engineering is extremely important. Accordingly a design can be considered adequately safe when ALARP is demonstrated on the prerequisite of the spectrum of failure consequences (and their associated probabilities) being tolerable to a given society [122]. As illustrated in Figure 3.3, one of the three routes can be considered to demonstrate the attainment of ALARP. Considering the pitfalls of *absolute acceptance criterion (AC3)* and *comparative acceptance criterion (AC5)* of cost benefit analysis [5,122] *ALARP acceptance criterion (AC4)* is (typically) the most appropriate when developing general guidance [122].

A general equation [5] that can be used to symbolically represent the ALARP principle considering the fact that beyond a certain point risk reduction measures are too expensive to implement is given as follows:

$$\frac{\Delta C}{-\Delta RI} \leq \alpha \qquad \text{Equation 5}$$

where $\Delta C$ is the cost of investigated safety feature, $\Delta RI$ is the associated change in a scalar risk indicator and $\alpha$ is interpreted as a proportionality constant [5].

In the perspective of life safety goals, CBA considers 'the value of human life' to judge which life saving measures are economical [21]. However, this should not be interpreted as assigning a direct value on human life. Therefore, Life Quality Index (LQI), an index of societal welfare [122] and an internationally accepted method to determine the monetory value of a risk reduction to human life is adopted [8]. Based on this method, the amount society is willing to pay to avoid exposure to risk and save a life ($\mathrm{SCCR}_{1life}$ - societal capacity to commit resources for risk reduction saving one statistical life) can be evaluated and further used as the proportionality constant $\alpha$ of Equation 5. As per Table A.2 of PD 7974:7-2019 [8], in the UK $\mathrm{SCCR}_{1life}$ is currently benchmarked as 2.6 million GBP (2.6 x $10^6$ GBP). For example, if it needs to be checked and decided whether installing sprinkler system in a floor of a building is a relevant option to reduce the risk, the reliability data of sprinkler is incorporated in the event tree analysis and $\Delta RI$ will be determined. Let $\Delta C$ be the installation and maintenance cost of sprinkler system in the floor of a building where the analysis is focused. Further analysis i.e. whether a specific type of a sprinkler system need to be installed or a smoke heat extraction system need to be installed etc. can be performed if the following condition is satisfied:

$$\Delta C \leq \mathrm{SCCR}_{1life}\,(-\Delta RI) \qquad \text{Equation 6}$$

If the above condition is not satisfied, the design is already ALARP.

## 4.2 Case Study 1 – Office Building, UK

An office building assumed to be located in England which is designed applying the guidance provided in BS 9999:2008 [123] is taken for the study. The building consists of eight floors where the floor to ceiling height is taken as 3.2 m, with storey-to-storey height of 3.4 m. The building is used as open-plan offices and consists of two stairs – central stairs and western stairs as shown in Figure 4.6. However, for PRA only sixth floor of the building is analyzed for which the net internal area (NIA) considered is 805 $m^2$ and the exit width is 0.85 m.

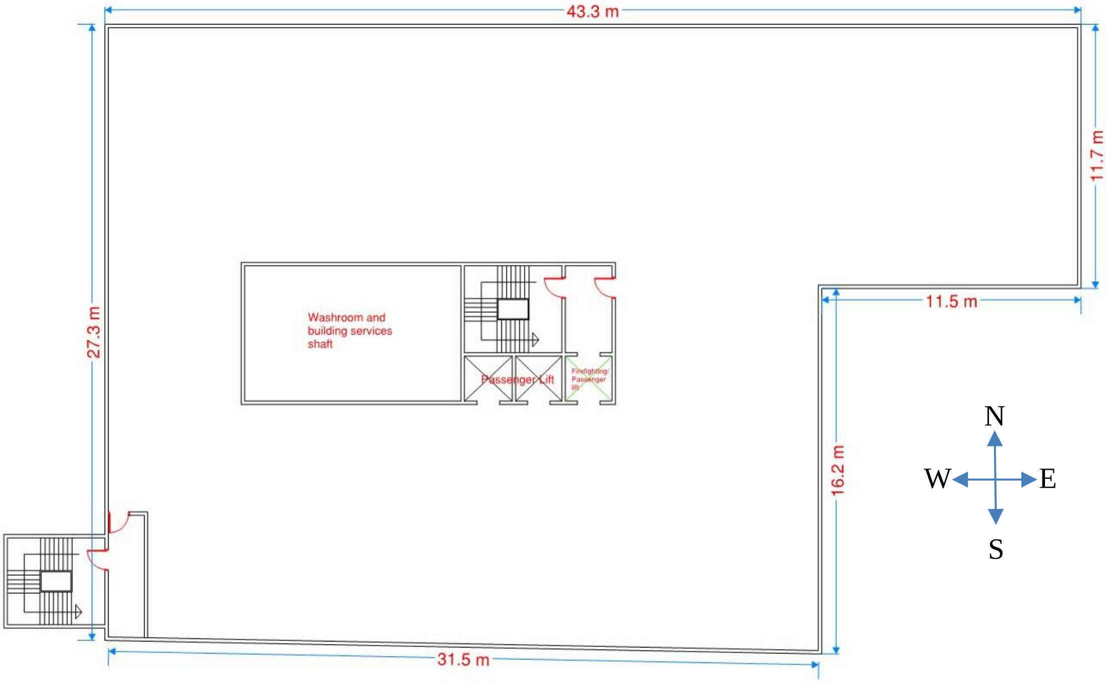


Figure 4.6: Floor plan of the sixth floor of office building considered for the study

### Step 1: Set fire safety goals, design objectives and performance indicators

The fire safety goal, design objective and performance indicators are set for office building as shown in Figure 4.7.

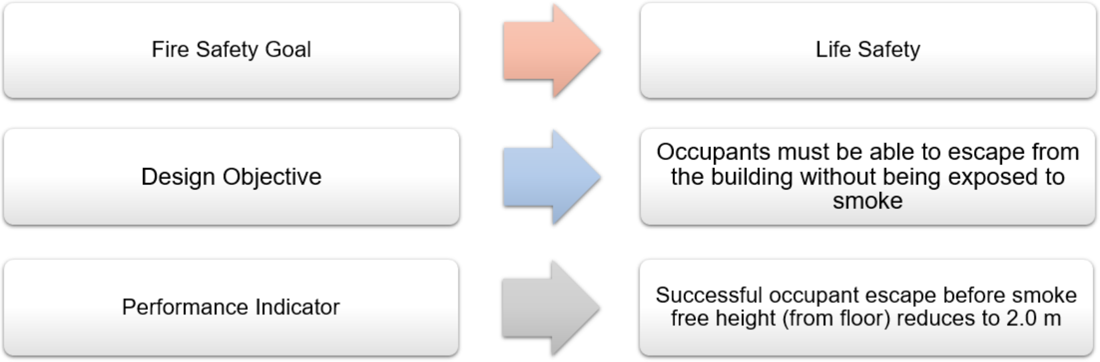


Figure 4.7: Fire safety goal, design objective and performance indicator for the office building case study

As per the Office for National Statistics (ONS) [124], UK the average man in England is 175.3 cm tall whereas the average woman in England is 161.6 cm tall. It is important to ensure that the occupants are not directly exposed to smoke. This can be done by keeping the smoke layer height above the head of the occupants. Considering this fact, this height is assumed to be 2 m above the floor level and is set as the performance indicator.

### Step 2: Set the risk tolerability limit and broadly acceptable limit

Step by step procedure as indicated in Figure 3.9 (risk tolerability framework) is followed here.

- *Step 1: Know the facility in question*

| Questions | Comments |
|---|---|
| • What is the occupancy type?<br>• Service provided by the building? | • Office (ADB Table D1 [107])<br>• Normal |
| • Who are exposed to the hazards? Any vulnerable population groups? | • There can be presence of disabled persons. But in general office buildings do not have vulnerable population groups. |
| • How many people are expected to be in the building? | • Only a particular floor is considered. Most conservative approach is to find the maximum number of people on this floor. From the literature review on the occupant density in office premises [125], a floor space factor of 0.5 $m^2$/person is found to be conservative. Accordingly, the maximum expected number of persons is 1610. |
| • Is the building occupied 24x7? | • No. Weekdays mainly with a 12 hrs. working time a day. |
| • Are there any sleeping risks? | • No |
| • Are people familiar with the building layout? | • In general, yes. But there can be visitors who might not be familiar with layout. However, in case of an emergency due to better fire safety management, they will be directed to a safe location by the employees. |

Table 4.1: Key questions answered for understanding the office building in question

- *Step 2: Choose a method for setting de minimis limit and tolerability limit*

Taking into account the limitations involved in other methods given in Figure 3.12, it is decided to set the *de minimis* limit and tolerability limit through stakeholder consultation.

- *Step 3: Consider different risk perception factors*

Considering different risk perception factors applicable to fire safety engineering, it is important to choose a risk aversion factor (steepness of proof lines). Table 4.2 shows the point-system analysis for office building to select risk aversion factor. It is clear that the steepness of proof line needs to be 1 for this office building.

| Risk Perception Factors | Points | Comments |
|---|---|---|
| Service of building under normal and emergency conditions | 0 | Service of building considered important in normal conditions as compared to a hospital building. |
| Importance of building | 0.5 | Medium importance since property protection and business continuity need to be considered from the perspective of fire safety goals. |
| Vulnerable population group | 0 | There can be presence of disabled persons. But in general office buildings do not have vulnerable population groups. |
| Sleeping Risk | 0 | No sleeping risk involved. |
| Potential for catastrophe and possibility to evacuate | 1 | Considering the fact that it is a high-rise building, there is potential for catastrophe and difficulties to evacuate. |
| Familiarity | 0 | In general, yes for office buildings. |
| Trust | 0.5 | In the wake of Grenfell Tower fire, the society losses trust on the government and authorities [58]. Thus, a moderate trust can be assigned. |
| **Total** | **2** | **Since total points is less than 3, the steepness of proof lines b = 1** |

Table 4.2: Point-system analysis for office building to select risk aversion factor (steepness of proof lines)

- *Step 4: Set de minimis limit and tolerability limit (Individual risk and Societal risk)*

Reference values for the individual tolerability limit and individual *de minimis* limit as mentioned in Table A.1 of PD 7974-7:2019 [8] is $10^{-4}$ per year and $10^{-6}$ per year respectively. This is set for the office building under consideration.

For setting societal risk limits, the steps mentioned in Figure 3.16 can be used. Accordingly, anchor point 1 is to be set with stakeholder discussion. For the tolerability limit and *de minimis* limit, considering the fact that the occupancy type considered is office, a less stringent criteria can be set. Therefore, from Figure 3.14 and Figure 3.15 considering the UK HSE criteria, the following anchor points are set for the tolerability limit and *de minimis* limit respectively: $(10, 10^{-3})$ and $(10, 10^{-5})$. Table 4.3 follows the steps mentioned in Figure 3.16 to construct the proof lines. Accordingly, Figure 4.8 shows the proof lines for the office building.

| **Steps** | **Tolerability Limit** | ***de-minimis* Limit** |
|---|---|---|
| 1 | *Anchor point*: (10, $10^{-3}$) | *Anchor point*: (10, $10^{-5}$) |
| 2 | m = $10^{-3}$ x $10^{1}$ = $10^{-2}$ per year<br>Point 2: (1, $10^{-2}$) | m = $10^{-5}$ x $10^{1}$ = $10^{-4}$ per year<br>Point 2: (1, $10^{-4}$) |
| 3 | F(2000) = $10^{-2}$ x $(2000)^{-1}$ = 5 x $10^{-6}$ per year<br>Point 3: (2000, 5 x $10^{-6}$) | F(1000) = $10^{-4}$ x $(1000)^{-1}$ = 1 x $10^{-7}$ per year<br>Point 3: (1000, 1 x $10^{-7}$) |

Table 4.3: Tolerability limit and de minimis limit for office building

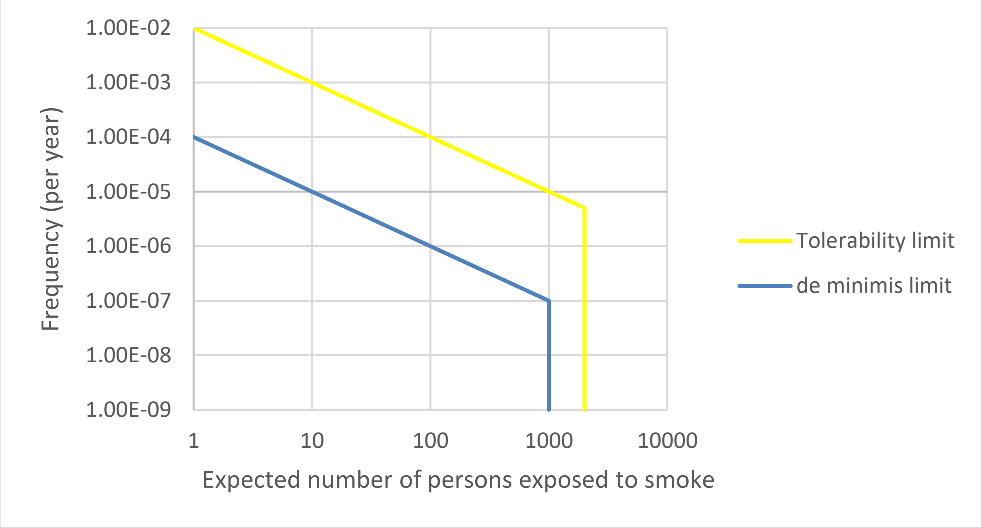


Figure 4.8: Proof lines for the office building

- *Step 5: Stakeholder discussion*

Since this is a hypothetical case study, there are no stakeholders involved for discussion. However, in reality, for a similar case study, the following will be considered as the stakeholders: owner, operator, insurer, fire brigade, representatives of the occupants of the office building (for instance health and safety team of the organization) and representatives of the occupants of the adjacent properties.

**Step 3: Select Design Fire - find ASET**

To determine ASET, the two-zone model B-RISK is used. As a starting point, data provided in table A.6 – office buildings: frequency distribution of area damage (in terms of number of fires) of PD 7974-7:2003 [6] is utilized. As per Eurocode EN 1991-1-2, 2002 [126] the suggested heat release rate per unit area (HRRPUA) for fuel-controlled fires for office occupancy is 250 kW/m$^2$. Using the data for area of damage and HRRPUA, the heat release rate (HRR) is determined. Accordingly, for medium fire growth rate which is the typical fire growth rates for office occupancies [4], time taken for smoke layer to reach 2 m above the floor level is determined using B-RISK (Table 4.4).

| **Area of damage ($m^2$)** | **HRR (kW)** | **HRR (MW)** | **Probability (out of 1860 fires)** | **Time taken for smoke layer to reach 2 m above floor (min)** | **Expected time[1] for smoke to reach 2 m above floor (min)** |
|---|---|---|---|---|---|
| 1 | 250 | 0.25 | 0.488 | 9.80 | **5.95** |
| 4 | 1000 | 1 | 0.204 | 5.73 | |
| 9 | 2250 | 2.25 | 0.077 | 5.58 | **1.45** |
| 19 | 4750 | 4.75 | 0.062 | 5.58 | |
| 49 | 12250 | 12.25 | 0.083 | 5.58 | |
| 99 | 24750 | 24.75 | 0.037 | 5.58 | |

Table 4.4: ASET for different area of damage in office floor

**Step 4: Evacuation calculations – find RSET**

RSET is determined employing the hydraulic model specified in SFPE Handbook of Fire Protection Engineering [120]. However, following assumptions are made in the evacuation calculations:

- Evacuation is only considered from 6th floor of the office building. Evacuation from other floors are not considered.
- For the initial assessment, one stair is discounted and only central stairs is available for evacuation.
- Once occupants enter the staircase, they are considered to be safe.
- Smoke detection system is provided in the building.
- Occupants start egress approximately at the same time.

The key evacuation calculation input parameters (occupant density, alarm time and pre-evacuation time) for office occupancy are adopted from the literature [125].

Table 4.5 shows the results of ASET-RSET analysis for the case where only the central staircase is available for evacuation. On the other hand, Table 4.6 shows the results of ASET-RSET analysis for the case where both staircases are available for evacuation. By performing ASET-RSET analysis, the expected number of persons who will be exposed to smoke (N) can be determined.

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[1] For example, for area of damage of 1 $m^2$ and 4 $m^2$, expected time = (0.488 x 9.8) + (0.204 x 5.73) = 5.95 mins.

| Sl. No | Floor Space Factor ($m^2$/p) | No. of people | Alarm time (min) | Pre-movement time (min) | Total evacuation time – RSET (mins) | Expected no. of people exposed to smoke - area of damage ≤ 4 $m^2$ | Expected no. of people exposed to smoke - area of damage > 4 $m^2$ |
|---|---|---|---|---|---|---|---|
| 1 | 101.50 | 8 | 0.50 | 0.00 | 0.85 | 0 | 0 |
| 2 | | | | 5.00 | 5.85 | 8 | 8 |
| 3 | | | | 1.16 | 2.01 | 0 | 8 |
| 4 | 0.50 | 1610 | 0.50 | 0.00 | 38.57 | 1392 | 1569 |
| 5 | | | | 5.00 | 43.57 | 1606 | 1610 |
| 6 | | | | 1.16 | 39.74 | 1442 | 1610 |
| 7 | 14.10 | 57 | 0.50 | 0.00 | 0.85 | 0 | 47 |
| 8 | | | | 5.00 | 5.85 | 56 | 57 |
| 9 | | | | 1.16 | 2.02 | 0 | 57 |

Table 4.5: ASET-RSET analysis result - only central staircase available for evacuation – office

| Sl. No | Floor Space Factor ($m^2$/p) | No. of people | Alarm time (min) | Pre-movement time (min) | Total evacuation time – RSET (mins) | Expected no. of people exposed to smoke - area of damage ≤ 4 $m^2$ | Expected no. of people exposed to smoke - area of damage > 4 $m^2$ |
|---|---|---|---|---|---|---|---|
| 1 | 101.50 | 8 | 0.50 | 0.00 | 0.79 | 0 | 0 |
| 2 | | | | 5.00 | 5.79 | 8 | 8 |
| 3 | | | | 1.16 | 1.96 | 0 | 8 |
| 4 | 0.50 | 1610 | 0.50 | 0.00 | 16.38 | 1174 | 1528 |
| 5 | | | | 5.00 | 21.38 | 1602 | 1610 |
| 6 | | | | 1.16 | 17.55 | 1274 | 1610 |
| 7 | 14.10 | 57 | 0.50 | 0.00 | 0.79 | 0 | 21 |
| 8 | | | | 5.00 | 5.79 | 32 | 33 |
| 9 | | | | 1.16 | 1.96 | 0 | 33 |

Table 4.6: ASET-RSET analysis result - 2 staircases available for evacuation - office

### Step 5: Identify the most conservative scenario

The most conservative scenario is when the following conditions are satisfied:

- Only central staircase available for evacuation
- Floor space factor is 0.50 $m^2$/person
- Pre-movement time is 5 minutes

Therefore, in Table 4.5 simulation 5 satisfies all these conditions and is considered as the most conservative scenario.

### Step 6 & 7: Event tree analysis (ETA) and FN curve, Risk evaluation

For the conservative scenario identified in step 5, an event tree is created. The ignition frequency is calculated based on the data given in table A.3 – probability of fire starting within given floor area for various types of occupancy of PD 7974-7:2003 [6]. Accordingly, FN curve is produced for the most conservative scenario as shown in Figure 4.9.

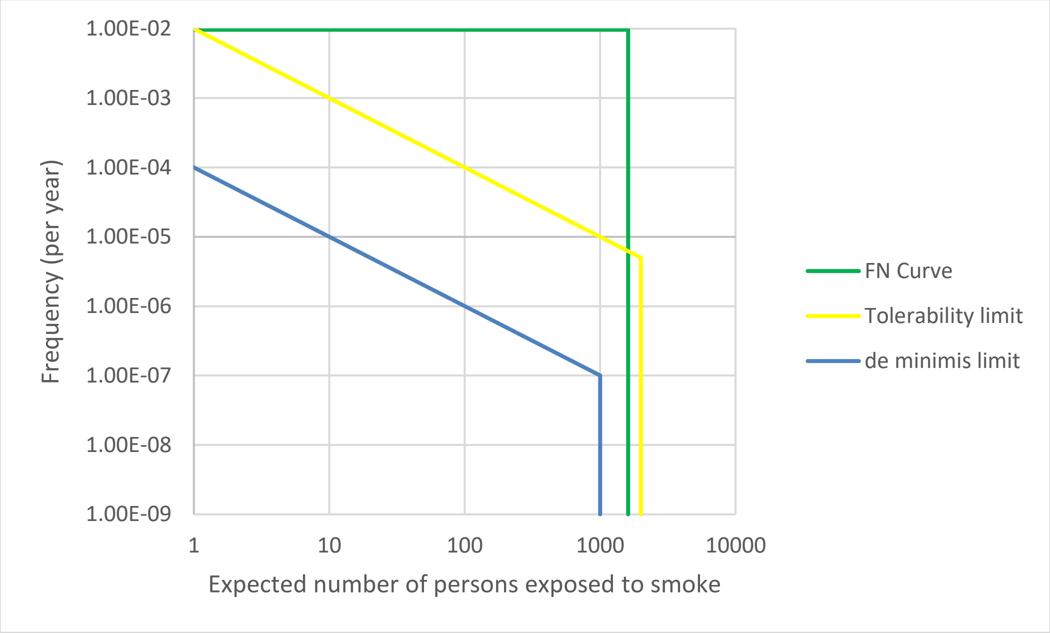


Figure 4.9: FN curve for the most conservative scenario – office

It is clear from Figure 4.9 that the estimated risk is not acceptable. Hence, as per the methodology given in Figure 4.3, it is important to add more details in the event tree. Therefore, it is important to know which are the parameters that can have an influence on the number of people exposed to smoke. For example, from Table 4.5 and Table 4.6, it is evident that area of damage, occupant density (floor space factor), pre-movement time and number of stairs available for evacuation have an influence on the number of people exposed to smoke. Accordingly, each of these details are included in the event tree till the point where FN curve falls in the tolerable region and ALARP can be demonstrated. The event tree developed for the office case study (floor 6) is given in Figure 4.10. The probabilities indicated in the branches of event tree is provided in Table 4.7.

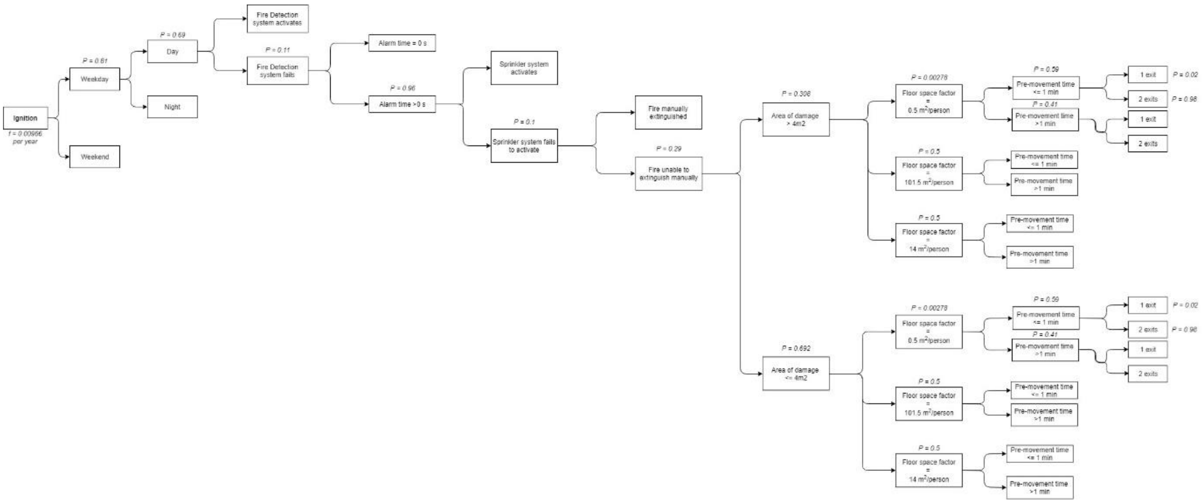
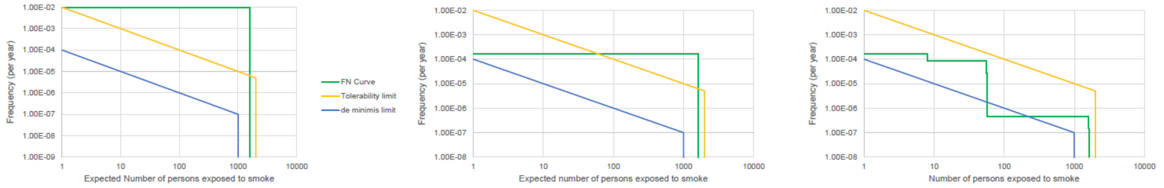


Figure 4.10: Event tree developed for the office building - floor 6

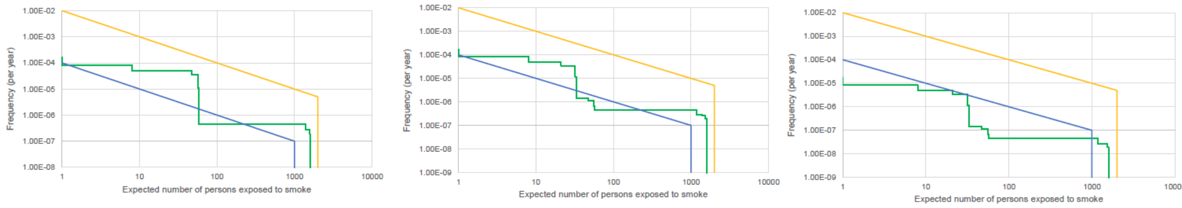
| Particulars | Value | Reference/Comments |
|---|---|---|
| Probability of fire occurring in the weekends | 0.19 | [127] |
| Probability of fire occurring in the weekdays | 0.81 | |
| Probability of fire occurring during the day | 0.69 | |
| Probability of fire occurring during the night | 0.31 | |
| Probability of fire occurring for fires causing damage ≤ $4m^2$ | 0.692 | [6] |
| Probability of fire occurring for fires causing damage > $4m^2$ | 0.308 | |
| Probability of successful extinguishment of fires by occupants | 0.71 | [128] |
| Probability of not successful extinguishment of fires by occupants | 0.29 | |
| Probability of fire detection and alarm system failed to give an alarm | 0.11 | [129] |
| Probability that alarm time is not equal to 0 s | 0.96 | [130] |
| Probability of having a floor space factor of 0.50 $m^2$/person | 0.00278 | On monthly basis. Assumed party in the floor once in a month (30 days), once in a day (24 hours) and 2 hours. |
| Probability of having a floor space factor of 101.50 $m^2$/person | 0.5 | Night time.<br>Less people expected |
| Probability of having a floor space factor of 14 $m^2$/person | 0.5 | In the normal working hours, more people are expected. |
| Probability of pre-movement time ≤ 1 min | 0.59 | [131] |
| Probability of pre-movement time >1 min | 0.41 | |
| Probability of failure of sprinklers in office buildings | | [6] |
| Probability 2 exits available | 0.98 | Assumed since both stairs will be available due to good fire safety management. |
| Probability only 1 available | 0.02 | |

Table 4.7: Probabilities assigned at each branch of event tree - Office building (floor 6)

Changes in the FN curve when more details are added into the event tree can be seen in Figure 4.11.



**Case 1: Conservative scenario** **Case 2: Area of damage details included** **Case 3: Occupant density details included**



**Case 4: Pre-movement time included** **Case 5: 2nd exit availability details added** **Case 6: Sprinkler reliability details added**

Figure 4.11: FN curves for office building (floor 6) when more details are added to event tree

When details related to area of fire damage is introduced in the event tree, FN curves goes down. When occupant density data is included in the event tree, more step formations in FN curve is visible. On the other hand, when pre-movement time is included in event tree, no significant change is seen in the FN curve. But when western stairs are also available for evacuation, it can be seen that more step formations occur in the FN curve. Finally, when the reliability of sprinkler data is introduced, a small portion of FN curve falls in the tolerable region (case 6). Thus, ALARP need to be demonstrated. At the same time, the person-specific individual risk for a hypothetical person is determined for the case 6 considering the occupancy patterns using Equation 3. The hypothetical person is assumed to be located at the farthest point of the compartment and is the last person to exit the door. The person-specific individual risk is found to be 8.33 x $10^{-6}$ per year which is in the tolerable region of risk.

**Step 8: ALARP assessment**

From the event tree, summing up the product of each scenario frequencies and the corresponding expected number of people exposed to smoke, the expected risk is determined. The expected risk in the absence of sprinkler system in the 6th floor of the office building is 2.36 x $10^{-3}$ per year. In the presence of a sprinkler system, the expected risk is 2.36 x $10^{-4}$ per year. Therefore, the residual risk ($-\Delta RI$) if the sprinkler is installed is 2.12 x $10^{-3}$ per year.

If both the cost of installation of sprinkler system and its maintenance is known for a single floor of the building ($\Delta C$) then Equation 6 can be used as shown below.

$\text{SCCR}_{1life}(-\Delta RI)$ = (2.26 million GBP per year) x (2.12 x $10^{-3}$ per year) = 5510 GBP per year for a floor.

If $\Delta C \leq$ 5510 GBP per year, then it is necessary to install the sprinklers. However, further analysis can be done such as whether a specific type of a sprinkler system need to be installed or a smoke heat extraction system need to be installed etc. On the other hand, if $\Delta C >$ 5510

GBP per year, then it is not necessary to install the sprinklers since the original design is already ALARP.

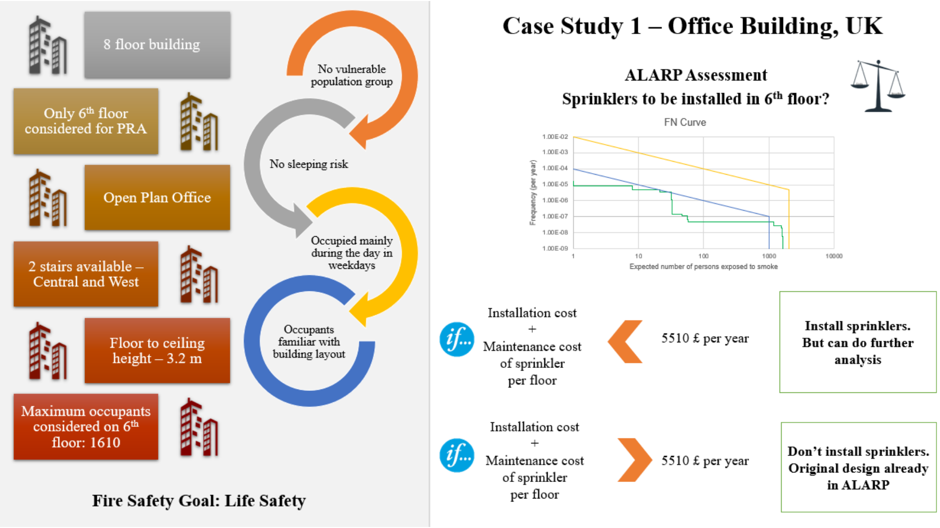


Figure 4.12: PRA for the 6th floor of the office building in a nut shell

## 4.3 Stakeholder feedback on suggested methodology

This office building case study demonstrating the methodology developed for the structured application of probabilistic methods in accordance with PD 7974-7:2019 has been presented in the Fire Forum Congress 2018 held at Brussels, Belgium [132]. Later the same has been discussed with IMFSE graduates [110,133] who are currently working as Fire Safety Engineer in Belgium.

The suggested methodology has been well received by the stakeholders who attended the Fire Forum Congress 2018. However, discussion of the case studies with fire safety engineers helped to clarify as well as improve the initial case studies [110,133].

# 5 Conclusion

This section will revisit the dissertation objectives and summarizes the important outcomes of this dissertation. Recommendation for future work is then discussed. Most importantly, the contribution of this work in the field of PRA in fire safety engineering, specifically to the built environment are clarified.

## 5.1 Dissertation Objectives: Outcomes and Conclusions

- *Objective 1: Study of PD 7974-7:2019 and literature review of risk acceptance in fire safety engineering*

It is evident from the study of PD 7974-7:2019 that it focusses on high level principles and that it attempts to provide a clear guidance on PRA in the built environment. At the same time, the hierarchy of risk acceptance concepts and the designer responsibility as a function of the applied acceptance concept is clearly explained in PD 7974-7:2019. Moreover, a great significance is provided on risk tolerability and acceptability. But it lacks an appropriate guidance on setting these limits for a project through stakeholder consultations. In addition, this published document touches upon risk perception and psychological factors, but fails to explicitly mention which factors are relevant when defining risk tolerability and acceptability criteria. Also, there are no reference examples demonstrating application of the principles highlighted in this published document to practicing fire safety engineers.

On the other hand, from the literature review on risk acceptance in fire safety engineering it is clear that there are no established risk criteria in the building sector when compared to the industrial sectors and transportation sectors. Furthermore, the challenges involved in setting up *de minimis* limits and the issues associated with the use of FN curves in risk assessment has been identified. A look into the risk perception in fire safety engineering indicates that voluntariness and artificiality of risk, culture and beliefs can be considered as trivial. This is due to the fact that few of the factors are debatable (voluntariness and artificiality of risk) and others cannot be ethically justified (culture and beliefs).

The main conclusion that can be drawn from this part of the study is that there should be a clear guidance on setting the *de minimis* and risk tolerability limit for a specific project in the built environment. The guidance should include relevant risk perception factors that need to be considered while setting up risk tolerability criteria. Moreover, it is also important to accommodate these risk perception factors in the risk tolerability criteria by adopting risk aversion factors. Lack of a clear guidance on these aspects make it difficult for the designer as well as the approver to determine whether a designed building is safe or not. Furthermore, reference case studies demonstrating application of the principles highlighted in PD 7974-7:2019 to practicing fire safety engineers are highly recommended.

- *Objective 2: Development of a framework for setting risk tolerability and broadly acceptable limit for projects in the built environment*

Based on the literature review on different aspects of fire safety engineering relevant to PRA in the built environment (risk perception, risk aversion, ethics, tolerability and *de minimis* limit established in different sectors), a risk tolerability framework is developed. This framework provides a step by step procedure to establish risk tolerability limits and broadly acceptable limits for a project in the built environment acknowledging the public risk perception. To incorporate different risk perception factors while setting risk tolerability limit, a point system is introduced which links the risk aversion factors. A clear guidance on constructing the proof lines are also included in this framework. It is also important to stress that this framework is developed foreseeing the future developments in the field of PRA in built environment. Therefore, it can be concluded that the use of this proposed risk tolerability framework takes a step towards providing a clear guidance for the designer as well as the approver to determine whether a designed building is safe or not. However, the conclusion has to be viewed in terms of a caveat. Firstly, the proposed risk tolerability framework looks only on the life safety goal of fire safety engineering. Secondly, there is no clear guidance on where individual risk is a more stringent requirement than the societal risk.

- *Objective 3: Development of case studies by structured application of probabilistic methods in accordance with the PD 7974-7:2019 and the developed risk tolerability criteria*

A proposed risk tolerability framework remains incomplete unless it is demonstrated through a case study. Similar is the case with the high-level principles presented in PD 7974-7:2019. Therefore, as a starting point, a methodology to utilize the probabilistic methods in a structured manner is developed based on the study of published document and discussion with a fire safety professional [116]. This methodology is further demonstrated in three different case studies – office building, night club and indoor kids play area. Therefore, a clear demonstration of the risk tolerability framework and application of the principles highlighted in PD 7974-7:2019 to practicing fire safety engineers is presented through different case studies. However, these case studies have some limitations. Firstly, the data considered for the case studies is not specific to the UK. Fire statistics of USA is also adopted in the study. Furthermore, at certain points, reasonable assumptions are made on probabilities. Secondly, all three case studies focus only on the life safety goal of fire safety engineering.

- *Objective 4: Presentation and discussion of developed risk tolerability framework and case studies to stakeholders*

As a starting point, a case study (office building, UK) demonstrating the methodology developed for the structured application of probabilistic methods in accordance with PD 7974-7:2019 has been presented in the Fire Forum Congress 2018 held at Brussels, Belgium [132]. Later the same has been discussed with an IMFSE graduate [133] who is currently working as Fire Safety Engineer in Belgium. For the proposed risk tolerability framework, as a part of stakeholder feedback, a recording of the presentation on this framework and its demonstration through a case study (office building) has been shared with fire safety professionals around the world. Moreover, it has been presented and discussed in person with few fire safety professionals [109,110].

- *Objective 5: Updating methodology, cases and report in function of stakeholder feedback. Identification of caveats in the methodology*

The methodology developed for the structured application of probabilistic methods in accordance with PD 7974-7:2019 was well received by the stakeholders who attended the Fire Forum Congress 2018. However, discussion of the case studies with fire safety engineers helped to clarify as well as improve the initial case studies [110,133].

On the other hand, for the proposed risk tolerability framework the stakeholder feedback [109–115] helped to understand its limitations from the practical point of view. At the same time, stakeholder feedback also helped to figure out who are the stakeholders that need to be involved in setting risk tolerability criteria for a project in the built environment. It is evident from the stakeholders' feedback that getting a quantitative target values from 'stakeholder consultation' is very difficult. This is due to the fact that many stakeholders do not understand risk well enough to contribute in a meaningful way.

The following people can be involved in setting up the *de minimis* limit and risk tolerability limit according to the proposed risk tolerability framework:

- The local authority
- Owners
- Operators
- Insurers
- Occupants or users of the building
- Fire Brigade
- Occupants of the adjacent properties who can be affected by a fire in the building under consideration

Therefore, to conclude the methodology developed for the structured application of probabilistic methods in accordance with PD 7974-7:2019 can be adopted in reality. On the other hand, realizing the fact that getting a quantitative target values from 'stakeholder consultation' is very difficult, the proposed framework can be well utilized by the fire safety engineers and authorities to set the risk tolerability criteria for a project in the built environment. This is due to the fact that an explicit consideration on various societal risk perception factors are incorporated in the proposed framework. However, it needs to be ensured that *an objective, diligent and competent fire safety professional considering the spectrum of possible consequences (and their associated probabilities) associated with the design (to be acceptable to normal societal stakeholders)* [5] is involved in setting up of the *de minimis* limit and risk tolerability limit for a specific project in the built environment. Accordingly, adopting the proposed risk tolerability framework, associations like Society of Fire Protection Engineers (SFPE) or Institution of Fire Engineers (IFE) can propose and establish the *de minimis* limit and tolerability limit for common buildings. However, for uncommon fire safety designs the *de minimis* limit and tolerability limit can be established specific to the building where the risk tolerability criteria established for common buildings can be used as a reference. Moreover, the use of the proposed risk tolerability framework will ease stakeholder communications and enhance their understanding on the set risk tolerability criteria.

## 5.2 Further Study

Further study could focus on areas that were touched on only briefly in this dissertation. For example, to offer an improved understanding on individual risk in the built environment, it would be fruitful to look into the determination of individual risk in building fire safety engineering. This will help to understand where individual risk is a more stringent requirement compared to societal risk. For example, in one family dwelling, individual risk is expected to be dominant. From the feedback of the stakeholders on the proposed risk tolerability limit, it is clear that determination of individual risk in the built environment can be explored if risk professionals in the insurance industry are involved in further studies. This is due to the fact that the fire, property and personal insurance coverages premiums are all based on acceptable and tolerable risks.

On the other hand, the study conducted in this dissertation focuses on the life safety goal of fire safety engineering. Similar case studies or same case studies can be extended to incorporate other fire safety goals like property protection, environment protection and business continuity. This will help the practicing fire safety engineers to perform PRA incorporating other fire safety goals.

## 5.3 Contribution to Knowledge

To date, in the context of PRA, the work produced by other researchers has concentrated more on the industrial sector than the building sector. However, in the building sector, researchers delve into the aspects of fire risk, fire risk acceptance criteria, risk perception and decision making. In that context, the importance of this work, compared to what has been produced hitherto, is that this study provides a clear guidance on setting *de minimis* limit and risk tolerability limit for a specific project in the built environment. Moreover, the important public risk perception factors in fire safety engineering has been identified based on explicit literature review and analyzing the reaction of public during past fire incidents. Furthermore, these factors have been incorporated into the risk tolerability framework with the help of risk aversion factors. Accordingly, a clear method to construct proof lines has been presented. Therefore, in the context of PD 7974-7:2019, this work will take a step towards providing an appropriate guidance on setting the *de minimis* limit and tolerability limit for a project in the built environment through stakeholder consultations. On the other hand, the study also presents different case studies following a well-structured methodology to apply probabilistic methods in accordance with the PD 7974-7:2019.

This dissertation will contribute to the field of PRA in fire safety engineering, specifically to the built environment in a number of important ways:

- Demonstration of the high-level principles involved in the PD 7974-7:2019 through reference case studies following a well-structured methodology will benefit the practicing fire safety engineers and the regulatory authorities in understanding the concepts and also in implementing these principles in reality.
- The critical evaluation of the relevant literature can enlighten fire safety community with the difficulties existing in the topic of risk acceptance in fire safety engineering. This can also motivate further studies in this field.
- A well-defined approach to set risk tolerability limit and *de minimis* limit for a project will be beneficial for the stakeholders involved in a project. This will also guide the stakeholders to consider different aspects (especially the public risk perception) while setting such criteria for a project in the built environment.
- Adopting the proposed risk tolerability framework, associations like Society of Fire Protection Engineers (SFPE) or Institution of Fire Engineers (IFE), UK can propose and establish the *de minimis* limit and tolerability limit for common buildings.
- For uncommon fire safety designs the *de minimis* limit and tolerability limit can be established specific to the building where the risk tolerability criteria established for common buildings can be used as a reference.
- The use of the proposed risk tolerability framework will ease stakeholder communications and enhance their understanding on the set risk tolerability criteria.

# References

[1] G. Ramachandran, D. Charters, Quantitative Risk Assessment in Fire Safety, Spon Press, London, 2011.

[2] A. Newton, A Short History of Fire Protection, From Ancient Rome to Today, (n.d.). https://medium.com/@alex.newton1992/a-short-history-of-fire-protection-from-ancient-rome-to-today-3c0999b6b380 (accessed February 13, 2019).

[3] G. Spinardi, L. Bisby, J. Torero, A Review of Sociological Issues in Fire Safety Regulation, Fire Technol. 53 (2017) 1011–1037. doi:10.1007/s10694-016-0615-1.

[4] British Standards Institution, PD 7974-0:2002, Application of fire safety engineering principles to the design of buildings Part 0: Guide to design framework and fire safety engineering procedures, London, UK, 2002.

[5] R. van Coile, D. Hopkin, D. Lange, G. Jomaas, L. Bisby, The Need for Hierarchies of Acceptance Criteria for Probabilistic Risk Assessments in Fire Engineering, Fire Technol. (2018) 1–36. doi:10.1007/s10694-018-0746-7.

[6] British Standards Institution, PD 7974-7:2003, Application of fire safety engineering principles to the design of buildings - Part 7: Probabilistic risk assessment, London, UK, 2003.

[7] M. Manes, D. Rush, A Critical Evaluation of BS PD 7974-7 Structural Fire Response Data Based on USA Fire Statistics, Fire Technol. (2018). doi:10.1007/s10694-018-0775-2.

[8] British Standards Institution, PD 7974-7:2019, Application of fire safety engineering principles to the design of buildings – Part 7: Probabilistic risk assessment, UK, 2019.

[9] W. Frank, J. Farquharson, Guidelines for Developing Quantitative Safety Risk Criteria, Center for Chemical Process Safety of the American Institute of Chemical Engineers, New York, 2009. doi:10.1002/9780470552940.

[10] W. Frank, D. Jones, Choosing appropriate quantitative safety risk criteria: Applications from the new CCPS guidelines, Process Saf. Prog. 29 (2010) 293–298. doi:10.1002/prs.10404.

[11] F. Olsson, An Engineering Approach to Determine Acceptable Risk, in: Proc. SFPE Symp. Risk, Uncertain. Reliab. Fire Prot. Eng., Baltimore, 1999.

[12] B.J. Meacham, Understanding risk: Quantification, perceptions, and characterization, J. Fire Prot. Eng. 14 (2004) 199–227. doi:10.1177/1042391504042454.

[13] D.J. Hopkin, Design Goals – Fire Resistance Demands for Tall Residential Design Goals – Fire Resistance Demands, in: Proc. Interflam 2016, 2016. doi:10.13140/RG.2.1.3159.1927.

[14] T. Aven, Quantitative Risk Assessment: The Scientific Platform, Cambridge University Press, Cambridge, 2011.

[15] A. Burgess, A. Alemanno, J. Zinn, Routledge Handbook of Risk Studies, 1st ed., Taylor & Francis, London, 2016.

[16] I.L. Johansen, M. Rausand, Foundations and choice of risk metrics, Saf. Sci. 62 (2014) 386–399. doi:10.1016/j.ssci.2013.09.011.

[17] A. Šotić, R. Rajić, The Review of the Definition of Risk, Appl. Knowl. Manag. 3 (2015) 17–26.

[18] S.N. Jonkman, Loss of life estimation in flood risk assessment Theory and applications, Delft University of Technology (TU Delft), 2007.

[19] S. Kaplan, B.J. Garrick, On The Quantitative Definition of Risk, Risk Anal. 1 (1981) 11–27. doi:10.1111/j.1539-6924.1981.tb01350.x.

[20] A.W. Evans, N.Q. Verlander, What is wrong with criterion FN-lines for judging the tolerability of risk?, Risk Anal. 17 (1997) 157–168. doi:10.1111/j.1539-6924.1997.tb00855.x.

[21] T. Bedford, R. Cooke, Probabilistic Risk Analysis: Foundations and Methods, Cambridge University Press, New York, 2001.

[22] V. Fire, S. Design, S. Buildings, F.S. Engineering, S. Safety, Verifying Fire Safety Design in Sprinklered Buildings, Lund University, 2011.

[23] L. Staffansson, Selecting design fires. Report 7032, Lund University, Sweden, 2010. http://www.lunduniversity.lu.se/o.o.i.s?id=12683&postid=1736727.

[24] J. Fleming, Safety Factor(s) and Deterministic Analysis, in: SFPE Symp. Risk, Uncertainty, Reliab. Fire Prot. Eng., Society of Fire Protection Engineers, Bethesda, MD, 1999.

[25] M.J. Hurley, E.R. Rosenbaum, Performance-Based Fire Safety Design, 1st ed., CRC Press, Boca Raton, 2015.

[26] C. Whipple, De Minimis Risk, Springer Science & Business Media, New York, 2012.

[27] K. Fisher, Societal decision-making for optimal fire safety, ETH Zurich, Switzerland, 2014. https://doi.org/10.3929/ethz-a-010164481.

[28] Health and Safety Executive (HSE), Reducing Risks, Protecting People, London, 2001. http://www.hse.gov.uk/risk/theory/r2p2.pdf.

[29] R. Bell, T. Glade, M. Danscheid, Challenges in defining acceptable risk levels, in: W.J. Ammann, S. Dannenmann, L. Vulliet (Eds.), Proc. RISK21 Work. Monte Verit. Ascona, Switzerland, 28 Novemb. - 3 December 2004., 1st ed., Taylor & Francis, London, 2006: pp. 1–10.

[30] J.K. Vrijling, W. van Hengel, R.J. Houben, A framework for risk evaluation, J. Hazard. Mater. 43 (1995) 245–261. doi:10.1016/0304-3894(95)91197-V.

[31] V. Rees, UK Regulatory Approach to ALARA / ALARP in Light Water Reactors at the Design Stage, 2018. http://www.isoe-network.net/docs/symposium-proceedings-classification/plant-design/national-international-guidance/4029-rees2018-ppt-

2/file.html (accessed March 16, 2019).

[32] Health and Safety Executive (HSE), The tolerability of risk from nuclear power stations, London, 1988. http://www.onr.org.uk/documents/tolerability.pdf.

[33] A. Wolski, N.A. Dembsey, B.J. Meacham, Accommodating perceptions of risk in performance-based building fire safety code development, Fire Saf. J. 34 (2000) 297–309. doi:10.1016/S0379-7112(00)00003-5.

[34] P. Slovic, The Perception of Risk, 1st ed., Taylor & Francis, London, 2016.

[35] G.K. Raphael, Perceptions of Risk and their Effects on Decision Making, in: Soc. Risk Assess. How Safe Is Safe Enough?, Springer US, Warren, Michigan, 1979: pp. 71–84.

[36] M.T. Kinateder, E.D. Kuligowski, P.A. Reneke, R. D.Peacock, A Review of Risk Perception in Building Fire Evacuation, Maryland, 2014. http://dx.doi.org/10.6028/NIST.TN.1840.

[37] P. Slovic, B. Fischhoff, S. Lichtenstein, Facts and Fears: Understanding Perceived Risk, in: Soc. Risk Assess. How Safe Is Safe Enough?, Springer US, Warren, Michigan, 1979: pp. 181–216. doi:10.1007/978-1-4899-0445-4.

[38] V. Doshi, Lonely struggle of India’s anti-nuclear protesters | Vidhi Doshi | Global development | The Guardian, Online News Rep. (2016). https://www.theguardian.com/global-development/2016/jun/06/lonely-struggle-india-anti-nuclear-protesters-tamil-nadu-kudankulam-idinthakarai (accessed February 24, 2019).

[39] G. Wachinger, O. Renn, C. Begg, C. Kuhlicke, The risk perception paradox-implications for governance and communication of natural hazards, Risk Anal. 33 (2013) 1049–1065. doi:10.1111/j.1539-6924.2012.01942.x.

[40] L. Sjöberg, B.-E. Moen, T. Rundmo, Explaining risk perception. An evaluation of the psychometric paradigm in risk perception research, Trondheim, 2004. http://www.svt.ntnu.no/psy/torbjorn.rundmo/psychometric_paradigm.pdf.

[41] H. Paek, T. Hove, Risk Perceptions and Risk Characteristics, 1 (2017) 1–14. doi:10.1093/acrefore/9780190228613.013.283.

[42] T. Rundmo, T. Nordfjærn, Does risk perception really exist?, Saf. Sci. 93 (2017) 230–240. doi:10.1016/j.ssci.2016.12.014.

[43] O. Renn, The role of risk perception for risk management, Reliab. Eng. Syst. Saf. 59 (1998) 49–62. doi:10.1016/S0951-8320(97)00119-1.

[44] S. Chaiken, Heuristic versus systematic information processing and the use of source verusu message cues in persuasion, J. Pers. Soc. Psychol. 39 (1980) 752–766. doi:10.1037//0022-3514.39.5.752.

[45] K. Hill, Using a modified heuristic-systematic model to characterize information seeking on the Internet, Marquette University, 2013. http://epublications.marquette.edu/theses_open/216.

[46] D. Kahneman, A. Tversky, Prospect Theory: An Analysis of Decision under Risk,

Econometrica. 47 (1979) 263–291. http://www.jstor.org/stable/1914185.

[47] S. Chan, S. Castle, After London Fire, 11 More High-Rises Found With Combustible Material - The New York Times, New York Times. (2017). https://www.nytimes.com/2017/06/22/world/europe/uk-grenfell-tower-london-fire.html.

[48] W. Isaacs, Understanding Society's Perception of Risk: The First Step in Understanding Why People Choose Not to Buy Flood Insurance, n.d. http://www.floods.org/Files/Conf2014_ppts/E6_Issacs.pdf (accessed February 26, 2019).

[49] K.B. Bates, Z.F. Peynircioğlu, Proximity to Task: A Prerequisite for Two Cognitive Biases, Am. J. Psychol. 130 (2017) 477–491. https://www.jstor.org/stable/10.5406/amerjpsyc.130.4.0477.

[50] T. Reuters, Angry crowds gather at Brazil's National Museum after devastating fire, CBC News. (2018). https://www.cbc.ca/news/world/brazil-museum-fire-reaction-1.4808950.

[51] A. Young-Joon, H.-J. Kim, Fire at hospital kills 37, injures scores in South Korea, AP News. (2018). https://www.apnews.com/bed37878219c42138f8384066e907505 (accessed February 27, 2019).

[52] Defective wiring suspected cause of South Korea hospital fire: Police | world news | Hindustan Times, Hindustan Times. (2018). https://www.hindustantimes.com/world-news/defective-wiring-suspected-cause-of-south-korea-hospital-fire-police/story-yMUAwVTPVrefKlTYD03OgP.html (accessed February 27, 2019).

[53] NFPA - People at risk from fire, (n.d.). https://www.nfpa.org/Public-Education/By-topic/People-at-risk (accessed February 27, 2019).

[54] K. Halvorsen, P.G. Almklov, G. Gjøsund, Fire safety for vulnerable groups: The challenges of cross-sector collaboration in Norwegian municipalities, Fire Saf. J. 92 (2017) 1–8. doi:10.1016/j.firesaf.2017.05.001.

[55] Baku Fire Kills 25 At "Decrepit" Drug-Addiction Clinic, RadioFreeEurope - RadioLiberty. (2018). https://www.rferl.org/a/azerbaijan-fire-baku-decrepit-drug-rehab-center-deaths-update/29072372.html (accessed February 27, 2019).

[56] Kemerovo fire: Russia crowd condemns officials over disaster - BBC News, BBC News. (2018). https://www.bbc.com/news/world-europe-43552165 (accessed February 27, 2019).

[57] D. Bruck, M. Ball, Sleep and Fire: Who is at risk and can the risk be reduced?, in: Fire Saf. Sci., 2005: pp. 37–51. doi:10.3801/IAFSS.FSS.8-37.

[58] T. Shildrick, Lessons from Grenfell: Poverty propaganda, stigma and class power, Sociol. Rev. 66 (2018) 783–798. doi:10.1177/0038026118777424.

[59] M. Gandit, D.R. Kouabenan, S. Caroly, Road-tunnel fires: Risk perception and management strategies among users, Saf. Sci. 47 (2009) 105–114. doi:10.1016/j.ssci.2008.01.001.

[60] D. Nilsson, M. Johansson, H. Frantzich, Evacuation experiment in a road tunnel: A study of human behaviour and technical installations, Fire Saf. J. 44 (2009) 458–468. doi:10.1016/j.firesaf.2008.09.009.

[61] P. Webster, Tunnel fire sparks anger as President visits site, The Irish Times. (1999). https://www.irishtimes.com/news/tunnel-fire-sparks-anger-as-president-visits-site-1.169973 (accessed February 28, 2019).

[62] Y. Ryu, S. Kim, S. Kim, Does trust matter? Analyzing the impact of trust on the perceived risk and acceptance of nuclear power energy, Sustain. 10 (2018). doi:10.3390/su10030758.

[63] C. Starr, Social Benefit versus Technological Risk, Science (80-. ). 165 (1969) 1232–1238. http://www.jstor.org/stable/1727970.

[64] A.A.F. Wahlberg, L. Sjoberg, Risk perception and the media, J. Risk Res. 3 (2000) 31–50. doi:10.1080/136698700376699.

[65] A. Purandare, Influencing Fire Safety By Altering Risk Perception, LindkedIn. (2017). https://www.linkedin.com/pulse/influencing-fire-safety-altering-risk-perception-abhay-purandare (accessed March 1, 2019).

[66] D. Fetherstonhaugh, P. Slovic, S.M. Johnson, J. Friedrich, Insensitivity to the Value of Human Life: A Study of Psychophysical Numbing, J. Risk Uncertain. 14 (1997) 283–300. http://www.jstor.org/stable/41760856.

[67] A. Enander, Ö. Lajksjö, Risk aversion: The term and the phenomena related to complex risk issues, Swedish Rescue Services Agency (SRSA), Karlstad, Sweden, 2003. https://rib.msb.se/filer/pdf/18963.pdf.

[68] V.M. Trbojevic, Risk acceptance criteria in Europe, in: C.G. Soares (Ed.), Saf. Reliab. Ind. Prod. Syst. Struct., 1st ed., CRC Press, 2010: pp. 65–73.

[69] I. Kroon, N. Peter Høj, Application of Risk Aversion for Engineering Decision Making, in: Safety, Risk Reliab. - Trends Eng., International Association for Bridge and Structural Engineering (IABSE), Malta, 2001: pp. 587–592.

[70] M. Faber, M. Schubert, J. Baker, Decision making subject to aversion of low frequency high consequence events, Spec. Work. Risk Accept. Risk Commun. (2007). https://web.stanford.edu/~bakerjw/Publications/Faber et al (2007) risk aversion workshop paper.pdf.

[71] J. Lundin, Quantification of a safety target for an underground CNG bus terminal in Stockholm, Fire Saf. J. 104 (2019) 57–66. doi:S0379711218304065.

[72] Health and Safety Executive, An independent review of HSE methodology for assessing societal risk Prepared by the Institution of Chemical Engineers for the, 2009. http://www.hse.gov.uk/societalrisk/review.pdf.

[73] P. Haastrup, K. Rasmussen, A Study of F-N Curves for Accidents involving Highly Flammable Gases and some Toxic Gases, Trans. Inst. Chem. Eng. 72 (1994) 205–210.

[74] C.R. Sunstein, S.C. R, Laws of Fear: Beyond the Precautionary Principle, Cambridge University Press, Cambridge, 2005.

[75] M.E. Paté-Cornell, Quantitative safety goals for risk management of industrial facilities, Struct. Saf. 13 (1994) 145–157. http://www.sciencedirect.com/science/article/pii/016747309490023X.

[76] J. Vrijling, P.H.A.J.M. Gelder, Societal Risk and the Concept of Risk Aversion, in: Adv. Saf. Reliab. (Proceedings Int. Conf. Saf. Reliab., Lisbon, Protugal, 1997: pp. 45–52. doi:10.1016/B978-008042835-2/50005-9.

[77] E. Vanem, Ethics and fundamental principles of risk acceptance criteria, Saf. Sci. 50 (2012) 958–967. doi:10.1016/j.ssci.2011.12.030.

[78] Stanford University., Center for the Study of Language and Information (U.S.), Stanford encyclopedia of philosophy., (1997). https://plato.stanford.edu/archives/spr2014/entries/consequentialism/#ClaUti (accessed March 4, 2019).

[79] R. Koivisto, D. Douglas, Principles and Approaches in Ethics Assessment, 2015. http://satoriproject.eu/media/1.h-Ethics-and-Risk1.pdf.

[80] Stanford University., Center for the Study of Language and Information (U.S.), Stanford encyclopedia of philosophy., Stanford University, 1997. https://plato.stanford.edu/archives/spr2014/entries/ethics-deontological/ (accessed March 4, 2019).

[81] D.J. Madden, Editorial: A catastrophic event, City. 21 (2017) 1–5. doi:10.1080/13604813.2017.1348743.

[82] Kaydee, Engineering Ethics Blog: The Grenfell Tower Tragedy, Eng. Ethics Blog. (2017). http://engineeringethicsblog.blogspot.com/2017/06/the-grenfell-tower-tragedy.html (accessed March 4, 2019).

[83] D.N.D. Hartford, Legal framework considerations in the development of risk acceptance criteria, Struct. Saf. 31 (2009) 118–123. doi:10.1016/j.strusafe.2008.06.011.

[84] J. Gough, A review of the literature pertaining to “perceived” risk and “acceptable” risk and the methods used to estimate them, Information paper no. 14, Centre for Resource Management, University of Canterbury and Lincoln University, 1990. https://core.ac.uk/download/pdf/35460397.pdf.

[85] F. Redmill, ALARP Explored, Report Number: 1197, Newcastle upon Tyne, School of Computing Science, University of Newcastle upon Tyne, 2010. https://eprint.ncl.ac.uk/file_store/production/161155/31B78A17-F466-49CF-81A7-48FD0351E510.pdf.

[86] R. Wilson, Commentary : Risks and Their Acceptability, Sci. Technol. Hum. Values. 9 (1984) 11–22.

[87] E. Meyer, G. Andreassen, C. Wei, S. Shaw, What risk should public accept from chemical process facilities?, Process Saf. Prog. 26 (2007) 90–94. doi:10.1002/prs.10185.

[88] B. Fischhoff, S. Lichtenstein, S.L. Derby, R.L. Keeney, Acceptable Risk, Cambridge University Press, New York, 1981.

[89] M. Peterson, What Is a de Minimis Risk ?, Risk Manag. 4 (2002) 47–55.

doi:https://doi.org/10.1057/palgrave.rm.8240118.

[90] B.J.M. Ale, Tolerable or Acceptable: A Comparison of Risk Regulation in the United King...: Discover for Liverpool John Moores University, Risk Anal. 25 (2005). http://eds.a.ebscohost.com/eds/pdfviewer/pdfviewer?vid=19&sid=2b4c092c-d17d-4321-8314-ad23b3ab7d7d%40sessionmgr4002&hid=4213.

[91] J.L. Saw, M. Wardman, J. Wilday, A. McGillivray, H. Balmforth, H. McManus, S. Reston, A. Rushton, Societal Risk: Initial briefing to Societal Risk Technical Advisory Group, 2009. papers3://publication/uuid/32F5887C-71C6-47CC-A5E8-4112851D5481.

[92] H. Frantzich, Uncertainty and Risk Analysis in Fire Safety Engineering, Lund University, Sweden, 1998. https://portal.research.lu.se/ws/files/4436608/2064098.pdf.

[93] D.A. Jones, Nomenclature for Hazard and Risk Assessment in the Process Industries, 2nd ed., Institution of Chemical Engineers (IChemE), 1985.

[94] S. Lewis, Risk Criteria – When is low enough good enough?, Warrington, 2007. https://pdfs.semanticscholar.org/9d81/f9b996a0928a8e5f1fdf53a4e55c4217c0ec.pdf.

[95] D. Proske, Objective Risk Measures, in: Cat. Risks, 1st ed., Springer Berlin Heidelberg, Dresden, 2008: pp. 267–327. doi:10.1007/978-3-540-79555-1.

[96] D. Ball, P. Floyd, Societal risks, London, 1998.

[97] D. Straub, Engineering Risk Assessment, in: C. Klüppelberg, D. Straub, I.M. Welpe (Eds.), Risk - A Multidiscip. Introd., 1st ed., Springer International Publishing, Switzerland, 2014: pp. 333–362. doi:10.1007/978-3-319-04486-6.

[98] M.K. Rad, Global Risk Assessment of Natural Disasters: new perspectives, University of Waterloo, 2014. https://uwspace.uwaterloo.ca/bitstream/handle/10012/8545/Khaleghy_Rad_Mona.pdf?sequence=1.

[99] C. Murphy, P. Gardoni, The role of society in engineering risk analysis: A capabilities-based approach, Risk Anal. 26 (2006) 1073–1083. doi:10.1111/j.1539-6924.2006.00801.x.

[100] H. Osborne, N. Hopkins, Most Grenfell Tower survivors show signs of PTSD – council study | UK news | The Guardian, Guard. (2018). https://www.theguardian.com/uk-news/2018/jul/24/most-grenfell-tower-survivors-suffering-from-ptsd-finds-report (accessed March 16, 2019).

[101] J.T. disaster changes thinking about social housing in the Uk. Bradshaw, R. Tunstall, Grenfell Tower disaster changes thinking about social housing in the UK, 2018.

[102] M.W. Merkhofer, Decision Science and Social Risk Management: A Comparative Evaluation of Cost-Benefit Analysis, Decision Analysis, and Other Formal Decision-Aiding Approaches, 1st ed., Springer Netherlands, 1987. doi:10.1007/978-94-009-4698-9.

[103] T. Aven, J.E. Vinnem, On the use of risk acceptance criteria in the offshore oil and gas industry, Reliab. Eng. Syst. Saf. 90 (2005) 15–24. doi:10.1016/j.ress.2004.10.009.

[104] F. Nystedt, On the Use of Risk Concepts in Fire Safety Engineering, J. Phys. Conf. Ser. 1107 (2018). doi:10.1088/1742-6596/1107/4/042034.

[105] F. Wang, S. Lu, C. Li, Analysis Of Fire Statistics Of China: Fire Frequency And Fatalities In Fires, IAFSS, 2005. doi:10.3801/IAFSS.FSS.8-353.

[106] F.R. Farmer, Siting Criteria - A New Approach, in: Contain. Siting Nucl. Power Plants, IAEA, International Atomic Energy Agency (IAEA), 1967: pp. 303–318. http://inis.iaea.org/search/search.aspx?orig_q=RN:44077180.

[107] HM Government, The Building Regulations (2010) Approved Document B (Fire Safety) Volume 2: Buildings Other Than Dwellinghouses (2006 Edition incorporating the 2010 and 2013 Amendments), HM Government, London, United Kingdom, 2010.

[108] A. Focaracci, Italian Risk Analysis Method, Rome, Italy, 2007. http://www.prometeoengineering.it/public/pdf/file/pdf_1377701753.pdf.

[109] F. Guay, personal communication, March 27, 2019.

[110] N. Verma, personal communication, March 31, 2019.

[111] B. Ralph, personal communication, April 9, 2019.

[112] M. Kamrujjaman, personal communication, April 9, 2019.

[113] A. Tamim, personal communication, April 9, 2019.

[114] H. Lewis, personal communication, April 12, 2019.

[115] S. Moya, personal communication, April 15, 2019.

[116] D. Hopkin, personal communication, November 1, 2018.

[117] SFPE, SFPE Engineering Guide to Performance-Based Fire Protection, Society of Fire Protection Engineers (SFPE), Quincy, MA, 2007.

[118] British Standards Institution, PD 7974-6: 2004, The application of fire safety engineering principles to fire safety design of buildings Part 6: Human factors: Life safety strategies - Occupant evacuation, behaviour and condition (Sub-system 6), UK, 2004.

[119] C. Hopkin, M. Spearpoint, D. Hopkin, A Review of Design Values Adopted for Heat Release Rate Per Unit Area, Fire Technol. (2019). doi:10.1007/s10694-019-00834-8.

[120] S.M.V. Gwynne, E.R. Rosenbaum, Employing the Hydraulic Model in Assessing Emergency Movement, in: M.J. Hurley (Ed.), SFPE Handb. Fire Prot. Eng., Fifth, Springer, New York, 2016: pp. 2115–2151.

[121] D.G.S. Mahapatra, B. Sinha Mahapatra, Intuitionistic Fuzzy Fault Tree Analysis Using Intuitionistic Fuzzy Numbers, Int. Math. Forum. 5 (2010) 1015–1024.

[122] D. Hopkin, M. Spearpoint, M. Arnott, R. Van Coile, Cost-benefit analysis of residential sprinklers – Application of a judgement value method, Fire Saf. J. 106 (2019) 61–71. doi:10.1016/j.firesaf.2019.04.003.

[123] British Standards Institution, BS 9999:2008, Code of practice for fire safety in the design, management and use of buildings, UK, 2008.

[124] J. Matheson, ‘Average’ Briton highlighted on UN World Statistics Day, London, 2010. https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=12&ved=2ahUKEwjvgJjAnsHaAhXLQ8AKHZLMCfMQFjALegQIABBd&url=https%3A%2F%2Fwww.ons.gov.uk%2Fons%2Fabout-ons%2Fget-involved%2Fevents%2Fevents%2Fun-world-statictics-day%2F-average--briton-highlight.

[125] D. Hopkin, R. Van Coile, C. Hopkin, I. Fu, M. Spearpoint, Transient reliability evaluation of a stochastic structural system in fire, in: Proc. 16th Int. Probabilistic Work. (16 IPW), 12-14/09, Vienna, Austria, 2018. http://dx.doi.org/10.1002/best.201800059.

[126] European Standard, Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fires EN 1991-1-2, 2002.

[127] R. Campbell, U.S Structure Fires in Office Properties, 2013. https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Building-and-life-safety/osoffices.ashx?la=en.

[128] B. Ghosh, M. Spearpoint, Assessment of the benefits of Fire Extinguishers as fire safety precautions in New Zealand Buildings, University of Canterbury, 2008.

[129] T. Nyyssönen, J. Rajakko, O. Keski-Rahkonen, On the reliability of fire detection and alarm systems - Exploration and analysis of data from nuclear and non-nuclear installations, Espoo, 2005.

[130] P.G. Holborn, P.F. Nolan, J. Golt, An analysis of fire sizes, fire growth rates and times between events using data from fire investigations, Fire Saf. J. 39 (2004) 481–524. doi:10.1016/j.firesaf.2004.05.002.

[131] G. Proulx, A. Kaufman, J. Pineau, Evacuation Time and Movement in Office Buildings, 1996. doi:Resolve DOI: https://doi.org/10.4224/20358733.

[132] R. Van Coile, D. Hopkin, A.T. Mohan, Probabilistic Risk Assessment in fire engineering. The new British PD 7974-7 Fire Forum Congress 2018, (2018). https://www.fireforum.be/images/Congress/FFC18-Downloads/SC1A_Ruben_Van_Coile.pdf.

[133] J. Vandekerckhove, personal communication, March 8, 2019.

[134] Technical and Safety Committee - Fire Safety Working Group, Q&As Concerning Fire of Flexible Polyurethane Foams: Hazards and Prevention For Houses and Buildings, 2010. http://www.urethane-jp.org/topics/doc/QA_on_a_Fire_and_Fire_prevention_of_Polyurethane_flexi.pdf.

[135] A. Gragnani, A.F. de Oliveira, D. Boro, T.N. Pham, L.M. Ferreira, Response and legislative changes after the Kiss nightclub tragedy in Santa Maria/RS/Brazil: Learning from a large-scale burn disaster, Burns. 43 (2017) 343–349. doi:10.1016/j.burns.2016.08.010.

[136] J. Strick, Development of Safety Measures for Nightclubs, Lund University, Sweden, 2014.

http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=4522713&fileOId=4522718.

[137] A.T. Mohan, B. Jovanovic, B.G. Branisteanu-Albulescu, I. Cilenti, S.P. Diettes, Analysis of Human Behavior in Fire at Nightclub ‘Santika’, Thailand - Lund University “Human Behaviour in Fire” course assignment, Lund, Sweden, 2018.

[138] M.J. Spearpoint, Network modeling of the Station Nightclub fire evacuation, J. Fire Prot. Eng. 22 (2012) 157–181. doi:10.1177/1042391512447044.

[139] E. Comeau, R.F. Duval, National Fire Protection Association (NFPA), Dance Hall Fire Gothenburng, Sweden October 28, 1998, Quincy, MA, 2000.

[140] R.F. Duval, NFPA Case Study: Nightclub Fires, Quincy, MA, 2006. https://www.nfpa.org/~/media/files/news-and-research/resources/fire-investigations/case_study_nightclub_fires.pdf?la=en.

[141] R. Campbell, National Fire Protection Association (NFPA), Structure Fires in Eating and Drinking Establishments, Quincy, MA, 2017. https://www.nfpa.org/News-and-Research/Data-research-and-tools/Building-and-Life-Safety/Eating-and-drinking-establishments.

[142] Chartered Institution of Building Services, Engineers (CIBSE), Means of escape and human factors, in: Fire Saf. Eng. CIBSE Guid. E, Third, The Chartered Institution of Building Services Engineers, London, 2010: pp. 7-1; 7-15.

[143] C. Fleischmann, Defining the heat release rate per unit area for use in fire safety engineering analysis, in: K. Harada, K. Matsuyama, K. Himoto, Y. Nakamura, K. Wakatsuki (Eds.), Fire Sci. Technol. 2015 Proc. 10th Asia-Oceania Symp. Fire Sci. Technol., Springer, Tsukuba, Japan, 2015.

[144] A.R. Larusdottir, A.S. Dederichs, D. Nilsson, Evacuation of Children Focusing on daycare centers and elementary schools, Technical University of Denmark, 2014. http://orbit.dtu.dk/files/103681293/Aldis_Run_Laurusdottir_afhandling..PDF.

[145] T. Rinne, K. Tillander, P. Grönberg, Data collection and analysis of evacuation situations, Finland, 2010. https://www.vtt.fi/inf/pdf/tiedotteet/2010/T2562.pdf.

[146] M.Y. Roytman, Process of Emergency Evacuation, in: Princ. Fire Saf. Stand. Build. Constr., Amerind, New Delhi, 1975: pp. 283–320.

[147] Adult Male and Female Height to Weight Ratio Chart - Disabled World, (n.d.). https://www.disabled-world.com/calculators-charts/height-weight.php (accessed April 16, 2019).

[148] R. Campbell, National Fire Protection Association (NFPA), Structure Fires in Educational Properties, Quincy, MA, 2017. https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Building-and-life-safety/oseducation.pdf.

[149] Fire Extinguishing Trades Association, Independent Fire Engineering & Distributors Association, Report on a Survey into Portable Fire Extinguishers and their use in the United Kingdom and other member countries of Eurofeu, 2003. https://ifeda.org/wp-content/uploads/2015/07/IFEDA-portable-fire-extinguisher-survey-results.pdf.

## Annexure A – Case Study 2 – Nightclub, UK

A nightclub assumed to be located in England is considered for the study. It is expected to be operational only during Friday, Saturday and Sunday from 18:00 hrs. to 03:00 hrs. The nightclub consists of a bar counter and a dance floor as shown in Figure A.1. The entrance door is 1.8 m wide and the emergency exit is 1 m wide. The building elements are constructed with concrete. However, to attenuate the noise, polyurethane (PU) foam is planned to be used on the walls of dance floor as indicated in Figure A.1. The floor to ceiling height is taken as 3 m.

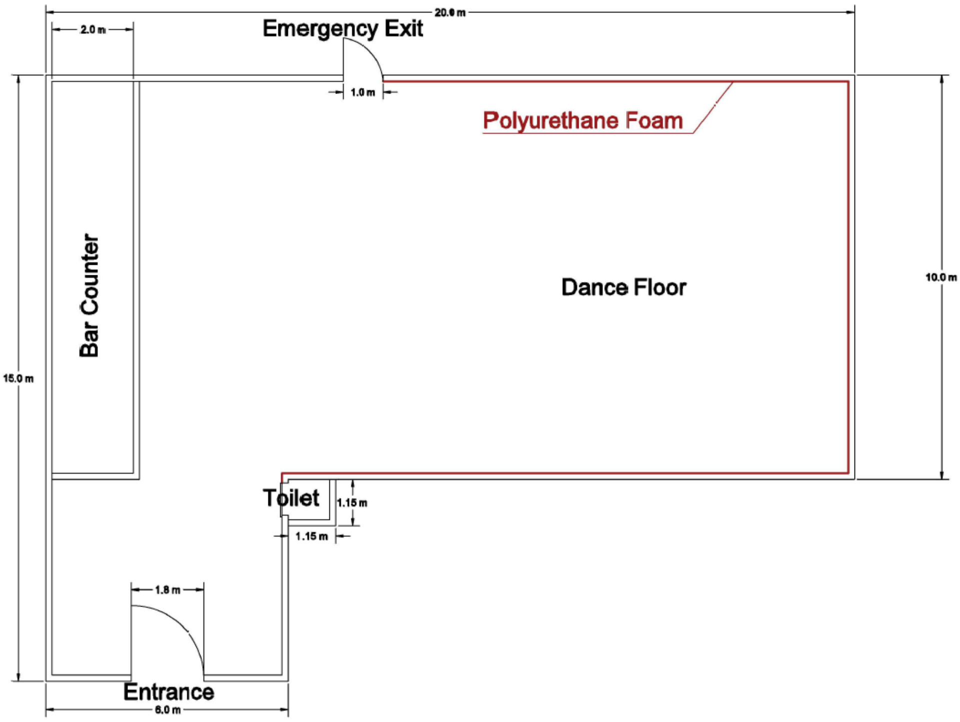


Figure A.1: Floor plan of the nightclub considered for the study

### Step 1: Set fire safety goals, design objectives and performance indicators

The fire safety goal, design objective and performance indicator set for this case study is the same as in the office building case study (Figure 4.7).

### Step 2: Set the risk tolerability limit and broadly acceptable limit

Step by step procedure as indicated in Figure 3.9 (risk tolerability framework) is followed here.

- *Step 1: Know the facility in question*

The key questions to understand the nightclub in question is discussed in Table A.1.

- *Step 2: Choose a method for setting de minimis limit and tolerability limit*

Taking into account the limitations involved in other methods given in Figure 3.12, it is decided to set the *de minimis* limit and tolerability limit through stakeholder consultation.

- *Step 3: Consider different risk perception factors*

Considering different risk perception factors applicable to fire safety engineering, it is important to choose a risk aversion factor (steepness of proof lines). Table A.2 shows the point-system analysis for the nightclub to select risk aversion factor. It is clear that the steepness of proof line needs to be 1.5 for the nightclub under consideration.

| Questions | Comments |
|---|---|
| • What is the occupancy type?<br>• Service provided by the building? | • Assembly and recreation (ADB Table D1 [107])<br>• Normal |
| • Who are exposed to the hazards? Any vulnerable population groups? | • Yes. Mostly youngsters will be visiting the nightclub. It is also important to note that people can be under the influence of alcohol. |
| • How many people are expected to be in the building? | • Fire investigation report of past nightclub fire incidents (Table A.5) were used to find the most conservative occupant density. Accordingly, it was found that a floor space factor of 0.33 $m^2$/person is the most conservative. Thus, for the nightclub in question, a maximum of 637 persons are considered. |
| • Is the building occupied 24x7? | • No. Only on Friday, Saturday and Sunday for 9 hours (from 18:00 hrs. to 03:00 hrs.) |
| • Are there any sleeping risks? | • No |
| • Are people familiar with the building layout? | • No |

Table A.1: Key questions answered for understanding the nightclub in question

- *Step 4: Set de minimis limit and tolerability limit (Individual risk and Societal risk)*

Reference values for the individual tolerability limit and individual *de minimis* limit as mentioned in Table A.1 of PD 7974-7:2019 [8] is $10^{-4}$ per year and $10^{-6}$ per year respectively. This is set for the nightclub under consideration.

For setting societal risk limits, the steps mentioned in Figure 3.16 can be used. Accordingly, anchor point 1 is to be set with stakeholder discussion. For the tolerability limit and *de minimis* limit, considering the fact that the occupancy is a nightclub with vulnerable population, a stringent criterion can be set. Therefore, from Figure 3.14 and Figure 3.15 considering the Hong Kong criteria, the following anchor points were set for the tolerability limit and *de minimis* limit respectively: (10, $10^{-4}$) and (10, $10^{-6}$). Table A.3 follows the steps mentioned in Figure 3.16 to construct the proof lines. Accordingly, Figure A.2 shows the proof lines for the nightclub under consideration.

| **Risk Perception Factors** | **Points** | **Comments** |
|---|---|---|
| Service of building under normal and emergency conditions | 0 | Service of building considered important in normal conditions as compared to a hospital building. |
| Importance of building | 0.5 | Medium importance since property protection and business continuity need to be considered from the perspective of fire safety goals. |
| Vulnerable population group | 1 | To be conservative, mostly vulnerable population is considered. |
| Sleeping Risk | 0 | No sleeping risk involved. |
| Potential for catastrophe and possibility to evacuate | 1 | Considering the past nightclub fire incidents. |
| Familiarity | 1 | Occupants are not familiar with the building layout. |
| Trust | 0.5 | In the wake of Grenfell Tower fire, the society losses trust on the government and authorities [58]. Thus, a moderate trust can be assigned. |
| **Total** | **4** | **Since total points is more than 3, the steepness of proof lines b = 1.5** |

Table A.2: Point-system analysis for nightclub to select risk aversion factor (steepness of proof lines)

| **Steps** | **Tolerability Limit** | ***de-minimis* Limit** |
|---|---|---|
| 1 | *Anchor point*: (10, $10^{-4}$) | *Anchor point*: (10, $10^{-6}$) |
| 2 | m = $10^{-4}$ x $10^{1.5}$ = 3.16 x $10^{-3}$ per year<br>Point 2: (1, 3.16 x $10^{-3}$) | m = $10^{-6}$ x $10^{1.5}$ = 3.16 x $10^{-5}$ per year<br>Point 2: (1, 3.16 x $10^{-5}$) |
| 3 | F(700) = (3.16 x $10^{-3}$) x $(700)^{-1.5}$ = 1.71 x $10^{-7}$ per year<br>Point 3: (700, 1.71 x $10^{-7}$) | F(700) = (3.16 x $10^{-5}$) x $(700)^{-1.5}$ = 1.71 x $10^{-9}$ per year<br>Point 3: (700, 1.71 x $10^{-9}$) |

Table A.3: Tolerability limit and *de minimis* limit for the nightclub under consideration

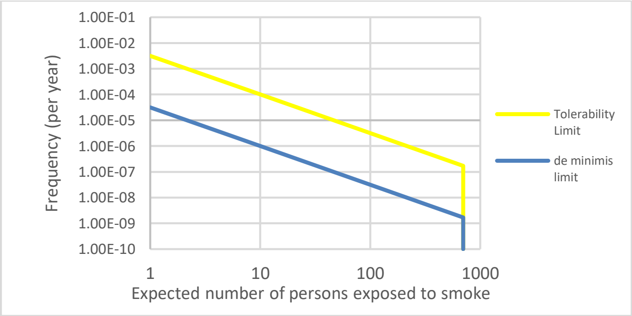


Figure A.2: Proof lines for the nightclub under consideration

- *Step 5: Stakeholder discussion*

Since this is a hypothetical case study, there are no stakeholders involved for discussion. However, in reality, for a similar case study, the following will be considered as the stakeholders: owner, operator, insurer, fire brigade, representatives of the occupants of the night club (for instance the student association members of the nearby university) and representatives of the occupants of the adjacent properties.

### Step 3: Select Design Fire - find ASET

To determine ASET the two-zone model B-RISK is used. As a starting point, data provided in table A.5 – area damage and percentage of fires for each category of fire spread (pubs, clubs, restaurants – all areas) of PD 7974-7:2003 [6] is utilized. As per Eurocode EN 1991-1-2, 2002 [126] the suggested heat release rate per unit area (HRRPUA) for fuel-controlled fires for theatre (cinema) occupancy is 500 kW/m$^2$. Due to the lack of data on the HRRPUA for nightclub and acknowledging the fact that a theatre contains similar materials for sound proofing as in a nightclub, HRRPUA for theatre is selected. Using the data for area of damage and HRRPUA, the heat release rate (HRR) is determined. Accordingly, for an ultra-fast fire growth rate (when non-fire retardant PU foam is used which is evident from past nightclub fires) and slow fire growth rate (when fire retardant PU foam is used [134]) time taken for smoke layer to reach 2 m above the floor level is determined (Table A.4) using B-RISK.

| Fire Growth Rate | Area of damage (m$^2$) | HRR (kW) | HRR (MW) | Time taken for smoke layer to reach 2 m above floor (min) | Remarks |
|---|---|---|---|---|---|
| **Ultrafast** | 1 | 500 | 0.50 | 1.70 | - |
| | 2 | 1000 | 1.00 | 1.42 | - |
| | 15 | 7500 | 7.50 | 1.40 | Flashover at 3.3 minutes |
| | 24 | 12000 | 12.00 | 1.40 | |
| | 101 | 50500 | 50.50 | 1.40 | |
| **Slow** | 1 | 500 | 0.50 | 4.45 | - |
| | 2 | 1000 | 1.00 | 4.45 | - |
| | 15 | 7500 | 7.50 | 4.45 | - |
| | 24 | 12000 | 12.00 | 4.45 | - |
| | 101 | 50500 | 50.50 | 4.45 | - |

Table A.4: ASET for different area of damage in nightclub under consideration

### Step 4: Evacuation calculations – find RSET

RSET was determined employing the hydraulic model specified in SFPE Handbook of Fire Protection Engineering [120]. However, following assumptions are made in the evacuation calculations:

- One exit is discounted and only main exit is available for evacuation.
- Once occupants pass through the exit, they are considered to be safe.
- Smoke detection system (an advanced multi-criteria detector) is provided.

- Occupants start egress approximately at the same time.

The key evacuation calculation input parameters (occupant density, detection time, alarm time and pre-evacuation time) for nightclub are adopted from the past nightclub fire investigation reports (Table A.5).

Table A.6 (slow fire growth rate) and Table A.7 (ultra-fast fire growth rate) shows the results of ASET-RSET analysis for the case where only the main entrance is available for evacuation. By performing ASET-RSET analysis, the expected number of persons who will be exposed to smoke (N) can be determined.

**Step 5: Identify the most conservative scenario**

The most conservative scenario is when the following conditions are satisfied:

- Only one exit is available for evacuation
- Fire growth rate is ultra-fast.
- Floor space factor is 0.33 $m^2$/person
- Detection time is 20 seconds (0.33 mins)
- Alarm time is 71 seconds (1.18 mins)
- Pre-movement time is 150 seconds (2.5 mins)

Therefore, in Table A.7, simulation 12 satisfies all these conditions and is considered to be the most conservative scenario.

**Step 6 & 7: Event tree analysis (ETA) and FN curve, Risk evaluation**

For the conservative scenario identified in step 5, an event tree is created. The ignition frequency is calculated based on the data given in table B.2 – overall probability of fire starting in various types of occupancy of PD 7974-7:2019 [8]. Accordingly, FN curve is produced for the most conservative scenario as shown in Figure A.3.

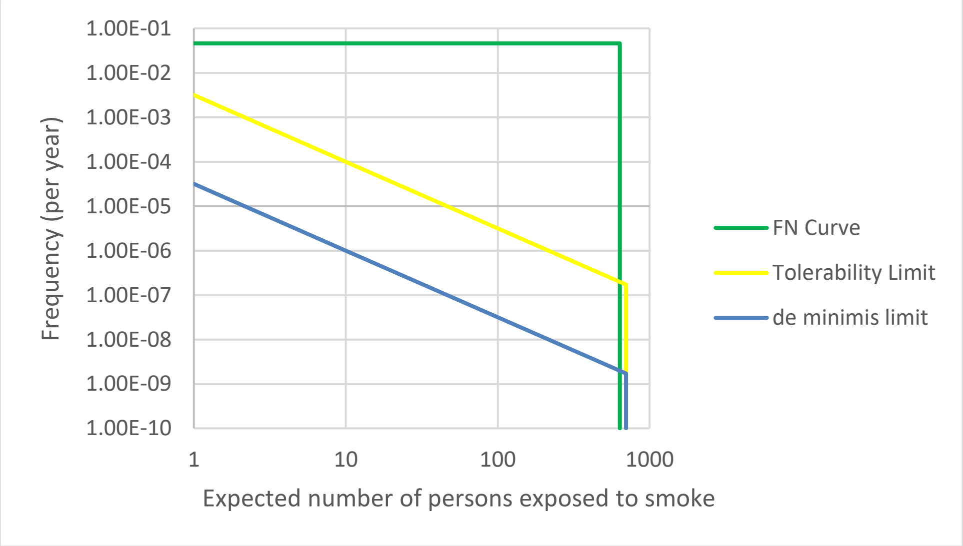


Figure A.3: FN curve for the most conservative scenario – Nightclub

It is clear from the Figure A.3 that the estimated risk is not acceptable. Hence, as per the methodology given in Figure 4.3, it is important to add more details in the event tree till a point where the risk can be tolerated demonstrating ALARP. Therefore, it is important to know which are the parameters that have an influence on the number of people exposed to smoke. For example, from Table A.6 and Table A.7, it is evident that area of damage, occupant density (floor space factor), pre-movement time and fire growth rate have an influence on the number of people exposed to smoke. Accordingly, each of these details are included in the event tree till the point where FN curve falls in the tolerable region and ALARP can be demonstrated. The event tree developed for the nightclub case study is given in Figure A.4. The probabilities indicated in the branches of event tree is discussed in Table A.8.

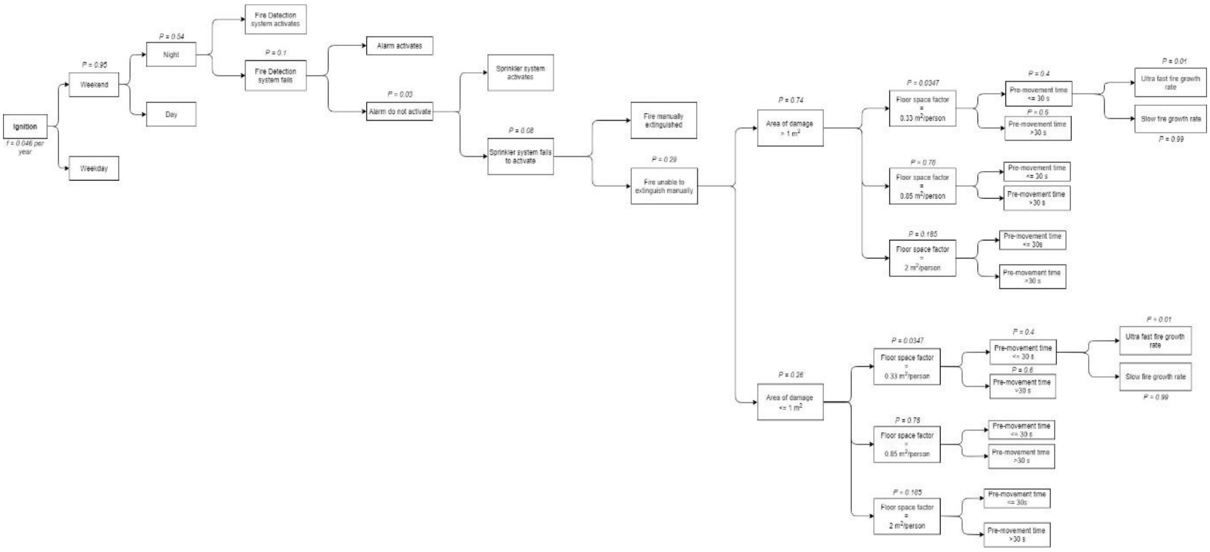
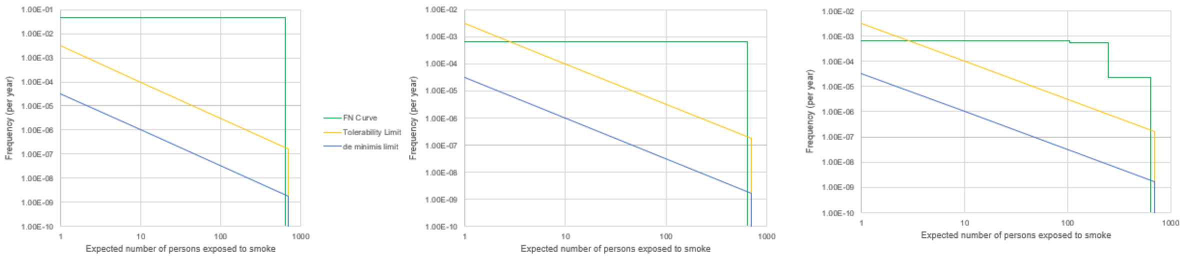
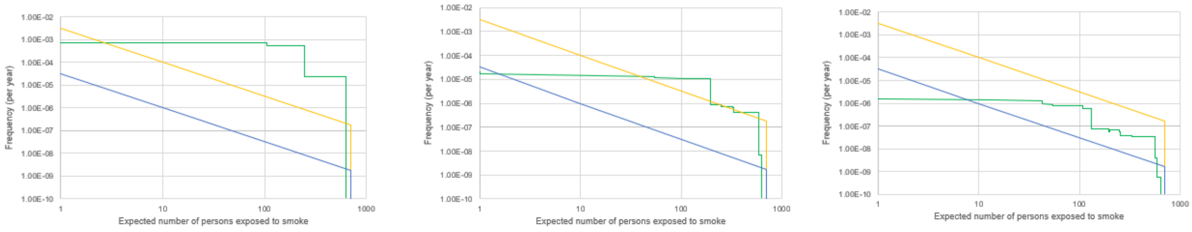


Figure A.4: Event tree developed for the nightclub case study

Changes in the FN curve when more details are added into the event tree can be seen in Figure A.5.



**Case 1: Conservative scenario** **Case 2: Area of damage details included** **Case 3: Occupant density details included**



**Case 4: Pre-movement time included** **Case 5: Fire Growth details included** **Case 6: Sprinkler reliability details added**

Figure A.5: FN curves for nightclub when more details are added to event tree

Since the expected risk falls in the tolerable region when more details are added to the event tree, it is important to demonstrate ALARP. At the same time, the person-specific individual risk for a hypothetical person is determined for the case 6 considering the occupancy patterns using Equation 3. The hypothetical person is assumed to be located at the farthest point of the compartment and is the last person to exit the door. The person-specific individual risk is found to be 1.35 x $10^{-6}$ per year which is in the tolerable region of risk.

**Step 8: ALARP assessment**

From the event tree, summing up the product of each scenario frequencies and the corresponding expected number of people exposed to smoke, the expected risk is determined. The expected risk in the absence of sprinkler system in the nightclub is 1.78 x $10^{-3}$ per year. In the presence of a sprinkler system, the expected risk is 1.42 x $10^{-4}$ per year. Therefore, the residual risk ($-\Delta RI$) if the sprinkler is installed is 1.64 x $10^{-3}$ per year.

If both the cost of installation of sprinkler system and its maintenance is known ($\Delta C$) then Equation 6 can be used to demonstrate ALARP. In this case,

$\text{SCCR}_{1life}$ ($-\Delta RI$) = (2.26 million GBP per year) x (1.64 x $10^{-3}$ per year) = 4250 GBP per year for a floor.

If $\Delta C \leq$ 4250 GBP per year, then it is necessary to install the sprinklers. However, further analysis can be done such as whether a specific type of a sprinkler system need to be installed or a smoke heat extraction system need to be installed etc. On the other hand, if $\Delta C$ > 4250 GBP per year, then it is not necessary to install the sprinklers since the original design is already ALARP.

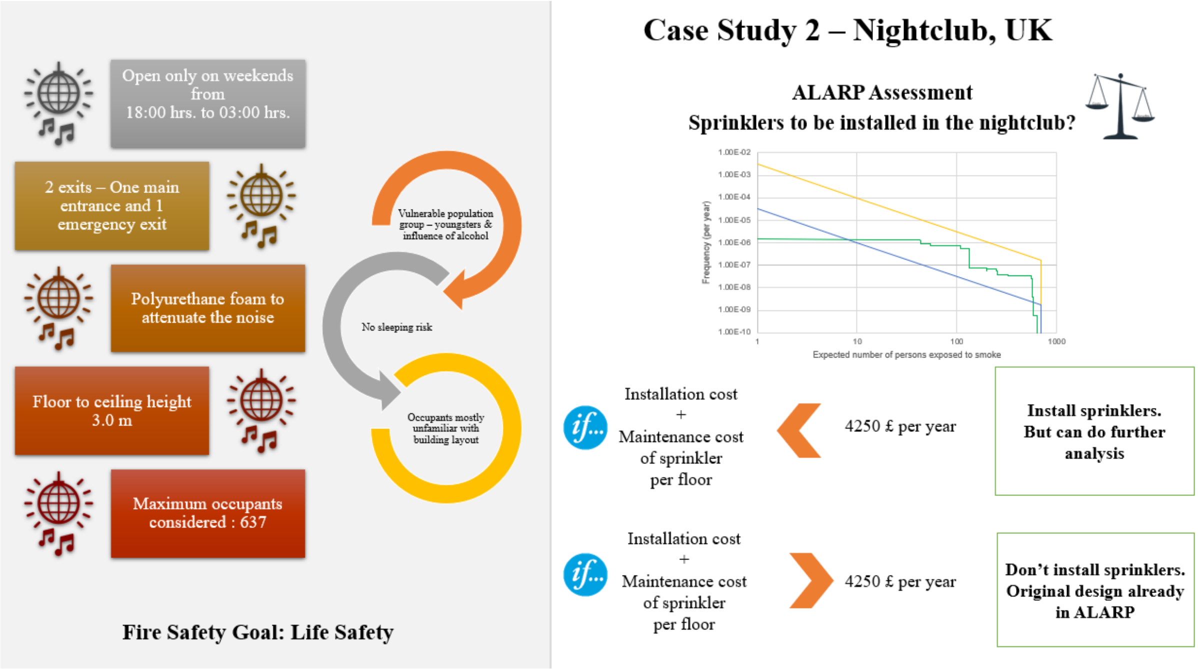


Figure A.6: PRA for the nightclub in a nutshell

Table A.5 provides the details of past night clubs fires so as to determine the occupant density during overcrowding and other evacuation time related parameters. Table A.6 and Table A.7 provides results of ASET-RSET analysis performed for the nightclub case study.

| **Sl. No.** | **Incident** | **Location** | **Year** | **No. of people** | **Conservative value for calculation – no. of people** | **Area ($m^2$)** | **Max. capacity** | **Floor space factor ($m^2$/person)** | **% exceedance than max. capacity** | **Fatalities** | **Detection time (s)** | **Alarm time (s)** | **Pre-movement time (s)** | **Reference** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Kiss | Brazil | 2013 | 1200-1300 | 1300 | 615 | 700 | 0.47 | 85.71 | 230 | - | - | - | [135,136] |
| 2 | Lame Horse Club | Russia | 2009 | > 200 and 280 invited for party | 300 | 500 | 450 | 1.67 | 33.33 | 156 | - | - | - | [136] |
| 3 | Santika | Thailand | 2009 | 1000-1200 | 1200 | 1683 | - | - | - | 67 | - | - | - | [136,137] |
| 4 | Lund | Scotland, UK | 2009 | 400 | - | - | - | - | - | - | - | 71 | 150 | [136] |
| 5 | República Cromañón | Argentina | 2004 | 2811-3000 | 3000 | - | 1031 | - | - | 193 | - | - | - | [136] |
| 6 | The Station | USA | 2003 | 455 | 455 | 412 | - | 0.91 | - | 100 | 10 to 20 (human detection) | 40 | 18, 24, 30, 41 | [136,138] |
| 7 | Fine Line Music Café | USA | 2003 | 120 | - | - | - | - | - | 0 | - | - | - | [136] |
| 8 | La Goajira | Venezuela | 2002 | 400 | 400 | - | - | - | - | 47 | - | - | - | [136] |
| 9 | Gothenburg Dancehall | Sweden | 1998 | 400 | 400 | 215 | 150 | 0.54 | 62.50 | - | - | - | - | [139] |
| 10 | Beverly Hills Supper club | USA | 1977 | 2400-2800 | 2800 | - | - | - | - | 165 | - | - | - | [140] |
| 11 | Cocoanut Grove | USA | 1942 | 1000 | 1000 | 335 | 600 | 0.33 | 66.67 | 492 | - | - | - | [140] |
| 12 | Rhythm club | USA | 1940 | 700 | 700 | 425 | - | 0.61 | - | 207 | - | - | - | [140] |

Table A.5: Analysis of past nightclub fire incidents

| **Sl. No** | **Floor Space Factor ($m^2$/p)** | **No. of people** | **Detection time (min)** | **Alarm time (min)** | **Pre-movement time (min)** | **Total evacuation time – RSET (mins)** | **Expected no. of people exposed to smoke - area of damage ≤ 1 $m^2$** | **Expected no. of people exposed to smoke - area of damage > 1 $m^2$** |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.33 | 637 | 0.16 | 0.66 | 0.30 | 7.35 | 249 | 249 |
| 2 | | | | | 0.52 | 7.57 | 274 | 275 |
| 3 | | | | | 2.5 | 9.55 | 506 | 507 |
| 4 | | | | 1.18 | 0.30 | 7.87 | 309 | 310 |
| 5 | | | | | 0.52 | 8.09 | 335 | 335 |
| 6 | | | | | 2.5 | 10.07 | 567 | 567 |
| 7 | | | 0.33 | 0.66 | 0.30 | 7.52 | 269 | 269 |
| 8 | | | | | 0.52 | 7.74 | 294 | 294 |
| 9 | | | | | 2.5 | 9.72 | 526 | 526 |
| 10 | | | | 1.18 | 0.30 | 8.04 | 329 | 329 |
| 11 | | | | | 0.52 | 8.25 | 354 | 355 |
| 12 | | | | | 2.5 | 10.24 | 586 | 587 |
| 13 | 0.85 | 248 | 0.16 | 0.66 | 0.30 | 3.47 | 0 | 0 |
| 14 | | | | | 0.52 | 3.69 | 0 | 0 |
| 15 | | | | | 2.5 | 5.67 | 118 | 118 |
| 16 | | | | 1.18 | 0.30 | 3.99 | 0 | 0 |
| 17 | | | | | 0.52 | 4.21 | 0 | 0 |
| 18 | | | | | 2.5 | 6.19 | 178 | 178 |
| 19 | | | 0.33 | 0.66 | 0.30 | 3.64 | 0 | 0 |
| 20 | | | | | 0.52 | 3.86 | 0 | 0 |
| 21 | | | | | 2.5 | 5.84 | 137 | 137 |
| 22 | | | | 1.18 | 0.30 | 4.16 | 0 | 0 |
| 23 | | | | | 0.52 | 4.37 | 0 | 0 |
| 24 | | | | | 2.5 | 6.36 | 197 | 198 |
| 25 | 2 | 105 | 0.16 | 0.66 | 0.30 | 2.20 | 0 | 0 |
| 26 | | | | | 0.52 | 2.42 | 0 | 0 |
| 27 | | | | | 2.5 | 4.40 | 0 | 0 |
| 28 | | | | 1.18 | 0.30 | 2.72 | 0 | 0 |
| 29 | | | | | 0.52 | 2.94 | 0 | 0 |
| 30 | | | | | 2.5 | 4.92 | 35 | 35 |
| 31 | | | 0.33 | 0.66 | 0.30 | 2.37 | 0 | 0 |
| 32 | | | | | 0.52 | 2.59 | 0 | 0 |
| 33 | | | | | 2.5 | 4.57 | 1 | 1 |
| 34 | | | | 1.18 | 0.30 | 2.89 | 0 | 0 |
| 35 | | | | | 0.52 | 3.10 | 0 | 0 |
| 36 | | | | | 2.5 | 5.09 | 55 | 55 |

Table A.6: ASET-RSET analysis result – Slow fire growth rate - only main entrance available for evacuation - Nightclub

| Sl. No | Floor Space Factor ($m^2$/p) | No. of people | Detection time (min) | Alarm time (min) | Pre-movement time (min) | Total evacuation time – RSET (mins) | Expected no. of people exposed to smoke - area of damage ≤ 1 $m^2$ | Expected no. of people exposed to smoke - area of damage > 1 $m^2$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.33 | 637 | 0.16 | 0.66 | 0.30 | 7.35 | 571 | 606 |
| 2 | | | | | 0.52 | 7.57 | 596 | 632 |
| 3 | | | | | 2.5 | 9.55 | 637 | 637 |
| 4 | | | | 1.18 | 0.30 | 7.87 | 631 | 637 |
| 5 | | | | | 0.52 | 8.09 | 637 | 637 |
| 6 | | | | | 2.5 | 10.07 | 637 | 637 |
| 7 | | | 0.33 | 0.66 | 0.30 | 7.52 | 590 | 626 |
| 8 | | | | | 0.52 | 7.74 | 616 | 637 |
| 9 | | | | | 2.5 | 9.72 | 637 | 637 |
| 10 | | | | 1.18 | 0.30 | 8.04 | 637 | 637 |
| 11 | | | | | 0.52 | 8.25 | 637 | 637 |
| 12 | | | | | 2.5 | 10.24 | 637 | 637 |
| 13 | 0.85 | 248 | 0.16 | 0.66 | 0.30 | 3.47 | 182 | 217 |
| 14 | | | | | 0.52 | 3.69 | 207 | 243 |
| 15 | | | | | 2.5 | 5.67 | 248 | 637 |
| 16 | | | | 1.18 | 0.30 | 3.99 | 242 | 637 |
| 17 | | | | | 0.52 | 4.21 | 248 | 637 |
| 18 | | | | | 2.5 | 6.19 | 248 | 637 |
| 19 | | | 0.33 | 0.66 | 0.30 | 3.64 | 201 | 237 |
| 20 | | | | | 0.52 | 3.86 | 227 | 248 |
| 21 | | | | | 2.5 | 5.84 | 248 | 248 |
| 22 | | | | 1.18 | 0.30 | 4.16 | 248 | 248 |
| 23 | | | | | 0.52 | 4.37 | 248 | 248 |
| 24 | | | | | 2.5 | 6.36 | 248 | 248 |
| 25 | 2 | 105 | 0.16 | 0.66 | 0.30 | 2.20 | 39 | 74 |
| 26 | | | | | 0.52 | 2.42 | 64 | 100 |
| 27 | | | | | 2.5 | 4.40 | 105 | 105 |
| 28 | | | | 1.18 | 0.30 | 2.72 | 99 | 105 |
| 29 | | | | | 0.52 | 2.94 | 105 | 105 |
| 30 | | | | | 2.5 | 4.92 | 105 | 105 |
| 31 | | | 0.33 | 0.66 | 0.30 | 2.37 | 58 | 94 |
| 32 | | | | | 0.52 | 2.59 | 84 | 105 |
| 33 | | | | | 2.5 | 4.57 | 105 | 105 |
| 34 | | | | 1.18 | 0.30 | 2.89 | 105 | 105 |
| 35 | | | | | 0.52 | 3.10 | 105 | 105 |
| 36 | | | | | 2.5 | 5.09 | 105 | 105 |

Table A.7: ASET-RSET analysis result – Ultrafast fire growth rate – only main entrance available for evacuation – Nightclub

Probabilities assigned at each branch of event tree developed for night club case study as given in Figure A.4 is provided in Table A.8.

| Particulars | Value | Reference/Comments |
|---|---|---|
| Probability of fire occurring in the weekends | 0.95 | [141] |
| Probability of fire occurring in the weekdays | 0.05 | |
| Probability of fire occurring during the day | 0.46 | |
| Probability of fire occurring during the night | 0.54 | |
| Probability of fire occurring for fires causing damage ≤ 1 $m^2$ | 0.26 | Table A.5 [6] |
| Probability of fire occurring for fires causing damage > 1 $m^2$ | 0.74 | |
| Probability of successful extinguishment of fires by occupants | 0.71 | [128] |
| Probability of not successful extinguishment of fires by occupants | 0.29 | |
| Probability of fire detection fails | 0.1 | Table A.17 [6] |
| Probability of failure of alarm box, wiring and sounders | 0.03 | Table A.17 [6] |
| Probability of having a floor space factor of 0.33 $m^2$/person | 0.0347 | Overcrowding assumes to happen 5 times a year (Halloween day, private events, new year, club promotion) i.e. 45 hrs. out of 1296 hrs. club operates in a year. |
| Probability of having a floor space factor of 0.85 $m^2$/person | 0.78 | Night club will not be always crowded. Thus, it is expected that 78% of the time, a floor space factor of 0.85 $m^2$/person can occur. |
| Probability of having a floor space factor of 2 $m^2$/person | 0.185 | Assumed since the chance of having a floor space factor of 2 $m^2$/person is not that likely compared to 0.85 $m^2$/person. |
| Probability of pre-movement time ≤ 30 s | 0.4 | Based on the past nightclub fire incidents |
| Probability of pre-movement time > 30 s | 0.6 | |
| Probability of ultra-fast fire growth rate with fire retardant PU foam | 0.01 | Assumed based on [134] |
| Probability of slow fire growth rate with fire retardant PU foam | 0.99 | |
| Probability of failure of sprinklers in nightclubs | 0.08 | Table B.1 – PD 7974:7-2019 [8] |

Table A.8: Probabilities assigned at each branch of event tree – Nightclub

## Annexure B – Case Study 3 - Indoor kids play area, UK

An indoor kids' play area assumed to be located in England is considered for the study. The indoor kids play area for the children aged between 3 years and 12 years is expected to be operational every day from 10:00 hrs. to 18:00 hrs. The entrance door and emergency exit as shown in Figure B.1 is 1.2 m wide respectively. The play area consists of a play structure which is 2.6 m high with various slides, tunnels and ball shooting arena. Apart from parents there are some staffs to take care of the children in the play area. The floor to ceiling height is taken as 4 m. The building elements are constructed with concrete. Fire detection (smoke detectors) and alarm systems are provided in the building.

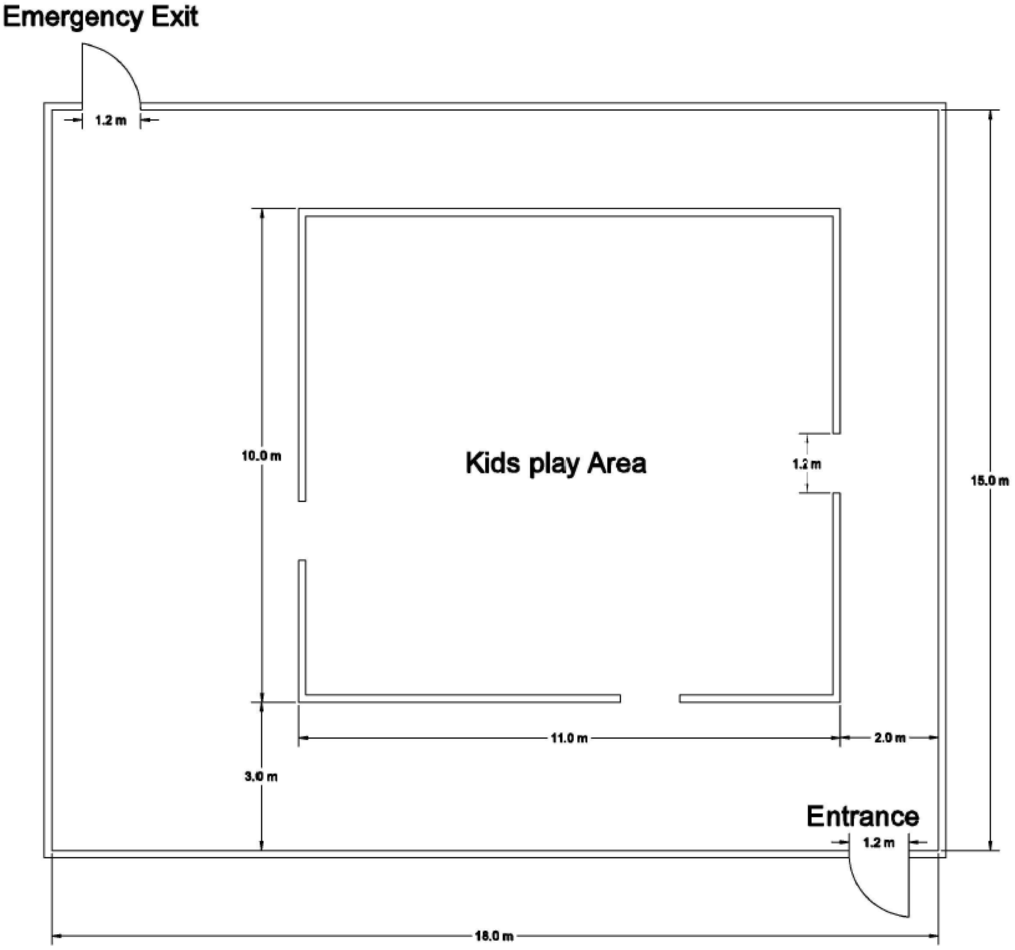


Figure B.1: Floor plan of indoor kids play area considered for the study

### Step 1: Set fire safety goals, design objectives and performance indicators

The fire safety goal, design objective and performance indicators are set for indoor kids play area as shown in Figure B.2.

The indoor play structure is 2.6 m high. Considering the fact that kids will be present at these heights when a fire breaks out, the performance indicator is set such that the occupants need to escape before the smoke free layer height from the floor level reduces to 2.8 m.

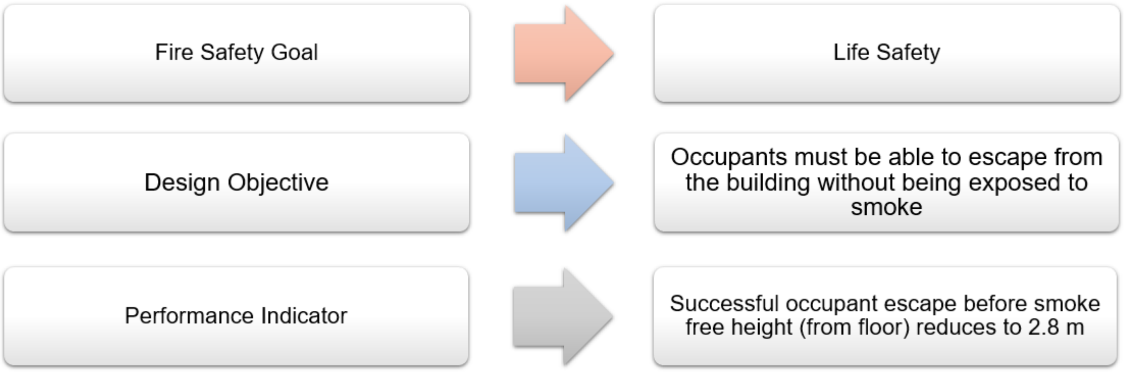


Figure B.2: Fire safety goal, design objective and performance indicator for the indoor kids play area case study

**Step 2: Set the risk tolerability limit and broadly acceptable limit**

- *Step 1: Know the facility in question*

Step by step procedure as indicated in Figure 3.9 (risk tolerability framework) is followed here. Table B.1 provides answers for the key questions so as to understand the indoor kids play area in question.

| Questions | Comments |
|---|---|
| • What is the occupancy type?<br>• Service provided by the building? | • Assembly and recreation (ADB Table D1 [107])<br>• Normal |
| • Who are exposed to the hazards? Any vulnerable population groups? | • Yes. Kids are considered as vulnerable population. Parents who accompany the kids and the staffs who will be taking care of kids in the play area will be exposed to the hazards. |
| • How many people are expected to be in the building? | • Since data pertaining to floor space factor of indoor kids play area is unavailable, Table C1 – floor space factors of ADB [107] is utilized. These values are usually very conservative [142]. Therefore, a floor space factor of 0.5 $m^2$/person corresponding to amusement arcade or assembly hall is chosen. Accordingly, a maximum of 320 people is expected in the building. |
| • Is the building occupied 24x7? | • No. |
| • Are there any sleeping risks? | • No |
| • Are people familiar with the building layout? | • No |

Table B.1: Key questions answered for understanding the indoor kids play area in question

- *Step 2: Choose a method for setting de minimis limit and tolerability limit*

Taking into account the limitations involved in other methods given in Figure 3.12, it is decided to set the *de minimis* limit and tolerability limit through stakeholder consultation.

- *Step 3: Consider different risk perception factors*

Considering different risk perception factors applicable to fire safety engineering, it is important to choose a risk aversion factor (steepness of proof lines). Table B.2 shows the point-system analysis for the nightclub to select risk aversion factor. It is clear that the steepness of proof line needs to be 1.5 for the indoor kids play area under consideration.

| Risk Perception Factors | Points | Comments |
|---|---|---|
| Service of building under normal and emergency conditions | 0 | Service of building considered important in normal conditions as compared to a hospital building. |
| Importance of building | 0.5 | Medium importance since property protection and business continuity need to be considered from the perspective of fire safety goals. |
| Vulnerable population group | 1 | Yes. Kids aged 3 years and 12 years. |
| Sleeping Risk | 0 | No sleeping risk involved. |
| Potential for catastrophe and possibility to evacuate | 1 | Considering the fact that parents try to take their kids from the play area before they evacuate can result in delays. Therefore, there is a potential for catastrophe. |
| Familiarity | 1 | Occupants will be unfamiliar with the building layout. |
| Trust | 0.5 | In the wake of Grenfell Tower fire, the society losses trust on the government and authorities [58]. Thus, a moderate trust can be assigned. |
| **Total** | **4** | **Since total points is more than 3, the steepness of proof lines b = 1.5** |

Table B.2: Point-system analysis for indoor kids play area to select risk aversion factor (steepness of proof lines)

- *Step 4: Set de minimis limit and tolerability limit (Individual risk and Societal risk)*

Reference values for the individual tolerability limit and individual *de minimis* limit as mentioned in Table A.1 of PD 7974-7:2019 [8] is $10^{-4}$ per year and $10^{-6}$ per year respectively. This is set for the indoor kids play area building under consideration. For setting societal risk limits, the steps mentioned in Figure 3.16 can be used. Accordingly, anchor point 1 is to be set with stakeholder discussion. For the tolerability limit and *de minimis* limit, considering the fact that the occupancy type considered is an indoor kids' play area (vulnerable population), a stringent criterion can be set. Therefore, from Figure 3.14 and Figure 3.15 considering the Hong Kong tolerability limit, an anchor point (10, $10^{-4}$) is set for the tolerability limit. Similarly, considering the Sweden underground bus station *de-minimis* criteria an anchor point (10, $10^{-7}$) is set as the *de minimis* limit. Table B.3 follows the steps mentioned in Figure 3.16 to construct the proof lines. Accordingly, Figure B.4 shows the proof lines for the indoor kids play area building.

| **Steps** | **Tolerability Limit** | ***de-minimis* Limit** |
|---|---|---|
| 1 | *Anchor point*: (10, $10^{-4}$) | *Anchor point*: (10, $10^{-7}$) |
| 2 | m = $10^{-4}$ x $10^{1.5}$ = 3.16 x $10^{-3}$ per year<br>Point 2: (1, 3.16 x $10^{-3}$) | m = $10^{-7}$ x $10^{1.5}$ = 3.16 x $10^{-6}$ per year<br>Point 2: (1, 3.16 x $10^{-6}$) |
| 3 | F(600) = (3.16 x $10^{-3}$) x $(600)^{-1.5}$ = 2.15 x $10^{-7}$ per year<br>Point 3: (600, 2.15 x $10^{-7}$) | F(600) = (3.16 x $10^{-6}$) x $(600)^{-1.5}$ = 2.15 x $10^{-10}$ per year<br>Point 3: (600, 2.15 x $10^{-10}$) |

Figure B.3: Tolerability limit and *de minimis* limit for indoor kids play area building

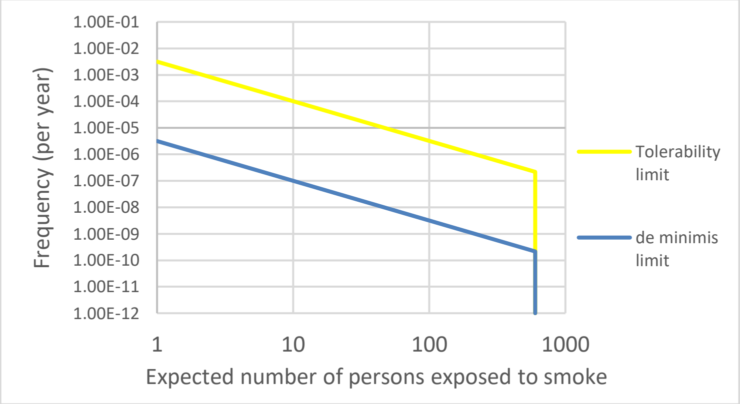


Figure B.4: Proof lines for the indoor kids play area building

- *Step 5: Stakeholder discussion*

Since this is a hypothetical case study, there are no stakeholders involved for discussion. However, in reality, for a similar project, the following will be considered as the stakeholders: owner, operator, insurer, fire brigade, representatives of the occupants of the indoor kids play area (for instance the community association of the nearby residential area) and representatives of the occupants of the adjacent properties.

**Step 3: Select Design Fire - find ASET**

To determine ASET, the two-zone model B-RISK is used. Since statistical data pertaining to area of damage of indoor kids play area is unavailable, the area of damage is assumed. For HRRPUA, the 'general' recommended values for use in fire safety design provided by Fleischmann [143] is referred. Accordingly, from a maximum HRRPUA range, 262 kW/m$^2$ is selected for the indoor kids play area. Comparing with the range of potential values of

HRRPUA for shops and offices [119], the selected HRRPUA value for the indoor kids play area is reasonable. Using the data for area of damage and HRRPUA, the heat release rate (HRR) is determined. Accordingly, for fast fire growth rate (if the materials of play structure are not fire retardant) and slow fire growth rate (if the materials of play structure are fire retardant), time taken for smoke layer to reach 2.8 m above the floor level is determined using B-RISK. Table B.3 to Table B.6 provides the ASET for different cases (in the absence and presence of ceiling vents - natural ventilation). The ceiling vents are expected to operate once smoke detection system activates. Therefore, to be conservative, a delay of 30 s is incorporated in B-RISK for the opening of the smoke vents.

**Step 4: Evacuation calculations – find RSET**

RSET is determined employing evacuation simulation software Pathfinder version 2018:3.0730. However, following assumptions are made in the evacuation calculations:

- Initially one exit is discounted and only main exit is available for evacuation.
- Once occupants pass through the exit, they are considered to be safe.

The key evacuation calculation input parameters (alarm time and pre-evacuation time) for indoor kids play area are adopted from the study conducted on evacuation of children focusing on daycare centers and elementary schools [144]. The input data for evacuation simulations are given in Table B.7.

Table B.8 to Table B.15 provides the results of ASET-RSET analysis for the following cases:

| **Fire growth rate** | **2 exits available for evacuation?**<br>✓- 2 exits available for evacuation<br>✗ - 1 exit available for evacuation | **Ceiling vents available?**<br>✓ - Yes<br>✗ - No | **Reference table in Annex B** |
|---|---|---|---|
| **Fast** | ✗ | ✗ | Table B.8 |
| | ✓ | ✗ | Table B.9 |
| | ✗ | ✓ | Table B.10 |
| | ✓ | ✓ | Table B.11 |
| **Slow** | ✗ | ✗ | Table B.12 |
| | ✓ | ✗ | Table B.13 |
| | ✗ | ✓ | Table B.14 |
| | ✓ | ✓ | Table B.15 |

**Step 5: Identify the most conservative scenario**

The most conservative scenario is when the following conditions are satisfied:

- Only one exit is available for evacuation and no ceiling vents available
- Floor space factor is 0.50 $m^2$/person
- Area of damage more than 1 $m^2$ and fast fire growth rate

Therefore, from Table B.8 simulation 1 satisfies all these conditions and is considered as the most conservative scenario.

### Step 6 & 7: Event tree analysis (ETA) and FN curve, Risk evaluation

For the conservative scenario identified in step 5, an event tree is created. The ignition frequency is calculated based on the data given in table A.3 – probability of fire starting within given floor area for various types of occupancy of PD 7974-7:2003 [6]. However, the ignition frequency considered in this case study is that of the school since occupants involves both adults and kids. Accordingly, FN curve is produced for the most conservative scenario as shown in Figure B.5.

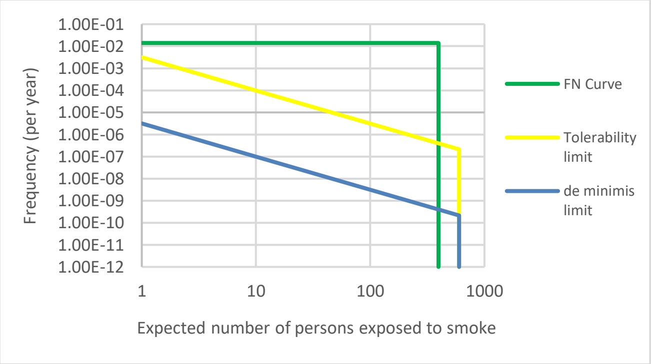


Figure B.5: FN curve for the most conservative scenario – Indoor kids play area

It is clear from the Figure B.5 that the estimated risk is not acceptable. Hence, as per the methodology given in Figure 4.3, it is important to add more details in the event tree. Therefore, it is important to know which are the parameters that can have an influence on the number of people exposed to smoke. For example, from Table B.8 to Table B.15, it is evident that area of damage, occupant density (floor space factor), area of damage, fire growth rate, number of exits available for evacuation and the presence of ceiling vents have an influence on the number of people exposed to smoke. Accordingly, each of these details are included in the event tree till the point FN curve falls in the tolerable region and ALARP can be demonstrated. The event tree developed for the indoor kids play area case study is given in Figure B.6. The probabilities indicated in the branches of event tree is discussed in Table B.16.

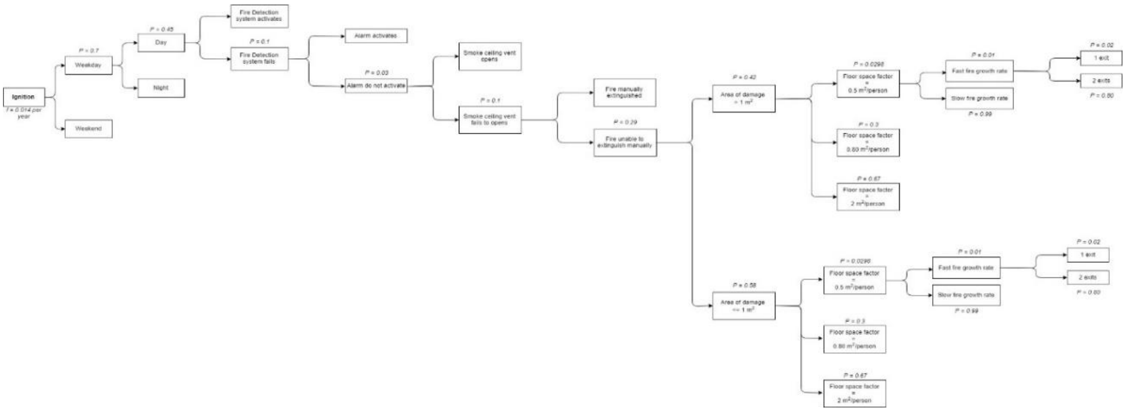
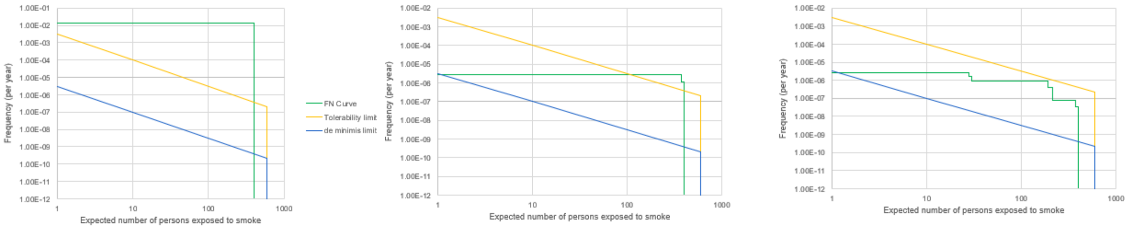
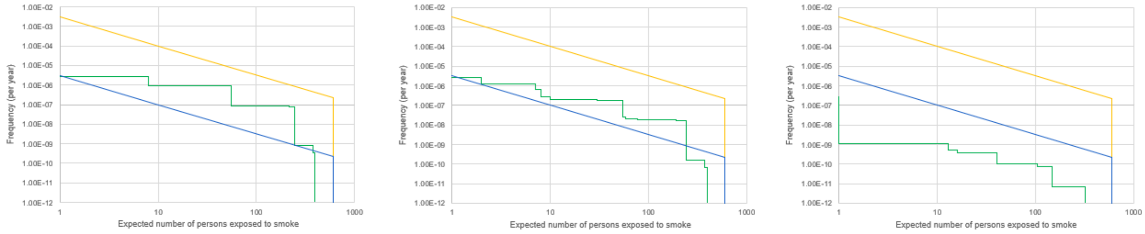


Figure B.6: Event tree developed for the indoor kids play area building

Changes in the FN curve when more details are added into the event tree can be seen in Figure B.7.



**Case 1: Conservative scenario** **Case 2: Area of damage details included** **Case 3: Occupant density details included**



**Case 4: Fire growth rate data included** **Case 4: 2 exits for evacuation data included** **Case 6: Smoke vent reliability details added**

Figure B.7: FN curves for indoor kids play area when more details are added to event tree

Since the expected risk falls in the broadly acceptable region, *AC2 de minimis acceptance criterion* applies. At the same time, the person-specific individual risk for a hypothetical person is determined for the case 6 considering the occupancy patterns using Equation 3. The hypothetical person is assumed to be located at the farthest point of the compartment and is the last person to exit the door. The person-specific individual risk is found to be 1.12 x $10^{-9}$ per year which is in the *de minimis* region.

### Step 8: ALARP assessment

In this case, it is not a requirement to demonstrate ALARP since the design is in the *de minimis* zone of the FN diagram. However, to illustrate the output of Equation 6, ALARP assessment is performed.

From the event tree, summing up the product of each scenario frequencies and the corresponding expected number of people exposed to smoke, the expected risk is determined. The expected risk in the absence of ceiling vents in the indoor kids play area is 2.47 x $10^{-5}$ per year. In the presence of ceiling vents and its successful operation, the expected risk is 3.59 x $10^{-8}$ per year. Therefore, the residual risk ($-\Delta RI$) if the ceiling vents are installed is 2.46 x $10^{-5}$ per year.

If both the cost of installation of ceiling vents and its maintenance is known ($\Delta C$) then Equation 6 can be used to demonstrate ALARP. In this case,

$\text{SCCR}_{1life}(-\Delta RI)$ = (2.26 million GBP per year) x (2.46 x $10^{-5}$ per year) = 64.00 GBP per year

Since $\Delta C$ > 64.00 GBP per year, it is not necessary to install the ceiling vents which will open once smoke detection system activates. This is due to the fact that the design is already ALARP. However, if the owner wants to include the ceiling vents even after knowing the investment to be made (and also that it is not mandatory as per the ALARP assessment), it can be included in the design.

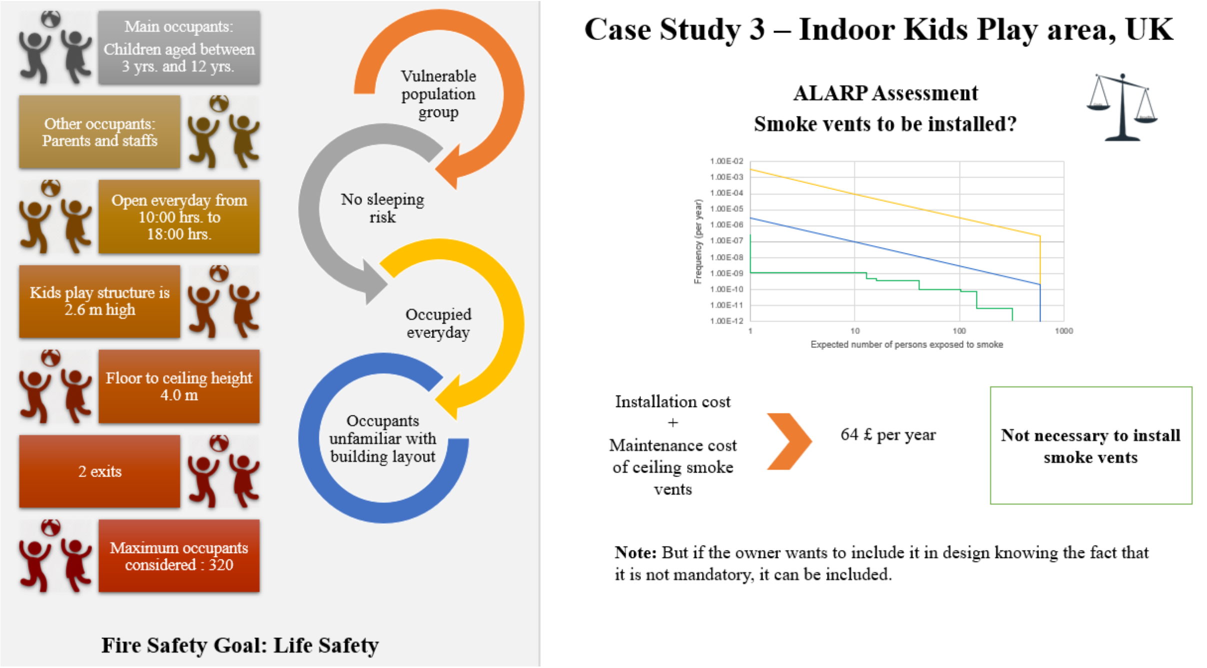


Figure B.8: PRA for the indoor kids play area in a nutshell

ASET analysis performed for different area of damage in the indoor kids play area provided one exit door is open and ceiling smoke vents are not available is given in Table B.3.

| Fire Growth Rate | Area of damage ($m^2$) | HRR (kW) | HRR (MW) | Time taken for smoke layer to reach 2.8 m above floor (min) | Remarks |
|---|---|---|---|---|---|
| **Fast** | 1 | 262 | 0.262 | 2.27 | - |
| | 2 | 524 | 0.524 | 1.98 | - |
| | 5 | 1310 | 1.310 | 1.97 | 4.7 mins. Ventilation limit 3.6 MW |
| | 20 | 5240 | 5.240 | 1.97 | |
| | 100 | 26200 | 26.200 | 1.97 | |
| **Slow** | 1 | 262 | 0.262 | 3.97 | - |
| | 2 | 524 | 0.524 | 3.97 | - |
| | 5 | 1310 | 1.310 | 3.97 | - |
| | 20 | 5240 | 5.240 | 3.97 | - |
| | 100 | 26200 | 26.200 | 3.97 | - |

Table B.3: ASET for different area of damage in the indoor kids play area – without vents at the ceiling – 1 door open

ASET analysis performed for different area of damage in the indoor kids play area provided one exit door is open and ceiling smoke vents are available is given in Table B.4.

| **Fire Growth Rate** | **Area of damage ($m^2$)** | **HRR (kW)** | **HRR (MW)** | **Time taken for smoke layer to reach 2.8 m above floor (min)** | **Remarks** |
|---|---|---|---|---|---|
| **Fast** | 1 | 262 | 0.262 | - | Smoke free layer height of 3.1 m from floor |
| | 2 | 524 | 0.524 | - | |
| | 5 | 1310 | 1.310 | 2.85 | - |
| | 20 | 5240 | 5.240 | 2.85 | - |
| | 100 | 26200 | 26.200 | 2.85 | 8.4 mins - flashover |
| **Slow** | 1 | 262 | 0.262 | - | Smoke free layer height of 3.1 m from floor |
| | 2 | 524 | 0.524 | - | |
| | 5 | 1310 | 1.310 | 9.28 | - |
| | 20 | 5240 | 5.240 | 9.28 | - |
| | 100 | 26200 | 26.200 | 9.28 | - |

Table B.4: ASET for different area of damage in the indoor kids play area – with vents at the ceiling ($2m^2$ ceiling vent[2] – total opening area) – 1 door open

ASET analysis performed for different area of damage in the indoor kids play area provided two exit doors are open and ceiling smoke vents are unavailable is given in Table B.5.

| **Fire Growth Rate** | **Area of damage ($m^2$)** | **HRR (kW)** | **HRR (MW)** | **Time taken for smoke layer to reach 2.8 m above floor (min)** | **Remarks** |
|---|---|---|---|---|---|
| **Fast** | 1 | 262 | 0.262 | 2.27 | - |
| | 2 | 524 | 0.524 | 1.98 | - |
| | 5 | 1310 | 1.310 | 1.97 | 4.7 mins. Ventilation limit 3.6 MW |
| | 20 | 5240 | 5.240 | 1.97 | |
| | 100 | 26200 | 26.200 | 1.97 | |
| **Slow** | 1 | 262 | 0.262 | 3.97 | - |
| | 2 | 524 | 0.524 | 3.97 | - |
| | 5 | 1310 | 1.310 | 3.97 | - |
| | 20 | 5240 | 5.240 | 3.97 | - |
| | 100 | 26200 | 26.200 | 3.97 | - |

Table B.5: ASET for different area of damage in the indoor kids play area – without vents at the ceiling – 2 doors open

ASET analysis performed for different area of damage in the indoor kids play area provided two exit doors are open and ceiling smoke vents are available is given in Table B.6.

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[2] 2 $m^2$ ceiling vent provided since it is seen from the zone modeling that it can maintain a smoke free layer height of at least 3.1 m from the floor level.

| Fire Growth Rate | Area of damage ($m^2$) | HRR (kW) | HRR (MW) | Time taken for smoke layer to reach 2.8 m above floor (min) | Remarks |
|---|---|---|---|---|---|
| **Fast** | 1 | 262 | 0.262 | - | Smoke free layer height of 3.2 m from floor |
| | 2 | 524 | 0.524 | - | |
| | 5 | 1310 | 1.310 | 2.93 | - |
| | 20 | 5240 | 5.240 | 2.93 | - |
| | 100 | 26200 | 26.200 | 2.93 | 8.7 mins - flashover |
| **Slow** | 1 | 262 | 0.262 | - | Smoke free layer height of 3.2 m from floor |
| | 2 | 524 | 0.524 | - | |
| | 5 | 1310 | 1.310 | 9.83 | - |
| | 20 | 5240 | 5.240 | 9.83 | - |
| | 100 | 26200 | 26.200 | 9.83 | - |

Table B.6: ASET for different area of damage in the indoor kids play area – with vents at the ceiling ($2m^2$ ceiling vent – total opening area) – 2 doors open

The input parameters for the evacuation simulations performed using Pathfinder for the indoor kids play area case study is provided in Table B.7.

| Category of people | Particulars | Distribution type | Minimum value | Maximum value | Reference |
|---|---|---|---|---|---|
| **Adults** | Movement speed | Uniform | 0.5 m/s | 1.7 m/s | [145] |
| | Diameter | | 0.45 m | 0.50 m | [146] |
| | Height | | 1.39 m | 2.13 m | [147] |
| **Kids ≤ 9 years old** | Movement speed | Uniform | 0.42 m/s | 1.36 m/s | [144] |
| | Diameter | | 0.38 m | 0.43 m | [146] |
| | Height | | 0.87 m | 1.28 m | [147] |
| | Delay time | | 10 s | 222 s | [144] |
| **Kids > 9 years old** | Movement speed | Uniform | 0.6 m/s | 2 m/s | [145] |
| | Diameter | | 0.30 m | 0.34 m | [146] |
| | Height | | 1.33 m | 1.49 m | [147] |
| | Delay time | | 10 s | 114 s | [144] |

Table B.7: Input details for the evacuation simulations - Indoor kids play area

Results of ASET-RSET analysis performed for the indoor kids play area case study provided there is a fast fire growth, only one exit available for evacuation and ceiling smoke vents are unavailable is provided in Table B.8.

| Floor space factor ($m^2/p$) | Total number of people | Detection time (min) | Total evacuation time – RSET (min) | Expected number of people exposed to smoke – area of damage ≤ 1 $m^2$ | Expected number of people exposed to smoke – area of damage > 1 $m^2$ |
|---|---|---|---|---|---|
| 0.5 | 540 | 0.42[3] | 7.8 | 374 | 396 |
| 0.8 | 337 | | 5.2 | 191 | 215 |
| 2.0 | 135 | | 4.3 | 28 | 30 |

Table B.8: Only 1 exit available for evacuation and no ceiling vents available - Fast fire growth rate

Results of ASET-RSET analysis performed for the indoor kids play area case study provided there is a fast fire growth, two exits are available for evacuation and ceiling smoke vents are unavailable is provided in Table B.9.

| Floor space factor ($m^2/p$) | Total number of people | Detection time (min) | Total evacuation time – RSET (min) | Expected number of people exposed to smoke – area of damage ≤ 1 $m^2$ | Expected number of people exposed to smoke – area of damage > 1 $m^2$ |
|---|---|---|---|---|---|
| 0.5 | 540 | 0.42 | 4.5 | 202 | 242 |
| 0.8 | 337 | | 4.4 | 58 | 78 |
| 2.0 | 135 | | 4.3 | 27 | 30 |

Table B.9: 2 exits available for evacuation and no ceiling vents available - Fast fire growth rate

Results of ASET-RSET analysis performed for the indoor kids play area case study provided there is a fast fire growth, only one exit is available for evacuation and ceiling smoke vents are available is provided in Table B.10.

| Floor space factor ($m^2/p$) | Total number of people | Detection time (min) | Total evacuation time – RSET (min) | Expected number of people exposed to smoke – area of damage ≤ 1 $m^2$ | Expected number of people exposed to smoke – area of damage > 1 $m^2$ |
|---|---|---|---|---|---|
| 0.5 | 540 | 0.42 | 7.8 | 0 | 325 |
| 0.8 | 337 | | 5.2 | 0 | 147 |
| 2.0 | 135 | | 4.3 | 0 | 16 |

Table B.10: Only 1 exit available for evacuation and ceiling vents available - Fast fire growth rate

Results of ASET-RSET analysis performed for the indoor kids play area case study provided there is a fast fire growth, two exits are available for evacuation and ceiling smoke vents are available is provided in Table B.11.

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[3] A conservative value assumed considering the height from floor and roof of the indoor kids play area building

| **Floor space factor ($m^2/p$)** | **Total number of people** | **Detection time (min)** | **Total evacuation time – RSET (min)** | **Expected number of people exposed to smoke – area of damage ≤ 1 $m^2$** | **Expected number of people exposed to smoke – area of damage > 1 $m^2$** |
|---|---|---|---|---|---|
| 0.5 | 540 | 0.42 | 4.5 | 0 | 104 |
| 0.8 | 337 | | 4.4 | 0 | 41 |
| 2.0 | 135 | | 4.3 | 0 | 13 |

Table B.11: 2 exits available for evacuation and ceiling vents available - Fast fire growth rate

Results of ASET-RSET analysis performed for the indoor kids play area case study provided there is a slow fire growth, only one exit available for evacuation and ceiling smoke vents are unavailable is provided in Table B.12.

| **Floor space factor ($m^2/p$)** | **Total number of people** | **Detection time (min)** | **Total evacuation time – RSET (min)** | **Expected number of people exposed to smoke – area of damage ≤ 1 $m^2$** | **Expected number of people exposed to smoke – area of damage > 1 $m^2$** |
|---|---|---|---|---|---|
| 0.5 | 540 | 0.42 | 7.8 | 244 | 244 |
| 0.8 | 337 | | 5.2 | 55 | 55 |
| 2.0 | 135 | | 4.3 | 8 | 8 |

Table B.12: Only 1 exit available for evacuation and no ceiling vents available - Slow fire growth rate

Results of ASET-RSET analysis performed for the indoor kids play area case study provided there is a slow fire growth, two exits are available for evacuation and ceiling smoke vents are unavailable is provided in Table B.13.

| **Floor space factor ($m^2/p$)** | **Total number of people** | **Detection time (min)** | **Total evacuation time – RSET (min)** | **Expected number of people exposed to smoke – area of damage ≤ 1 $m^2$** | **Expected number of people exposed to smoke – area of damage > 1 $m^2$** |
|---|---|---|---|---|---|
| 0.5 | 540 | 0.42 | 4.5 | 10 | 10 |
| 0.8 | 337 | | 4.4 | 7 | 7 |
| 2.0 | 135 | | 4.3 | 2 | 2 |

Table B.13: 2 exits available for evacuation and no ceiling vents available - Slow fire growth rate

Results of ASET-RSET analysis performed for the indoor kids play area case study provided there is a slow fire growth, only one exit is available for evacuation and ceiling smoke vents are available is provided in Table B.14.

| Floor space factor ($m^2/p$) | Total number of people | Detection time (min) | Total evacuation time – RSET (min) | Expected number of people exposed to smoke – area of damage ≤ 1 $m^2$ | Expected number of people exposed to smoke – area of damage > 1 $m^2$ |
|---|---|---|---|---|---|
| 0.5 | 540 | 0.42 | 7.8 | 0 | 0 |
| 0.8 | 337 | | 5.2 | 0 | 0 |
| 2.0 | 135 | | 4.3 | 0 | 0 |

Table B.14: Only 1 exit available for evacuation and ceiling vents available - Slow fire growth rate

Results of ASET-RSET analysis performed for the indoor kids play area case study provided there is a slow fire growth, two exits are available for evacuation and ceiling smoke vents are available is provided in Table B.15.

| Floor space factor ($m^2/p$) | Total number of people | Detection time (min) | Total evacuation time – RSET (min) | Expected number of people exposed to smoke – area of damage ≤ 1 $m^2$ | Expected number of people exposed to smoke – area of damage > 1 $m^2$ |
|---|---|---|---|---|---|
| 0.5 | 540 | 0.42 | 4.5 | 0 | 0 |
| 0.8 | 337 | | 4.4 | 0 | 0 |
| 2.0 | 135 | | 4.3 | 0 | 0 |

Table B.15: 2 exits available for evacuation and ceiling vents available - Slow fire growth rate

Probabilities assigned at each branch of event tree developed for indoor kids play area case study as given in Figure B.6 is provided in Table B.16.

| Particulars | Value | Reference/Comments |
|---|---|---|
| Probability of fire occurring in the weekends | 0.3 | A comparison was made to the fires in schools as per NFPA fire statistics [148]. However, the probability of fire occurrence on weekends was less since schools are not working on weekends. But in this case, people are expected to be present in the weekend. Therefore, a probability of fire occurring in the weekend is assigned 0.3. |
| Probability of fire occurring in the weekdays | 0.7 | |
| Probability of fire occurring during the day | 0.45 | |
| Probability of fire occurring during the night | 0.55 | |
| Probability of fire occurring for fires causing damage $\leq 1\ m^2$ | 0.58 | [148] |
| Probability of fire occurring for fires causing damage $> 1\ m^2$ | 0.42 | |
| Probability of successful extinguishment of fires by occupants | 0.799 | [149] |
| Probability of not successful extinguishment of fires by occupants | 0.201 | |
| Probability of fire detection fails | 0.1 | Table A.17 [6] |
| Probability of failure of alarm box, wiring and sounders | 0.03 | Table A.17 [6] |
| Probability of having a floor space factor of 0.5 $m^2$/person | 0.0298 | Overcrowding assumed to happen 10 times a year (especially during festive seasons and vacations) i.e. 80 hrs. out of 2688 hrs. of operation of indoor kids play area. |
| Probability of having a floor space factor of 0.80 $m^2$/person | 0.3 | Night club will not be always crowded. Thus, it is expected that 30% of the time, a floor space factor of 0.80 $m^2$/person can occur, especially in holidays and weekends. |
| Probability of having a floor space factor of 2 $m^2$/person | 0.67 | Assumed since the chance of having a floor space factor of 2 $m^2$/person is likely (especially in weekdays) compared to 0.80 $m^2$/person. |
| Probability of fast fire growth rate with fire retardant kids play structure | 0.01 | Assumed since the likelihood of having a fast fire growth on a fire-retardant material is very low. |
| Probability of slow fire growth rate with fire retardant kids play structure | 0.99 | |
| Probability of failure of smoke vent | 0.1 | Table A.17 [6] |
| Probability of having 2 exits | 0.8 | Assumed |
| Probability of having only 1 exit | 0.2 | Since the other door is behind, the chance of being locked need to be accounted. |

Table B.16: Probabilities assigned at each branch of event tree – Indoor kids play area