Towards Resilience Evaluation of Buildings When Exposed to Fire

Based on English and USA fire statistics.

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by

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The thesis has been supervised by

Dr David Rush

Prof Luke Bisby

To Mom and Dad,

the reason for who I became today.

Declaration

The thesis and the research presented herein have been completed solely by the author Martina Manes at The University of Edinburgh under the supervision of Dr David Rush and Prof Luke Bisby as the result of the author's original research. I also confirm that where others have contributed or other sources are quoted such contribution are clearly indicated. The thesis has not been submitted for any other degree or professional qualification and any included publications are the author's own, except where indicated throughout the thesis.

Martina Manes

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Abstract

This research arises from the necessity to fill the lack of data present in the international fire safety community related to pre and post-fire conditions of real buildings subjected to real fires and create probabilistic risk assessments able to quantify structural damage according to possible mitigation factors and related financial losses.

Resilience is defined as the capacity of a building to absorb, mitigate and recover from a fire incident. It includes life safety, property protection and continuity, however, continuity plans and business impact analyses are rarely developed in common design practices, unless in exceptional cases. Moving from prescriptive to performance-based design appears as a natural evolution in understanding the response of buildings and proof that a selection of design drivers could lead to the same or greater level of safety than the one indicated following prescriptive methods. Fire resilience codes are investigated to understand how this problem is addressed and to evaluate the aspects considered in terms of prevention, response, absorption, mitigation and adaption. Understanding fire safety processes, flow charts are developed to create a holistic view and optimize choices of fire safety and structural engineers.

Fire statistics are composed of data collected by fire departments in the aftermath of a fire event. In the cases of England and the USA, this is done by filling in an online form per event that it is consequently submitted into national databases. Annual reports are published to summarise the trends and allow further research. Fire statistics from the Incident Reporting System in England and the National Fire Incident Reporting System in the USA are analysed to understand causes of fire, such as item first ignited, fire location and building descriptions, as well as consequences, such as response time from fire brigades, the influence of automatic extinguishing systems on fire spread and damage. Once fire damage and total damage are quantified, financial losses can be evaluated considering the Building Valuation Data formula which multiplies damage and unit cost per ft^2 according to different building construction and occupancy types. Comparisons between the two countries allow comments and reflections about the different safety measures, preparedness and similar trends where possible. The idea is to address complex problems affecting the fire safety community, to understand fundamental relationships between fire incidents and structural response to fire, to quantify structural damage scale and to estimate direct costs. The study considers also the improvement of English fire statistics to include fire safety fields not currently covered. An international database based on the data available in the fire statistics from England and the USA is developed as guidelines able to support fire safety community.

British Standards PD 7974-7:2003 (referred as PD 7974-7), is related to the probabilistic risk assessment. Its data is based on fire incidents from 1966 to 1987 need to be compared to current statistics to understand if the fields described are still representative of fires in buildings. The comparison appears necessary to understand potential improvements from the past and possible optimization for the future. Moreover, the use of fire statistics is representative of current fire safety fields and is adopted to create contemporary comparisons. Fire frequency is obtained considering also building stock and the number of properties for each building type. Furthermore, fire frequency is plotted to building floor space according to a power law with positive, as suggested by Rutstein and adopted in the PD 7974-7, or a negative exponent or to a polynomial function of second or third order which presents the highest R^2 and seems to better approximate the sample. The fire spread and damage are analysed considering the presence or absence of automatic extinguishing systems. In the USA, the trends for the fire damage present higher percentages than those of PD 7974-7 while English fire damage data are consistent with those of PD 7974-7. In English statistics, response time assumes a relevant influence on fire spread and damage especially in the first minutes after the fire notification.

The research continues evaluating probabilistic risk assessments in buildings that are based on the concept of risks, hazards and consequences and how to reduce them. They are derived considering English fire statistics in event tree analysis to evaluate the likelihood of fire scenarios with the presence or absence of safety systems and their effects in terms of human response and structural damage. Deductive procedures are used in event tree analysis, to highlight how potential events could mitigate outcomes related to an initiating event represented by a fire in specific buildings. These methods have the aim to better understand possible fire incidents and identify realistic fire scenarios to be implemented in fire and evacuation models. Probabilistic techniques evaluate key parameters to assess factors contributing to ignition, growth and effects of fire in terms of consequences and likelihood that a given set of consequences occurs.

The impact of the research results could create fire safety tools able to automatically process the fire information collected over a time period to ensure updated data and controlled trends which will be adopted in fire risk assessment and prevention methods to absorb and recover during and after a fire incident. Furthermore, methods to identify indirect losses will be assessed. Future research could involve the investigations on how these data could inform the design of practising engineers and on how fire statistics influence the code guidelines. Moreover, it would be important to understand how governments adopt this information for decisions about resources allocation and how the fire safety approaches change considering different authorities and locations.

Lay summary

The research developed in this thesis has sought to understand the resilience components and characteristics to apply them in the fire safety problems affecting buildings with the specific goals to create a fire resilience framework collecting evidence of building performances affected by fired based on data of fire statistics from different countries such as England and the USA.

A deep analysis of the literature review about the main concepts of resilience developed in other disciplines (e.g. earthquake engineering and critical infrastructures) has been examined and applied to the conceptual analysis of building affected by fires considering people involved, characteristics and capacities and subdividing resilience in internal and external according to technical, organizational, economic and social dimensions to enhance resilience-based optimization and improve preparedness and continuity plans. Standards and codes have been examined to understand the resilience aspects covered and missed in their guidelines. Moreover, a fire resilience design has been created examining the various phases present in a design highlighting deterministic and probabilistic variables, structural components and fire parameters.

The fire design and framework need to be based on an extended analysis of data of previous fire incidents in buildings that have been obtained evaluating various fire statistics. The fields covered by England and the USA fire statistics have been investigated considering pre- and post-fire conditions in terms of fire causes, growth and consequences evaluating structural damage and financial losses, presence and operation of various safety measures and fire brigade response time. Analogies and differences in the two sources of fire statistics have been examined to understand potential improvements.

The fire safety data available in the British Standard PD 7974-7:2003 (named herein PD 7974-7) (BSI PD 7974-7, 2003) from 1966 to 1987 appear to be not representative of the fire incidents in current building stock if compared to English and the USA statistics. In particular, in PD 7974-7 fire frequency appears greater than the one described by current statistics. Area damage of PD 7974-7 is different than the one provided by England and the USA statistics suggesting that different countries could have different safety measures. Therefore, the need for updates and continuous analysis of fire safety data appear necessary to understand the evolution of fire safety parameters. Furthermore, the response time of the fire brigades has been examined to understand the fire scenarios that fire fighters could face at the arrival on fire scene in terms of fatalities, casualties, fire spread and damage for various attendance times.

Once the fire safety variables available have been determined, the research developed in this thesis has considered their application in probabilistic risk assessments. Automatic deductive event tree analyses for fire response and damage have been created for various property types able to estimate likelihood and consequences of fire scenarios based on safety measures such as response time of occupants and fire brigades, detectors and sprinklers. The values obtained could automatically be modified changing the parameters required for successful sub-events. The differences in the fields recorded by England and the USA have determined differences in the event tree analysis for the two fire statistics.

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Publications

Journal Papers

Manes M. & Rush D. 'Assessing Fire Frequency and Structural Fire Behaviour of England Statistics According to BS PD 7974-7' accepted for oral presentation in the International Symposium on Fire Safety Science (IAFSS 2020). Fire Safety Journal (2020) https://doi.org/10.1016/j.firesaf.2020.103030

Manes M. & Rush D. 'A Critical Evaluation of BS PD 7974-7 Structural Fire Response Data Based on USA Fire Statistics' Fire Technology Journal vol. 55 no.4 pp. 1243-1293 (2018) https://doi.org/10.1007/s10694-018-0775-2

Conference Papers

Manes M. & Rush D. 'Probabilistic fire risk assessment in buildings using event tree analysis based on UK and USA fire statistics.' International Conference and Exhibition on Fire Science and Engineering (Interflam 19), Royal Holloway College, Nr London, UK (2019)

Manes M. & Rush D. 'Fire response time: effects on life safety and property. Response time and consequences on life safety, spread and damage based on UK fire statistics.' Applications of fire engineering: proceedings of the international conference of applications of structural fire engineering, Applications of Structural Fire Engineering (ASFE 19), Nanyang Technological University, Singapore (2019)

Van Coile R., Bisby L., Rush D. & **Manes M.** 'Design for post-fire use: a case study in fire resilience design.' In 2nd International Conference on Structural Safety under Fire and Blast (CONFAB 17), London, UK, pp 263-270, (2017)

Manes M. & Rush D. 'Meta-analysis of response times and safety systems to the fire size, growth and damage, based on UK, USA and New Zealand fire statistics databases.' In 2nd International Conference on Structural Safety under Fire and Blast (CONFAB 17), London, UK, pp 108–117, (2017)

Manes M. & Rush D. 'Meta-analysis of UK, USA and New Zealand fire statistics databases with respect to damage and financial loss.' Applications of fire engineering: proceedings of the international conference of applications of structural fire engineering, Applications of Structural Fire Engineering (ASFE 17), Manchester, UK, pp 179–188, London: CRC Press (2017) https://doi.org/10.1201/9781315107202-21

Posters

Manes M. & Rush D. 'Probabilistic fire risk assessment in buildings using event tree analysis based on UK and USA fire statistics' International Conference and Exhibition on Fire Science and Engineering (Interflam 19), Royal Holloway College, Nr London, UK (2019)

Manes M. & Rush D. 'A critical evaluation of PD 7974-7 structural fire response data based on USA fire statistics' School of Engineering Postgraduate Research Conference, Edinburgh, UK (2018)

Manes M. & Rush D. 'Meta-analysis of UK, USA and New Zealand fire statistics databases with respect to damage and financial loss' Infrastructure & Environment Scotland 4th Postgraduate Conference, Edinburgh, UK (2017)

Invited Presentations

Manes M. 'Presentation of UK and USA fire statistics and the updates of BS PD 7974-7' Queensland Fire and Emergency Service, Brisbane, Australia (2019)

Manes M. 'Analysis of UK and USA fire statistics to update BS PD 7974-7 and evaluate risk assessment' CPD event of Institution of Fire Engineers (IFE) Singapore (2019)

Manes M. 'Ignite session to support Women in Engineering', SFPE European Conference, Malaga, Spain (2019)

Manes M., Rush D. 'A critical evaluation of PD 7974-7 structural fire response data based on USA fire statistics', Structures in Fire Forum (StiFF), Edinburgh, UK (2017)

Awards

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Awarded by the Royal Society of Edinburgh with a travel scholarship at the University of Queensland for three months to work with Dr David Lange on 'Fire codes updates and application of fire statistics in building resilience plan' (2019)

Contents

List of Figures

List of Tables

Chapter 1. Introduction

> "Fire safety engineers need to be 'tough enough to stand up to a good deal of questioning' and in turn 'to be able to push other people in the same way: justify what you are saying if you expect to be taken seriously'."
>
> - Margaret Law

1.1 Context

Currently, there is a strong need and desire to understand the real behaviour of buildings subjected to fires based on technical, economic and social reasons in the light of possible design optimization, evacuation preparedness as well as global harmonization of codes and standards (Hadjisophocleous et al., 1998). After the Grenfell Tower fire in the UK, the trend from prescriptive to performance-based approaches has been reversed. This is supported by Regulation 7 that now restricts the use of combustible materials in external walls on buildings over 18 m (The Building Regulations 2010, 2018). However, guidelines of prescriptive codes are not always representative of the real fire response of buildings and often deduced from data no longer representative of the current situation. Ideally, performance-based design results in fire protection strategies in which systems are integrated and not isolated, cost-effective optimizations evaluated, and knowledge of potential losses improved (Meacham & Custer, 1995).

Therefore, fire safety engineers need to demonstrate that a greater or equivalent level of safety is achieved than that assumed to be delivered by the prescriptive codes. Moreover, a holistic approach of the fire incident should be adopted evaluating its possible effects on life safety, property protection and continuity. These factors lead back to the concept of resilience and preparedness, where resilience is defined as ‘the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner’ (United Nations, 2009).

Fire safety design needs to use accurate input data, operational rules and protocols to assess structural pre and post-fire capacity of the building and different level of refinement for the verification methods (Twilt & Vrouwenvelder, 1986). Moreover, deterministic variables need to be integrated with probabilistic variables covering all the relevant input factors for probabilistic risk assessment able to implement continuity plans and business impact analyses. While deterministic variables can be obtained from various scale experiments as well as from fire science equations, probabilistic variables need to be based on real structural fire incidents and the evaluation of risk given by the likelihood of an event and its expected consequences.

However, in the British Standard PD 7974-7:2003, fire safety data are approximately 30 to 40 years old and the comparison with current data is essential to evaluate if the predictions are still representative of fires incidents in building stocks. Currently, fire statistics from different countries represent the primary means by which to collect data on buildings subjected to fire in the aftermath of an event (Home Office, 2017c). Moreover, fire statistics could be adopted to design buildings in fires because it provides pre- and post-fire descriptions as building characteristics, ignition causes, fire response, spread and damage and direct financial losses.

Finally, probabilistic risk assessments need to be investigated to find a methodology able to highlight fire scenarios and understand how different safety measure strategies can intervene to mitigate and reduce fire effects in terms of risk and impact on property protection and on life safety. Therefore, the objectives of this research aim to address complex problems affecting the fire safety community to understand fundamental relationships between fire incidents and structural response to fire.

1.1 Statement of the problems

Currently, there is a paucity of data related to real buildings subjected to real fires. Fire safety data of buildings affected by fires need to be based on credible events to be representative of real scenarios and they are usually collected by fire statistics from different countries generated by information recorded by fire brigades after fire incidents. In prescriptive codes and national guidelines, such data are usually not representative of the current situation of building stock and the introduction of new structural techniques (e.g. facades, cross-laminated timber, etc.) generate new hazards not previously considered and that need a better understanding of their possible implications when exposed to real fires.

The need to address this paucity of data in the current fire safety community affects inputs related to pre and post-fire conditions such as fuel types, ignitions, and causes, as well as structural performances, evaluation of damage, and financial losses considering the presence or absence of automatic suppression systems. Fire statistics from different countries present similarities and differences in the fields recorded; for example, the fire financial losses are estimated in USA statistics, but not in England.

Furthermore, data on building fires in the British Standard PD 7974-7:2003 are dated from 1966 to 1987 (BSI PD 7974-7, 2003). If a British Standard committee decides to revise or amend an existing document, a committee draft is prepared. The draft is then available for public comments for two or three months and finally, the national committee votes to approve and publish the new version of the Standard (BSI, 2012). In 2019, the PD 7974-7:2003 underwent a review process based on the updates required by the international community and by practising fire engineers wishing to implement the performance-based design on real projects.

In this research, the term structural fire data is referred not to the mechanics based assessments of fires affecting structural elements but to the analyses of fires within buildings where the data could be used to understand probable fire events to aid in the design of buildings to fires. Moreover, in this thesis, "structural damage" is referred to the building consequences caused by the fire incident in terms of fire spread and area damage. The structural fire data are used as inputs in computational models and as design drivers able to quantify structural response and performance including fire damage, spread, and fatalities and casualties in different building types. In light of the current tendency moving towards performance-based design, an in-depth and quantified understanding of candidate safety strategies is needed. Possible active and passive fire safety systems can influence structural damage and evacuations, and the relations between them need to be quantified to the extent possible to provide potential hazard reduction analysis.

Statistical data and engineering judgements may be adopted to estimate the severity of the outcomes in event tree analysis. This methodology investigates different fire scenarios with different degrees of complexity, enables the assessment of multiple functioning and failing systems, and quantifies the potential benefits of fire precautions based on related cost-benefit analyses (Rutstein & Cooke, 1979).

Resilience-based design is necessary to evaluate the building, organizational, and ambient resilience and loss assessment (Almufti et al., 2013). While in critical infrastructure resilience plans have been developed (IMPROVER, 2016), currently there is no corresponding assessment in structural fire safety to reduce the fire frequency, mitigate the consequences of fire, and reduce and manage crises due to fire incidents in buildings (Hynes et al., 2016).

1.2 Motivation and objectives of the research

In order to create a fire resilience framework able to apply a holistic view of the fire problem which includes life safety, property protection and continuity, it is important to understand the scope and the components that need to be evaluated, how to address fire resilience approaches collecting data on real building fires to understand performances, and the best solutions to apply moderation processes investigating fire scenarios and the measures able to reduce fire impacts on lives and property.

Investigate and increase awareness on fire incidents affecting buildings have the aim to analyse the users involved and the parts of the systems which can be affected based on a collection of data for engineers to be used as inputs in fire safety design and to create fire safety tools and methodologies determining probabilistic risk assessments. While for simple buildings, prescriptive codes and standards provide sufficient guidance, for complex buildings, they may not meet the expectations where potentials high losses in property and life could be created by fire incidents (Meacham & Powell, 1995). The definition of structural requirements allows for equivalency of different design solutions and assessments of the degree of reliability leading to probabilistic approaches (Twilt & Vrouwenvelder, 1986).

Based on the motivations of this research, the objectives aim to address complex problems affecting the fire safety community to understand fundamental relationships between fire incidents and structural response to fire. The high level of uncertainties related to fire parameters such as fire loads, compartment size and probability occurrence of fire, moved the fire community to probabilistic framework estimating the probability of structural failure where structural damage and fire intensity given a fire scenario must be defined (Gernay et al., 2016). The reliability of the computer model to describe structural behaviour becomes more uncertain when the structure is pushed to its limit (Almufti et al., 2013). Moreover, the idea at the base of the research is to apply a fire resilience assessment based on a holistic approach in which life safety and property protection will be considered and to investigate the interdependencies between fire safety variables. The objectives can be summarized as to:

1. create a fire resilience framework able to improve preparedness, response, absorption, mitigation, recovery, and adaption before, during, or after a fire incident considering users and addressing administrative and engineering features;
2. improve fire resilience and preparedness plans for fire affecting buildings according to methodologies adopted in other disciplines (e.g. critical infrastructures and earthquakes) and guidelines present in British Standards and codes addressing resilience to provide directions for new resilience-based optimizations;
3. investigate the paucity of fire safety data present in the international fire community related to pre- and post-fire conditions of real buildings subjected to real fires, gathering information from current fire statistics of different countries;
4. develop an international database based on the fire safety data available in contemporary fire statistics from England and the USA as a tool able to support the fire safety community;
5. examine the British Standard PD 7974-7:2003 (BSI PD 7974-7, 2003) data from 1966 to 1987 in the light of current fire statistics of England and the USA, highlighting similarities and differences to understand the relationships between fire safety variables applied in structural fire design;

6. enable probabilistic risk assessments able to evaluate risk, frequencies, consequences, fatalities and casualties related to fire incidents in building types; and
7. develop event tree analysis for various property types to determine likelihoods and consequences of fire scenarios and evaluated how the introduction of safety measures can impact fatalities/casualties, fire response and structural damage.

1.3 Novelty of the research

The novelty of the research involves practical significance, especially for the fire safety community. The fire resilience framework arises from a deep analysis of the resilience literature, methodologies adopted in other disciplines (critical infrastructure and earthquake engineering) and current British Standards and Codes addressing resilience. The framework has the aim to apply on a holistic view of the fire problems considering the objectives of life safety, property protection and continuity and applying the resilience missions, characteristics and capacities. It could be used as a tool to increase preparedness and mitigation strategies considering technical aspects and highlighting organizational improvements.

A relevant novelty of the work is the investigation of two national fire statistics databases (England and the USA) that create awareness on the available factors representing pre- and post-fire conditions in various property types specifying the impact of different safety measures in reducing fire consequences on buildings. The data could also inform the design of practising engineers and influence the code guidelines.

This research has updated the fire safety data present in the British Standard PD 7974-7 (BSI PD 7974-7, 2003) from 1966 to 1987 with current English and the USA fire statistics extending the variables and tables present in the Standard based on the presence or absence of safety systems. Moreover, the comparison between PD 7974-7 and USA statistics has already been referenced in the new version of the British Standard PD 7974-7 in Annex B (Table B.3) published in 2019 (BSI PD 7974-7, 2019) for what concerns the overall probability of a fire starting in various types of occupancy.

The analysis of fire brigade response time and the implications on fatality/casualty rate, fire spread and fire and total damage caused by fire incidents in various property types, is important to evaluate the impact of the response time in the operations for occupant rescues and fire extinguishment. It could be adopted in the evaluation of the optimization of fire stations number and location and in the analysis of resources allocations for governments and local authorises.

Finally, the evaluation of probabilistic risk assessments based on event tree analyses investigates the fire scenarios in several property types and it provides useful information about the impact that success and failure of several safety systems such as alarms and automatic extinguishing systems, could have on building damage and fatalities and casualties.

1.4 Outline of the thesis

This thesis is composed of six chapters, excluding the introduction, and an Appendix in which complementary data are presented. Outline of each chapter is summarized in this section:

Chapter 2: Literature review

The literature review provides an overview of previous work about resilience definitions, objectives, mission and framework and investigates how resilience is addressed in current British Standards and Codes. Moreover, fire statistics of England and the USA are described highlighting the data collection and fire safety fields covered. Based on fire statistics, methodologies for the evaluation of direct and indirect fire financial losses are discussed. Furthermore, the historical development of the British Standard PD 7974-7:2003 is investigated to understand the origin of the fire safety data available in its Annex. Finally, previous research about the impact on lives and properties of the response time of fire brigades and probabilistic fire risk assessments are studied.

Chapter 3: Fire resilience

The resilience concepts developed in other disciplines (e.g. critical infrastructure and earthquake engineering) are applied in this Chapter considering the fire safety problem. Fire resilience categories, dimensions and characteristics are defined assuming a holistic view based on internal and external resilience. In order to be able to quantify the resilience of a system or building, fire resilience measures are introduced and a fire resilience approach is discussed to evaluate objectives, risk assessment and treatment and improvement of performances. A practical example is provided by applying a fire resilience framework in an educational building. Finally, a fire resilience design framework is introduced highlighting the steps to follow in a flow chart considering structural and fire design of a building.

Chapter 4: Fire statistics

The necessity of the fire safety community to understand the data available supports the analysis and investigation of English and USA fire statistics datasets. The fire statistics contain information filled in by the fire brigades in the aftermath of an event and the two databases are studied according to pre- and post-fire conditions as the number of fire incidents, fire causes, fire growth and consequences in terms of damage and financial losses, and fire safety measures such as detectors and automatic extinguishing systems. Analogies and differences between England and the USA are determined to evaluate possible changes. Finally, potential improvements in the Incident Recording System in England are established.

Chapter 5: Evaluation of British Standard PD 7974-7:2003 based on English and the USA statistics

This Chapter is focused on the updates of the tables present in the British Standard PD 7974-7:2003 with more recent fire statistics of England and the USA. The analysis of current building stock of England and the USA is necessary for the evaluation of the overall probability of fire starting and the evaluation of the fire frequency according to the total floor area in various property types. Area damaged and financial losses are estimated to increase the awareness of fire consequences in buildings. The analyses consider the presence or absence of automatic extinguishing systems. Moreover, the fatality/casualty rate for various discovery and response times are evaluated and how the response time could reduce life and consequences on the property is estimated.

Chapter 6: Probabilistic fire risk assessment

Probabilistic risk assessments have been developed in this Chapter considering English and USA statistics in terms of fire response and damage. The differences in the fields recorded in the two fire statistics have determined the creation of specific event tree analysis for England and the USA. In particular, when the fire response is investigated, fire brigade and occupant response are combined with the presence and performances of alarms. The evaluation of damage due to fire incidents is estimated considering the presence and absence of safety systems, the operation and effectiveness, fire spread and fire damage. The results obtained by the event tree analyses increase awareness on the most likely fire scenarios and structural damage and could be considered as inputs in fire safety design of various buildings affected by fire incidents.

Chapter 7: Conclusions

The Chapter related to the conclusions presents a summary of the research undertaken in this thesis with discussions and comments about main outcomes, findings and potential future research.

Chapter 2. Literature review

"Knowledge is cumulative and therefore innovation is not only about the great idea, but it is determined by one's capacity to understand what has been done and where are the gaps of knowledge. We all stand on the shoulders of others and nobody is capable of reinventing a discipline without understanding prior successes and failures."

- Jose Torero

2.1 Resilience

2.1.1 Resilience definition

The concept of resilience is widely used and due to its application in several disciplines, it is difficult to find a unique definition. The root of resilience comes from the Latin word *resilio* that means 'jump back' (Cimellaro et al., 2010). According to the terminology of the United Nations, resilience is generally expressed as:

"The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management. (United Nations, 2009)*"*

The Presidential Policy Directive (PPD 8) defines resilience as "*the ability to adapt to changing conditions and withstands and rapidly recover from disruption to emergencies*" (U.S. Department of Homeland Security, 2011). Linkov considers resilience as a complimentary attribute able to apply adaptation and mitigation strategies to improve risk management where risk is the loss in functionality and it depends on threats, vulnerabilities and consequences given by a specific risk (Linkov et al., 2014). In seismic engineering, resilience is also defined as "*the ability social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes*" (Bruneau et al., 2003).

The reason why resilience is important is that at the moment, there are not the right engineering and management tools to systematically analyse resilience and then integrate its aspects in developing programmes. A common shared vision about risks and their mitigations does not exist and it is not clear how to increase the resilience of individuals, communities and built environment (Organization for Economic Co-operation and Development, 2014).

The idea at the base of the resilience concept applies a holistic view and covers *societal risks* as social stability and public health; *organizational or geopolitical risk* affecting political decisions, resolution of conflicts and disputes on resources; *economical risk* as a failure of critical infrastructures on which economic activities are based; and *technological risk* involving for example infrastructure disruptions (World Economic Forum, 2014). Resilience dimensions can be classified in *internal resilience* (technological, organizational and economical resilience) and *external resilience* which includes the four dimensions (Labaka et al., 2016). It is clear then that resilience needs to be defined in multiple domains (Linkov et al., 2014). Despite the dimension considered, resilience has to present the following characteristics:

- *robustness*: the ability of a system to withstand stress without loss in functionality,
- *redundancy*: the capacity of satisfying function in case of disruption,
- *resourcefulness*: the capacity to establish priorities and mobilize resources in the presence of disruption, and
- *rapidity*: ability to meet priorities in a time-effective manner to contain losses (Bruneau et al., 2003).

Moreover, resilience has three fundamental capacities:

- *absorptive capacity*: ability to prepare for, mitigate and prevent negative impacts to prevent and restore basic functions,
- *adaptive capacity*: ability to modify or change to mitigate potential damage and guarantee the continuity of functions, and
- *transformative capacity*: ability to create a new system to avoid the impact of disruption (Organization for Economic Co-operation and Development, 2014).

Therefore, resilience is a process that links a network of adaptive capacities to adaptation after a disruption (Norris et al., 2008), it results as a dynamic process that could be continuously improved and involve a collaborative team composed of *private users* as individuals, families, business and organizations and *public ones* as communities, local and national governments (National Institute of Standards and Technology, 2016).

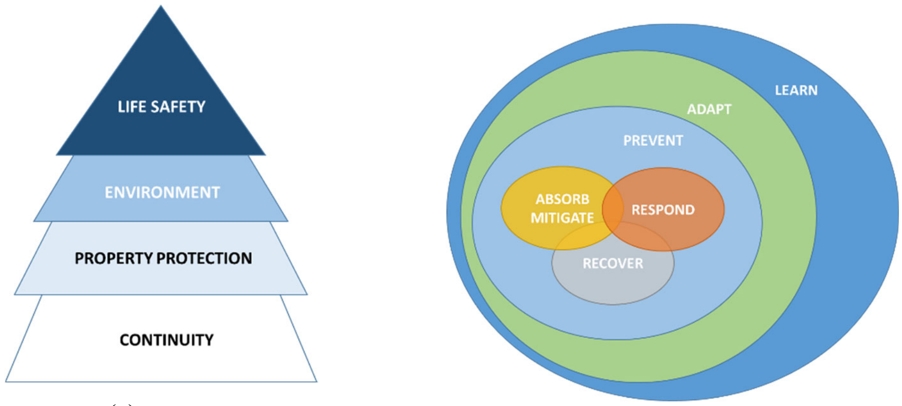
Analysing all the resilience definitions, it is possible to deduce common aspects such as:

- <u>categories</u>: Users, Community, Property, Business, Environment,
- <u>dimensions</u>: Societal, Organizational, Technical, Economical,
- <u>characteristics</u>: Resistance, Robustness, Redundancy, Rapidity, and
- <u>capacities</u>: Absorptive, Adaptive, Transformative.

2.1.2 Resilience objectives and missions

The main objective of life safety which is usually considered as a necessary requirement needs to be incorporated with property protection (Gernay et al., 2016) and continuity. In general, the objectives can be summarized according to this hierarchy in life safety, environmental protection, property protection and continuity to families and business shown in Figure 1 (a).

In the field of seismic engineering, Bruneau defines the resilience objectives more generally to minimize life and economic losses that could be summarized in the reduction in life quality due to the earthquake event (Bruneau et al., 2003).



(a) (b)

Figure 1: Resilience objectives and missions

The National Infrastructure Protection Plan (NIPP) 2013 for critical infrastructures establishes as objectives to:

- assess and analyse hazards to inform risk management activities;
- secure against threats through actions to reduce risk, while considering a cost-benefit analysis of security investments;
- enhance resilience by minimizing the consequences of incidents based on planning and mitigation, and applying effective responses and ensure quick recovery;
- share action and vision with the community and enable risk-informed approaches; and
- promote learning and adaptive capacity before and after an incident (U.S. Department of Homeland Security, 2013).

Similar goals and objectives are defined by the National Institute of Standards and Technology (NIST) and involved the definition of community hazards and levels; prediction of performance before and after hazards to guarantee social functions; definition of desired recovery performance goals based on social needs and the identification of dependencies and cascading events (National Institute of Standards and Technology, 2016). In particular, the evaluation of cascading events is fundamental in fire incidents where system failures and consequences have an impact on lives and property.

For building codes, the primary objective considering specific events is to guarantee life safety and prevent collapse defining an acceptable level of threat tolerable by a building. However, in reality, the objectives can also involve property protection and continuity providing:

- the minimum level of functionality in the aftermath of an event;
- quick recovery to normal functionality; and
- improvement for potential future hazards (Kurth et al., 2019).

Once the objectives have been established, missions to achieve resilience need to be defined.

Resilience is composed of *engineering and administrative features* where the former considers the technical aspects of disaster resilience while the latter includes elements as prepare for, plan for, respond to and recover from (The Fire Protection Research Foundation, 2014). Therefore, resilience missions can be expressed as:

- *prevention* or Preparation to potential hazards;
- *mitigation/absorption* with the reduction of the impacts on lives and property, this mission usually includes *protection* for occupants, visitors and community against hazards;
- *response* to protect humans and the environment in the aftermath of the event; and
- *recovery* through restoration and strengthening of communities and built environment (U.S. Department of Homeland Security, 2018).

In some studies, the characteristic of a system to adapt is considered in the list of resilience missions (Linkov et al., 2014). The activities of planning, preparing and absorbing are generally linked to risk management integrating risk mitigation techniques (Kurth et al., 2019).

Therefore, if the dependencies of the resilience missions are analysed, it is clear that the ability to prevent needs to include those of mitigation, quick response and recovery leading the system to adapt and inevitably learn from the incidents as described in Figure 1 (b).

Table 1: Concepts pertinent to the idea of Resilience

Categories	**Dimensions**	**Characteristics**	**Capacity**	**Missions**	**Objectives**
Users	Societal	Resistance	Absorptive	Prevent	Life safety
Community	Organizational	Robustness	Adaptive	Absorb	Property Protection
Property	Technical	Redundancy	Transformative	Respond	Continuity
Business	Economical	Rapidity		Recovery	
Environment				Adapt	
				Learn	

The concepts pertinent to the idea of Resilience are summarized in Table 1. The definitions of resilience above imply the presence of an incident, natural hazards or negative events and for this reason, the concept of resilience is strongly linked to the one of risk. At the moment, there is not a unique definition for risk but usually, it refers to the possibility that "*human actions or events lead to consequences that affect the aspects of what human's value*" (Renn, 1998). Resilience and risk are complimentary and reducing losses inevitably require risk management and resilience (Kurth et al., 2019). Based on the Improver project, funded by the European Union's Horizon 2020 research, with the aim to establish resilience in critical infrastructures, risk assessment is evaluated as one of the crisis management phases considering also prevention, preparedness, monitoring, response, recovery and warning (IMPROVER, 2016). Further explanations about risk and risk assessment are investigated in detail in section 2.6.

2.1.3 Measuring resilience

The quantification of resilience is complex, difficult to evaluate and needs to involve the resilience dimensions defined in section 2.1.1. The National Institute of Standards Technology (NIST) quantifies resilience for a building or infrastructure (referred as built environment) in terms of functionality against the time to recovery after a disruption (National Institute of Standards and Technology, 2016). In Figure 2, two-building conditions are evaluated:

A. improved level of functionality due to design, mitigation measures and maintenance giving moderate loss and quick recovery; and
B. deterioration due to ageing and lack of appropriate maintenance generating a high loss in functionality and longer recovery time.

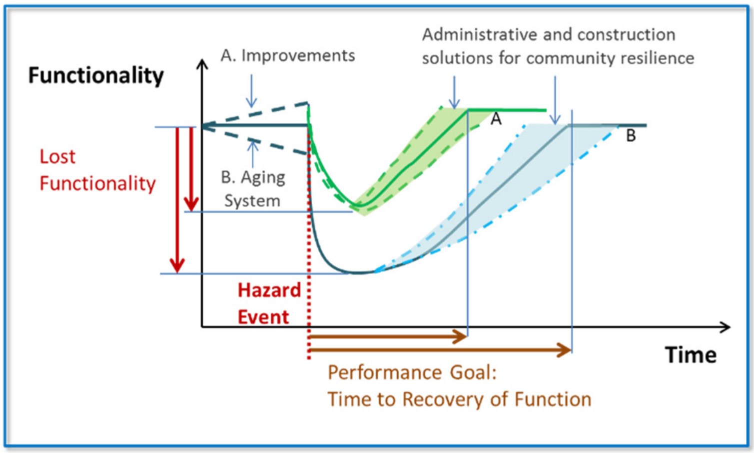
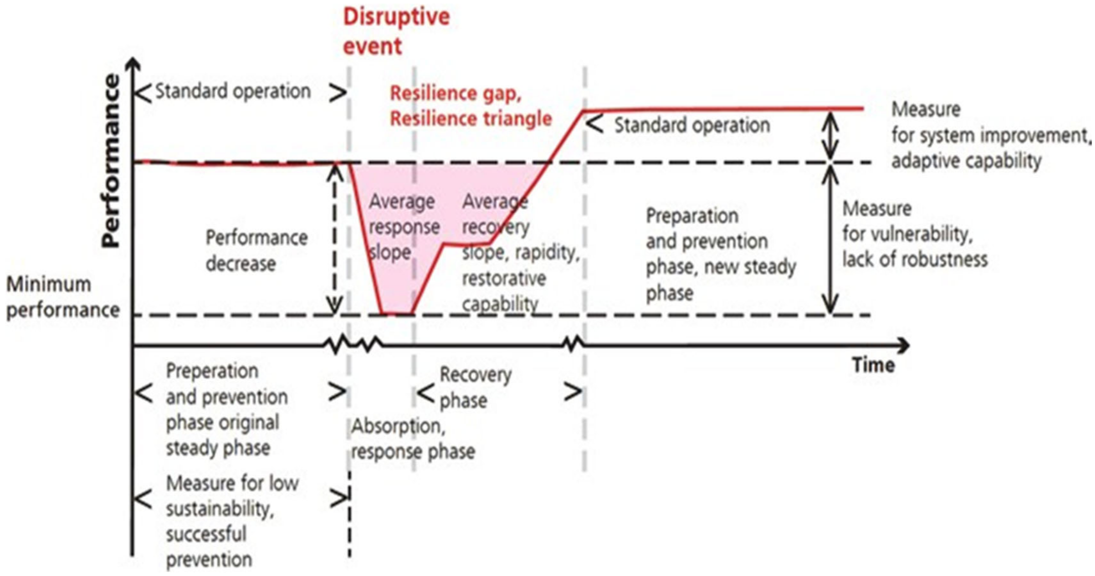


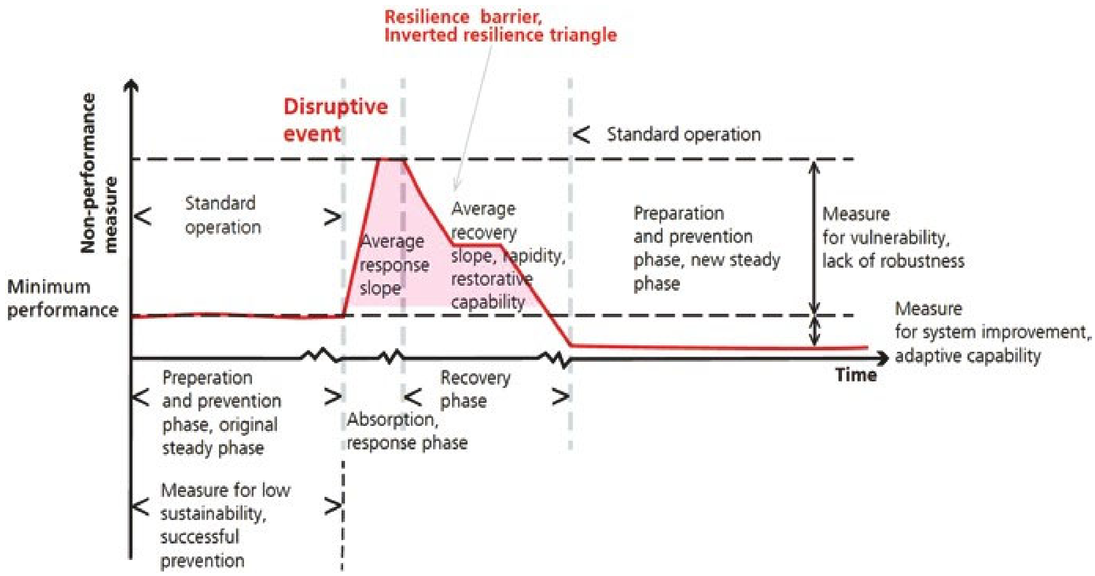
Figure 2: Resilience in terms of functionality and time to recovery after disruption (National Institute of Standards and Technology, 2016)

Resilience is measured by the area generated by the incident to regain the normal functionality. For the resilience quantification, the process could be based on the evaluation of system performance and no-performance functions (Linkov & Palma-Oliveira, 2017) (Figure 3).

Linkov affirms that resilience is related to the loss of functionality and recovery curve where the resilience missions of a system to plan, absorb, recovery and adapt are now considered as life-cycle stages and can be plotted in the graph of critical functionality against time as shown in Figure 4. Another fundamental life-cycle stage is learning from the event and from the previous conditions that caused the disruption. Furthermore, resilience could be analysed in different time horizons as *immediate* to guarantee life safety, *intermediate* for essential functions and *long-term* to establish normal functionality (Linkov et al., 2014). Indeed, risk composed of threat, vulnerability and consequences, is strictly connected to the concept of resilience where risk analysis and management have been widely used to predict the likelihood and consequences of potential hazards and quantify the complexity of uncertainties.



(a)



(b)

Figure 3: Resilience assessment based on the time-dependent function to system service (a) performance and (b) non-performance (Linkov & Palma-Oliveira, 2017)

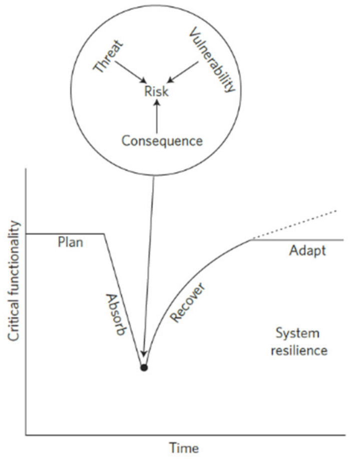
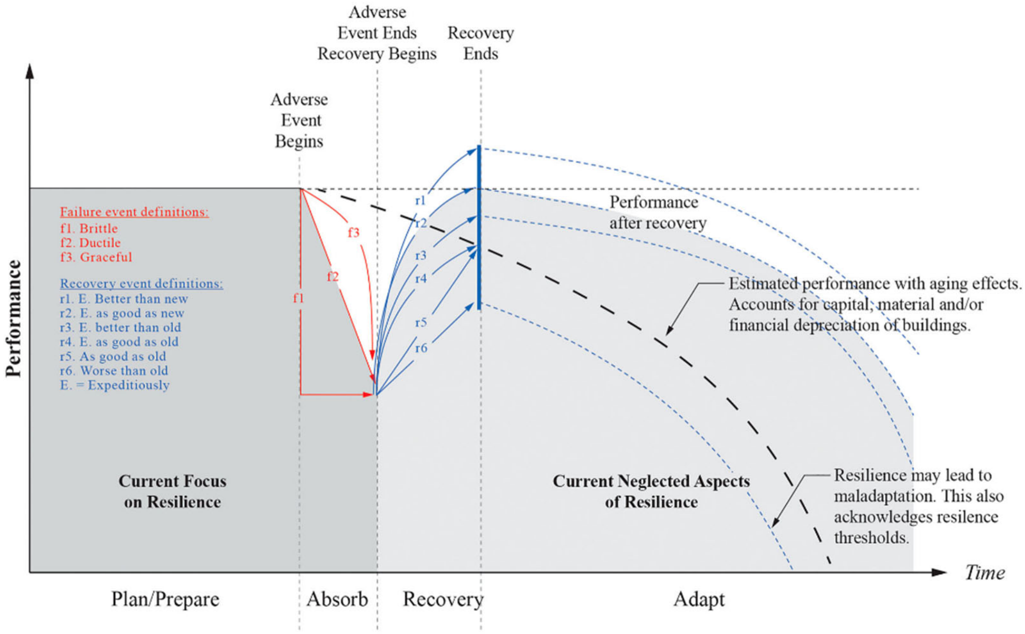


Figure 4: Graph of critical functionality against time with life-cycle stages of resilience (Linkov et al., 2014)

The resilience curve has been expressed with more details by Kurth summarizing previous studies, amongst which the one of Linkov (Linkov et al., 2014) and Ayyub (Ayyub, 2014) as described in Figure 5 which adapts the resilience definition given by the National Academy of Science. The three main concepts that are at the base of the graph are *functionality*, *recovery* and *adaption*. For the *functionality*, satisfy minimum code criteria could not guarantee functionality and inoperability could affect community resilience. Intrinsic and connected building functions need to be evaluated in terms of interdependencies and ability to function. *Recovery* implies quick reparability from failure and when system recovery is discussed, it is important to shift from the evaluation of failures to the understanding of the interdependencies and the ability to function. *Adaption* represents the ability to accommodate unknown events and be more capable to recover (Kurth et al., 2019).



NAS Stages of Resilience

Figure 5: Resilience function (Kurth et al., 2019)

In earthquake engineering, the resilience concept has been quantified in three main conditions:

- reduction of failure probabilities;
- reduction of consequences from failures; and
- reduction of time to recovery (Bruneau et al., 2003).

It is in this light, that this research will translate the above conditions for seismic analysis to fire safety engineering evaluating the failure probabilities, identified as fire incident, and its effects on people and buildings in several property types. Cimellaro et al. (2010) stated that the evaluation of resilience is based on dimensionless analytical functions linked to the variation in functionality evaluated over a time which includes losses due to disaster and recovery path. The recovery process depends on technical and human resources, societal preparedness and public policies.

There are also some resilience indicators or metrics that are defined to match the outcomes of the impact of social capital and wellbeing of a population or a system evaluated in different levels considering threat and consequences (Kurth et al., 2019). Those presented by OECD (Organization for Economic Co-operation and Development, 2014) are categorized as:

- *system resilience indicators* considering the components of the system over time and how people and buildings are affected when the shock occurs;
- *negative resilience indicators* considering how strategies could have negative impacts on other areas of the system;
- *process indicators* ensuring that actions are used in decision making;
- *output indicators* showing results of implementing different parts of the systems; and
- *proxy indicators* creating one indicator able to show the status of resilience.

Some examples of metrics for resilience are defined by Kurth such as:

- the functionality of building after the incident;
- recovery time;
- operational and maintenance costs; and
- likelihood of collapse (Kurth et al., 2019).

The aim is, therefore, to refine the social and economic measures of community resilience and translate them in technical and organizational system performance criteria (Bruneau et al., 2003). Therefore, the system performance criteria appear as a tool to guarantee resilience for social and economic aspects.

2.1.4 Resilience frameworks

Several resilience frameworks have been created in other disciplines than fire safety but common aspects are present and similar purposes can be established in various contexts such as critical infrastructures, seismic engineering and fire safety. It would be useful to have a common definition and general resilience framework independently of the hazard analysed (Gernay et al., 2016).

Critical infrastructures

The Critical Infrastructure Resilience Framework defined by NIPP 2013 (U.S. Department of Homeland Security, 2013) considers physical, cyber and human elements critical in infrastructure and the framework supports a decision-making process to inform risk-management actions. The five steps of the framework include:

- setting goals and objectives based on national priorities;
- identify infrastructures and fundamental systems to guarantee operation;
- assess and analyse risks subdivided in threats, vulnerability and consequences;
- implement risk management activities: identifying hazards, reduce vulnerability (defined as entity susceptible to hazards due to physical feature or operational attribute (U.S. Department of Homeland Security, 2013)) and mitigate consequences; and
- measure effectiveness within the sector and at a national level.

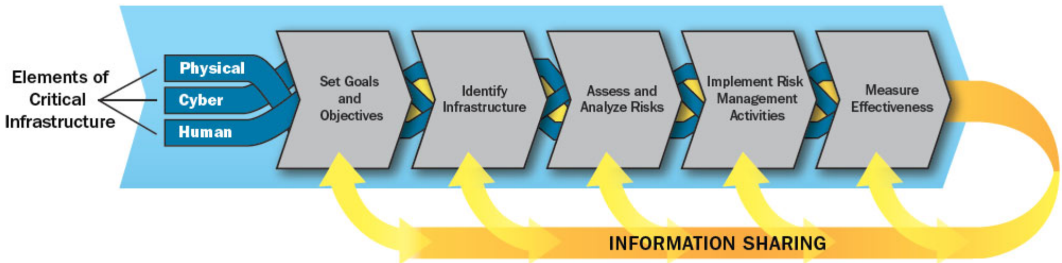


Figure 6: Critical Infrastructure Risk Management Framework (U.S. Department of Homeland Security, 2013)

NIST has created a community resilience plan for buildings and infrastructures (National Institute of Standards and Technology, 2016) in which actions and activities are defined as planning steps involving the:

1. creation of a collaborative planning team identifying members, roles and responsibilities in private and public sectors;
2. understanding of the social dimension and built environment highlighting relationships between them;
3. determination of goals and objectives as described in section 2.1.2;

4. planning of developments identifying gaps and prioritizing solutions and improvements;
5. definition of plan, review and approval with feedback received by community and stakeholders;
6. implementation and maintenance of the plan.

The Organization for Economic Co-operation Development (OECD) defines a resilience system analysis in which four questions are answered: resilience of who, of what, to what risks and over which timeframe and this questions will be at the base of the analyses developed in section 3.1 highlighting the scopes of a resilience framework. The target depends on the categories (individuals, communities, etc.), which determine the participants, and on the dimension of the plan that is focused on the system or part investigated. Furthermore, the critical aspects in a resilience system analysis are certainly the timing, the clarity, the transparency and accountability about the process. The OECD introduces the suggested six fundamental actions to:

1. determine the questions;
2. understand risks and effects to secondary risks;
3. evaluate the probability of risk occurrence;
4. identify key aspects of the system;
5. analyse how each risk affects the system; and
6. determine the severity of different risks.

In order to address the actions above, experts in both the systems and risks are necessary, key decision-makers, such as local and national authorities, are essential and technical experts in the field are required (Organization for Economic Co-operation and Development, 2014).

The UK Government published a "Public summary of sector security and resilience plans" in 2018 (Cabinet Office, 2018) in which it defines the critical national infrastructures as "*those facilities, systems, sites, information, people, network and process necessary for a country to function and upon which daily life depends. It also includes some functions, sites and organisations which are not critical to the maintenance of essential services but which need protection due to the potential dangers they could pose the public in the event of an emergency*". The characteristics of critical infrastructures are *resistance* preventing damage and disruption and reducing vulnerability, *reliability* represented by the capacity to maintain operation, *redundancy* with the availability of backup installations and *response and recovery* to rapidly respond to and recover from an incident (Cabinet Office, 2018).

Seismic design

The REDi rating System (Resilience-based earthquake design initiative for the next generation of buildings) evaluates resilience in buildings subjected to earthquakes and is assessed according to two phases: resilience design and planning and evaluation. The first phase presents three subclasses given by *building resilience*, *organizational resilience* and *ambient resilience*, while the evaluation phase represents the *loss assessment* as shown in Figure 7. *Building resilience* involves the analysis of reliable damage-control technologies and methods for non-structural components; *organizational resilience* defines the time to achieve functional recovery while *ambient resilience* determines external hazards to the building. Finally, the *loss assessment* quantifies risk based on direct financial losses and downtime (Almufti et al., 2013).

The REDi framework has three tiers: Platinum, Gold and Silver. The expected maximum downtime, direct financial loss and occupant safety are defined going from immediate re-occupancy to up to 6 months and from unlikely to possible physical injury due to failure of building components in Platinum, Gold and Silver, respectively (Almufti et al., 2013).

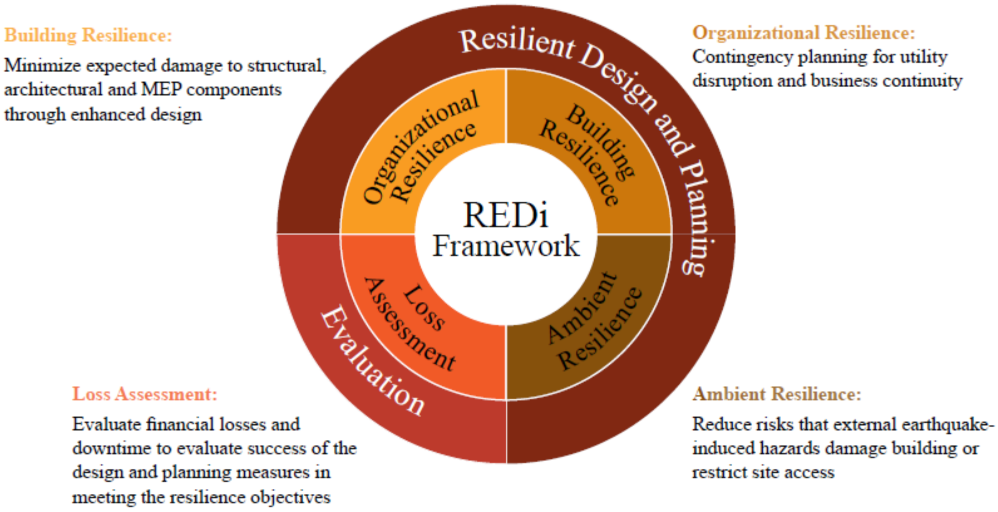


Figure 7: REDi roadmap to resilience (Almufti et al., 2013)

Bruneau identifies system resilience in the scenario of earthquakes considering robustness and rapidity. The framework shows how the resilience dimensions can be integrated into a method able to evaluate resilience for infrastructural system and community (Bruneau et al., 2003). The framework for an infrastructure system, presented in Figure 8, shows that the technical and organizational resilience can be measured as the annual probability of satisfying robustness and rapidity criteria thanks to the evaluation of the performance during earthquake scenarios. At the community level, social and economic resilience can be evaluated with the economic consequences of damage and disruption. Moreover, Bruneau identifies actions that are necessary prior to the event (clockwise flow on the left, e.g. seismic retrofit) or post-event (counter-clockwise flow on the right, e.g. response and recovery) according to three layers: the first one in which no interventions are made, the second one which addresses the first level of actions and simple decisions and the third one where multi-attribute information is gathered to support decisions as shown in Figure 9 (Bruneau et al., 2003).

In some studies, the analysis involves the possibility of having a fire following earthquake scenario because cascading events can cause social and economic losses (Khorasani et al., 2015). Indeed, it is hypothesized that cities prepared for several hazards are more resilient than those for single hazard (Joffe et al., 2016), as responsibilities shift from individuals to communities (Joffe et al., 2019). Moreover, the evaluation of common indicators, quantified measures and structural effects of natural hazards will define the building response (Vamvatsikos et al., 2010).

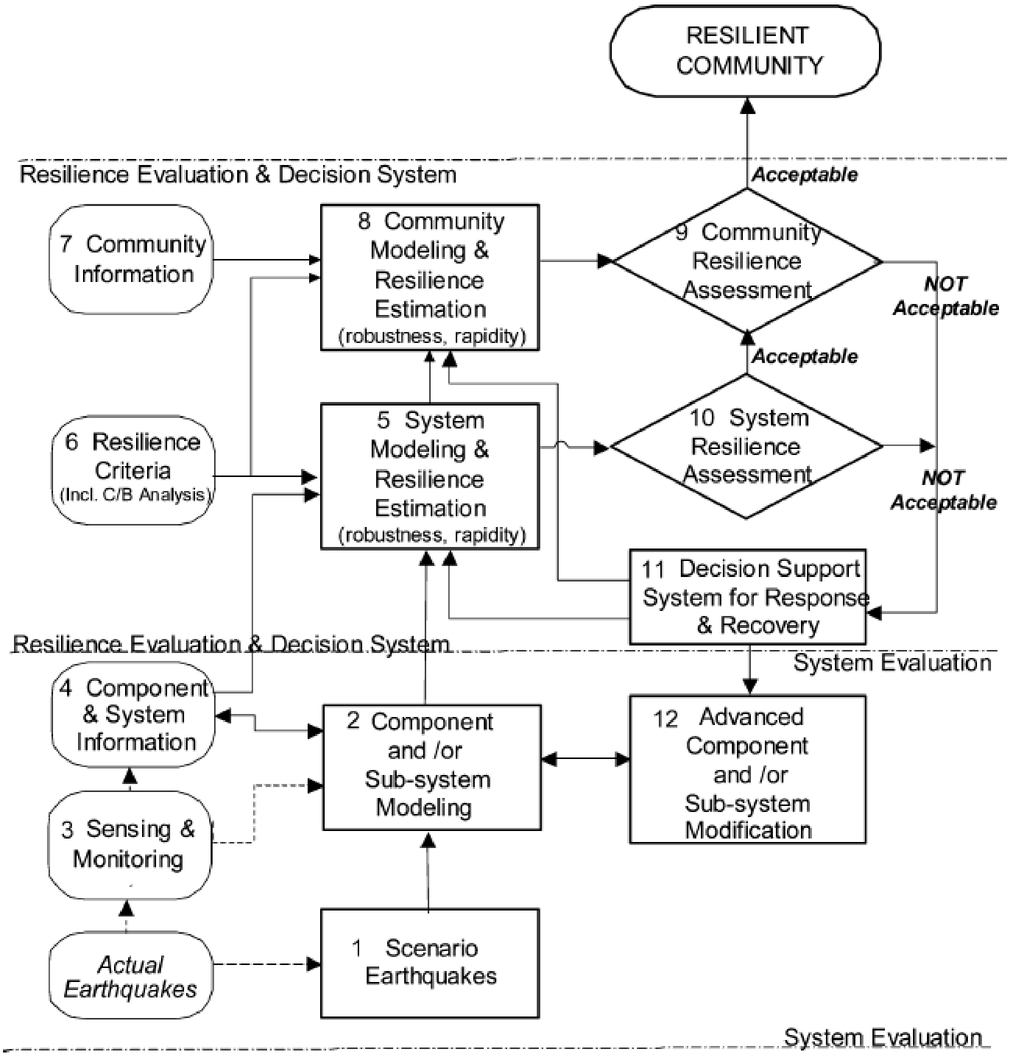


Figure 8: Bruneau's resilience framework diagram for earthquake scenario (Bruneau et al., 2003)

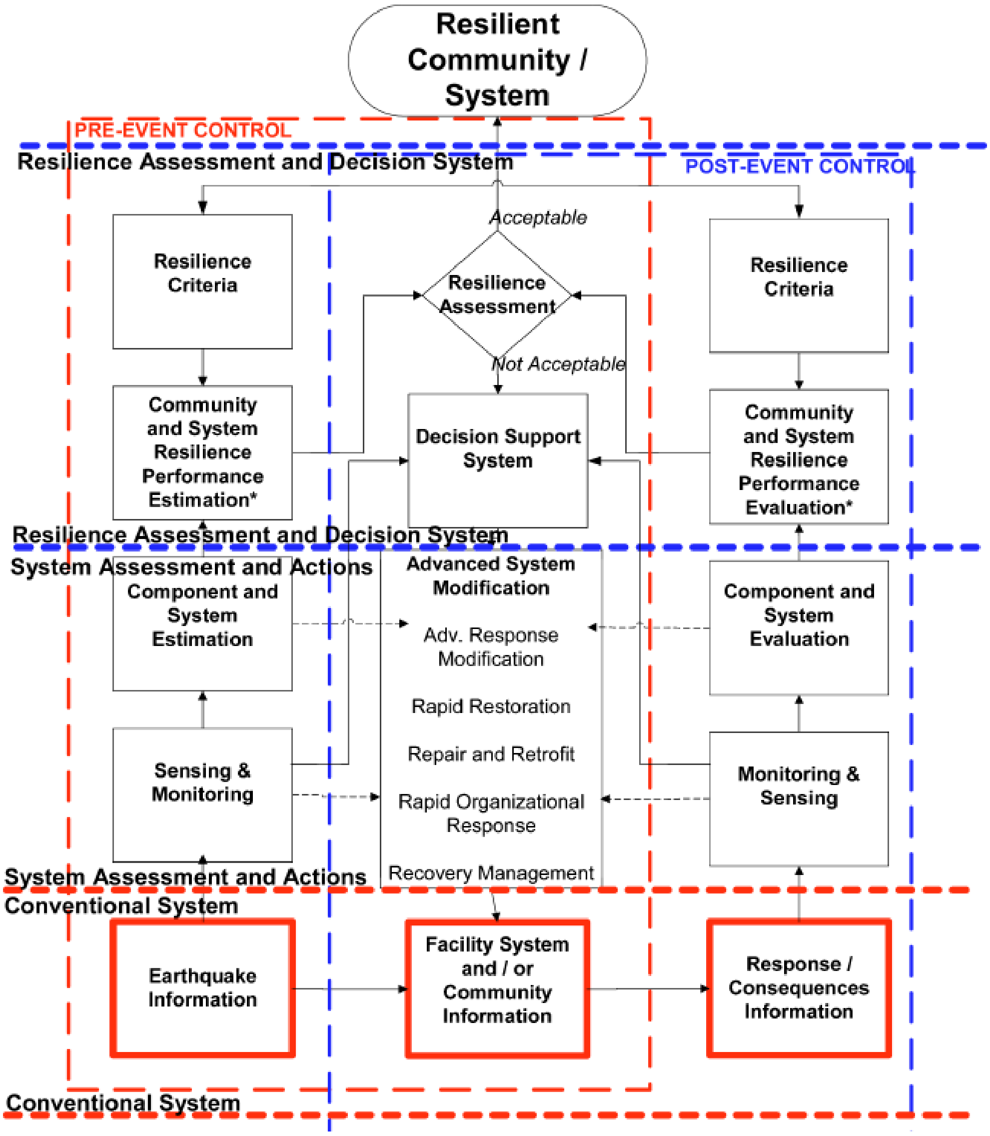


Figure 9: Bruneau's system diagram with a schematic level of details (Bruneau et al., 2003)

Fire safety

Fire resilience framework is usually based on those developed for critical infrastructures or earthquake engineering. According to Gernay et al. (2016), life safety and property protection need to be considered as fire safety requirements and the role of fire responders has to be deeply investigated to improve safety and reduce fire damage allowing prompt recovery after a fire incident. Fire damage can range from destruction of belongings to structural damage and collapse. When considering the latter, three problems should be analysed modelling fires: fire development, heat transfer model and thermomechanical response. Gernay et al. (2016) affirmed that the infrastructure resilience subjected to fires needs to be based on three stages analysis: a *resistant capacity* that includes the limitation of fire load and effective use of the fire protection system such as sprinklers; the *absorptive capacity* which prevents cascading events and spread of damage and the reduction of the impact of fire to maintain residual functionality, and also the *restorative capacity* linked to the recovery time after the disruption. According to Table 1, the capacities include the *adaptive* and *transformative capacity* while the *resistant* and *restorative capacity* are covered by the characteristics of robustness and the mission to recover.

The prescriptive fire codes mainly used in various countries address life safety without explicitly considering financial losses and disruption due to fire incidents. In order to address the progress in fire engineering adopting a resilient and holistic approach, the following problems are defined:

- *goal problem*: ensuring not only life protection but also property protection given by direct losses;
- *scale problem*: shifting the approach from individual components to the system;
- *uncertainty problem*: accounting for uncertainties and evaluate probabilistic risk assessment to reduce risks; and
- *hazard scenario problem*: considering not only single hazard but multi-hazards scenarios (Farsangi et al., 2019).

The related framework based on the above problems is the one shown in Figure 10 where the steps imply: the data collection, the characterization of design fire scenarios, the analysis of structural response, the assessment of damage and the calculation of the consequences. All these steps will be analysed in Chapter 4 and Chapter 6 of this thesis, where fire statistics are evaluated and fire scenarios investigated.

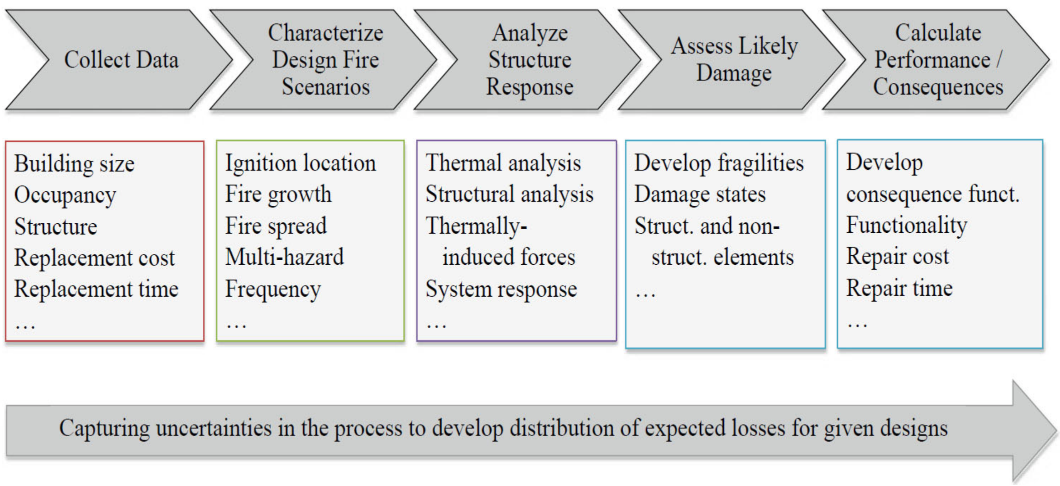


Figure 10: Methodology for evaluating the performance of a given design under fire (Farsangi et al., 2019)

The NFPA 550 provides a systematic approach to evaluate a fire safety strategy where an initiating event creates a risk to exposed populations. This represents a tool to inform disaster resilience decisions (National Fire Protection Association, 2007). In general, fire resilience is evaluated in terms of performance of specific design subjected to fire and the evaluation of the related direct financial losses without considering the impact and downtime due to fire on community and indirect financial losses, respectively. Fire resilience plans, then, are usually focused on the technical and partially economical dimensions neglecting those that are societal and organizational. Therefore, it is in this light that fire resilience is usually evaluated in fire risk assessment in which fire hazards and people at risk are identified and risk is evaluated, removed and reduced. It is important to record incidents, plan activities, instruct and train people and constantly review the process (Surrey Fire and Rescue Service Fire, 2019).

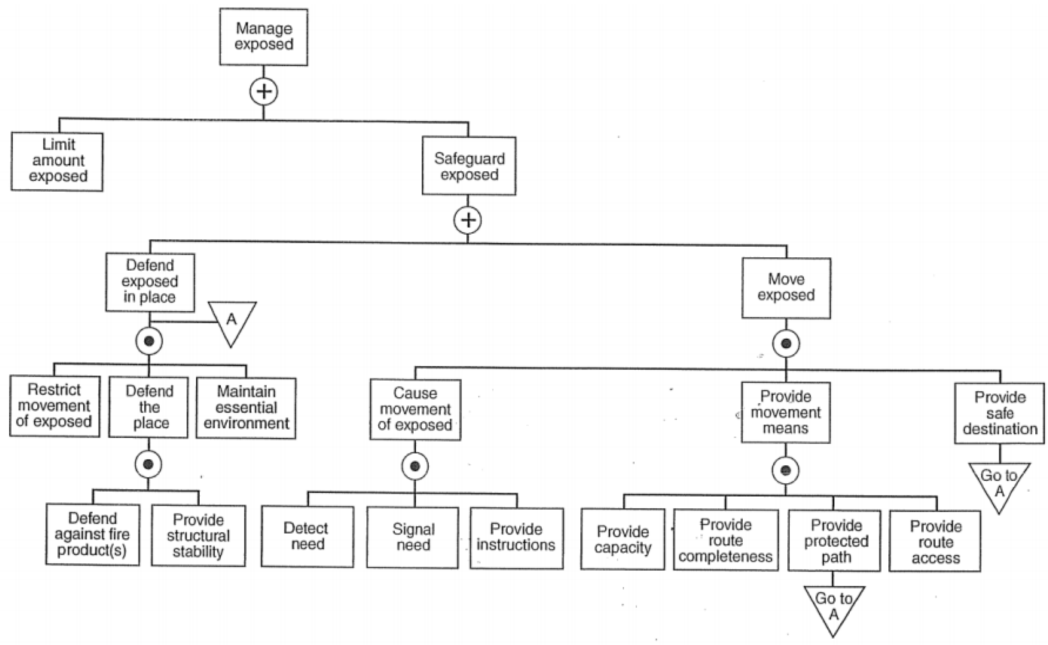


Figure 11: Manage exposed branch of fire safety concepts tree (National Fire Protection Association, 2007)

The UK Fire and Resilience Offer in the UK covers various sectors such as infrastructures, constructions, services and aviation. In particular, for constructions, it offers a range of fire engineering design, services, fire modelling, and development of standards for construction materials. Moreover, there is a specific section for safety and resilience in which the aim is to deliver plans for services to secure, protect and guarantee the first response and sustain resilience for communities (Home Office, 2017d).

Fire risk assessment is explained in detail in Chapter 6 of this thesis where the likelihood and consequences of fires in different property types are evaluated according to several safety measures.

2.2 Resilience in British Standards and Codes

Building codes are mainly prescriptive and usually provide minimum requirements to guarantee life safety but do not address the life quality of survivors after the incident. Prescriptive codes ensure that occupants are able to escape but this does not necessarily imply that the building would be functional or able to be re-occupied (Almufti et al., 2013). Therefore, the performance of the system could be very different during and after the fire and influenced by a variety of different factors.

As expressed in the REDi rating system framework addressing the resilience of buildings considering earthquakes, prescriptive or performance-based design does not include verification of non-structural elements and do not consider factors affecting the functionality of the building after an incident (Almufti et al., 2013).

Resilience is addressed in codes and standards where some policies require others to be implemented or need longer time to have an effect (Labaka et al., 2016). For this reason, Labaka develops research in which resilience policies are investigated, their influence on resilience analysed in terms of prevention, absorption and recovery and a methodology defined for the best order in which they should be implemented (Labaka et al., 2016).

2.2.1 Investigation of resilience in British Standards and Codes

In the research of this thesis, British Standards and codes are deeply investigated to understand how resilience and its dimensions are addressed, which are the common fields and differences and how fire safety is considered and evaluated. A distinction between *administrative* and *engineering features* has been established and the fields evaluated are those presented by the Fire Protection Research Foundation for the analysis of NFPA codes and standards that embodies the resilience and presents information adopted in technical references (The Fire Protection Research Foundation, 2014). In particular, the *administrative features* are divided into definition, performance goals and suggested framework. For the *engineering features*, the fields considered are the resilience characteristics in terms of the fire problem. Finally, the documents evaluated are described in relation to resilience missions.

The documents analysed are the following listed below in chronological order of publication and specifying the documents which have been replaced:

– Publicly available specification PAS 911:2007, Fire strategies – guidance and framework for their formulation (BSI PAS 911, 2007)

- British Standard BS 65000:2014, Guidance on organizational resilience (BSI BS 65000, 2014)
- British Standard BS 25999-1:2006, Business continuity management - Part 1: Code of Practice (BSI BN 25999-1, 2006)

  Replaced by: British Standard BS EN ISO 22313:2014, Societal security – Business continuity management systems – Guidance (BSI BS EN ISO 22313, 2014)
- British Standard BS 25999-2:2007, Business continuity management – Part 2: Specifications (BSI BS 25999-2, 2007)

  Replaced by: British Standard BS EN ISO 22301:2014, Societal security – Business continuity management systems – Requirements (ISO 22301:2012) (BSI BS EN ISO 22301, 2014)
- British Standard BS PD 7974-8:2012, Application of fire safety engineering principles to the design of buildings. Part 8: Property protection, business and mission continuity, and resilience (BSI PD 7974-8, 2012)

  Replaced by: British Standard BS 7974:2019, Application of fire safety engineering principles to the design of buildings – Code of practice (BSI BS 7974, 2019)
- British Standard 9991:2015 'Fire safety in the design, management and use of residential buildings – Code of practice' (BSI BS 9991, 2015)
- British Standard 9999:2017 'Fire safety design, management and use of buildings – Code of practice'(BSI BS 9999, 2017)

BS 25999-2:2007 and BS EN ISO 22301:2014 specify requirements of BS 25999-1:2006 and BS EN ISO 22313:2014, respectively. All the documents investigated are described with the previous and the updated versions and summarized for clarity in Table 2. Moreover, they need to be studied in light of their role in current practice.

PAS 911:2007 (2007) is intended to provide guidance to create and review fire strategy and does not give detailed recommendations or specifications for the applications of fire safety and protection which are usually covered in national standards and codes. It explains a methodology to integrate national standards within a framework giving tools and methodologies that can be adopted in the analytical phases of the preparation of fire strategies.

Indeed, BS 25999-1:2006 (2006), BS 7974-8:2012 (2012) and BS 65000:2014 (2014) take the form of guidance and recommendations and are not quoted as specifications or code of practice where qualified people can apply their provisions and need to justify any actions that deviate from the recommendations.

BS EN ISO 22313:2014 (2014) which updated BS 25999-1:2006, affirms that the Standard provides guidance on the requirements specified in BS EN ISO 22301:2014 (2014) giving recommendations and permissions. It does not cover all aspects of business continuity.

The BS 9999:2017 (2017) provides an approach to the fire safety design through a structured approach and risk-based design. However, despite the recommendations are based on fire safety engineering principles, the Standard is not considered as a guide for fire safety engineering even if it is considered as an advanced approach. The fire safety engineering approach is covered by the BS 7974 (2019) where suggestions for a way to achieve satisfactory fire safety standard in large and complex buildings are available. Finally, BS 9999:2017 does not apply to dwellings, residential accommodation blocks and specialized housing which are covered by BS 9991:2015 (2015). In the BS 9999:2017 and BS 9991:2015, there is an aspect related specifically to the fire safety management and this is the reasons why these two Standards are included in the engineering features.

Table 2: British Standards addressing resilience aspects

Codes	**Replaced by**
PAS 911:2007 Fire strategies – Guidance and framework for their formulation	
BS 65000:2014 Guidance on organizational resilience	
BS 25999-1:2006 Business continuity management - Part1: Code of practice	BS EN ISO 22313:2014 Social security – Business continuity management systems – Guidance
BS 25999-1:2007 Business continuity management - Part2: Specifications	BS EN ISO 22301:2014 Societal security – Business continuity management systems – Requirements
BS PD 7974-8:2012 Application of fire safety engineering principles to the design of building. Part 8: Property protection, business and mission continuity, and resilience	BS 7974:2019 Application of fire safety engineering principles to the design of buildings – Code of practice
BS 9991:2015 Fire safety in the design, management and use of residential buildings – Code of practice	
BS 9999:2017 Fire safety design, management and use of buildings – Code of practice	

2.2.2 Administrative features

2.2.2.1 Resilience definitions

For the *administrative features*, the definition of resilience involves organizations and it is expressed by BS 65000:2014 (2014) as "*a strategic objective to help an organization to survive and prosper*" and it involves characteristics such as being adaptive, competitive and robust. Moreover, the organizational resilience involves the capacity to anticipate, respond and adapt from minor incidents to major shocks or constant changes. The BS 65000:2014 affirms that resilience deals with disruption, changes and uncertainties. It appears as a combination of continuity and long-term viability based on strategic changes.

More generally, organizational resilience is defined by BS 25999-1:2006 (2006), BS 25999-2:2007 (2007) and BS 7974-8:2012 (2012) as "*the ability of an organization to resist being affected by an incident*".

2.2.2.2 Performance goals

The BS 65000:2014 (2014) provides guidance on building resilience clarifying the nature and scope for top management, identifying main components reviewing and implementing measures for improvements and recommending the good practice. Furthermore, resilience is considered as an outcome of effective governance that correctly evaluates opportunity, mitigates risks and adopts appropriate people and teams to account for decisions. BS 65000:2014 defines also people involved in the application of resilience. Innovations and investments are encouraged, and their impacts evaluated by the leaders who should build a culture of resilience. Staff should assume ownership and risks where responsibilities should be delegated to individuals during usual days and in case of crisis. Therefore, the purpose is to guarantee a transparent process in which a common vision is assumed so that opportunities and challenges are evaluated against the scope and vision.

BS 65000:2014 presents organizational resilience, while BS 25999-1:2006 (2006) introduces business continuity and BS 25999-2:2007 (2007) defines specifications to assess the organization's ability to meet regulatory, customer and the organization's own requirements related to what is described in BS 25999-1:2006. In BS 25999-1:2006, business continuity management guarantees critical activities in various time steps establishing the maximum tolerable period of disruption and identifying inter-dependent activities. The mission is to understand the effects of fire incidents on the ability to satisfy the objectives. Business continuity management is a critical review of products and services necessary to continue obligations and protect people, premises, technology and reputation. Benefits are seen in a proactive approach able to effectively respond to and manage risk.

BS 25999-1 and 2 have been replaced by BS EN ISO 22313:2014 (2014) and BS EN ISO 22301:2014 (2014), respectively. They discuss social security and business continuity management systems providing guidance and requirements. BS EN ISO 22313:2014 defines the importance of a business continuity management system to understand the organization's necessity and to implement the overall capacity to deal with disruption. Moreover, continuous improvements are guaranteed thanks to a constant monitor and review of performances. For a business continuity management system to be effective, it is important to define priorities, understand threats and establish arrangements to resume activities.

The PAS 911:2007 (2007) and BS PD 7974-8:2012 (2012), are focused on fire strategies and fire safety engineering principles, respectively. In PAS 911:2007 (2007), the benefits of fire strategy are listed as a complete understanding of fire safety requirements for premises and occupants, consideration of fire precautions including life safety, property protection, business continuity and environment (Figure 12), a review of fire safety design criteria and the creation of a framework to integrate all fire protection measures. Indeed, all the objectives criteria need to be "SMART": specific, measurable, achievable, realistic and time-related.

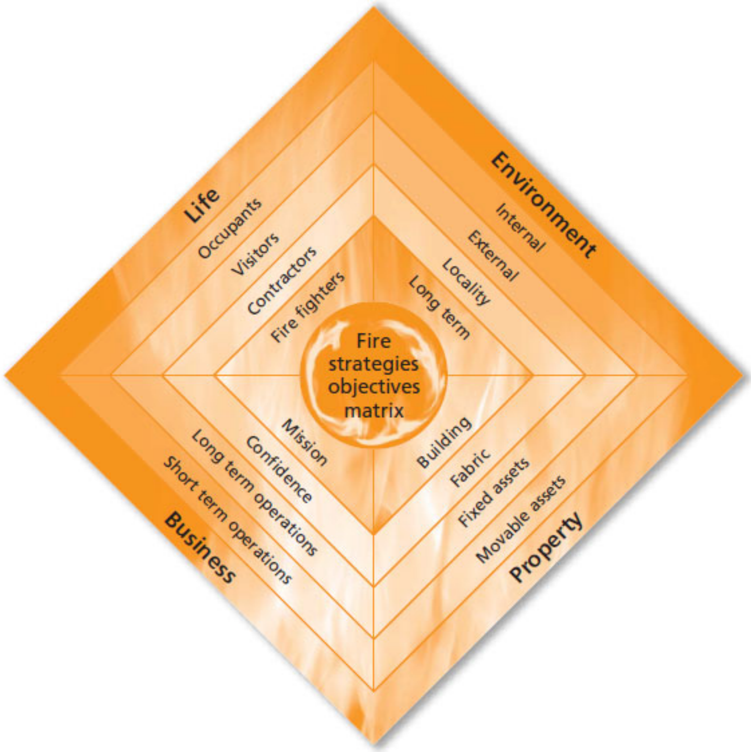


Figure 12: PSA 911 fire strategy objectives matrix (BSI PAS 911, 2007)

BS PD 7974-8:2012 (2012) affirms that despite life safety is a mandated requirement by national building regulations, property protection and business continuity are fundamental to increase resilience to fire incidents and future use describing a business impact analysis process (BIA) to inform qualitative design review (QDR). This British Standard document has been replaced by BS 7974:2019 which present the principles of fire safety engineering and provides an approach to assess the effectiveness of fire safety strategies and achieve the functional objectives. It also affirms that an "*important use of fire safety engineering is to determine an optimum level of fire protection features which together cost-effectively provide a level of protection against fire, appropriate to the financial consequences of fire related to fire-fighting causing: damage of property or contents, loss of productive capacity or reputation*". It also defines, as for its previous version, how to create business impact analysis.

2.2.2.3 Suggested resilience framework

In this section, the frameworks suggested by the Standards of Table 2 are presented to critically evaluate how resilience could be addressed.

In BS 65000:2014 (2014), building resilience is described according to six main steps, as shown in Figure 13, to:

1. be informed to:
    a. identify what has to be protected;
    b. prepare resources to anticipate, identify, review and control problems and improvements;
    c. optimize risk management framework(s); and
    d. understand lessons to be learnt;
2. set directions, specifying clear roles and responsibilities;
3. bring coherence: knowledge needs to be shared to coherently address risks and opportunities amongst all parts of organizations;
4. develop an adaptive capacity to:
    a. quickly respond to changes;
    b. support innovations, flexibility and agility; and
    c. promote activities and behaviours to facilitate new conditions;
5. strengthen the organizations to:
    a. reduce the likelihood of disruptions;
    b. improve adaptability increasing redundancy; and
    c. predict and mitigate foreseen and unforeseen impacts;
6. validate and critically review previous experiences creating appropriate training.

BS 25999-1:2006 (2006) presents a business continuity management program based on lifecycle in which four steps should be followed as shown in Figure 14 to:

1. understand the organization, evaluate impacts and define a maximum period of disruption and a minimum level of functionality;
2. determine business continuity management strategies considering people, premises, information, technology, supplies and stakeholders;
3. develop and implement business continuity management response establishing incident response structure and actions to contain events; and
4. exercise, maintain and review.

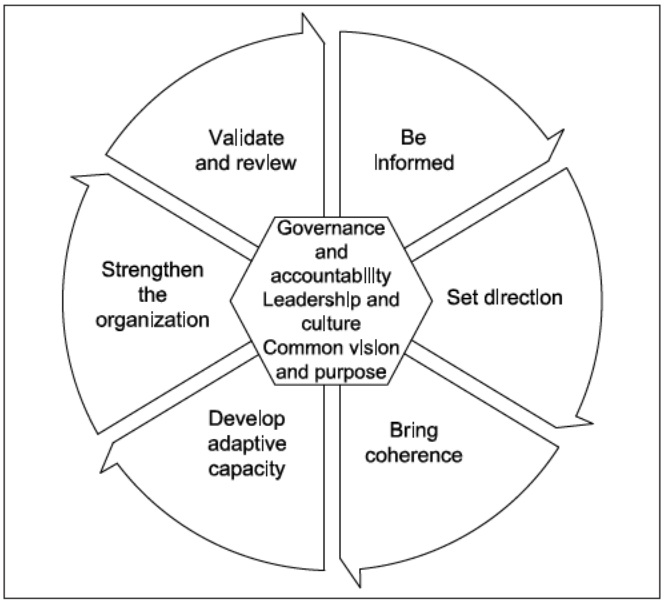


Figure 13: BS 65000:2014 Building resilience (BSI BS 65000, 2014)

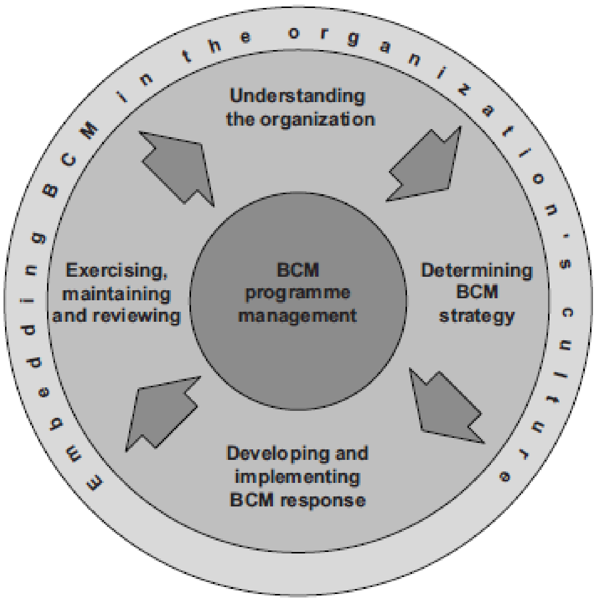


Figure 14: BS 25999-1 the BCM lifecycle (BSI BN 25999-1, 2006)

Within the phase of the developing and implementing a business continuity management response, the incident response structure enables rapid response and recovery after disruptions and defines three main time steps and the dependencies between business impact analysis, which manages the acute phase, and business continuity (Figure 15).

In BS 25999-2:2007 (2007), the Plan-Do-Check-Act cycle explains how the business continuity requirements and the expectations of interested parties are considered as inputs to generate business continuity outcomes based on actions and processes (Figure 16). This cycle has been introduced in the updated document of BS EN ISO 22313:2014 (2014) as shown in Figure 16.

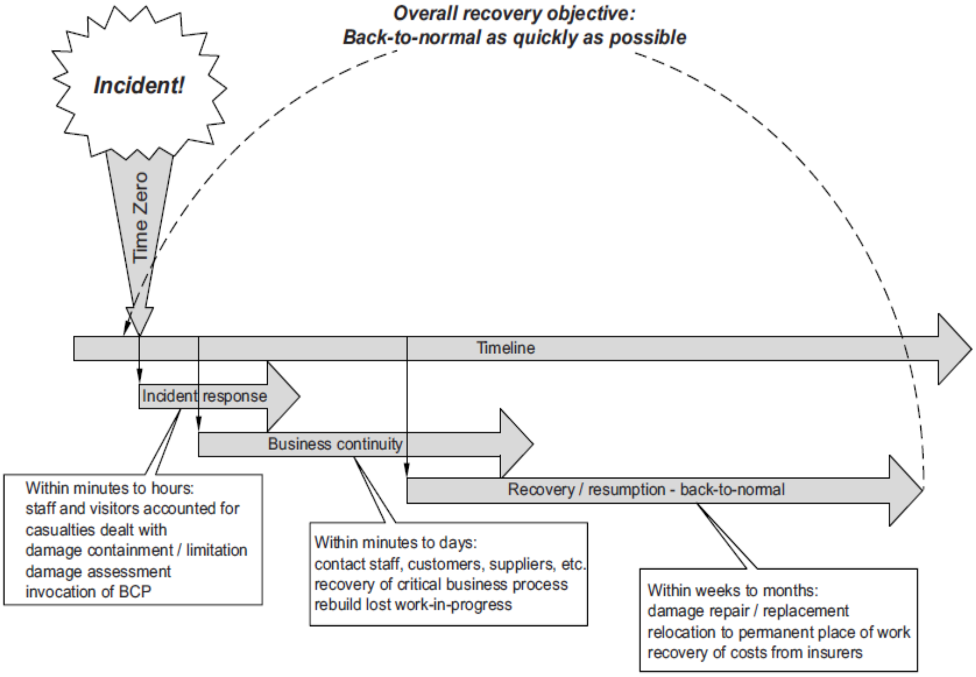


Figure 15: BS 25999-1 Incident timeline (BSI BN 25999-1, 2006)

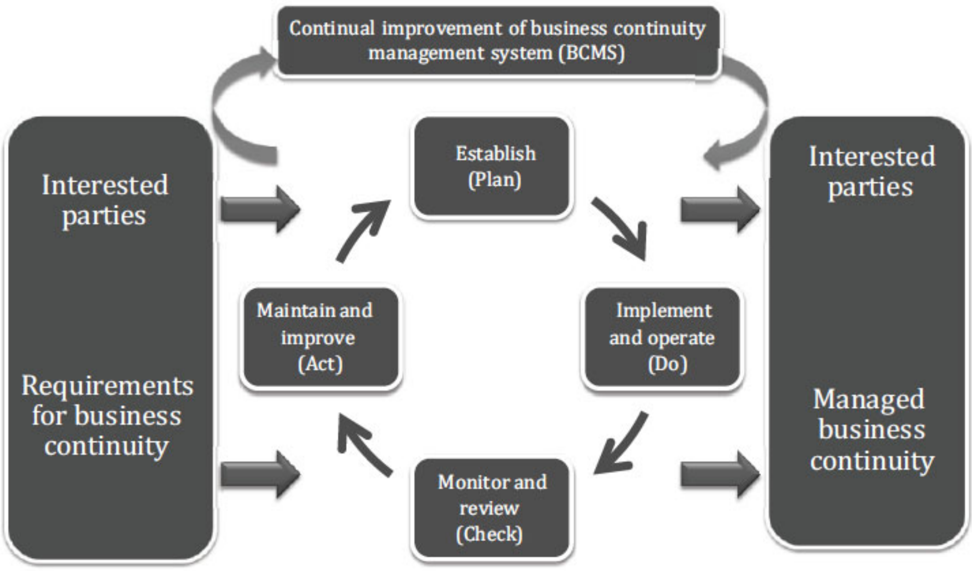
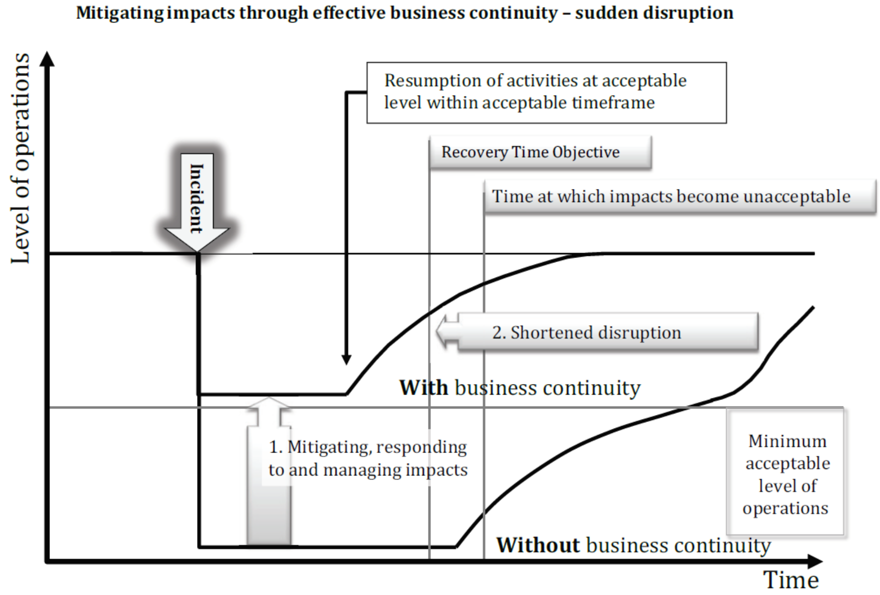
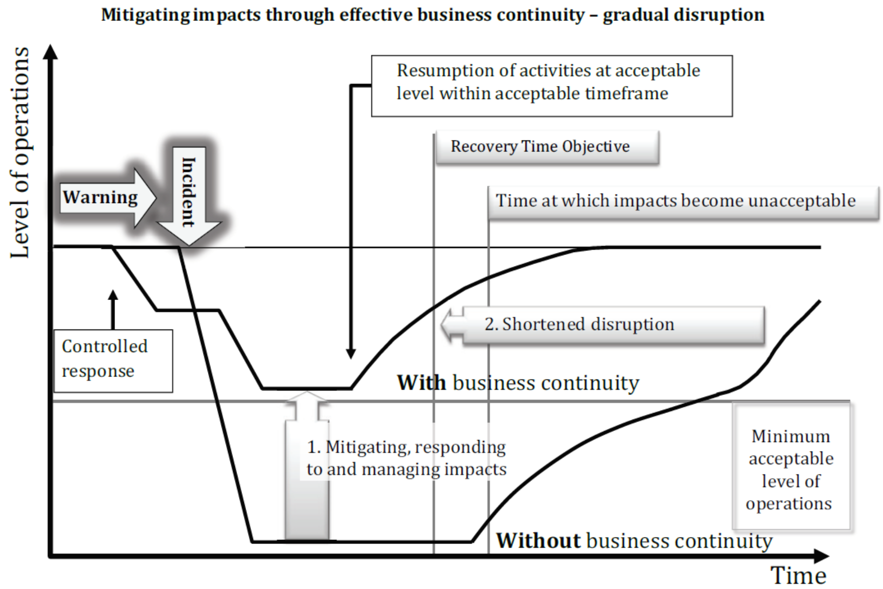


Figure 16: BS EN ISO 22313:2014 Plan-So-Check-Act

Furthermore, BS EN ISO 22313:2014 explains how business continuity could be beneficial in sudden or gradual disruption considering the graph level of operations-time (Figure 17) presented in section 2.1.3. This British Standard introduces also the parties to be considered in private and public sectors illustrating the complexity of the creation of business continuity.



(a)



(b)

Figure 17: BS EN ISO 22313:2014 Business continuity in mitigating impacts of (a) sudden or (b) gradual disruption (BSI BS EN ISO 22313, 2014)

While the above documents are referred to organizations and could be also valid for buildings, BS 7974-8:2012 (2012) is specifically focused on fire safety engineering including property protection, business and mission continuity and resilience. It defines a fire safety engineering framework considering a *qualitative design review* to define objectives and identify hazards, a *quantitative analysis* to consider solutions and *assessment against criteria* in which the outcomes of quantitative analysis are compared against agreed criteria. These three phases are considered as the fundamental ones in fire engineering processes. In particular, qualitative design review is useful to review evidence and fire statistics to establish scenarios for quantified evaluations and a business impact analysis is usually considered as input in every qualitative design review. According to BS PD 7974-8:2012, a business impact analysis is composed of:

- definition of scope, specific for fire disruptions;
- data collection, considering a maximum tolerable period and recovery time; and
- moderation process.

Therefore, data collection represents an essential part in fire safety engineering highlighting previous incidents and understanding the performances of organizations or buildings.

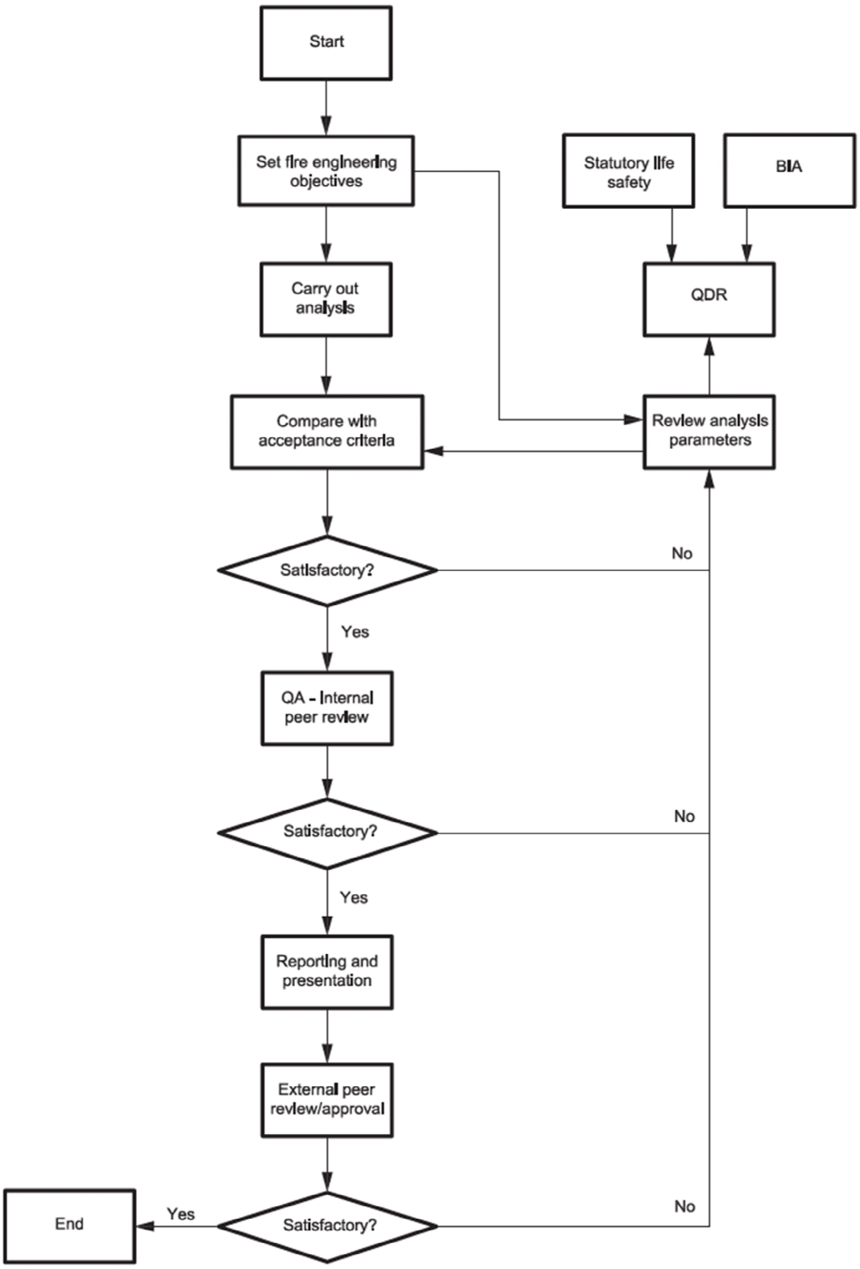


Figure 18: BS 7974:2019 Fire safety engineering process (BSI BS 7974, 2019)

The updated version BS PD 7974:2019 (2019) considers the same fire safety engineering framework like the one described in BS PD 7974-8:2012 (2012) where it does not necessarily guarantee adequate design and approval bodies should be consulted. However, the framework is expanded in BS PD 7974:2019 and it is represented by the following main stages:

- qualitative design review;
- analysis;
- assessment against criteria;
- internal peer review and quality assurance;
- report and presentation of results; and
- external peer review (Figure 18).

Again, the qualitative design review includes the:

- definition of objectives for fire (life safety, loss prevention and environment);
- identification of fire hazards and possible consequences;
- the setting of acceptable criteria;
- identification of the method of analysis; and
- establishment of fire scenarios.

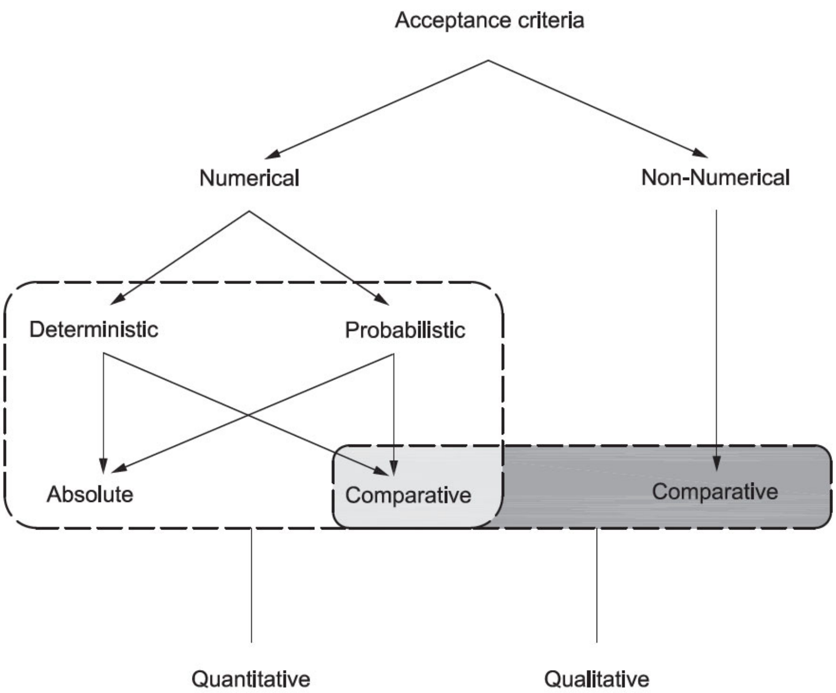


Figure 19: BS 7974:2019 Acceptance criteria (BSI BS 7974, 2019)

Based on these considerations, this research is focused on the identification of fire hazards and structural consequences after fire incidents and the likelihood of several fire scenarios in various property types considering several fire safety measures. For what concerns the acceptable criteria, these could be numerical or non-numerical also named as qualitative and quantitatively, respectively (BSI BS 7974, 2019). While qualitative criteria are only comparative, quantitative ones could be developed with deterministic or probabilistic analyses based on absolute or comparative criteria (Figure 19). Again, the research presented within this thesis is based on probabilistic analysis deduced by current national fire statistics and compares fire statistics data with those present in BS PD 7974-7:2003 (2003).

BS 7974:2019 (2019) presents an example of a timeline between fire development, evacuation and damage to property (Figure 20) which is further implemented in this thesis. While the timeline of BS 7974:2019 considers only the fire response of occupants, the improvements developed in the research of this thesis also investigates the contribution of firefighters with the dispatch, preparation, travel time, set-up, occupant rescue and fire extinguishment highlighting the components of fire response and mitigation. Furthermore, BS 7974:2019 does not extend the timeline after the incident neglecting the recovery time and the possible implications on activity restoration and property repairs for a short or long disruption. Once the normal level of functionality is reached, performances could be implemented to achieve a higher level than the one before the incident (Figure 21).

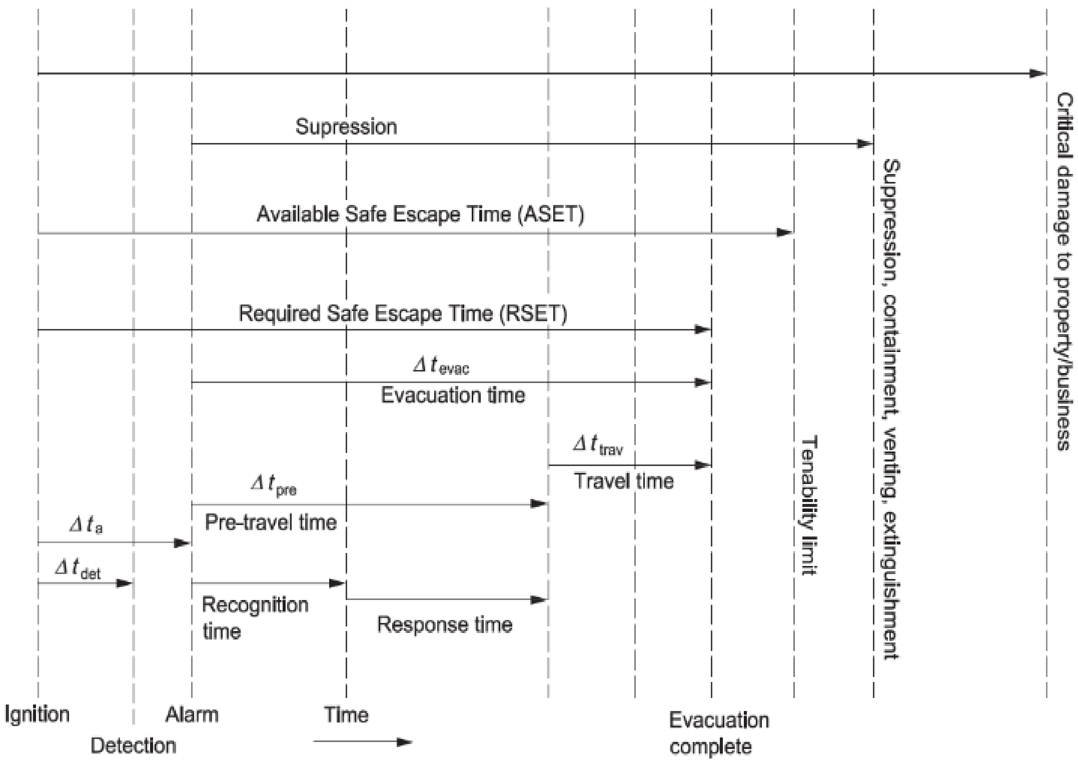


Figure 20: BS 7974:2019 Example of timeline comparison between fire development and evacuation/damage to property (BSI BS 7974, 2019)

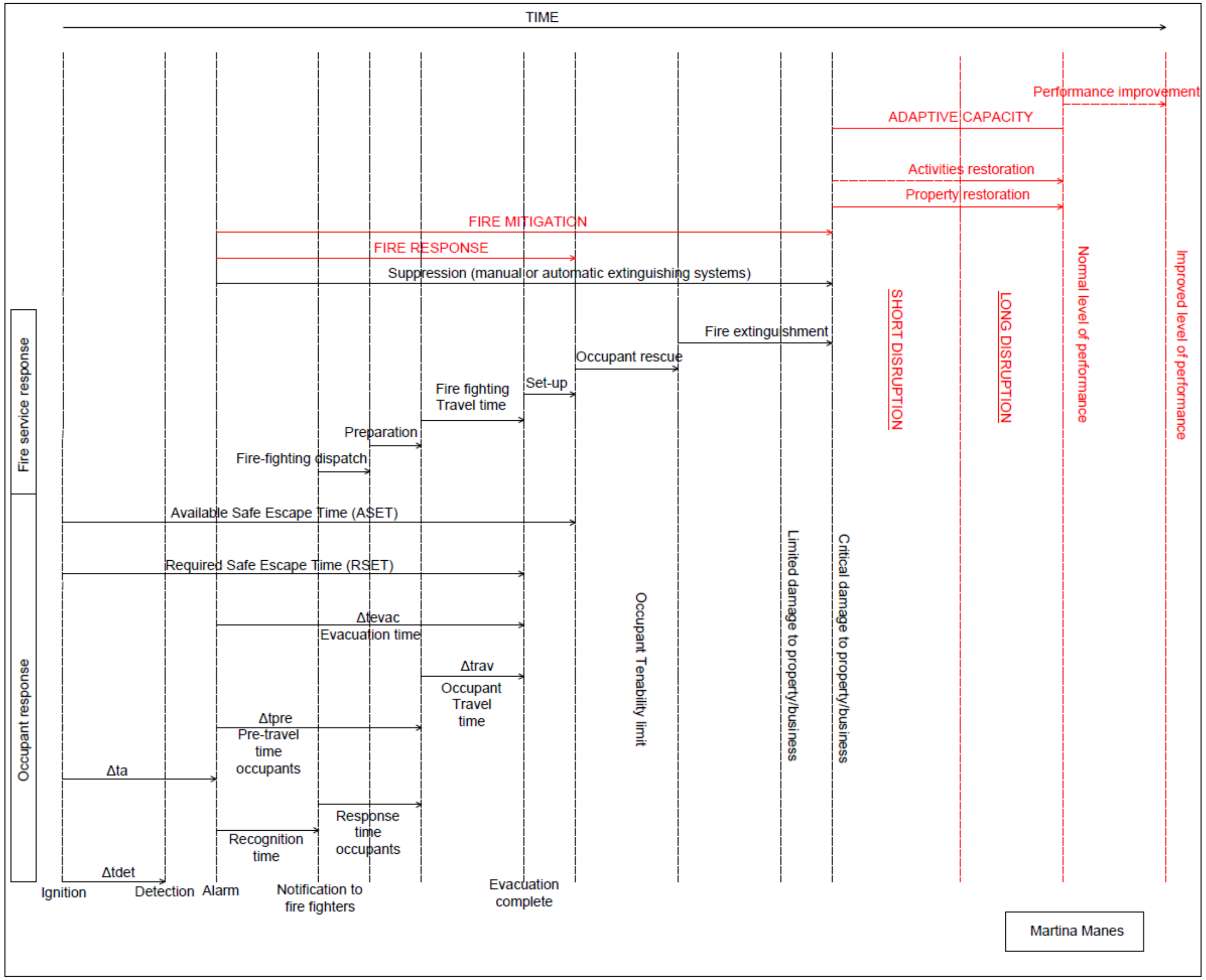


Figure 21: Improved example of the timeline provided by BS 7974:201

2.2.2.4 Administrative features and missions

The six missions to prevent, respond, absorb/mitigate, recover, adapt and learn, introduced in section 2.1.2, need to be considered if resilience approaches are adopted. Usually, the missions to prevent, respond, absorb and adapt are referred to specific parts of the resilience function as explained by Linkov et al. (2014) in Figure 4 and by Kurth at al. (2019) in Figure 5 while the analysis developed in this section also considers the phase of learning after the incident. Generally, resilience approaches investigate the resilience function with the aim to reduce the loss of performances and quickly return to normal functionality after a disruption. The evaluations and improvements of each mission could influence or enhance different parts of the resilience function applied to a specific system.

The research developed within this thesis investigates the Standards described in section 2.2.1 and listed in Table 2 and evaluates in detail if they address the six resilience missions. The guidelines introduced by the Standards are summarized in this section in terms of their *administrative features* and in section 2.2.3.1 in terms of their *engineering features* according to the six missions to prevent, respond, absorb/mitigate, recover, adapt and learn.

PREVENT

- PAS 911:2007, fire precautions with respect to broader objectives that may include life safety, property protection and environmental considerations.
- BS 65000:2014, to predict and mitigate foreseen and unforeseen events.
- BS 25999-1:2006, to identify what needs to be done before an accident occurs to protect people, premises, technology, information, supply chain, stakeholders and reputation.

  Replaced by: BS EN ISO 22313, to monitor and review the performances and effectiveness of business continuity management systems.
- BS PD 7974-8:2012, to control fire to prevent the destruction of a building.

  Replaced by: BS 7974:2019, to identify fire hazards and potential consequences.

RESPOND

- PAS 911:2007, components of the fire strategy timeline.
- BS 65000:2014, measures to develop and implement the business continuity management response and containing the incident.
- BS 25999-1:2006, methods of restoring an organization's ability to supply products and services to an agreed level within an agreed time after a disruption.
- BS 7974:2019, fire and human response translated into the building design process.

ABSORB/MITIGATE

- PAS 911, to enhance business continuity.
- BS 65000:2014, to establish a resilient organisation.
- BS 25999-1:2006, to improve the ability to achieve objectives against disruption.
  Replaced by: BS EN ISO 22313:2014, to implement and operate control measures for the overall capability to manage disruptive incidents. Mitigating, responding to and managing impacts.
- BS PD 7974-8:2012, business impact analysis in combination with business continuity management to ensure adequate availability of critical activities.
  Replaced by: BS 7974:2019, fire safety measures to ensure that the functional objectives are met. Protect people and buildings.

RECOVER

- PSA 911, analysis of business interruption (short and long term).
- BS 65000:2014, to strengthen the ability to address disruptive events, emergent risks and changes through recovery to an agreed state.
- BS 25999-1:2006, to provide a method of restoring the ability to supply products and services to an agreed level within an agreed time after the disruption.
  Replaced by: BS EN ISO 22313, business continuity strategies – stabilizing, continuity, resuming and recovering prioritized activities.
- BS PD 7974-8:2012, business impact analysis defines the timescale for the disruption.
  Replaced by: BS 7974:2019, to maintain ongoing business viability.

ADAPT

- BS 65000:2014, to develop adaptive capacity.

LEARN

- PAS 911:2007, to investigate the existing management of fire safety systems.
- BS 65000:2014, to identify and capture lessons to be learnt.
- BS EN ISO 22313, to maintain and improve the business continuity management adopting corrective actions, based on the results of management review. Continuous management review and improvement.

2.2.3 Engineering features

The *engineering features* consider the technical aspects of disaster resilience (The Fire Protection Research Foundation, 2014). However, it is important to combine the *engineering features* with the *administrative* ones to obtain a comprehensive view of the problem and address not only the technical aspects but also the organizational ones. The PAS 911:2007 (2007), BS PD 7974-8:2012 (2012) updated by BS 7974:2019 (2019), BS 9991:2015 (2015) and BS 9999:2017 (2017) are the Standards mainly focused on the technical measures required to address fire safety issues while the other Standards, listed in Table 2 and described in section 2.2.1, cover the main aspects related to organizational and management issues.

Moreover, a code is analysed in this section which is the Approved Document B – Volume 2 Buildings other than dwelling houses 2010 (Building Regulations, 2010) (named herein AD B Vol. 2 2010). This document provides practical guidance with respect to Regulation 7 and Building Regulation 2010 for England and Wales. The role of this code is to provide guidance for common buildings but there could be alternative approaches to achieve compliance with requirements. Therefore, there is no obligation to adopt this document if it is preferred to use another way to reach the requirements. The difference between Building Regulations and Standards is that while Building Regulations are created for specific purposes such as health and safety, welfare and convenience of people, Standards are guidance that extends these considerations (Building Regulations, 2010). The AD B Vol. 2 2010 is composed of five functional requirements from B1 to B5 where many of the provisions are related and guidance is provided according to performance related to standard fire test methods. It assumes that the building is properly managed to protect life while property protection often requires additional measures.

2.2.3.1 Engineering features and missions

In this section, the *engineering features* in the British Standards summarized in Table 2 and the AD B Vol. 2 2010 (Building Regulations, 2010), are classified according to five of the six resilience missions introduced in section 2.1.2 such as to prevent, respond, absorb/mitigate, recover and learn. The mission to adapt is considered related more to the *administrative features* than to the *engineering ones* which are focused on technical solutions and measures, and it is not considered in the analysis of this section.

PREVENT

- PAS 911:2007, to define design criteria, assess risks and hazards and model fire with simulation techniques.

- BS PD 7974-8:2012, to define property protection objectives controlling fire to prevent the destruction of the building. The fire safety engineering framework includes qualitative design, quantitative design and acceptance against criteria.

  Replaced by: BS 7974 Annex B, to guarantee property protection and mission resilience.
- BS 9991:2015, to establish functional objectives for fire.
- BS 9999:2017, to identify and design the management of fire risk, to manage occupied buildings, to identify special risk protection and to ensure effective fire protection in the design, construction and maintenance stage.
- AD B Vol. 2 2010, (B3) to ensure a sufficient degree of fire separation within buildings and with adjoining ones; (B4) to restrict the spread of fire from the building to another one.

RESPOND

- PAS 911:2007, to identify occupants and building characteristics (means of escape and provision for fire-fighting) and assess methods of evacuation.
- BS PD 7974-8:2012, to establish fire protection tactics for improving resilience as manual fire-fighting.

  Replaced by: BS 7974, to provide fire and rescue service intervention, occupant evacuation, behaviour and condition.
- BS 9991:2015, to design means of escape, stairs and final exits, access and facilities for fire-fighters.
- BS 9999:2017, to design means of escape, access and facilities for fire-fighters.
- AD B Vol. 2 2010, (B1) to define means of giving alarm and means of escape, (B5) to guarantee access to fire appliances and facilities in the building to support fire-fighters in their rescue operations.

ABSORB/MITIGATE

- PAS 911:2007, to define fire compartments and separations, identify fire and smoke movement, assess internal linings, furnishings and processes.
- BS PD 7974-8:2012, to establish fire protection tactics for improving resilience such as minimizing ignition source and combustible, effective fire detection and suppression, passive fire protection, compartmentation and ventilation.

  Replaced by: BS 7974, to identify fire hazards and possible consequences.
- BS 9991:2015, to determine the presence of active fire protection, effective design for construction, mechanical system for deducted heating ventilation and air conditioning.

- BS 9999:2017, to design the building structure considering load-bearing and non-load-bearing elements to fire.
- AD B Vol. 2 2010, (B2) to inhibit fire spread over internal linings and (B3) spread of fire and smoke in concealed spaces, (B3) to ensure building stability in a fire incident and provide automatic fire suppression, (B4) to determine the adequate fire resistance of external walls and roofs to protect the external envelope.

RECOVER

- BS PD 7974-8:2012, to guarantee redundancy and prioritize activities for resuming resources.

  Replaced by: BS 7974, to create business impact analysis (BIA).

LEARN

- BS PD 7974-8:2012, to establish fire protection tactics for improving resilience such as training and management and evaluate cost-benefit analysis to determine the most cost-effective solution.

  Replaced by: BS 7974, to define fire protection tactics for improving resilience.

2.2.4 Standards and Codes in the resilience function

Once the evaluation of Standards and Codes have been investigated in terms of *administrative* and *engineering features* and their relation with the resilience mission, it is important to understand how the Standards of Table 2, currently in place, and the AD B Vol.2 2010 (Building Regulations, 2010) contribute in the resilience function described in section 2.1.3 and expressed as performance against time as shown in Figure 22. The resilience function is divided according to the resilience missions such as prevention, absorption and response, recovery and adaption considering a fire incident as suggested by Linkov et al. (2014).

Based on Figure 22, the Standards and Code appear to be concentrated in the first part of the function and in particular in the sector of prevention and absorption and response and their guidelines decrease moving towards the recovery and adaption phases. In particular, the AD B Vol.2 (Building Regulations, 2010) provides guidance for prevention, absorption and response without considering the recovery after an incident and potential measure of adaption to improve the performance from what learnt in the incident.

Therefore, it is fundamental to integrate *administrative features* with *engineering* ones to cover all the entire resilience assessment in the case of fire events integrating social, organizational and technical aspects. Further research about resilience is developed in Chapter 3 and covers how fire resilience is assessed, the definition of fire resilience measures and approaches, the creation of a fire resilience framework for educational building and a fire flowchart to integrate structural and fire safety design.

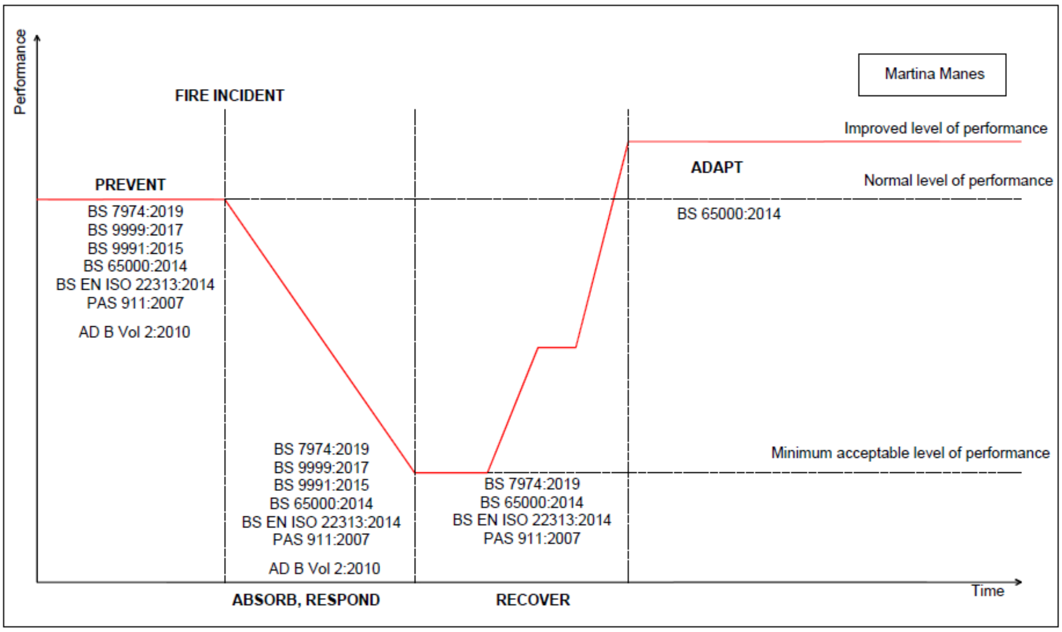


Figure 22: Standards and Codes in the resilience function

2.3 Fire statistics

2.3.1 Importance of fire statistics

As expressed in section 2.1.2, criteria for fire safety need to guarantee life safety, property protection, environmental safeguard and business continuity. They should be assigned in every fire design as presented in Chapter 3. The problem is represented by the lack of data related to the response of real buildings affected by real fires. When performance-based designs are applied, these are based on advanced computer simulations using 3D models which are usually rarely validated due to the paucity of structural data of buildings subjected to fires. At the same time, experiments are often focused on the response of single elements exposed to fire conditions (Bisby et al., 2013) where research has demonstrated that frames show better performances than those presented by individual elements if exposed to fires thanks to the interactions given by the connections (Cooke & Latham, 1987) (Rubert & Schaumann, 1986). The conditions under which materials are tested could only represent only a small proportion of the uses of the materials in real practice (America Burning, 1973). The complexity of fire characteristics and structural configurations does not allow the collection of all the data required through experimentations which are usually expensive and time-consuming. To bypass this limitation, research has been focused on probabilistic performance-based design (Borg et al., 2015) where academic investigations usually study the probability of failure based on structural collapse or life safety (Wang et al., 2013) with few cases investigating damage and use of the property after the incident (Kirby et al., 1993).

Several countries have developed national fire statistics with similar reporting system where fire brigades fill in an online form in the aftermath of an event with mandatory fields such as response time, area of damage, size of the fire at arrival and after extinguishment. The data collected are then merged in a dataset and reports are published yearly. Thanks to the fire statistics, useful information is collected about pre- and post-fire conditions as well as development and spread of building fires in various property types. Direct financial losses are also evaluated in relation to the structural damage exhibited by the building.

The Geneva Association published in 2014 a report of world fire statistics in which fire and climate risk are evaluated, disseminating data on fire deaths, injuries and damage to property and associating fires with other natural disasters (e.g. wildfires, earthquakes). The report is evaluated in terms of costs of direct and indirect fire losses according to percentages of global GDP, human fire losses, costs of firefighting organisations, insurance administration and fire protection to buildings and forest and wildland fires. Nine United Nations Economic commissions for Europe including the United Kingdom and responses of Australia, New Zealand, Japan and others are examined (The Geneva Association, 2014).

At the beginning of the research of this thesis, five of the ten provinces in Canada had their fire statistics which were Alberta, British Columbia, Manitoba, Nova Scotia, Ontario and Saskatchewan. Nowadays, Statistics Canada presents Incident-based fire statistics which summarizes the trends for the whole country and each province according to specific filters (Statistics Canada, 2015). In Australia, each state has its fire statistics like the one of the Queensland Fire and Emergency Service (QFES) yearly published in which all incidents attended are available (Queensland Fire and Emergency Service, 2019).

Due to the lack of national statistics and differences in the fields and number of fires recorded in the datasets for the various provinces in Canada and states in Australia, the analysis of this thesis has been mainly focused on a deep analysis of English and USA fire statistics for which row data are available or provided and the highest number of fields recorded as described in section 2.3.2 and 2.3.3 and deeply evaluated in Chapter 4.

Fire statistics data provide a quantification of the effects and consequences of fires in buildings addressing the efficiency of alarms in the notification to occupants and safety systems in reducing structural fire impacts. Fire occurrences, fire size, damage and the effects that a prompt fire-fighters response could have on life safety and damage reduction are evaluated and these variables describe inputs parameters for fire risk assessment, risk-based approaches and performance-based design methodology. The results are beneficial for the fire safety community, fire brigades, local and national governments and international administrations.

2.3.2 Incident Recording System

The Home Office Incident Recording System (IRS) is developed by the Home Office and gathers data on incidents attended by the fire and rescue services (FRSs) in England, Wales and Scotland. It is composed of a pre-populated web-based form with information from the Command and Control systems, and it is filled in and submitted by those present during the incident (Home Office, 2017c). A quarterly release on Fire and rescue service statistics collecting national statistics on fires, casualties, false alarms and non-fire incidents attended by the fire and rescue service in England and annual releases with more-detailed analyses and non-fire incidents, is published by the Home Office (Home Office, 2019). The quality of data is ensured by the collaboration between the Home Office and FRSs but unidentified inconsistencies may be present in the datasets (Home Office, 2017c).

Table 3: Fields in English fire statistics 2014/2015

	English Fire statistics 2014/2015	
Incidents	Cause of fire	Workforce and workforce diversity
Dwelling fires	Smoke alarms	Fire prevention
Non-dwelling fires	Temporal and seasonal	Fire pensions
Deliberate fires	Special service incidents	Other
Fatalities and casualties	Response time	

The IRS (Department for Communities & Local Government, 2012) is composed of questions covering the complete description of the fire incidents from fire causes to the evaluation of structural damage. Moreover, the IRS covers information for all incidents rather than primary fires defined as serious fires that affect people or cause property damage. Dwellings, Other buildings, Road vehicles and Other outdoor fires are the four categories in which primary fires are sub-divided. The focus of this thesis is mainly on *Other buildings* fires and partially on *Dwellings* fires. At the beginning of this research, the most recent fire statistics available for England was one of 2014/15 summarized in the Statistical Bulletin 08/16 (Gaught et al., 2016) and adopted in Chapter 4. The spreadsheets are grouped as described in Table 3 and the dataset contains 155,000 total fires including 71,089 primary fires with 31,329 *Dwellings* and 15,548 *Other building* fires.

When the analysis of Chapter 5 was developed, a new fire statistics dataset published by the Home Office was available and the research considers the new released *Other building* fires dataset in which data are collected from 2010/11 to 2016/17 including 121,558 fire incidents (Home Office, 2017b) with 41 columns of fields recorded for each fire incident. This dataset has been adopted for all the analyses developed in Chapter 5 except for the evaluation of fire frequency in relation to the total floor space of the building. The reason is that the aforementioned dataset does not include the total floor area of the building. The Home Office kindly provided an additional database from 2010/11 to 2016/17 which includes information about the building dimension and only the data of 2014/15 have been analysed to create a direct comparison. In order to guarantee data quality, entries where the building room or floor of origin are equal to 0 m^2, the number of floors above or below ground/main level is recorded as 99 or 999, and fires, where the fire damage is greater than the total damage, are removed. The *Other building* fires dataset has been reduced from 15,561 to 11,168 fire incidents of approximately a quarter. The *Dwellings* fires datasets published in 2017 by the Home Office with data from 2010/11 to 2016/17 including 230,205 fires with 37 columns of fields recorded (Home Office, 2017a) has been adopted for the fatality rate in section 5.7 and response time impact in section 5.8.

In England, information about causes, spread and damage is present and in particular, the fire damage is classified according to *fire* and *total damage* where *fire damage* is defined as the total horizontal area damaged by the flame and heat in m^2 at the stop of the fire; and *total damage* as the area damaged by the flame, heat, smoke and water in m^2 (Home Office, 2017b). No direct financial losses caused by fire incidents are recorded. The datasets of the English fire statistics adopted in this thesis have been summarized in Table 5 for clarity.

2.3.3 National Fire Incident Reporting System

In 1973, the Report of the National Commission on Fire Prevention and Control America Burning outlined important tasks for the US Fire Administration as to develop a comprehensive national fire data system able to establish priorities for research and actions and to monitor fire research in governmental and private sectors (America Burning, 1973).

The National Fire Prevention and Control Act, Public law 93-498 established the National Fire Prevention and Control Administration and mandated the collection of national fire data thanks to the National Fire Incident Reporting System (NFIRS). In 1976, The U.S. Fire Administration developed the NFIRS which is considered as the largest collection of incidents in which fire departments take part with 15,000 fire departments from 50 States and more than

40 metropolitan areas. Since NFIRS is a voluntary system, not all states participate but the majority do. States can adapt their reporting system to their needs but the NFIRS is designed in a way that states' data can be converted in a single format used at the national level. Yearly, 600,000 incidents and more than 5 million non-fire incidents are reported in the database. The NFIRS is used at local and state levels. At the local level, is adopted for setting priorities and addressing resources to create fire prevention and education programmes while at the state level, the State legislatures justify budgets and analyse fire problems (USFA, 2014).

Table 4: NFIRS modules

NFIRS modules		
Basic	Fire Service	Apparatus or Resources
Fire	EMS	Personnel
Structure Fire	Hazardous Materials	Arson
Civilian Fire Casualty	Wildland Fire	Supplement Form - additional

After an incident, the fire department personnel fill in one or more modules of the NFIRS where the Basic one is compulsory (Table 4) according to the characteristics of the event, the time of occurrence, the resources adopted, information and losses to investigate fire nature and causes. The National Fire Data centre (NFDC) combines the information provided by the State agency which merges the data collected from the fire departments (USFA, 2014).

NFIRS reports causes of fire such as heat source, item and material first ignited, factors affecting the spread as materials contributing most to flame, and consequences defined as the number of stories damaged by the flame where flame damage is the area burned or charred not including areas receiving heat, smoke or water damage. The damage classes are: Minor Damage (from 1 to 24%); Significant Damage (25 to 49%); Heavy Damage (50 to 74%); Extreme Damage (75 to 100%). Response time is expressed not only as fire brigade time of attendance but also time from alarm or arrival to the last unit cleared. Information about detectors and automatic extinguishing systems are reported in terms of presence, operation, failure and types. NFIRS also contains the number of floors of building below and above the fire floor and the average floor area. This allows an evaluation of the total floor area of the building in ft^2 (converted into m^2 for comparison to English statistics).

The NFRIS reports fire loss data considering the following definition: "Fire loss is an estimation of the total loss to the structure and contents in terms of replacement in like kind and quantity. This estimation of fire loss includes contents damaged by fire, smoke, water and overhaul. It does not include indirect loss, such as business interruption". The estimated dollar losses are divided into property and contents losses and assessed based on their values pre- and post-incident to evaluate the magnitude of the fire problem. Fire losses are estimated using the International Code Council's Building Valuation Data (BVD) formula (International Code Council, 2017) considering the average construction cost per square feet (Eq. 1).

$$\$\,loss = Total\ ft^2\ of\ damage\ x\ ft^2\ construction\ cost \qquad \text{Eq. 1}$$

In Chapter 4, the investigations on the USA statistics are developed adopting the Fire Incidents dataset of 2014 provided by the US Fire Administration for the evaluations of the fire incident characteristics (area of origin, item first ignited, cause of ignition, etc.) considering 596,521 fires with 80 columns of fields recorded for each fire incident. The 'residential non-residential fire loss estimates from 2003 to 2017' spreadsheet is used for the analysis of the number of fires, property types and causes with a total of 379,500 residential fires and 99,500 non-residential fires. For the financial losses, the 'US fire loss datasets from 2005 to 2014' spreadsheet is investigated with a total financial loss of $6,9000,300 in residential and $2,628,000,000 in non-residential fires. Consequently, the information of the two spreadsheets is combined to obtain a more complete database.

In Chapter 5, only USA fire statistics modules of Fire Incidents, Basic Incident and Causes for 2014/15 are considered. However, the datasets adopted for the USA fire statistics in the various analyses developed in this thesis have been summarized in Table 5 for clarity.

2.3.4 Data quality of English and USA fire statistics

The English and USA fire statistics datasets described in section 2.3.2 and 2.3.3, present analogies in the methodology adopted for the collection of the fire data in the aftermath of an incident. Since fire brigades are usually responsible for transmitting fire information, misreading of the questions or mistakes in filling in the form could lead to potential errors.

The England Statistical Bulletin 08/16 (Gaught et al., 2016) and the *Other buildings* fire incidents database published in 2017 (Home Office, 2017b) have been cleaned from potential errors by the Home Office before being publicly available. In the datasets provided to the author by the Home Office, inconsistencies have been removed explained in section 2.3.2.

The fire statistics database provided by the US Fire Administration is composed of several datasets, summarized in Table 4, due to a large number of fires and fields recorded. It is not clear if potential errors have been investigated and it would be easier to have a unique dataset or present a full description of each fire instead of subdividing it into several parts.

Despite, the potential uncertainties contained in the fire statistics analysed, the data sample considered appears to be representative of the population and the similar trends found for the analysis of various properties support this assumption.

Table 5: Summary of the fire datasets adopted in the sections of this thesis

Thesis sections	Dataset	Year considered	Fires
	England		
4.1	England Statistical Bulletin 08/16	2014/15	155,000 total 71,089 primary 31,329 *Dwellings* 15,548 *Other building*
5.3	Fire dataset provided by the Home Office	2014/15	11,168
5.2 5.4 5.5 5.6 5.8 6.1.1 6.2.1	*Other building* fires dataset publicly released by the Home Office	2010/11 to 2016/17	121,558
5.7 5.8	*Dwellings* fires dataset publicly released by the Home Office	2010/11 to 2016/17	230,205
	USA		
4.2.1.1 4.2.1.2	'Residential non-residential fire loss estimates from 2003 to 2017' US Fire Administration	2014/15	379,500 residential 99,500 non-residential
4.2.1.3	'US fire loss data sets from 2005 to 2014' US Fire Administration	2014/15	$6,9000,300 residential $2,628,000,000 non-residential
4.2.2 5.2 5.3 5.4 5.5 5.6 6.1.2 6.2.2	Fire Incidents dataset provided by the US Fire Administration	2014/15	596,521

2.3.5 Applications of fire statistics in research

Fire statistics are studied worldwide to investigate several aspects of interest related to human losses, fire design and prevention. The aim is to provide an overview of some applications and the reasons for the beneficial effects of understanding fire statistics.

In 2019, Hu et al. (2019) investigated statistical data of 283 Chinese cities considering fourteen socioeconomic characteristics and seven socioeconomic determinates having impacts on fire risk considering the data of the China City Statistical Yearbook from 2013 to 2015 and validated with those of 2016. The cities are clustered in high and low per capita GRP (Gross Regional Product) according to socioeconomics determinants. Multivariate regression models are constructed and the impacts of seven socioeconomic determinants on fire risk are evaluated. Even if fire risk is defined as the fire frequency and the consequences or expected damage, the study is only focused on the evaluation of fire incident and direct economic loss of fire where the methodology to determine the fire financial losses of the China Fire Yearbook is not provided. The multivariate regression models show that for low and high per capita GRP cities, population size, industrial development level and consumption capacity are positively related to fire incidents and direct economic losses. However, the lack of data on specific characteristics enables the investigation of a limited number of socioeconomic determinants.

In 1993, Ramachandran studied the effectiveness of fire detection in early warning to reduce life risk in terms of fatality and casualty rate per fire in single and multiple occupancy dwellings. The data investigated are the one published by the Home Office in the annual booklet Fire Statistics United Kingdom from 1978 to 1991 (Ramachandran, 1993). A linear relationship is determined between the fatality rate and the discovery time of fires. Moreover, a conservative estimate is assumed in which sprinklers reduce the discovery time to 3 minutes and the time of a combustion product to produce untenable condition to 4 minutes.

In 1993, fire statistics of the US NFIRS was investigated to determine the fire and personal characteristics that lead to a high risk of casualties. For the fire characteristics, the area of origin, area damage and type of material ignited were considered while for the personal ones, conditions preventing escape and before the injury, activity at the time and causes of the injury and location at ignition are identified (A. M. Hasofer & Thomas, 2006). According to the study, the number of casualties and proportion of fatalities depends mainly on the extent of fire damage, area of fire origin, material ignited and ignition factor while the absolute number of fatalities only on the material ignited and the form of heat of ignition. The fire cause, the location and activity at ignition, the condition before the injury and preventing escape have a significant influence on personal factors attributable to high fatalities.

In Sweden, Rosenberg developed research on activities, risk resources and fire causes to understand the extent of available data and to evaluate how to improve fire prevention at the local level. The data were derived from the Swedish rescue Service agency, the Swedish Fire Protection Association and some insurance companies. Data were collected from 1992 for the fire causes and from 1982 to 1991 for the annual statistical reports including a survey to evaluate fire prevention and information from the rescue service were available from 1988 to 1995 (Rosenberg, 1999). The survey on the Swedish statistics proved that there is no reliable basis to improve fire prevention: the coding systems have changed over time for the evaluation of fire losses and causes, no distinction between fire cause and the object causing a fire is available and no analysis on fire causes and effects on measures reducing fires is present. The use of historical data should be based on social development factors and risk evaluation.

In the UK, the London Fire Brigade's fire library was studied by Holborn et al. (2004) to define the distribution of fire sizes (area damage), growth rates and times between fire discovery and call to the fire brigade in building fires. The data are from 1996 to 2011 and the factors include occupancy type, ignition source, effects of first-aid to occupants and first material ignited. Even if data uncertainties may be present, it is assumed that statistical meaningful distributions are obtained. The expected fire size is lower for distributions with the presence of sprinklers than the one for their absence suggesting their positive effects in preventing large fire size.

Fire statistics of the New Zealand Fire Service from 2001 to 2010 (Frank et al., 2014) is investigated to understand the ability of sprinklers to alter the growth of fire neglecting the notification to occupants and fire services to create risk-informed safety design. The effectiveness and the number of sprinklers are evaluated investigating the possible source of uncertainties that may arise by the errors and inaccurate information collected during the fire investigations. The research affirms that the data coding setup is not ideal for collecting the effectiveness of sprinklers and the ability to control and notify fire. Reports could be linked to data addressing the various phases of design, inspection and maintenance.

Design tool methodology helps fire engineers to calculate the reduced cost in the design stage based on fire statistical data in the UK considering non-residential buildings. The evaluation of Fire Damage Report 1 (FDR 1) data appears limited in the accurate prediction of fire size and when data collected at the design stage are compared to those after fires, loss adjustor's cost estimates are similar to the original cost of the building (Salter et al., 2013).

The deterministic parameters usually adopted in the design of residential design fires in England are also compared to those deduced by the Home Office *dwelling fires dataset* from 2010 to 2017 considering the area damage which appears on average greater in houses than in apartments. Moreover, lognormal distribution has been obtained for growth rates in fire incidents (Hopkin et al., 2019).

It is clear that the analyses of current fire statistics enable the investigations of the response of fire in residential and not residential buildings evaluating factors and interdependencies considered in fire safety design and risk-informed assessments.

2.4 Fire costs

In this section, an analysis of the cost of the fire is developed according to previous studies of different countries. The total cost of fire could be described according to the *cost of anticipation* considering protection and prevention measures, *cost in consequences* due to the individuals, property and environment exposed to the fire and *cost in response* for extinguishing and cleaning after a fire (Ashe et al., 2009). For each of these three main classes, components are presents and classified in Table 6.

Table 6: Fire costs in Australia (Ashe et al., 2009)

Cost in anticipation	**Cost in consequences**	**Cost in response**
Fire safety equipment Fire safety in buildings Fire safety measures Fire safety education Insurance administration Fire safety in consumer items Fire safety research Safety equipment maintenance	Property losses Lost output - indirect loss Fatalities, injuries Healthcare costs Loss of business Environmental costs Heritage and cultural costs Clean up Wider economic distortions	Fire service response costs Volunteer fire service Private fire brigade responses Criminal justice costs, arsons

In his study on the economic costs of fire, Weiner affirms that reducing these costs would imply significant savings to individuals, public and private sectors (Weiner, 2001). The analysis is also helpful in understanding how resources can maximize the impact, the effectiveness of prevention measures and the best trade-off between fire education, protection and response. Weiner adopts the categories defined by Brand and Price (Brand & Price, 2000) with *costs in anticipation*, *as a consequence* and *in response*.

The above classification of costs in three main groups is also adopted by the Department for Communities and Local Governments in the estimates of the economic cost of fire for 2008 (Department for Communities and Local Government, 2011b) and the evaluation for the fire costs in England in 2008 was equal to £8.3 bn. These estimates are based on the previous methodology developed in 2006 with the main objective to provide an evaluation of potential costs of fire to the economy and consequently expand the model created (Department for Communities and Local Government, 2011a). The total costs in the report are calculated as a percentage of the English Gross Value Added which is a measure of 'the total economic value of goods and services produced in an area or sector of an economy minus the cost of the raw materials and other inputs used to produce them' (Department for Communities and Local Government, 2011a). The economic losses in England are subdivided into *costs in anticipation*, *costs as a consequence* and *costs in response* as summarized in Table 7 with the related sub-classes. Furthermore, the financial losses are also estimated by building types.

Table 7: Fire costs in England (Department for Communities and Local Government, 2011b)

Costs in anticipation	**Costs as consequences**	**Costs in response**
Costs of fire protection Resource and costs of training Non-pay related costs Insurance administration	Costs of fatality and casualty Costs of loss of business Costs of property damage Costs to victims, police, justice	Fire Service response Capital costs in response

A different classification considers the *cost of direct and indirect loss* due to the fire incident, the *cost of fire protection*, the *cost of fire services* and the *cost of fire safety* built into equipment, vehicles and operations (U.S Fire Administration, 1980). In 1991, Meade affirmed that the total cost of fire in the USA was estimated at $115 bn (Meade, 1991). The fire costs were then classified considering four different categories as grouped in Table 8 where direct and indirect losses are indicated in Category A. However, in Category D there is a potential component of indirect losses which is indicated as disaster recovery.

Table 8: Fire costs in the USA (Meade, 1991)

Category A **Losses**	**Category B** **Insurance**	**Category C** **Fire Service**	**Category D** **Preventative**
Residential property Industrial property Other property Residential interruption Business interruption Product reliability	Product reliability Net fire insurance	Paid Net fire insurance	Built into structures Built into equipment Standards activity Retardants/testing Fire maintenance Disaster recovery

In 2008, the total cost of fires was equal to $362 bn including the fire consequences such as human and economic losses, costs of provision to prevent or mitigate the consequences of fire. In particular, the economic loss was composed of property damage and business interruption (Hall, 2011). Moreover, the financial loss could be classified according to the *costs of actual transaction payments* and the *value of the donated time*. The estimates were reported by fire departments and published yearly by the National Fire Protection Association (Hall, 2011).

Another approach considers three main categories: *costs of risk reduction*, *costs of readiness and response* and *costs of recovery and consequences*. While the first two describe the economic losses of fire risk management, the last one provides the fire losses. Components of each of them are presented in Table 9. The incidents can also be subdivided into three main sectors: household, commercial and private sectors (Goodchild et al., 2005).

Table 9: Fire costs in New Zealand (Goodchild et al., 2005)

Costs Risk reduction	Costs Readiness, response	Costs Recovery, consequences
Fire protection measures	Water supply systems	Property damage
Fire safety regulations	Fire emergency service	Loss of output
Insurance service	False alarms	Direct injury costs
		Indirect injury costs

In general, **direct losses** are defined as the damage caused by a fire to a building, contents and occupants, while the losses associated with the fire but generated after its extinguishment, are called **indirect or consequential losses** (Ramachandran, 2002).

The research presented in this thesis is focused on the evaluation of direct financial losses with the description of several approaches in section 2.4.1 and the prediction of current statistics in Chapter 4. Moreover, details on the indirect financial loss are provided in section 2.4.2.

2.4.1 Direct financial losses

As discussed in section 2.3, the Geneva Associations evaluated direct fire losses as a percentage of GDP in several countries around the world in the period from 2008 to 2010. In this case, fire losses include explosion losses following the fire but exclude explosion losses where no fire occurs. In the report, it is affirmed that some of the decreases could be related to the decrement of GDP caused by the global financial crisis and austerity measures (The Geneva Association, 2014).

Evaluating *costs as a fire consequence*, Weiner defines the damage to property classified according to domestic and commercial properties (Weiner, 2001). Property damage considers the cost of repairing and replacing damaged property. The majority of such losses are usually covered by insurance which represents transfer payment and no goods or services are produced in return. For this reason, the insurance reimbursements should not be included in the fire costs. The estimates are based on the total value claims of the Association of British Insurances. However, this is unlikely to reflect the actual losses because it does not represent the entire insurance market and some domestic properties could not be insured.

The Department for Communities and Local Government examines the *costs as a consequence* evaluating the property damage using the Association of British Insurers claims fire data. The model adopted in the estimate of 2006 revised the assumptions of the one of 2004 including an estimate of domestic, commercial and public losses based on insurance claims with data from the National Health Service buildings (Department for Communities and Local Government, 2011a). The problem with domestic buildings is that some properties or contents may not be insured and it is necessary to make assumptions about the size of the average loss and the number of fire in uninsured properties. At the same time, there is a little evidence of the insurance market in commercial properties and therefore, it is now clear the importance of national fire statistics able to collect information about all fire incidents in property types.

In the Report of the National Commission on Fire Prevention and Control America Burning of 1973, it is affirmed that the built environment is composed of complex materials, finishes, chemical and utility system. It is also stated that, based on the available statistics of that period, 95% of America’s fire losses in terms of life and property derived from fires in the built environment. The 85% of the total property losses of $2.7 bn is attributable to fires in buildings and explanations of the type of building involved are shown in Table 10. When building fires are examined in terms of property loss, 39% is attributed to residential, 36% to industrial and storage and 25% to commercial, public and institutional buildings (America Burning, 1973).

Table 10: Estimated 1971 Building Fire Losses (America Burning, 1973)

Table 8-1. Estimated 1971 Building Fire Losses and Relationship to Total Fire Record *

Category	Life loss		Property loss		Fires	
	Number	Percent of total	Dollars, Millions	Percent of total	Number	Percent of total
Residential (houses, apartments and hotels)	6,600	56	874.1	31.9	699,000	25.6
Commercial (Public assembly, educational, institutional, mercantile and office)	970	8	580.5	21.1	141,400	5.2
industrial (basic industry, storage, manufacturing and miscellaneous)			811.6	29.6	156,500	5.7
Building total	7,570	64	$2,266.2	82.6	996,900	36.5

* From published and unpublished NFPA data. Refer to Appendix V for complete table of fire losses in U. S.

Hall estimated the total cost of fire in the USA in 2008 (Hall, 2011) and, based on the fires reported by the fire departments and published by the National Fire Protection Association, he expressed the direct damage according to reported and unreported fires as indicated by Eq. 2 and Eq. 3, respectively. Based on a 2004 estimate, it is considered that the unreported home fires increase the total dollar loss of reported fires of 13.6% (Hall, 2011).

$$Direct\ damage\ in\ reported\ fire = statistical\ projection\ of\ the\ NFPA\ survey \qquad \text{Eq. 2}$$

$$Direct\ damage\ in\ unreported\ fire = 13.6\% \times Diret\ damage\ in\ reported\ fires \qquad \text{Eq. 3}$$

Nowadays, the US Fire Administration explains in the NFIRSGrams how to evaluate fire losses in the NFIRS where the NFIRSGrams are bulletins which help the fire brigades in the use of the NFIRS (U.S Fire Administration, 2019). Fire loss estimates the total loss of structure and contents considering damage by fire, smoke, water and overhaul not including indirect losses. The US Fire Administration recommends the fire departments to use the International Code Council's (ICC) Building Valuation Data (International Code Council, 2017) to determine the financial losses due to fire based on Eq. 1. The collection of the property and content losses defines the magnitude and the severity of fire problem and, as an inverse measure, the benefits of successful fire strategies. Where high monetary losses occur, the information can target prevention programs in evaluating the effectiveness of fire protection (U.S Fire Administration, 2019). The formula expressed in Eq. 1 is the one adopted for the evaluation of the financial losses in England of Chapter 5, where no direct estimates are provided in current English statistics of the Home Office.

In New Zealand, property damage is considered as a cost of recovery and consequences due to fire incidents where the cost of damage to structures, household content, stocks and equipment is seen as one of the highest (Goodchild et al., 2005).

In 1995, the total cost of fire in Canada is evaluated (Schaenman et al., 1995) and direct dollar loss due to fire is defined as the 'value of the property that is destroyed or damaged by fire or fire protection efforts'. The damage includes the damage caused by flame, heat, smoke, water, extinguishing agents and fire-fighters actions. In this study, an essential problem arises when the estimates of the property loss are evaluated because it could imply three different values:

- cost of repairing,
- depreciated value after the fire, and
- market value prior to the damage.

The Canadian system of reporting fire losses collects data from the fire departments and the insurance companies. The province office chooses the one which provides the better loss estimate. However, when a fire is recorded, methods used by the insurance companies could be completely different than those by the fire departments. Furthermore, there could be errors due to the use of single or multiple sources and unique recording systems should be adopted (Schaenman et al., 1995).

The research developed in this thesis presents an investigation of current property damage in terms of quantification of structural damage and evaluation of related financial losses in Chapter 4 according to current statistics of different countries.

2.4.2 Indirect financial losses

Even if indirect financial losses originated by fire incidents are not studied in this thesis, it is important to define the fields that could be affected and to investigate previous approaches. Moreover, when indirect and direct monetary losses are available, they are considered as components of the total fire cost in particular building types.

The Geneva Association defines in the world statistics the cost of indirect fire losses in three years (2008-2010) and only USA and New Zealand produced the complete assessments for the period examined while partial estimates are provided by Finland, France, Germany, Japan and the UK. The indirect fire losses evaluation shows a high lack of reliability and needs to be considered with major reservations. According to the obtained values, direct losses generally decrease while indirect ones increased if compared to the values of 2009 (The Geneva Association, 2014).

As *costs as consequences*, the Department of Communities and Local Governments analyses the lost business considered as an indirect cost caused by fires. The model adopted in 2006 evaluates the data of business interruption claims of the Association of British Insurers with a transfer payments of 75% (Department for Communities and Local Government, 2011a).

In 1979, the US Fire Administration published a report about the 'Indirect costs of residential fires' (U.S Fire Administration, 1980) considering 883 households and interviewing them after 4 months of their fire experience. However, some costs may have incurred after the surveys. Due to the small sample, estimates may be affected by statistical sampling errors. Indirect losses are defined as costs other than those of direct property damage. Two estimates are given: the total indirect losses to which it is possible to assign a monetary value and out-of-pocket costs affecting directly the households. The indirect losses analysed in the report are summarized in Table 11.

Table 11: Indirect losses (U.S Fire Administration, 1980)

Temporary shelter	Legal expenses
Medical care	Transportation
Missed work	Emotional counselling
Funeral expenses	Child care
Extra food	Other
Demolition	

In particular, for the class of Other, the cost of moving, dry-cleaning clothes, utility payments while households do not live in the dwellings or others could be considered. According to the report, the highest indirect costs are represented by a temporary shelter, medical care and missed work for the total fire costs while for the out-of-pocket costs the order slightly changes with medical care, temporary shelter and missed work. Moreover, in addition to Table 11, non-monetary costs should be considered as changes in the household composition, emotional disturbance and losses of irreplaceable objects.

The US Fire Administration defines three techniques for the local estimation of residential indirect costs. The first one is the use of a *simple average* multiplying the total number of residential fires in a year of a particular area by the average total indirect cost caused by each residential fire where the total indirect cost assumes the value of $440 but can have variation in location and time. The second technique is the *simple averages for classes of residential fires*, classifying the residential fires into classes and using different averages for each of them. In the study, the three classes are: Class I fires causing injuries or deaths, Class II with no reported injuries or deaths and property loss greater than $1,000 and Class III with no injuries or deaths and property loss equals or less than $1,000. The evaluation of the total indirect costs is calculated according to Eq. 4 where N_1, N_2 and N_3 are the fires in the three classes.

$$total\ indirect\ costs = \$3{,}275 \times N_1 + \$1{,}185 \times N_2 + \$80 \times N_3 \qquad \text{Eq. 4}$$

The third technique is the *simple averages for direct property loss categories*. According to the surveys, the US Fire Administration affirms that the residential fires with high indirect loss are also those experiencing large direct losses. Therefore, the data are classified according to four classes of residential fires of property loss: N_1 up to $500, N_2 from $501 to $5,000, N_3 from $5,001 to $10,000 and N4 greater than $10,000. Based on Eq. 5, the total indirect costs are evaluated.

$$total\ indirect\ costs = \$118 \times N_1 + \$812 \times N_2 + \$1{,}312 \times N_3 + \$3{,}353 \times N_4 \qquad \text{Eq. 5}$$

The analysis reported by the US Fire Administration in 1979 and explained above (U.S Fire Administration, 1980) appears as a valuable methodology for the analysis of indirect costs of fires. However, average estimates need to be updated and contextualized in specific areas.

In 1991, Meade affirmed that US industry confronts increasing competition and difficulties in establishing and maintaining market share after fire incidents. The loss in productivity may lead a company to face the difficulties of surviving in the competitive market. The business loss was estimated to be three or four times greater than the property loss where 40% of small companies never reopened if affected by a large fire (Meade, 1991).

Hall defined the indirect loss in the USA as those covering the costs of temporary housing, missed work, loss business and potential intangible losses. They could also include dollars equivalents for the damage to the environment and cultural heritage. Hall provided an evaluation of the indirect losses due to fires, analysing 109 incidents from 1989 recorded by high-protected-risk insurance carriers to develop multipliers for major occupancy group. The results showed the following percentages to direct losses of reported or unreported fires:

- 65% manufacturing and industrial;
- 25% public assembly, educational, institutional, store and office;
- 10% residential, storage and special properties; and
- 0% vehicle and outdoor.

Therefore, a formula was created to calculate indirect losses based on the previous assumptions as a function of direct damage for reported fires as shown below:

$$\begin{aligned}&Indirect\ fire\ damage\\&= (Business\ Interruption + temporary\ lodging + Intangible\ losses)[65\%\\&\times direct\ damage\ manufacturing, industrial\ ]\\&+ [25\% \times direct\ damage\ public\ assembly, educational, storage, office]\\&+ [10\% \times direct\ damage\ residential, storage, special\ structures]\\&+ (Value\ of\ closed\ business) \times [4 \times 2\%\\&\times direct\ damage\ nonresidential\ structures\ excluding\ storage, special\ structures]\end{aligned} \quad \text{Eq.6}$$

In New Zealand, indirect costs can be regarded as the reduction of business outputs which have a permanent or temporary disruption. However, the loss in productivity for one firm could be gained by another one and this is the reason for the discussion in the international community if the output losses need to be included in national frameworks (Goodchild et al., 2005).

In 1995, in Canada, an analysis of the total cost of fires was developed (Schaenman et al., 1995) according to several aspects amongst which the evaluation of indirect losses from fires. The analysis for the *indirect losses in business* includes renting office space or equipment, paying salaries for workers not able to produce and potential demolition. Since the disruption can affect an extended period, the time of restoration could generate a loss in clients and market share. The business interruption could also have impacts on dependent businesses and, in some cases, on community. For the *indirect losses for residences*, in the study, it is affirmed that for the majority of fires, people try to occupy the non-damage parts. However, occupants need to leave for repairs and cleaning and this implies several days in a hotel or with relatives and friends. Examples of *Other indirect costs* are stated such as legal costs and environmental impact of fires and fire protection.

The overview above considers the complexity of the components of the fire costs. Future work will be focused on the evaluation of indirect costs for residential and business including the previous studies presented in this section and applying them in current fire scenarios and building stocks.

2.5 Updates of British Standard PD 7974-7:2003

In the UK, fire safety data collected by the fire brigades were analysed in several studies and were collected in the British Standard PD 7974-7 *Application of fire safety engineering principles to the design of buildings — Part 7: Probabilistic risk assessment* (BSI PD 7974-7, 2003) published in 2003. The standard sets out the general principles and suggests techniques of risk analysis used in fire safety including fire safety data for probabilistic risk assessment and criteria in absolute and comparative terms where absolute terms are referred to the performance of one situation against predetermined criteria while comparative terms involve reliability analysis between two or more competing solutions. The Tables in Annex A of PD 7974-7:2003 present the fields reported in Table 12 covering frequency of fire, fire damage and discovery times in various property types according to the presence or absence of sprinklers.

Table 12: Annex A Tables of PD 7974-7:2003

Tables	Fields
A.1	Probability of fire starting
A.2	Overall probability of fire starting in various types of occupancy
A.3	Probability of fire starting within given floor area for various types of occupancy
A.4	Area damage and percentage of fires for each category of fire spread (textile industry)
A.5	Area damage and percentage of fires for each category of fire spread (pubs, clubs, restaurant – all areas)
A.6	Office buildings: frequency distribution of area damage (in terms of number of fires)
A.7	Retail premises: frequency distribution of area damage (in terms of number of fires)
A.8	Hotels: frequency distribution of damage (in terms of number of fires)
A.9	Probable damage in fire
A.10	Spinning and doubling industry: places of origin of fires and sources of ignition
A.11	Extent of fire spread and average area damaged (textile industry, UK)
A.12	Average loss per fire at 1966 prices (£'000)
A.13	Discovery time and fatal casualties
A.14	Frequency distribution of number of deaths
A.15	Probability of flashover
A.16	Building characteristics
A.17	Reliability data

The British Standard PD 7974-7:2003 *Application of fire safety engineering principles to the design of buildings — Part 7: Probabilistic risk assessment* has been updated in 2019 (BSI PD 7974-7, 2019) with flowcharts to evaluate risk assessment and reasons for acceptance criteria. However, no absolute risk criteria are included, the document is entirely informative and it is not imposed on engineering practice. If statistical analyses are assumed, data of real fire incidents in buildings are required to determine likelihood and consequences as specified in the data collection section of the PD 7974-7:2019. In Annex B of the PD 7974-7:2019, the tables are related to the reliability and effectiveness of sprinklers in the USA and New Zealand, respectively; fire growth rate distributions; occupancy dependant fire load energy densities;

and extent of damage in USA fire incidents from 1989 to 1994. Moreover, the analyses developed in this thesis related to the critical evaluation of structural fire data of PD 7974-7:2003 based on USA fire statistics (Manes & Rush, 2018) have been referenced in the new version of PD 7974-7 published in 2019 in Annex B Table B.3 for the overall probability of fire starting in various types of occupancy. Finally, the comparison between PD 7974-7:2003 and English fire statistics has been created showing analogies and differences with USA statistics (Manes & Rush, 2020).

The data of the previous version of PD 7974-7:2003 between 1968 and 1987 provide more detailed fields. These data from PD 7974-7:2003 that could be considered as inputs for probabilistic risk assessment (PRA), vary from 1966 to 1987 (except Table 2 with data from 1995) and are no longer representative of the current situation regarding fire statistics. Therefore, the need to re-examine the relationships using current fire statistics has brought this research to enable deeper analyses of the actual response to fire of different occupancy types subjected to real fires and to evaluate the reliability of current safety systems as described in Chapter 5 comparing PD 7974-7:2003 with current English and USA statistics.

Section 2.5.1 examines the studies of several authors that have contributed to the development of PD 7974-7:2003 and explains the origin of the formula adopted in Table A.1 in which the probability of fire starting is expressed.

The updated fire safety data, discussed in Chapter 5, are able to represent the current behaviour of buildings subjected to fires and they are fundamental to understand the effect of fire safety systems and quantify structural consequences. The building stocks of England and the USA adopted to evaluate the overall probability of fire starting and the fire frequency is described in section 5.1.1. The fire statistics of England and USA used to develop the comparison with PD 7974-7:2003 are introduced in section 2.3.2 and 2.3.3 and deeply described in Chapter 4. Table 5 presents a summary of the various fire statistics datasets adopted in each analysis developed in this thesis to enable clarity.

Furthermore, the current fire statistical fields investigated are considered as engineering parameters able to evaluate fire frequency in different property types, the effectiveness of active safety systems, compartmentation in fire spread reduction and damage caused by fire incidents. They could be adopted in business impact analysis, continuity or preparedness plans to determine potential strategies to improve prevention, absorption, mitigation and recovery after a fire incident (BSI BS EN ISO 22301, 2014; BSI BS EN ISO 22313, 2014). They could also determine the expected fire impact on the building and optimize evacuation plans.

2.5.1 Historical development of BS PD 7974-7:2003

Table A.1 of PD 7974-7:2003 describes the frequency of ignition considered as a key parameter for a probabilistic risk assessment (BSI PD 7974-7, 2003) defined:

$$F = aA^b \qquad \text{Eq. 7}$$

where A is the total floor area of the building. The two constants a and b are determined for specific building types and a represents the ratio of the total number of fires in a period to the number of buildings at risk while b the measure of the increase in the value of frequency for an increase of total floor area of the building. The constants b usually assumes values lower than one because the probability of fire does not increase directly with building size (BSI PD 7974-7, 2003).

Thanks to a critical evaluation of the studies investigating the origin of Eq. 7, the research of this thesis has developed a historical overview of such equation as explained hereafter.

Professor Sergius von Sawitsh in 1907 defined fire insurance claims frequency as a linear relationship with volume or value at risk. His study was followed by the one of Berge in 1937, based on Swedish dwellings and statistics, in which the claims frequency and the fire loss ratio increase with the size of the house (Benktander, 1972). In 1940, D'Addario (D'Addario, 1940) defined the claims frequency, *f(s),* as a function of the size (s, sum insured) expressed in Eq. 8 where A and α are empirically fitted coefficients. It is already clear an analogy with the power law assumed in Eq. 7 adopted in PD 7974-7:2003.

$$f(s) = As^{\alpha} \qquad \text{Eq. 8}$$

In 1968, Ramachandran combined national fire statistics with financial loss data derived from local authority fire brigades and British Insurance Association, respectively. The total number of fires and the total cost in thousands of pounds for large fires, defined as fires requiring five or more jets to be extinguished, was estimated by Ramachandran for different occupancy types (Ramachandran, G, Kirsop, 1969b). In 1969, Ramachandran developed a brief analysis considering large fires from 1965 to 1968 identifying the total number of fires and the total cost in thousands of pounds for different occupancy types assessing fire frequency, place of origin, source of ignition, material first ignited, age of the building, number of storeys, spread of fire, attendance time and fire protection devices (Ramachandran, G, Kirsop, 1969a). The fire loss index defined as loss per ft^2 of floor area or loss per hundred pounds of value at risk was produced by Ramachandran in 1970 (Ramachandran, 1970).

The risk of fire intended as the probability of fire and its consequences can only be expressed in probabilistic terms and can be estimated by examining past fire incidence data and this was affirmed by Rutstein in 1979 (Rutstein, 1979b). Furthermore, Rutstein evaluated the probability of fire comparing the number of fires reported by the fire brigades divided by the total amount of property at risk obtained from survey data of manufacturing industry undertaken by the Home Office Scientific Advisory Branch in 1977. This study introduced the power law assumed in Eq. 7 with the fire probability, F, based on the total area of the building A:

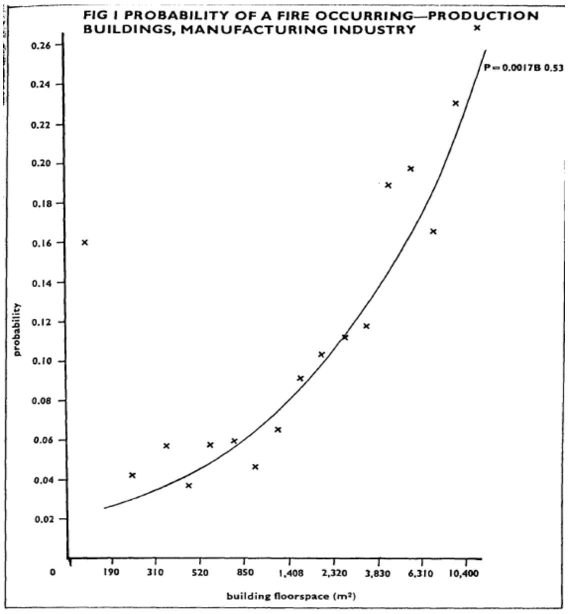
$$F = aA^b \qquad \text{Eq. 9}$$

where a and b are empirical constants which assume different values for each occupancy type. In particular, a defines the total number of fires divided by the total number of buildings at risk and b defines the total number of fires divided by the building maximum floor area.

The analysis developed by Rutstein considered only industrial buildings with no other property types examined (Rutstein, 1979b). The Home Office Scientific Advisory 1977 survey investigated by Rutstein enumerated the number of buildings and the floor space of each building occupied by the industry. The total number of buildings of each size in each industry in the UK was obtained thanks to the information related to 6,000 separated buildings. A nonlinear function was estimated considering the building floor space in m^2 on the x-axis and the probability of fire on the y-axis as represented in the original graph reported in Figure 23 (a). According to Rutstein, the non-linearity could be attributed to two main reasons:

- *a genuine scale effect*: if a building is enlarged to double its original size, not all the services would double in size or fire risk, therefore, the risk of fire in a larger building could be less than twice than the one of the original building; and
- *composition of the sample*: if larger buildings are investigated they may present different processes, fire prevention management or first aid-firefighting capability or may have lower fire risk than the smaller ones.

Rutstein estimated the probability of a fire considering initially all buildings within each industry type where the majority were used for production and a smaller number for storage, office and other buildings and consequently, he investigated only buildings primarily used for production as represented by the original table described in Figure 23 (b). The important aspect to highlight in Rutstein's functions is that the exponent in the power law assumes always a positive value and the probability of fire increases non-linearly with the increase of the dimension of the buildings. Table A.1 of the PD 7974-7 (BSI PD 7974-7, 2003) reports the coefficients a and b according to different industry types only considering production buildings neglecting those obtained for all buildings.



(a)

INDUSTRY (SIC Order)	ALL BUILDINGS		PRODUCTION BUILDINGS	
	Probability function	Probability of fire in 1500m² building	Probability function	Probability of fire in 1500m² building
Food, Drink and Tobacco (III)	0.0054 $B^{.33}$	0.058	0.0011 $B^{.60}$	0.086
Chemical and Allied (V)	0.017 $B^{.27}$	0.12	0.0069 $B^{.46}$	0.21
Metal Manufacture (VI)	0.011 $B^{.36}$	0.14	*	
Mechanical Engineering (VII)**	0.00036 $B^{.59}$	0.027	0.00011 $B^{.75}$	0.027
Instrument Engineering (VIII)	0.000027 $B^{.96}$	0.031	*	
Electrical Engineering (IX)	0.0011 $B^{.49}$	0.040	0.00061 $B^{.59}$	0.046
Shipbuilding (X)	0.0062 $B^{.30}$	0.055	*	
Vehicles (XI)	0.00030 $B^{.74}$	0.065	0.00012 $B^{.86}$	0.062
Metal Goods not elsewhere specified (XII)**	0.0027 $B^{.46}$	0.078	0.00158 $B^{.54}$	0.082
Textiles (XIII)	0.0036 $B^{.42}$	0.079	0.0075 $B^{.35}$	0.097
Clothing and Footwear (XV)	0.0017 $B^{.40}$	0.032	*	
Bricks, Pottery, Glass, etc. (XVI)	0.0013 $B^{.54}$	0.067	*	
Timber, Furniture, etc. (XVII)	0.00074 $B^{.64}$	0.077	0.00037 $B^{.77}$	0.10
Paper, printing, publishing (XVIII)	0.00010 $B^{.85}$	0.052	0.000069 $B^{.91}$	0.054
Other Manufacturing Industries (XIX)	0.0023 $B^{.54}$	0.12	0.0084 $B^{.41}$	0.17
All Manufacturing Industry (III-XIX)	0.0019 $B^{.50}$	0.072	0.0017 $B^{.53}$	0.083

* The sample was too small to allow a separate probability estimate for the production buildings.
** Some of the fires which should properly be classified as "mechanical engineering" may have been included with "metal goods n.e.s". This would cause an underestimate of the probability in mechanical engineering and an overestimate in metal goods n.e.s. If the two groups, mechanical engineering and metal goods n.e.s are combined the probability function for all buildings is 0.00056 $B^{.60}$ and for production buildings 0.00086 $B^{.56}$.

(b)

Figure 23: (a) Probability of fire occurring (Production building, manufacturing industry) and (b) the estimated probability of fire in different industries (Rutstein, 1979b)

As expressed in the x-axis of Figure 23(a), in the research of 1979 (Rutstein, 1979b), Rutstein assumed the term probability but the author believes that the frequentistic definition is adopted where probability is defined as the relative frequency of occurrence of an event given by the number of times that it occurs divided by the number of experiments if the number of experiments approaches infinity (Faber, 2012). Therefore, the values obtained by Rutstein are relative frequencies given by the presence of increasing but finite total floor spaces and the term frequency instead of probability should be presented in Table A.1 of PD 7974-7:2003.

Table A.9 of PD 7974-7:2003 given by the probable damage in fire is based on a study of Rutstein developed in 1979 (Rutstein, 1979a) in which the fire damage A_d is expressed as a power law, as for Eq. 9, function of the total area of the building A and presented in Eq. 10:

$$A_d = cA^d \qquad \text{Eq. 10}$$

where c and d are obtained considering different industrial occupancy types. As explained in section 2.5, Table A.9 of PD 7974-7:2003 will be studied and updated in future research and it is not an object of this thesis.

Finally, Rutstein (Rutstein, 1979a) was able to relate direct losses to the fire-damaged area based on a constant loss per unit area estimated dividing the total fire loss in any class of buildings by the total area of fire damage. Once the probability of fire, the average fire damage and the unit losses were obtained, Rutstein multiplied them together to provide an estimate of the fire risk (Rutstein, 1979a).

The studies of the researchers mentioned above such as those of D'Addario, Ramachandran, and Rutstein have converged into PD 7974- 7:2003. The Tables present in Annex A of PD 7974-7 are recreated in Chapter 5 based on recent fire statistics of England and USA applying the same methodology expressed in this section for Table A.1 and statistical evaluations for the other tables. Moreover, the analyses present in the Tables of PD 7974-7:2003 have been extended considering, for English and USA fire statistics, presence and absence of safety systems and an increased number of property types than those available in PD 7974-7:2003. Finally, a critical analysis of the response time obtained for English fire statistics has been developed considering its effects on the spread of fire, area damage and fatalities/casualties.

2.5.2 Fire response time

Table A.13 of PD 7974-7 describes the discovery time, the number of deaths and the fatality rate per fire defined as the number of deaths divided by the number of fires. This table has been recreated in section 5.7 considering the *Other building datasets* for English statistics with data from 2010/11 to 2016/17 as described in section 2.3.2 and shown in Table 5. In this section, a description of the current fire response problem is introduced.

Response time is defined as the time interval between the call being made (notification of incident) and the first fire vehicle attending the scene (Home Office, 2017b). Seven-time steps are defined between ignition and firefighter intervention which are the notification of the incident, fire-fighter dispatch, preparation, travel time, set up after the arrival at the fire scene, occupant rescue and fire extinguishment. The response time is also defined as the sum of dispatch preparation and travel time. The increase in response time could increase the risk of trapped people to be exposed to untenable conditions and the risk of property loss affected by wide fire spread before the intervention of the fire department (Yung, 2008). Yung affirmed that a quick response determines a more effective intervention (Yung, 2008).

In the UK, a specified minimum level of response time and brigade attendance is determined for the fire risk areas in which the city is usually subdivided considering commercial and industrial city complex, centres of large towns, built-up areas of towns, and rural areas. In a community, fire protection assumes the form of *potential demand* which can be reduced with active or passive measures, and *realised demand* for which the fire brigade is responsible. Moreover, type of hazards, geography and peak-period time determine the resources allocated by the fire brigades to guarantee the best occupants rescue and fire suppression (Ramachandran & Charters, 2011).

The fatalities and the spread beyond the room of origin, usually through openings or due to convection, are attributable to the exposure to toxic gases and the collapse of a compartment or structural member, respectively. The latter usually happens when flashover occurs. The factors influencing fatalities and fire spread are the presence of automatic extinguishing systems, the material involved in the fire and the response time of the fire brigade (Ramachandran & Charters, 2011) while the response time is influenced by the traffic conditions and distance from the fire stations to the fire incident.

Optimization of the number and location of fire stations could substantially reduce the time between the notification to the arrival at the fire scene reducing occupants and property losses (Hogg, 1968). The reduction in response time determines an improvement in fire protection and reduce the direct financial losses that could be invested in prevention, regular maintenance and detection and suppression systems (Halpern et al., 1979). Furthermore, the goal to better cover the area assigned to each fire stations is to reduce the response time of fire brigades and have several fire sites within a fixed distance range. In the majority of studies, response time is evaluated to measure performance. However, few studies demonstrate the relationship between response time and fire losses (Halpern et al., 1979).

Hogg affirmed that: “Every additional station, if properly sited will reduce the overall time between call and arrival but each additional station should pay for its upkeep in terms of the resultant saving in life and monetary loss from fire” (Hogg, 1968).

The relationship between response time, fatalities and property loss is difficult to obtain being affected by the speed in fire spread and fire growth rate due to material involved, ventilation or number of openings as well as the delay in discovering and notifying the fire incident (Ignall et al., 1979). Therefore, fire statistics data are essential to evaluate how the response time could influence the scenarios that fire brigades face once arrived at the fire scene.

The response time is considered as one of the most relevant factors able to improve the occupant rescue operations and limit the spread of fire affecting a building. The trends considering the influence of the response time on fatalities/casualties, fire spread and damage are obtained in the research of this thesis for various occupancy time and developed in section 5.7 and 5.8.

2.6 Risk assessment

Risk assessments are created to identify the combinations of building sub-systems able to provide the required level of safety in a cost-effective manner (A. Hasofer et al., 2006); however, the definition of risk appears very complicated due to its use in various aspects and disciplines and in literature a unique definition is not available.

Risk is usually based on probability or expected values, uncertainties or undesirable events and it can be divided into the evaluation of risk itself or in how risk is managed (Aven, 2012). Renn stated that risk refers to the "possibility that human actions or events lead to consequences that affect human values" (Renn, 1998). Therefore, the risk is usually classified as objective and subjective by physical facts and social construction, respectively (Hansson, 2010). However, the various definition of risk are provided such as expected value loss; the probability of undesirable event; uncertainty related to cost, loss or damage; potential loss; probability, scenarios and consequences; consequences and related uncertainties (Aven, 2012). As already introduced in section 2.1.3, the risk could be considered as a combination of threat, vulnerability and consequences (Linkov et al., 2014) which reduces the normal performances of a system providing a negative resilience. According to Ramachandran and Charters, "risk can be defined as the combination of frequency of an unwanted event, such as fire and its consequences, i.e. how often and how bad the outcome might be" (Ramachandran & Charters, 2011). This thesis assumes the risk definition of ISO 31000:2009 in which "risk is characterized by reference to potential events and consequences or combination of these" (ISO 31000:2009, 2009).

The components of risk can be quantified with risk assessments. According to Hasofer et al. (2006), "a risk assessment is defined as the process of assigning the magnitude and probabilities to adverse effects resulting from fires in buildings". According to the British Standard PD 7974-7:2003, probabilistic risk assessment is "the generic term applied to studies where the objective is to generate a measure of risk" expressed as "likelihood that a set of consequences will occur so that the probabilistic risk assessment studies produce numbers that represent the level of hazard posed to persons and property but take into account how likely the event is" (BSI PD 7974-7, 2003) as described in Figure 24. In particular, fire risk assessments are the risk of fires affecting people and property (Yung, 2008). It is necessary to define and quantify the undesirable outcomes providing a general definition of what is expected to be an undesirable outcome (Renn, 1998) addressing uncertainties, the complexity of relationships and limiting ambiguity.

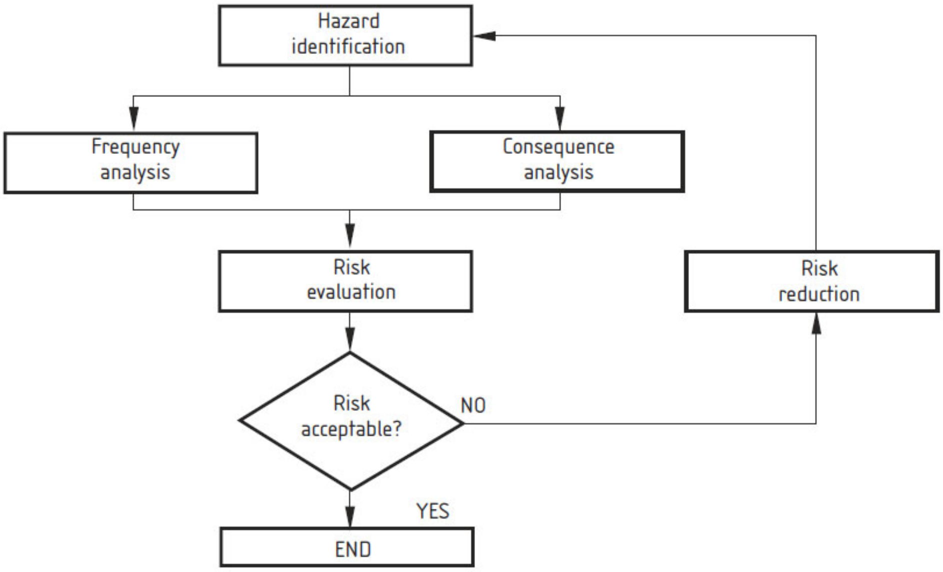


Figure 24: General approach to probabilistic risk assessment (BSI PD 7974-7, 2003)

Deterministic approaches usually consider the worst-case possible in specific conditions and cannot be adopted to estimate the likelihood and safety level of the fire scenarios (A. Hasofer et al., 2006). While the traditional fire safety techniques assume that a fire has started evaluating the growth and the number of subsequent events, a more detailed analysis could be developed considering the fire development and interaction with structure and occupants providing a more flexible approach than the deterministic study (BSI PD 7974-7, 2003). Furthermore, deterministic designs are usually based on two safety foundations which are the collective experience of profession where longstanding design approaches have not led to unacceptable fire performance, and large level of conservativism (BSI PD 7974-7, 2019).

Risk assessments evaluate all the various components of risk and how they affect the system in an undesirable event by assessing not only the consequences but also the likelihood that a set of consequences occur (BSI PD 7974-7, 2003). An approach to deal with the random nature of the fire problem is based on probabilistic fire risk assessments (Ramachandran & Charters, 2011) considering uncertainties and the probability of assessment (BSI PD 7974-7, 2003). Moreover, probabilistic risk assessment could evaluate the difference between two systems defining the most reliable one (*comparative studies*) or investigating performances against predetermined criteria (*absolute studies*) (BSI PD 7974-7, 2003).

Risk assessments are characterized by information which supports decisions on possible risk reduction and mitigation. Therefore, risk assessments are able to support risk-informed decisions and not risk-based because risk assessments are not unique tools for the decisions of a responsible group (Apostolakis, 2004).

Fire scenarios are defined as a set of fire events linked together considering the performance of fire protection measures such as fire protection systems or action (Yung, 2008). Several fire scenarios and system failure modes are investigated in risk assessments to evaluate the interaction between events, systems and operators, quantify the uncertainties and provide analysis on physical phenomena and human behaviour facilitating risk treatment and management (Apostolakis, 2004). According to ISO/IEC 31010:2009 and as represented in Figure 25, risk assessments usually includes five main phases: the establishment of the context, risk assessment composed of risk identification, risk analysis and risk evaluation, and risk treatment (ISO/IEC 31010, 2009).

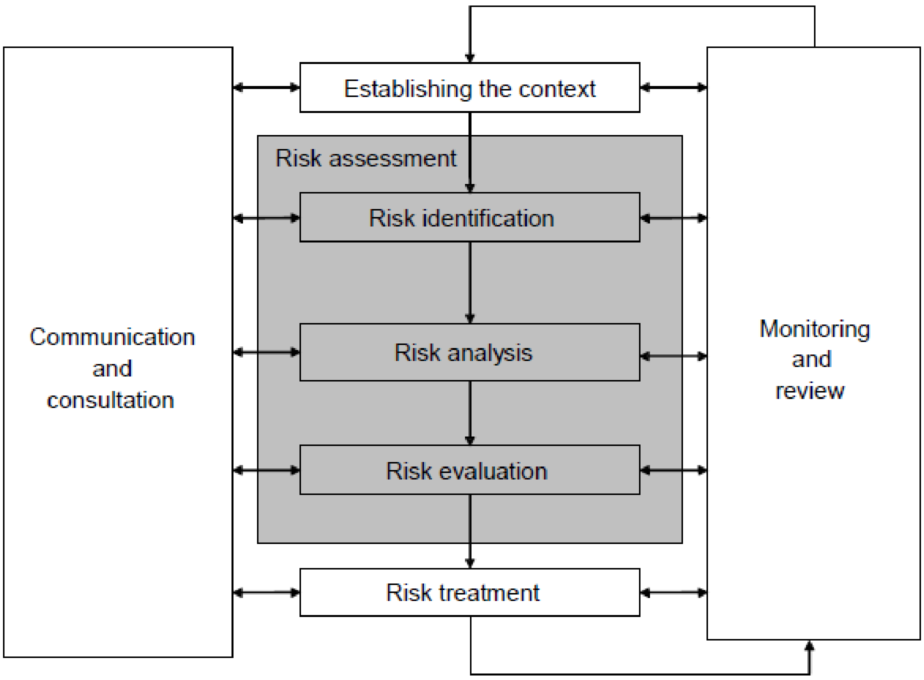


Figure 25: Risk assessment and management process (ISO/IEC 31010, 2009)

Based on Figure 25, the general framework for a risk assessment also includes establishing the context, the definition of values and objectives. All the above-mentioned phases contribute to the monitoring and review stage and influence communication and consultation. For the risk management, it would be important to: define a strategic policy, guarantee resources, competencies and responsibilities, create and implement risk assessment, monitor control measures and review the system for improvements. Instead, once the risk has been assessed, the risk treatment can be applied thanks to elimination, prevention, mitigation and control of consequences actions while the remaining risk can be transferred or absorbed (Ramachandran & Charters, 2011).

In particular, the fire risk estimation flow chart by ISO/FDIS 16732-1:2011(E) and described in Figure 26, contains the following steps: the establishment of the context, the identification of fire scenarios and selection of a cluster representative of the fire scenario, the estimation of frequency, consequences and risk, the analysis of various scenarios and the combination of their risks (ISO/FDIS 16732-1:2011(E), 2011).

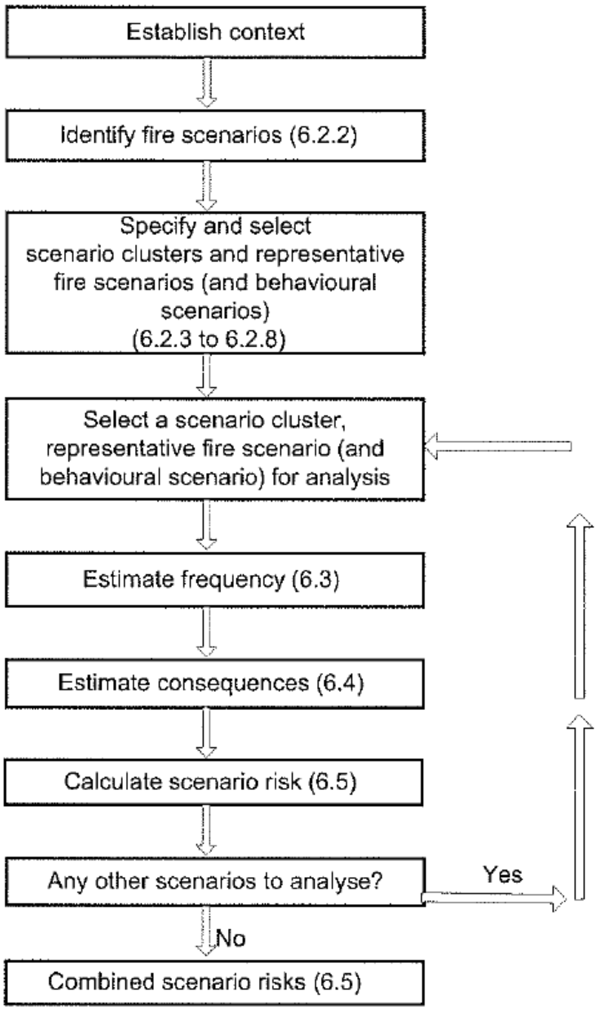


Figure 26: Fire risk estimation flow chart (ISO/FDIS 16732-1:2011(E), 2011)

The two objectives of probabilistic risk assessments are to demonstrate *adequate safety*, for example where it is not possible through deterministic evaluation (design not based on experience and conservativeness leads to undue design), and *rank design alternatives* respecting safety performances (BSI PD 7974-7, 2019).

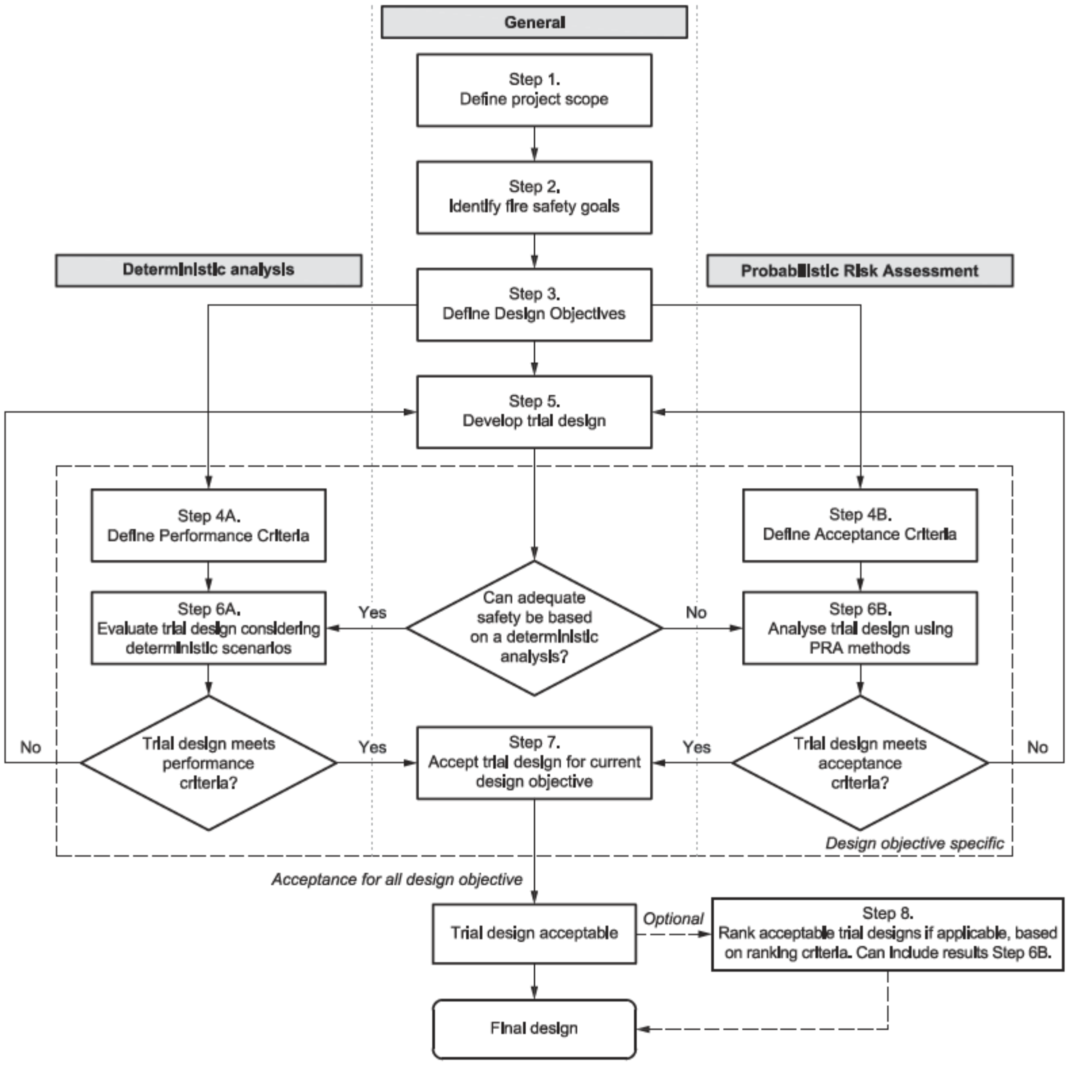


Figure 27: Flow chart to demonstrate adequate safety (BSI PD 7974-7, 2019)

Figure 27 represents a flow chart to demonstrate *adequate safety* presents in the British Standard PD 7974-7:2019 (BSI PD 7974-7, 2019) comparing deterministic analysis and probabilistic risk assessment in general design. Figure 28 provides a general flowchart for the design assessment based on probabilistic risk assessments (BSI PD 7974-7, 2019) and it appears as an updated version of the one available in the British Standard PD 7974-7:2003 and described in Figure 24.

The new version of the British Standard PD 7974-7 published in 2019 (BSI PD 7974-7, 2019) presents a discussion about acceptable criteria that aims to maximize societal welfare evaluating risk across several domains considering societal risk. The acceptable criteria are highly connected to the related fire safety objectives and can be determined by consultation with stakeholders. However, acceptable criteria need to establish acceptable risk and adequate safety level where private safety investments can exceed societal requirements if they do not affect other societal requirements. In general, the design is tolerable if the risk is considered "As Low As Reasonably Practicable" (ALARP) unless the risk is considered to be negligible (BSI PD 7974-7, 2019).

Based on the knowledge introduced in this Chapter about the risk and flowcharts to follow in the design, further discussions will be provided in section 3.4 of Chapter 3 about the fire design for resilience where deterministic and probabilistic assessments are combined to provide a comprehensive approach to the fire issue.

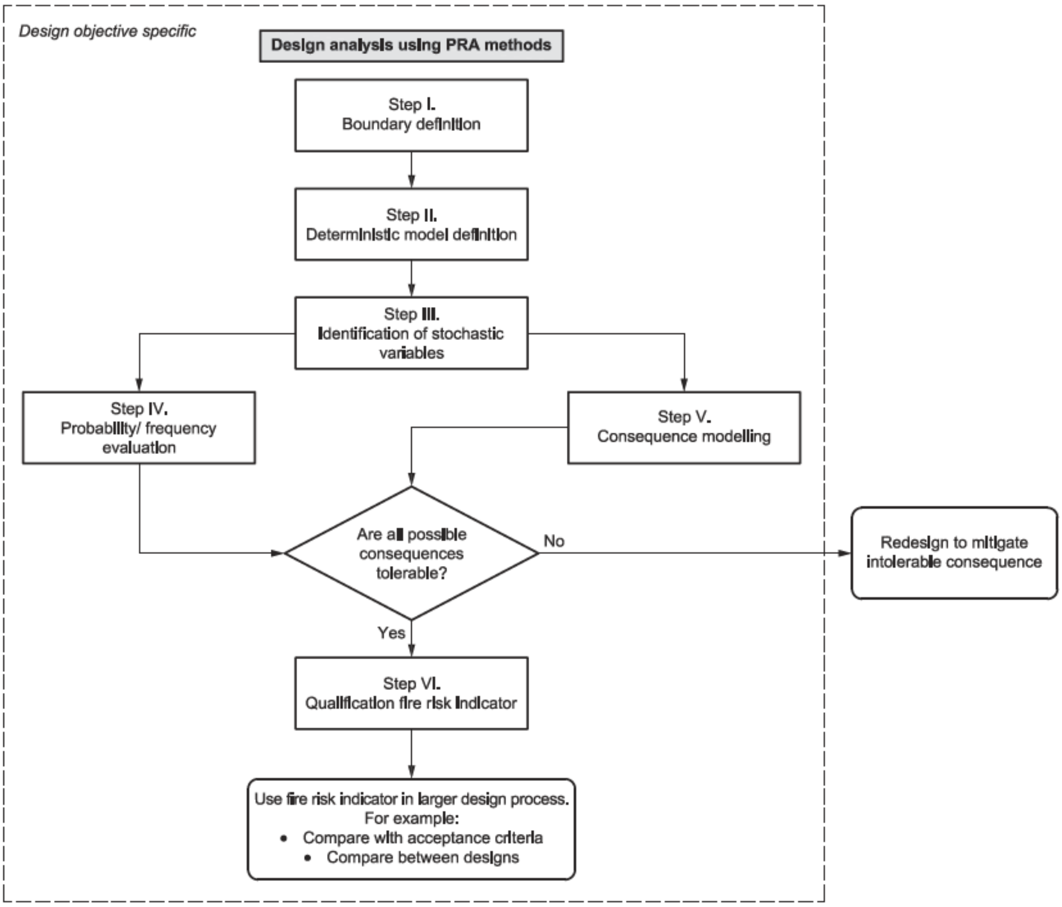


Figure 28: General flowchart for design assessment using PRA methods (BSI PD 7974-7, 2019)

It is clear how similarities are visible with the resilience definition and assessment discussed in section 2.1 where a continuous process of evaluation and improvement is established. The evaluation of risk scenarios, likelihood and consequences are fundamental to be able to present and evaluate risk (Tehler, 2013). The analysis developed in this thesis follows these steps where possible, to provide a comprehensive evaluation of the fire risk in property types.

2.6.1 Risk assessment methods

Risk assessments can be developed according to *qualitative*, *semi-qualitative* or *quantitative methods* based on the objectives that need to be addressed and investigated as expressed by Ramachandran and Charters in Figure 29 (Ramachandran & Charters, 2011).

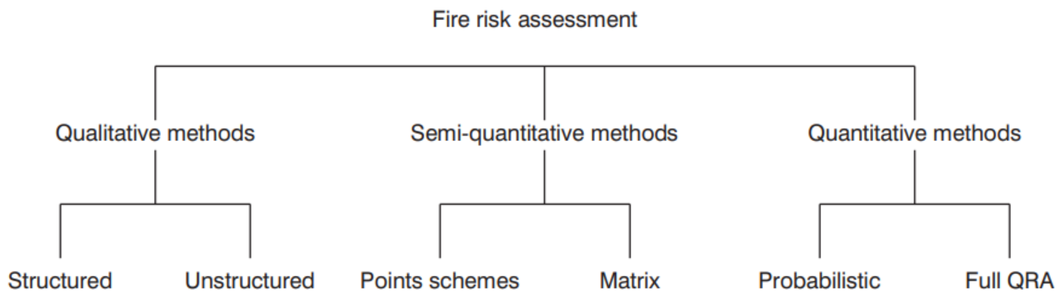


Figure 29: Fire risk assessment methods (Ramachandran & Charters, 2011)

The factors affecting the risk are defined in *qualitative* methods highlighting the hazards or the effects of the mitigations on those hazards. *Qualitative* risk assessments are based on subjective judgements of hazards and consequences and they are usually adopted to determine rapid assessments (Yung, 2008). Factors are investigated against benchmarked values and *qualitative* risk assessments are distinguished in unstructured and structured methods. The only difference between unstructured and structured methods is given by the presence of prescribed standards to define the precautions appropriate for the hazards in structured methods. The steps to follow in *qualitative* risk methods are given by the identification of fire hazards and the people in danger, evaluation of risk, communication to people involved and continue implementation of the assessment (Ramachandran & Charters, 2011). However, the other two methods considered as *qualitative* are the checklist which estimates hazards and protection measures in place or that need to be installed, and event tree analysis based only on qualitative evaluations (Yung, 2008).

Based on Figure 29, *semi-quantitative* assessments are classified in points scheme and matrix. In points scheme, fire safety factors are scored and multiplied by the related weights. The total value obtained in the points scheme provides the overall score assessed. Matrix methods are usually based on decisions assumed in round-table discussions identifying, rating and providing a list of major and minor hazards and estimating consequences.

Finally, *quantitative* assessments are composed of probabilistic assessments, which adopt statistical analysis for the prediction of frequency of events, or full quantitative risk assessments able to predict frequency and consequences (Ramachandran & Charters, 2011) as described in Figure 30.

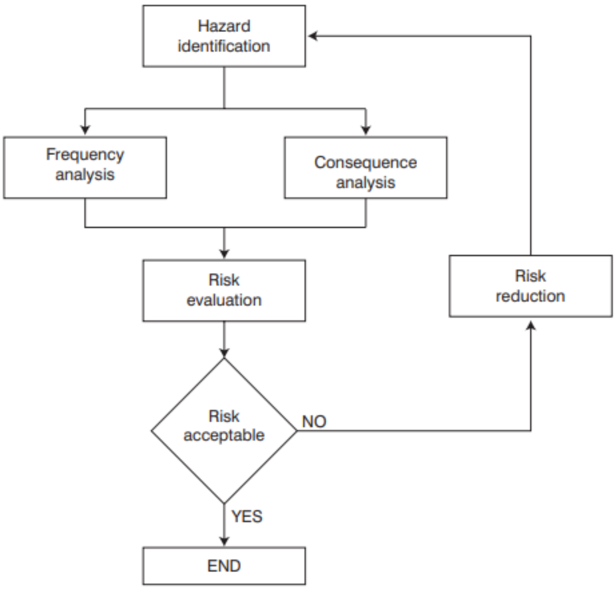


Figure 30: Full quantitative risk assessment process (Ramachandran & Charters, 2011)

According to the British Standard PD 7974-7:2019, a different classification of methods to estimate the probability is provided where the evaluation methods are given by *statistical analysis* based on statistical data, *analytical method* calculated for stochastic distribution of input variables, *logic tree analysis*, *Monte Carlo simulations* and *other methods* that aim to reduce the computational procedures related to Monte Carlo simulations (BSI PD 7974-7, 2019).

Benefits of quantitative risk analysis are that they: consider several scenarios and are able to include various failure modes; understand the probability given by the interactions between systems, events and operators; apply an integrated approach facilitating a common understanding; and they evaluate uncertainties and enable risk management (Apostolakis, 2004). In particular, probabilistic risk assessments are applied to identify fire scenarios and input data for a deterministic analysis, analyse parts (levels of performances, failure rates on demand, failure consequences) or the whole fire safety building design (BSI PD 7974-7, 2003).

The large uncertainties of quantitative risk assessments are due to potential human errors during maintenance; failure of digital software; safety culture not perfectly integrated into the building or business and errors during the design and manufacturing phases of equipment (Apostolakis, 2004). Moreover, the probabilistic risk assessment could be limited by data availability (such as data of organization processes, previous incidents, and fire statistics) (BSI PD 7974-7, 2003). In the following section, logic tree analysis is introduced as a means of developing probabilistic risk assessments based on quantitative methods.

2.6.2 Logic trees

Logic trees provide a methodology to determine the probability of occurrence of undesirable events where the sub-events leading to or originating from the initiating event are placed in sequential order. Usually, the basic event and sub-events are associated with a probability determined by statistical data. The sub-events can be external or internal to the system. Furthermore, the loss scenario needs to be structured in time, credible in realistic outcomes and able to provide information to quantify the real scenario (A. Hasofer et al., 2006). Logic trees are usually represented by *fault tree* and *event tree* analysis. *Fault tree* evaluates the causes of a top event-based determining backwards sub-events connected with AND or OR gates relationships reaching the roots of the undesirable event. *Event tree analysis*, on the contrary, works forward from an initiating event defining branches and paths resulting from secondary events providing a full range of outcomes (Ramachandran & Charters, 2011). Therefore, *fault tree* analysis investigates the causes (inductive procedure) of an event while *event tree* analysis the related consequences (deductive procedure). As described in Figure 31, once causes and consequences have been examined, the procedures continue with sensitivity and cost-benefit analysis.

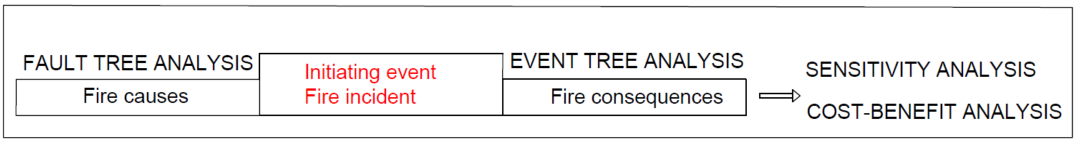


Figure 31: Fault tree and event tree analysis procedure

The analyses developed in Chapter 6 are focused on the deduction of the consequences considering various safety systems. Therefore, event tree analyses have been developed and the procedure adopted is described more in detail in the following section.

2.6.2.1 Event tree analysis

The severity of the outcomes in event tree analysis is estimated thanks to statistical data and engineering judgements. Event tree analysis is considered as a graphical approach to represent dependencies of events (A. Hasofer et al., 2006) and it investigates different fire scenarios based on multiple degrees of complexity enabling the assessment of several functioning and failing systems and quantifying the benefits of fire precautions based on related cost-benefit analysis (Rutstein & Cooke, 1979). Event trees are applied to predict frequencies of infrequent events by the logical connections of more frequent sub-events (BSI PD 7974-7, 2003). This type of deductive logic tree involves the investigation of several fire scenarios subsequent to an initiating event providing information on probability, consequences and risk (Yung, 2008). As stated by Del Prete et al. (2016) the aims of this analysis cover life safety and property protection. Moreover, it is possible to quantify hazards and risks, evaluate analytically the optimum safety measures able to limit the consequences due to fire incidents (Del Prete et al., 2016) and guarantee continuity to people or business involved in the fire incident. Therefore, event tree analysis appears as an optimum approach to estimate and optimize building fire resilience defining the ability to absorb and mitigate from disruption.

Event tree analysis is based on the identification of an initiating and undesirable event (fire incident) causing the final outcomes (safety of occupants and/or structural damage). All the sub-events are located in branches based on a sequential order and have to respect two conditions being independent and mutually exclusive. The branches represent a discretization of a finite number of macroscopic events associated with an intervention aimed to modify the fire development (Del Prete et al., 2016). The point in which a new variable is introduced is called node (A. Hasofer et al., 2006). For each branch in the logic tree analysis, a probability is evaluated and probabilities for each sub-event, including the consequences happening, are combined to obtain the overall risk of a specific path. Moreover, the joint probability of events, which constitutes a sequence, is called a scenario (A. Hasofer et al., 2006). Finally, multiplying the overall risk of a specific path by the frequency associated with that particular event, the frequency is obtained (Figure 32).

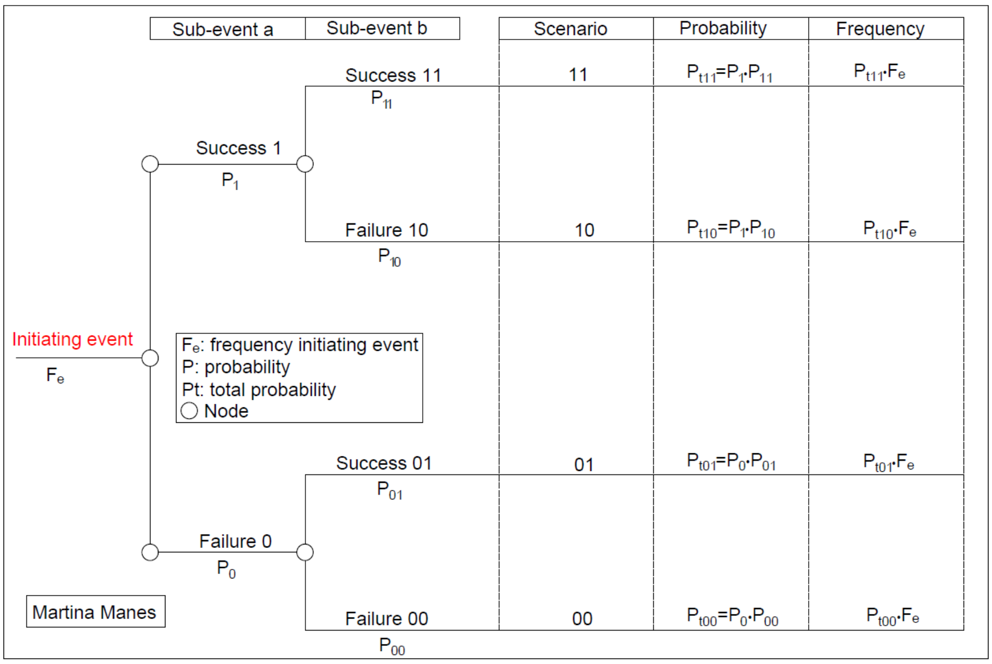


Figure 32: Event tree analysis scheme

The analyses developed in Chapter 6 for several property types, evaluate the probability and frequency of various scenarios which consider the presence of detectors and fire safety systems based on the examination of fire incidents collected in English and USA statistics.

2.7 Summary of literature review

This Chapter related to the literature review of this thesis provides an overview of the complexity of addressing the various aspects and people involved in fire incidents evaluating a comprehensive and holistic resilience approach. The resilience definitions, missions, objectives, characteristics and capacities have been deduced from those available in other disciplines such as critical infrastructures and earthquake engineering. Furthermore, resilience measures and frameworks have been critically evaluated to understand the system components involved and how they participate in the resilience enhancement. From the analysis of British Standards and Codes, their resilience guidelines are mainly concentrated in the phases of the resilience function related to the prevention, response, absorption and mitigation missions and it is clear how the resilience applications in fire safety appear limited. Therefore, since fire resilience approaches need to be based and supported by data of system processes and previous incidents, national fire statistics appear as a tool for the evaluation of the structural response of buildings subjected to fires. English and USA fire statistics have been described in detail with a deep discussion of the available fields recorded. The direct and indirect financial costs of fires have been examined in all their components and available methodology for their estimates provided. Finally, amongst the probabilistic risk assessments, the quantitative methodology of logic trees is described to evaluate the fire risk. In particular, event tree analysis adopts a deductive procedure to identify the effects that various safety measures, such as detectors and sprinklers, could have in the notification of the fire to occupants and on the reduction of fire consequences.

The resilience definitions, missions and objectives will now be applied in the fire safety field in Chapter 3. The description of the fire statistics of England and USA will facilitate the understating of the investigations developed in Chapter 4 and could be used as inputs variables in fire design. Moreover, fire safety data available in the British Standards PD 7974-7:2003 will be compared to those of English and USA statistics and analysis on the effects of response time in terms of fatality, casualty and property damage will be estimated in Chapter 5. Finally, the description of risk assessments introduced in this Chapter will be applied in event tree analyses considering fire incidents for different safety measures in various property types in Chapter 6.

Chapter 3. Fire resilience

"Fire safety engineering currently lacks a generally accepted framework or process for alternatively applying a performance-based approach."

- Brian J. Meacham

This Chapter explores the application of fire resilience in current practice based on the information presented in section 2.1 where resilience concepts and characteristics are explained in detail to provide a holistic view and different approaches compared to determine fire safety engineering solutions. Moreover, the suggestions of Standards and Codes of section 2.2 are grouped according to the resilience missions or life-cycles which are composed of six phases to prevent, respond, absorb/mitigate, recover, adapt and learn.

After a deep literature review about the concept of resilience in fire safety engineering and its applications in other disciplines of section 2.1 and 2.2, the research developed in this Chapter is focused on the comprehensive fire safety problem ables to consider all the resilience categories, dimensions and characteristics, evaluate fire resilience measures, define resilience approaches to identify, mitigate and treat fire risk and determine a fire resilience design able to include structural and fire assessments in a continuous flow.

3.1 Fire resilience categories, dimensions and characteristics

The concept of resilience covers several dimensions, characteristics, capacity, missions, objectives and users. The creation of a resilience framework appears complex including not only the technical dimension but also the organizational, economic and societal ones and investigating the differences in internal and external resilience as expressed by Labaka et al. (2016).

Table 13: Internal and external resilience and resilience dimensions (Labaka et al., 2016)

Internal Resilience	Technical	Safety design and construction Maintenance Data acquisition and monitoring Crisis response equipment
	Organizational	Organizational procedures for crisis management Top management commitment Crisis manager preparation
	Economic	Crisis response budget
External Resilience	Technical	External crisis response equipment
	Organizational	First responder preparation Government preparation Trusted network community Crisis regulation and legislation
	Economic	Public crisis response budget
	Social	Societal situation awareness

As shown in Table 13, Labaka et al. (2016) consider for the technical dimension in the internal resilience, the aspects that include safety design, maintenance, crisis response and especially data acquisition and monitoring and for external resilience the external crisis response equipment, while for the organizational dimension, highlight the role of management and organizational procedures during crises as well as the involvement of government, regulations and legislations and most of all a trusted network of community which in the social dimension of external resilience assumes a fundamental role for the societal situation awareness.

As explained in section 2.1.4, the Organization for Economic Co-operation and Development (2014) states that a resilience system can be described according to the following questions: Resilience of what?; Resilience to what?; Resilience of who?; Resilience achieved with?; Resilience over which timeframe? This Chapter has answered those questions considering the fire incidents affecting buildings and grouping the analyses according to the five resilience categories (property, business, users, community and environment) and for each of them the most appropriate resilience dimensions and characteristics evaluated as shown in Table 14.

The category of *property* implies considerations related to the technical, organizational and economic dimensions where robustness and rapidity are required. The property needs to be prepared for fire incidents and damage, investigating deeply the likelihood and potential consequences, respectively. When a building fire occurs, there are directly affected actors, such as occupants and owners, and indirectly affected actors, such as stakeholders, experts, regulators and governments. Furthermore, the means of achieving resilience can be classified according to the resilience dimensions where technical aspects involve fire prevention, with fire design, code application, and fire risk assessment, and fire mitigation including fire safety measures, fire response, limitation of ignition sources and combustible materials, and effective compartmentation. The preparedness of building and the evaluation of the economic impact is fundamental to guarantee organizational and economic resilience for the property. All these aspects are evaluated in the design, construction and maintenance phases where there is a continuous evaluation of the situation, development of strategies, application of improvements and ongoing maintenance.

As for *property*, *business* evaluation comprehends not only organizational resilience but also aspects linked to the technical and economic dimensions where the system should present redundancy of resources and rapidity of response. The impact of fire on property and disruption of activity need to be investigated before and after an incident, because the negative consequences could highly affect the business continuity involving not only owners, stakeholders and workers but also costumers, investors, reputation and most of all the community who benefits of the business activities. It is, therefore, important to establish impact and continuity plans in the design and maintenance phases, respectively. Managers and staff need to continuously attend training programmes to guarantee preparedness and effective response and review fire safety measures able to limit consequences of fire incidents and enhance continuity of business. Economic losses particularly influence business continuity and this is the reason why direct and indirect losses need to be deeply assessed to understand the implications of potential negative events in various aspects and sectors of the business.

The category of *users* implies social and technical resilience dimensions related to the fire incidents involving the potential harms to occupants and visitors present in the building and fire-fighters during the rescue and fire-extinguishment operations. In this case, resilience is achieved with appropriate evacuations plans and ensuring the structural stability of the building if subjected to fires both during design, maintenance and clean-up after fires.

The effects of fire in one or adjacent buildings could have implications not only on occupants but also on the surrounding *community*, especially if the event affects a functional property as an educational building or hospital. The rapidity of response and resourcefulness are required to limit the fire consequences and the impacts on the social and organizational resilience dimensions could be reduced by arranging alternative services to decrease disruption time and evaluating the potential fire social impact with prevention and mitigation measures. These aspects affecting communities should be included and analysed in national and local policies applied by local authorities and national governments.

Finally, the last resilience category involves the negative effects of fire incidents on the *environment* produced by the combustion of toxic materials which could pollute the air and natural resources. The negative impact on the environment determines the necessity to reduce and absorb the social consequences for the affected communities and in some cases for future generations. It could lead to the modification of natural ecosystems of vegetation and animals. Therefore, it is important to define certificates for materials and establish appropriate protocols to protect natural resources and guarantee sustainable engineering approaches and solutions. National and international policies should agree on specific guidelines able to help and sustain the fire safety community in appropriate choices to safeguard natural resources.

This research is mainly focused on the technical dimension of the fire resilience problem. Table 14 provides a method to include *property*, *business*, *users*, *community* and *environment* in fire resilience assessments evaluating actors involved, means of achieving resilience and how to apply them in the design or maintenance stages. It is clear how within a category, multiple domains could exist covering and limiting impacts of different aspects. Certainly, a correct application of this method implies the collaboration and co-operation of several experts as fire safety engineers, structural engineers, business managers, social scientists as wells as local, national and international authorities.

Table 14: Fire resilience questions according to resilience categories

RESILIENCE							
Of What? Categories			To What?	Of Who? Actors	Resilience achieved with?	Over timeframe?	
Category	Dimension	Characteristic					
Property	Technical Organizational Economic	Robustness Rapidity	Fire Incidents (likelihood) Fire damage (consequences)	Owners Stakeholders Occupants Governments Regulators Experts	**Technical** FIRE PREVENTION Fire design Codes application Fire risk assessment FIRE MITIGATION Fire safety measures (active, passive) Fire response (occupants, firefighters) Limited ignition sources, combustible materials Compartmentations **Organizational** Building structural preparedness **Economic** Economic impact (direct, indirect losses)	Design	Maintenance
Business	Organizational Technical Economic	Redundancy Resourcefulness Rapidity	Fire impact on property Activity disruption	Owners Stakeholders Workers Costumers Investors Community	**Organizational** Impact analysis Continuity plans **Technical** Training programme **Economic** Economic impact (direct, indirect losses)	Design Design	Maintenance
Users	Social Technical	Rapidity Resourcefulness	Fire incident	Occupants Visitors Firefighters	**Technical** Evacuation plans Structural stability **Social** Reduction of toxic material	Design	Maintenance
Community	Social Organizational	Rapidity Resourcefulness	Fire in building Fire adjacent buildings Fire in functional property: - Schools - Hospitals	Occupants People in the surrounding area	**Organizational/Social** Alternative services Fire social impact	National, local policies	
Environment	Social	Rapidity Resourcefulness	Toxic material combustion Resource pollution	Surrounding communities Nature	**Technical** Material certificate and protocols	National, local policies	

3.2 Fire resilience measures

In section 2.1.3, some indicators of resilience have been evaluated based on what suggested by the Organization for Economic Co-operation and Development (OECD) (2014) such as system resilience indicators, negative resilience indicators, process indicators, output indicators and proxy impact indicators. The results are summarized in Table 15 classified according to the resilience categories. Furthermore, the recovery indicator is added in the list of fire resilience measures able to describe how quickly a system or components go back to normal functionality.

System resilience indicators describe how the system is affected when a fire occurs over time. For property, likelihood and damage could be considered and for the latter, an analysis of material deterioration and reduction in property life could be investigated. An indicator for business is the disruption time or maximum tolerable period of inactivity and this indicator is highly dependent on leadership, level of flexibility and the ability to be supported by a good network of people and companies. Usually, fatalities and casualties are recorded while the level of service and pollution are evaluated for community and environment, respectively.

If a strategy has a negative impact on other areas, this is represented as a *negative resilience indicator*. Over-protection for properties or over-allocation of resources for business could lead to severe economic impact without applying effective measures as well as lack of strategy optimization. For instance, the excessive use of materials will have an impact on production and indirectly on sustainable approaches, or poor maintenance of alarms or evacuation systems and routes can increase the risk of loss of lives for occupants having negative consequences on life safety.

Process indicators describe how actions are used for decisions and a set of measures need to be defined in the resilience time frame or as milestones in fire resilience assessments to understand if the outcomes are generating the expected performances.

The *output indicators* are strictly related to the system resilience indicators and measure the results of activities or programmes in a system or building. For example, if property protection is analysed, the lack of structural failure and the limited or null cost of repairs and maintenance after fire incidents are signals of good output indicators. In business, high functionality level after negative events and high achievements of benefits based on resource investments show positive fire resilience applications. A reduction of fatalities and casualties proves successful evacuation strategies in combination with appropriate alarm systems.

The research developed in this section also considers *recovery indicators* defined as how rapidly a system recover to normal functionality. In this case, specific tolerable time of recovery should be established to guarantee continuity for families and business. Recovery time of system or component could be adopted for property and downtime period for activities.

Finally, a *proxy impact indicator* approximates or represents a phenomenon in the absence of a direct measure and this is very complex and highly dependent on the objectives of the plan.

Table 15: Fire resilience measures

STAGE	TYPES	CATEGORIES	MEASURES	
	System resilience indicators			
Immediate Review	How a system is affected when a fire occurs	Property	Likelihood	
			Damage	Material deterioration Reduction in property life
		Business	Disruption	Leadership Network Flexibility
		Users	Fatalities Casualties	
		Community	Level of service	
		Environment	Pollution level	
	Negative resilience indicators			
Immediate Review Post-fire	How a strategy can have negative impacts on other areas	Property	Over-protection	Economic impact Lack of optimization of strategies
			Poor maintenance	Likelihood
				Damage
		Business	Over allocation of resources	Economic impact Lack of business optimization Impact on climate change
		Users	Poor evacuation plans	Life safety
	Process indicators			
Immediate Review	How actions are used for decisions	Business	Achievements of milestones in the resilience plan	
			Applications of improved safety measures	
	Output indicators			
Review	Related to system resilience indicators	Property	No structural failures Cost of repairs Cost of maintenance	
		Business	Functionality level Benefit of investigating resources	
		Users	Successful evacuation plans	Limited fatalities/casualties
	Recovery indicators			
Post-fire	How a system recovers to normal functionality	Property	Recovery of components Recovery of systems	
		Business	Recovery of activities	
		Users	Recovery to usual life	
	Proxy impact indicators			
	Approximate or represent a phenomenon in the absence of a direct measure			

3.3 Fire resilience approach

Based on Table 14 and the analyses of Standards and Codes in section 2.2, it is also important to define an appropriate fire resilience approach highlighting the main steps to follow in every design as presented in Table 16. The idea is to provide a general approach that could be applicable to various property types.

The evaluation starts with the definition of the occupancy type because specific buildings could require appropriate measures according to their functions. Moreover, as expressed by Table 14, the five resilience categories of property, business, users, community and environment need to be included in the choices without neglecting the impacts that a specific decision could have in other areas. The objectives need to be established according to the required level of performance. It is fundamental to evaluate system conditions before and after an incident and potential consequences, in the short and long-term.

Fire risk evaluation includes fire risk assessments in multi-hazards and multiple domains identifying gaps, processes and conditions affecting the system to highlight interdependencies and connections between several parts and ensure continuity. Risk treatment includes the resilience life-cycle stages that provide a quick response, effective mitigation strategies and prompt recovery after fire based on administrative and engineering features as specified in section 2.2. Resistance, robustness, rapidity and resourcefulness are necessary characteristics to ensure the success of the fire resilience approach. The part related to the fire risk assessment is further studied in Chapter 6 where event tree analyses are developed to investigate the likelihood of fire scenarios in various property types and the effects of alarms and safety measures on human response and damage, respectively.

Finally, the analysis needs to improve the performances of the systems with a continual review of the process to ensure flexibility and applying changes to enhance absorptive capacity to limit damage, adaptive capacity to deal with unforeseen events, transformative capacity to learn from negative incidents and strengthen the system.

Once a general approach has been described in Table 16, the research developed in this Chapter has adopted the concepts and information gathered from previous analyses and has applied it in section 3.3.1 in a specific fire resilience framework considering educational buildings to explain the complexity of fire frameworks based on all the resilience categories, characteristics and missions in real life. A specific distinction is developed for internal and external resilience with clear objectives and steps to follow.

Table 16: Fire resilience approach

RESILIENCE APPROACH			
Define property type			
Who needs to be considered	Property Business Users Community Environment		
Define objectives			
Define time	Pre- Post-	Event	
	Immediate Short-term Long-term		
Risk evaluation			
Risk assessment	Multi-hazards Multi-domains		
	Identify gaps		
	Processes Conditions	affecting the system	
Risk treatment	Respond Absorb/mitigate Recovery Learn	Rapidity Robustness Resourcefulness	Administrative and engineering features
Improve performance	Absorptive capacity Adaptive capacity Transformative capacity Learn from past incidents	Stability Flexibility Change	

3.3.1 Fire resilience framework in educational buildings

This section aims to create a fire resilience framework investigating current risk assessments in educational buildings considering internal and external resilience as discussed in section 3.1 to provide a general methodology to follow as shown in Table 17. Certainly, the framework needs to be adapted to the building considering specific characteristics and functions and Table 17 covers life safety, property protection and educational continuity.

Based on internal resilience, the United Nations Office for Disaster Risk Reduction (2017) states that the objectives for comprehensive school safety are to protect students and staff during the fire incidents and firefighters in the rescue operations, guarantee continuity of education and strengthen risk reduction and resilience. It also defines three main phases of achieving these objectives represented by:

A. safe facilities,
B. risk reduction, and
C. Disaster management.

Starting now with the evaluation of a *safe facility*, it is fundament to define the type of school and the building characteristics. In particular, existing or new facilities have different fire safety requirements. In existing buildings, it is necessary to assess vulnerability, identify and evaluates mitigation options and develop and implement plans while if a new school has to be built, a smart size selection and an optimized fire resilience plan need to be established (Federal Emergency Management Agency (FEMA), 2017). Structural and non-structural stability is ensured (UNISDR United Nations Office for Disaster Risk Reduction, 2017) evaluating building and contents (Readiness and Emergency Management for Schools (REMS) and Technical Assistance (TA) Center, 2017). As for any other property type, educational buildings have to be compliant with fire codes and regulations (MSBA Risk Management, 2018). The building design is an essential component in the assessment of a safe facility and it is subdivided into the evaluation of size and shape of the building (e.g. total floor area, the dimension of openings, etc.), thermal insulation of walls and ceilings (Hassanain, 2006), effective compartmentation to limit fire spread and optimized fire safety systems which include detection, notification and suppression (Johansson & Van Hees, 2011). The evaluation of fuel load in schools is analysed according to fuel nature, load and arrangements (Hassanain, 2006) and a particular contribution to the fire spread in educational facilities is given by the presence of decorative materials and bulletin boards on walls and decoration on ceilings (MSBA Risk Management, 2018). Moreover, means of escapes have to address the high number of students and staff present in the building with an appropriate design of corridors and hallways (MSBA Risk Management, 2018) and considering people with disabilities and appropriate access for firefighters (UNISDR United Nations Office for Disaster Risk Reduction, 2017).

The second phase in the evaluation of internal resilience of Table 17 is the *risk reduction*. Research has shown the benefits of the integration of risk reduction in school curricula (UNESCO, 2014) where this involves the education of staff and students (MSBA Risk Management, 2018), the establishment of a strong relationship with the community and frequent training exercises (Readiness and Emergency Management for Schools (REMS) and Technical Assistance (TA) Center, 2017). For the technical characteristics of fire reduction, an analysis of pre-fire conditions, including possible fire locations, causes and potential ignition sources (MSBA Risk Management, 2018), and fire spread with appropriate control measures for fire development and life safety (Hassanain, 2006), need to be development pre- and post-fire incidents and be effective during the potential event.

The third step is represented by the *disaster management* which is usually continuously implemented according to three actions of:

- assessing the school or educational building;
- creating a fire strategy; and
- implementing the fire resilience plan (National Clearinghouse for Educational Facilities, 2008).

In order to create a successful *disaster management plan*, it is important to strengthen leadership, identify, acquire and store emergency resources and potentially purchase an insurance (Readiness and Emergency Management for Schools (REMS) and Technical Assistance (TA) Center, 2017). If a network of redundancy facilities is created, this could reduce disruption time and guarantee continuity of education for students. The actions to be applied after an incident involve the resilience mission of learning from past experiences and evaluating the significance of losses and the availability of alternatives (NZIER and Corydon Consultants Ltd, 2002). Finally, recovery is highly dependent on how wealth is the school, the community response, how quick is the replacement of damage and destroyed resources based on the responsiveness of contractors, and how actively the school deals with the trauma (NZIER and Corydon Consultants Ltd, 2002).

The objectives of <u>external resilience</u> could be seen in the improvement of health safety and wellbeing of people attending the school, protect the environment from the combustion of toxic material (Staffordshire Fire and Rescue Service, 2017), increase preparedness and strengthen awareness. The means of achieving external resilience is to educate community providing useful information (Staffordshire Fire and Rescue Service, 2017). The involvement of national and local authorises is again fundamental in creating emergency plans.

Sometimes the educational building could assume the role of emergency shelter and in this case, a high level of functionality after a fire needs to be ensured to guarantee that the facility is able to continue its role limiting potential negative consequences on structural and non-structural components in the aftermath of an event.

The fire resilience framework present in Table 17 provides a potential methodology to follow during the design and maintenance phases to assess prevention, protection, mitigation, response and recovery before, during and after an incident. It is clear that not only experts as engineers and authorities play a fundamental role but also staff, students and most of all community. Therefore, a trusted network of support has beneficial impacts on the mitigation of negative consequence and response.

Table 17: Fire resilience framework for educational buildings

INTERNAL RESILIENCE			
Objectives Protect students, staff and fire-fighters Continuity of education Strengthen risk reduction and resilience ***How?*** A. Safe facilities B. Risk reduction C. Disaster management			
A. Safe facilities			
Type of school	Existing	Assess vulnerability Identify and evaluates mitigation options Develop and implement a plan	
	New	Smart size selection Resilience plans	
Structural and non-structural stability	Building Contents		
Fire codes and regulation compliance			
Building design	Size and shape		Total floor area Room Doors Windows
	Thermal insulation		Walls Ceilings
	Compartmentations		
	Safety systems	Detection	
		Notification	Alarms Human response
		Suppression	Extinguishing systems Firefighters
	Fuel	Fuel nature Fire load	
		Fuel arrangements	Decorative materials Bulletin boards Ceiling decoration
	Means of escape		Corridors Hallways People with disabilities Firefighter access
B. Risk reduction	Pre-, post- and during fires		
Risk reduction in school curricula	Staff and students education Establish and strengthen the relationship with communities Conduct exercises		
Fire reduction	Pre-fire conditions	Fire location Causes of fire Item first ignited	
	Fire spread	Material affecting spread Control fire development	
	Life protection	Protect the exposed	

C. Disaster management	Pre-, post- and during fire
Assess the school	
Make a plan	
Implement plan (short and long-term)	
Identify, acquire and store emergency resources	
Purchase insurance	
Create redundancy facilities	
Strength leadership	
<u>Post-Incident</u>	<u>Recovery</u>
Significance of what lost	Wealth of school
Time of the year	Community response
Availability of alternatives	Replaced of damage or destroyed resources
	Responsiveness of contractors
	Actively dealing with trauma
EXTERNAL RESILIENCE	
Objectives	
Improve health, safety and wellbeing	
Increase preparedness	
Strengthen awareness	
Protect the environment	
How?	
Educate the community	
Information	
Involve national/local authorities	
Is the educational building an emergency shelter?	

3.4 Fire design for resilience

Based on the considerations of adopting a view in which several categories are assumed to include benefits for users, property, business and environment, it is now important to define an approach able to integrate fire safety engineering in the design for structural systems. This goal supports the capacity to understand building performances subjected to fire rather than applying prescriptive codes (Johann et al., 2006).

A fire design framework has been developed by Van Coile et al. (2019) with the aim to demonstrate adequate fire safety design process based on a hierarchy of acceptance concepts. The authors present a clear distinction between deterministic and probabilistic approaches able to provide adequate safety. However, these methods could be combined because deterministic evaluations ignore probability failures while probabilistic ones could not highlight performances of buildings with specific characteristics.

The research developed in this section considers the framework created by Johann et al. (2006) and illustrated in Figure 33, rearranges and improves the information in a unique flowchart which describes the steps to follow in the design. The new framework created in this thesis provides an engineering tool able to include fire safety approaches in structural design as shown in Figure 34 and Figure 35.

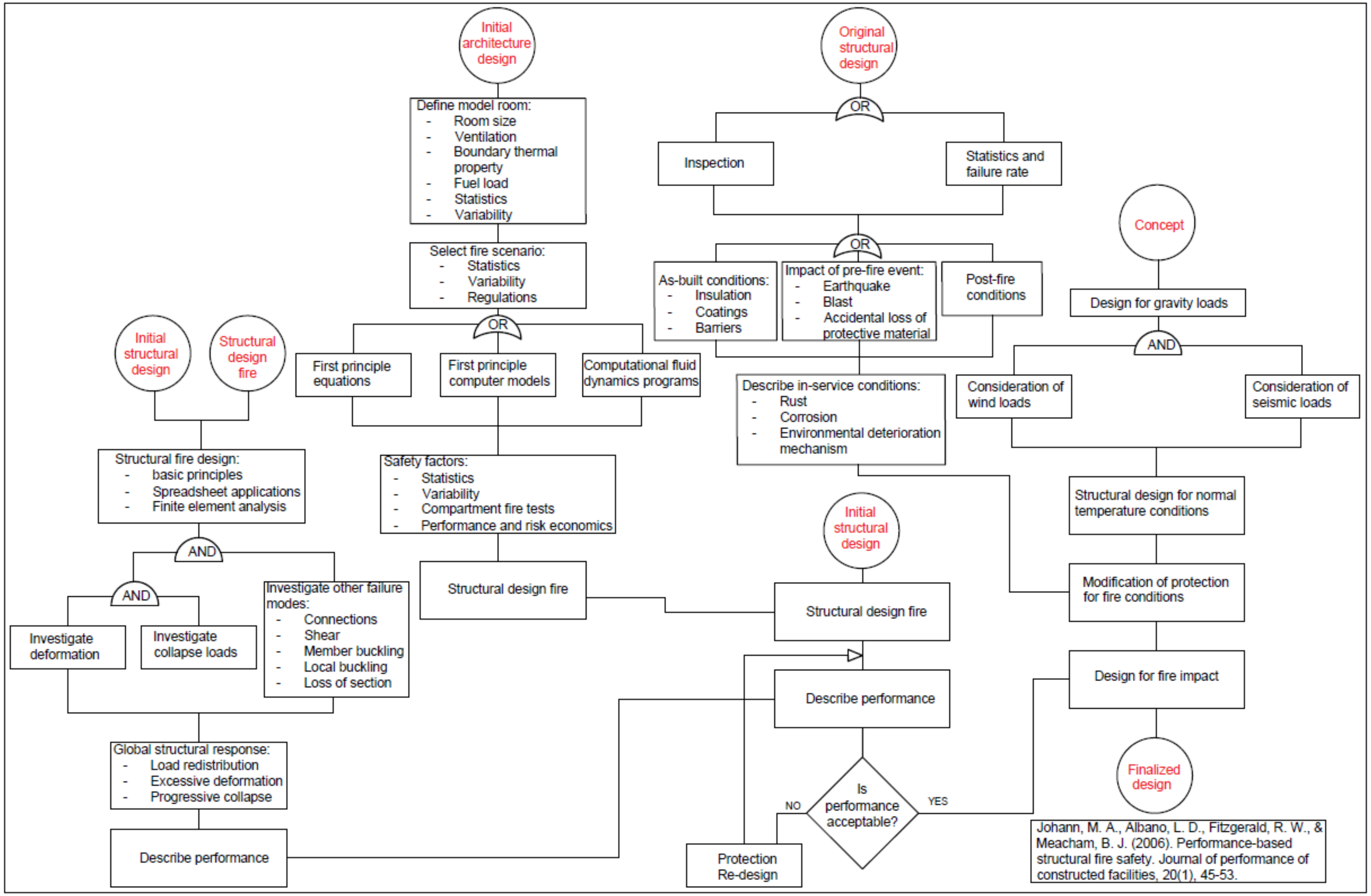


Figure 33: Performance-based structural fire safety chart (Johann et al., 2006)

Johann et al. (2006) describe a flowchart subdivided in three main areas that converged in the final design and have to be analysed separately and in their combination. The areas are:

A. the design for gravity loads considering wind and seismic loads for the structural design in normal temperature conditions;
B. the modification or protection for fire conditions; and
C. the design for fire impact.

In particular, the *modification or protection for fire conditions* implies in-service building evaluations with the description of in-situ characteristics with analysis of the original structural design based on inspection, statistics and failure rate according to built, pre- and post-fire conditions. It is important to highlight how statistics play again an important role in the evaluation of building performances.

The *design for fire impact* is composed of three main phases: structural design fire; description of performances and decision on acceptable performances.

In the structural design fire, there is a need to model room and related characteristics (size, ventilation, boundary thermal properties, etc.) and select fire scenarios considering statistics, variability and regulations based on computational dynamic problems, first principle equations and first principle computer models. The structural fire analysis investigates deformation, collapse loads and other failure modes to provide the global structural response and a description of performances. Finally, the decision on acceptable performances are necessary and if the results do not satisfy the criteria then re-design or protection is necessary.

In Johann et al.'s flow-chart, evaluations on sprinkler suppression are not included and further research could involve the development of standard fire scenarios for specific property types and construction systems, and a user-friendly resource including specifications of guidelines for the practice of structural design.

Johann et al.'s framework and the above considerations have been included in the research of this thesis developing a fire design framework which has the aim to provide a useful tool for current practice to merge structural and fire design. The framework created is shown in Figure 34 and Figure 35 and it is divided into four main areas:

A. inputs variables,
B. requirements and objectives,
C. structural design, and
D. fire design.

Figure 34: Improved flow chart for fire design based on (Johann et al., 2006) – *Part 1*

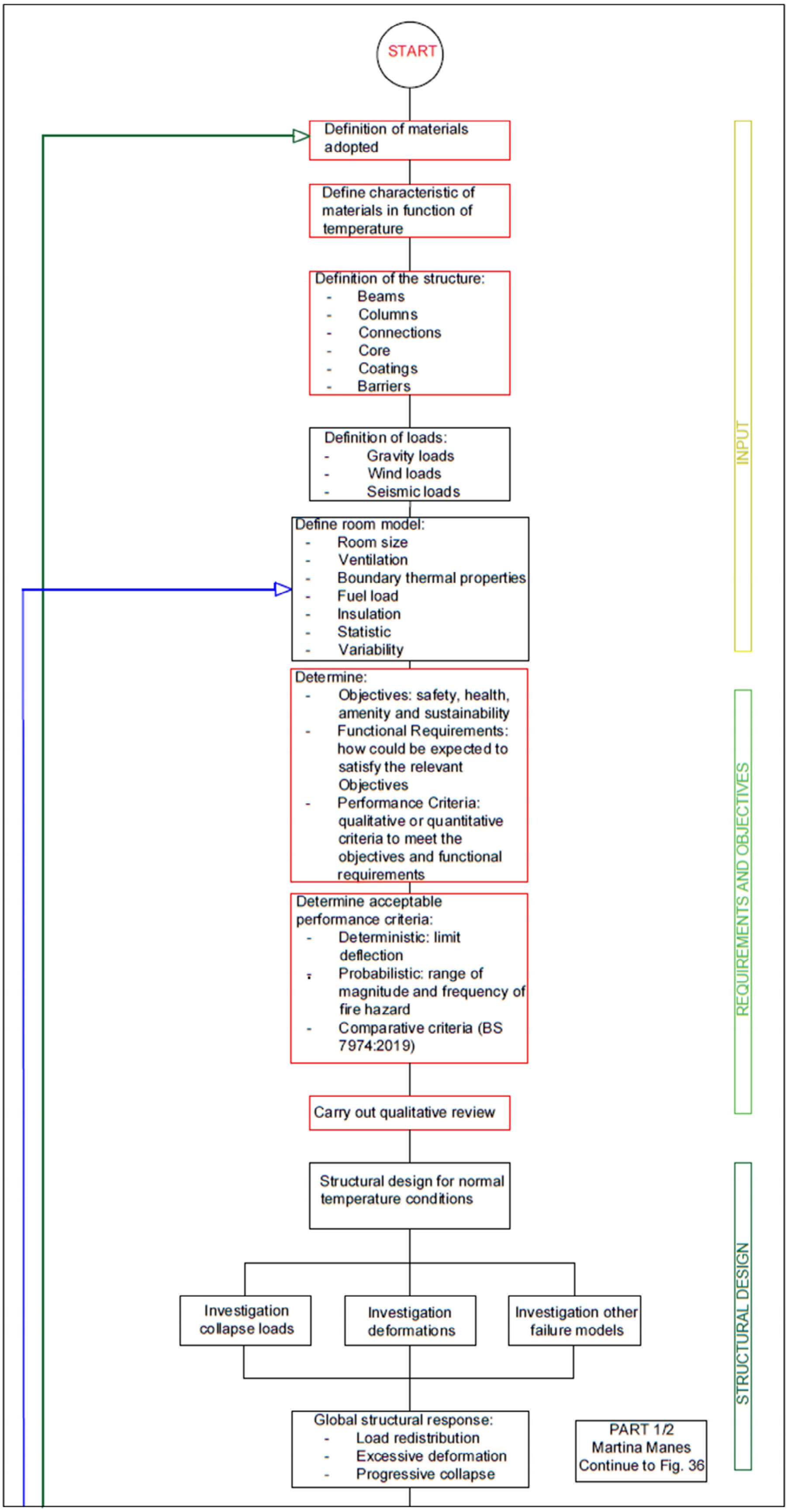
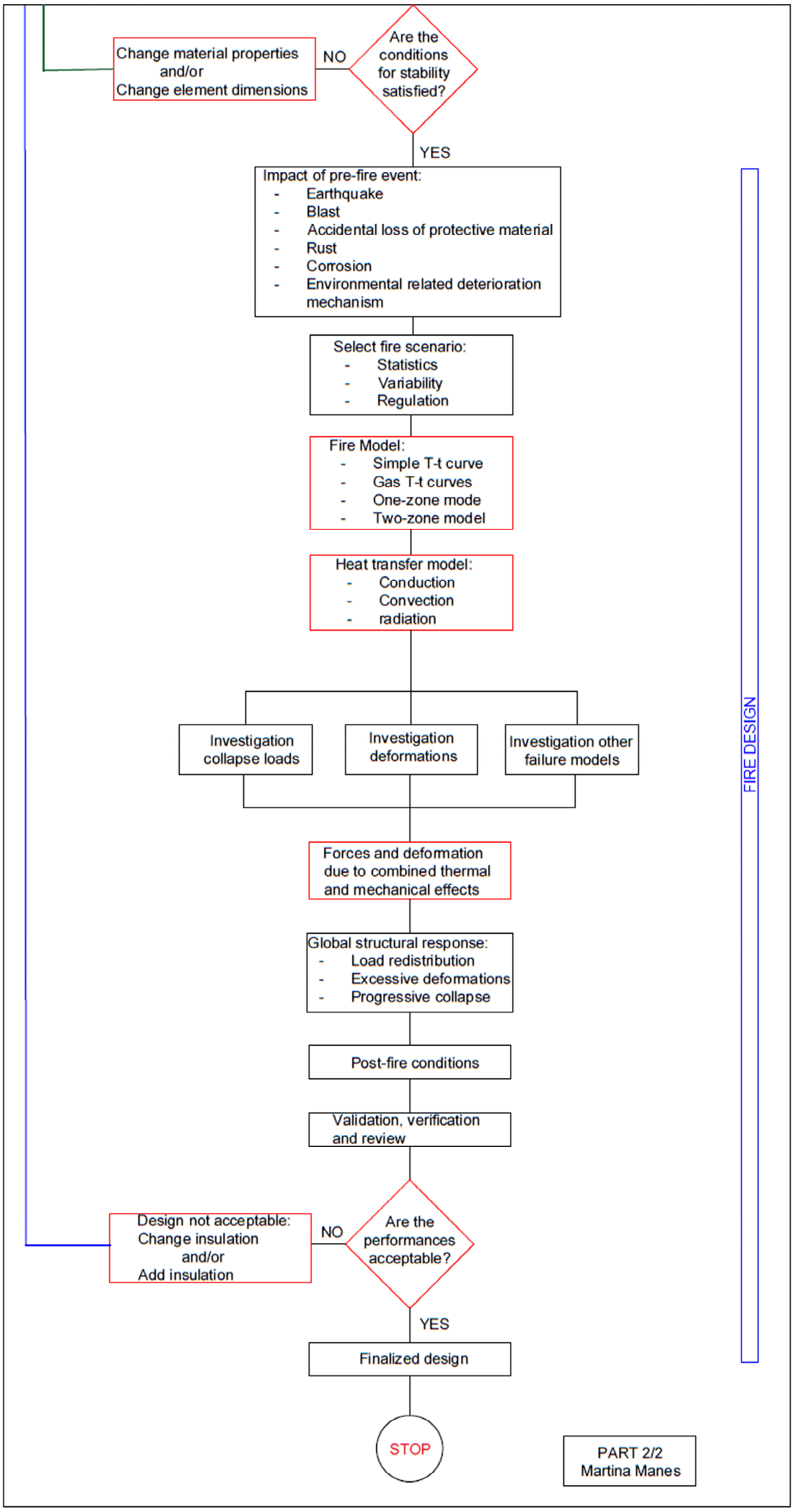


Figure 35: Improved flow chart for fire design based on (Johann et al., 2006) – *Part 2*



The first area regards the description of the *inputs* necessary for the structural and fire design and it involves the definition of the materials adopted and their characteristics in function of the temperature. For the building, structural element dimensions, connections, coatings and barriers need to be established as well as loads considering gravity, wind and seismic loads. Moreover, the room needs to be modelled in terms of room size, ventilation, boundary thermal properties, fuel load, insulations and considering statistics and potential variability.

The *requirements and objectives* are based on acceptable criteria considering deterministic (e.g. deflection limit) and probabilistic (e.g. range of magnitude and frequency for fire hazards) criteria or applying a comparative approach based on performance-based approaches as described in BS 7974:2019 (2019).

Once inputs and objectives have been defined, designers could consider *structural design* for normal temperatures in which investigation of collapse loads, deformations and failure modes need to be developed. Completed the structural design phase in Figure 34, the first diamond shape on top of Figure 35 defines the question if the conditions for stability are satisfied. In case of a negative answer, it is necessary to change material properties and/or element dimensions and go back to the definition of inputs and re-start the design. If the structural stability is satisfied, then it is possible to proceed with the fire design.

In *fire design*, pre-fire events could impact the building as earthquakes, blast, accidental loss of protective materials, rust, corrosion or environmental related deterioration mechanisms. A fire scenario needs to be chosen based on statistics, variability and regulations and several fire models could be adopted such as simple T-t curve, Gas T-t curves, One or two-zones models. Consequently, the following steps are the evaluation of heat transfer models developed for conduction, convection and radiation and, as suggested by Johann et al. (2006), investigation of collapse loads, deformation and other failure models. Furthermore, considerations on forces and deformations due to combined thermal and mechanic effects need to be deeply analysed to be able to provide a global structural response considering load redistribution, excessive deformation and progressive collapse. The fire design phase is also composed of post-fire conditions evaluation and validation, verification and review.

The second diamond shape at the bottom of Figure 35 asks if the performances are acceptable. If the answer is negative, then the design needs to be modified with changes in insulations or adding insulation if not present and going back to the definition of the room model. Otherwise, the design is finalized. This fire design methodology could be applicable to every property type equipped with different safety measures. In Figure 34 and Figure 35, all the new parts added and improved are surrounded in red.

In this Chapter, the fire resilience categories, dimensions and characteristics have been defined providing a fire resilience approach to address the complexity of the fire resilience problem. It is, therefore, important to evaluate not only the technical aspects but also the organizational, economic and social ones. Moreover, a practical example of a fire resilience framework applied in educational buildings has been discussed considering internal resilience for a safe facility, risk reduction and disaster management, and external resilience. Finally, a fire resilience design has been created improving the one developed by Johann et al. (2006) in which not only structural but also fire design are considered clarifying the steps to follow in a comprehensive design process based on a flow chart.

3.5 Research knowledge gaps

It is important to understand the knowledge and methodological gaps on the light of the considerations expressed in Chapter 2 and Chapter 3 before starting with the discussion about the work developed in the following Chapters of this thesis.

The resilience definitions, concepts and fundamental approaches are expressed and applied in other disciplines as explained in Chapter 2 highlighting the beneficial effects that a resilience approach could have in terms of life safety, property protection and continuity after disruption for families and business. However, the application of resilience theories and approaches are limited in the current fire safety discipline due to the complexity of the fire safety problem and to the involvement and collaboration of various experts. Therefore, the first attempt of a fire resilience framework has been developed in Chapter 3 based on the knowledge of internal and external resilience, dimensions, characteristics and capacities necessary to apply a comprehensive and holistic approach able to address various problems and actors involved before, during and after the fire incident. Within the resilience categories, this thesis will be mainly focused on property protection and partially on users without considerations about business continuity and environmental impacts. Moreover, technical, economic and partially social resilience dimensions will be evaluated while the organizational one will be part of future research. The resilience missions will be studied in this thesis considering the evaluation of fire frequency for the prevention phase, the response time of fire brigade and occupant notification for the response to incidents, the effects of various safety measures on fire consequences for the absorption and mitigation stage, the evaluation of direct financial cost for the recovery and a critical analysis of past fire incidents for the learning phase. The only mission not covered by this research is the one in which a system needs to adapt after being subjected by fires. The resilience measures that could be derived by the data obtained in the research of this thesis are system resilience indicators related to how a system is affected when a fire occurs, and process indicators defined as how the actions are used for decisions. The other resilience measures are related to the strategy applied (negative resilience indicators and output indicators) or to the recovery after an incident. Fire risk evaluation and assessment will be based on fire statistics and fire risk treatment by the development of probabilistic risk assessment considering various safety measures. A specific educational building has been examined in section 3.3.1 assessing risk identification, risk reduction and disaster management. However, it is not possible to improve resilience performances over time and they need to be specific for the building, system and users considered. If the fire resilience design introduced in section 3.4 is investigated, this thesis will be mainly focused on the definition of the requirements and objectives and fire design analysis adopting the assumption that a valid structural design has already been developed and applied.

A fundamental aspect of every resilience framework and fire design is related to the knowledge that inevitably arises from a critical analysis of the data of previous incidents. Data of buildings affected by fires are limited in the fire safety community. However, they are fundamental to understand the real performances of buildings subjected to fire incidents. Data can support fire engineering in correctly assessing the fire input variables able to be representative of fire scenarios involving causes, fire origin and item first ignited. Therefore, in order to fill the paucity of available information on structural response to fire, it appears necessary to investigate fire safety data of previous incidents affecting buildings gathered by the fire brigades in the aftermath of events and collected in fire statistics of several countries in terms of variables recorded and methodology adopted for the evaluation of consequences such as damage and financial losses. It is important to initially evaluate the fire safety fields available in the fire statistics to understand the data missing and how the information recorded can support fire safety design and assessments based on likelihood and structural performances to determine fatalities, casualties and damage such as fire spread, fire and total damage. The comparison between fire statistics of various countries (England and USA) defines similarities and differences and enables the investigation of potential improvements or unified methodologies of data collection.

A critical analysis of Standards and Codes appear necessary to determine the fire resilience aspects not currently covered by their guidelines. The British Standard PD 7974-7:2003 related to the probabilistic risk assessment (BSI PD 7974-7, 2003), presents fire safety data collected from 1966 to 1987; therefore, a comparison with current fire statistics appears relevant in determining their application nowadays and in understanding if its predictions are still able to appropriately describe building performances when affected by fires. This necessity is also supported by the fact that the research developed in Chapter 5 of this thesis for what concerns the comparison between PD 7974-7:2003 and USA fire statistics, has been referenced in the new version of the British Standard PD 7974-7 published in 2019 (BSI PD 7974-7, 2019).

Finally, once the likelihood and consequences of fire have been determined based on various property types, it is relevant to apply them in the evaluation of fire risk. Risk is usually addressed in probabilistic risk assessments able to quantify risk and determine fire scenarios and fire consequences according to the presence and operation of various safety measures such as detectors. Event tree analyses are able to determine the consequences of fire and have been created in terms of response to fire of occupants and fire brigades for presence and absence of detectors, and fire damage based on fire spread and area damage in building equipped and not equipped with sprinklers. The results obtained could be considered in future research related to sensitivity analysis and cost-benefit analysis.

This thesis has the aim to fill the research knowledge and methodological gaps stated above to help and support the fire safety community with an international dataset of fire safety data, quantifying fire risk and providing a resilience framework characterized by aspects related to prevention, response, absorption, mitigation, recovery and adaption.

The following Chapter involves the analysis on the performances on buildings subjected to real fires based on the investigations of fire statistics of England and the USA to understand the fire safety fields recorded in terms of pre- and post-fire conditions of several property types for the presence or absence of safety measures.

Chapter 4. Fire statistics

"The concept of safety itself is one of the uncertainties,
there is no such thing as absolute safety."

- G. Ramachandran

Chapter 2 and Chapter 3 have highlighted the need for updated data to be adopted in resilience design for fire hazards and quantitative risk assessments. Indeed, the collection and analysis of available data not only describe past incidents and current performances but enable the potential optimization measures and strategies for the future. Therefore, fire statistics of England and USA have been already introduced and described in section 2.3 highlighting the importance of filling the paucity of fire safety data available.

This chapter investigates the fields covered by each of the two fire statistics datasets and it begins by assessing the fire statistics from England focusing the research on the fire incidents, causes, growth and consequences, safety measures and response times of the fire brigades in attending the fire scene. This is consequently followed by separate assessments of USA fire statistics based on the same fields of investigations related to fire description, causes, consequences on buildings, the presence and operation of safety measures and the fire service response. The assessments of the two datasets have then been compared to investigate potential analogies and differences to define the variables gathered and which fields are assessed. The methodology adopted for data collected have been investigated and possible improvements defined.

The fire safety data of English and USA statistics examined in this Chapter will be adopted in the following Chapters for the analyses developed in the research of this thesis. In particular, they will be used in Chapter 5 to compare the predictions of PD 7974-7:2003 (BSI PD 7974-7, 2003) with contemporary fire statistics and examine how the response time could influence the fire scenarios that fire brigades face at arrival in terms of occupant safety and structural damage, and in Chapter 6 to provide input data for event tree analyses to evaluate the fire response of occupants and fire brigades and damage of the building according to presence and absence of alarms and automatic extinguishing systems, respectively.

4.1 Fire statistics in England (IRS)

The Incident Recording System (IRS) (Department for Communities & Local Government, 2012) is composed of questions to describe the fire incidents as already explained in section 2.3.2. The current section adopts the fire statistics available for England of 2014/2015 described in the Statistical Bulletin 08/16 (Gaught et al., 2016) which was available at the beginning of the research of this thesis and its spreadsheets published in the Home Office website (Home Office, 2015). The spreadsheets present fields described in section 2.3.2 and the dataset is composed of 155,000 total fires in which 71,089 are primary fires with 31,329 *Dwellings* and 15,548 *Other building* fires.

4.1.1 Fire incidents

Starting with the description of the fire incidents, in the period from April 2014 to March 2015, in England there were 496,051 incidents attended by the Fire and Rescue Service.

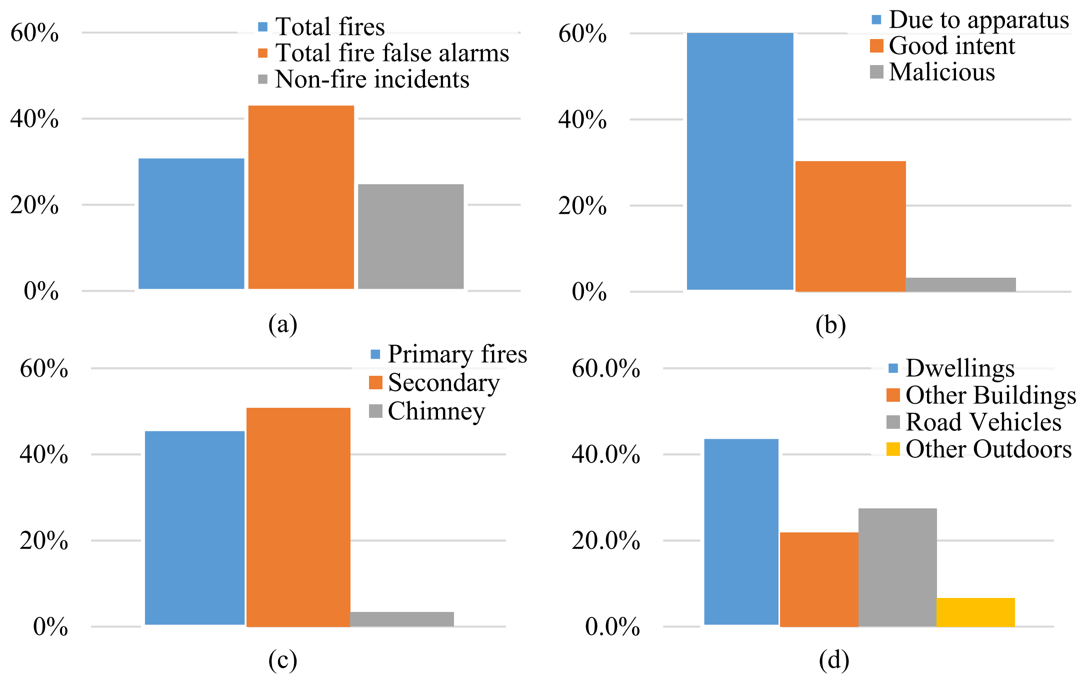


Figure 36: Total (a) incidents, (b) fire false alarms, (c) fire incidents and (d) primary fires, England

These incidents are divided into three categories and the related percentages are reported: 31.2% of total fires, 43.5% of fire false alarms and 25.2% of non-fire incidents (Figure 36 (a)). If only fire false alarms (215,826 incidents) are investigated, 66.6% is due to apparatus, 30.3% are good intents and 3.2% are malicious (Figure 36 (b)). The majority of fire false alarms are due to fire alarms not operating properly represented by 66.6% and this represents a relevant datum which leads to significant resource waste.

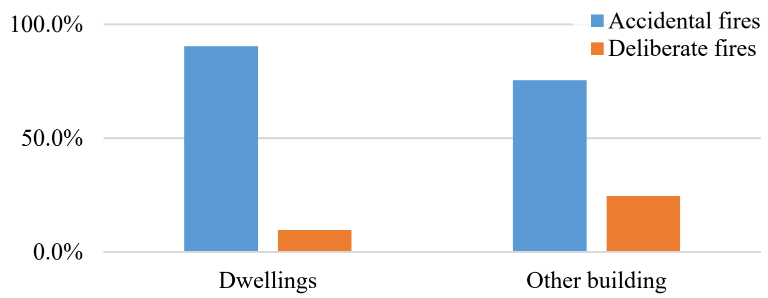
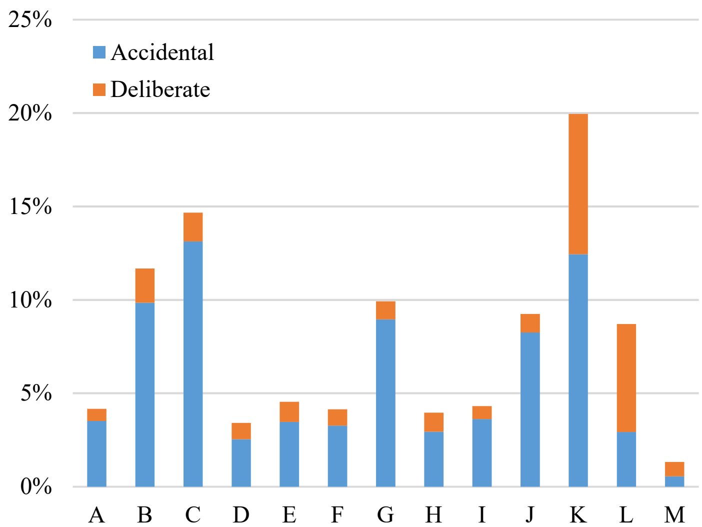


Figure 37: Accidental and deliberate fires in Dwellings and Other buildings, England

Total fires are consequently classified in primary fires and secondary fires. Primary fires respect the conditions that fires occur in a non-derelict building, involves fatalities, causalities and rescues and are attended by five or more pumping appliances (Home Office, 2016) while secondary fires include small outdoor fires not involving people or property, and chimney fires. Primary and secondary fires account for the 45.9% and 50.8% of the total fires, respectively (Figure 36 (c)). The classes of the primary fires (71,089 fires) are fires in *Dwellings* (31,329 fires – 44.1%), *Other buildings* (15,548 fires – 21.9%), road vehicle (19,464 fires – 27.4%) and other outdoor fires (4,748 fires – 6.7%) as shown in Figure 36 (d).

Accidental and deliberate fires in *Dwellings* and *Other buildings* are evaluated in Figure 37. For *Dwellings* fires, 90.4% are accidental while for *Other buildings* the value is reduced to 75.4%. Considering *Other building* fires, they are grouped according to 13 sub-classes and for each of them, accidental and deliberate fires are provided. The highest percentages of fires are reached in private non-residential buildings 20%, Industrial premises 14.7% and Retail premises 11.7%. Usually, the major component of the total fires in *Other buildings* is given by accidental fires where deliberate ones never exceed 2% except for 7.5% in Private non-residential and the 5.8% in Other public buildings and services (Figure 38).



A. Offices and call centres;
B. Retail premises;
C. Industrial premises;
D. Agricultural premises;
E. Hospitals and medical care;
F. Education premises;
G. Food and drink premises;
H. Entertainment, culture and sport;
I. Hotels, boarding houses, hostels;
J. Communal living;
K. Private non-residential buildings;
L. Other public buildings and services;
M. Unspecified

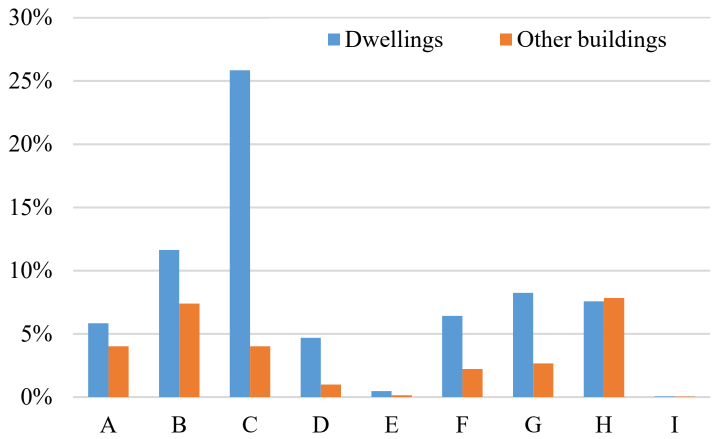
Figure 38: Accidental and deliberate fires in Other buildings, England

4.1.2 Fire causes

The data of the England fire statistics of 2014/2015 are summarized in the Statistical Bulletin 08/16 (Gaught et al., 2016) and present the causes of accidental fires for *Dwellings* (28,310 fires) and *Other buildings* (15,547 fires) with a total of 43,857 fire incidents. The fields recorded for the fire causes are subdivided into four distinct areas: cause of the fire, ignition source, material first ignited, and material mainly responsible for the development of the fire.

In *Dwellings*, the major accidental fire incidents are given by 25.8% misuse of equipment or appliances, 11.6% faulty appliances and leads and 8.2% placing articles too close to the heat.

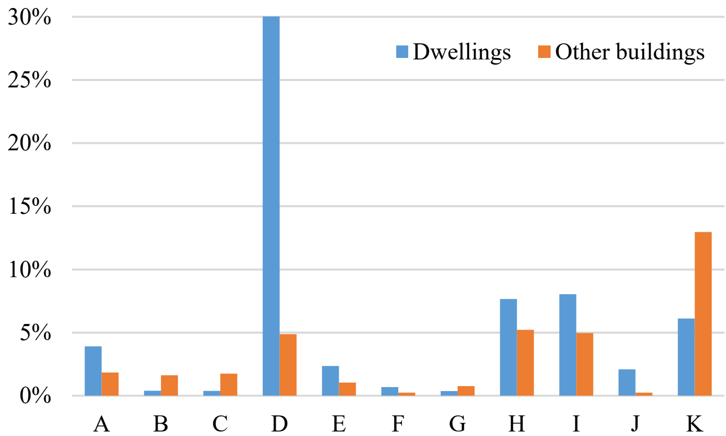
In *Other buildings*, the main cause is due for 7.4% to faulty appliances and leads, for 4% to both faulty fuel supplies and misuse of equipment or appliances. The class of other accidental causes assumes an average of 7.7% in both properties (Figure 39).



A. Faulty fuel supplies;
B. Faulty appliances and leads;
C. Misuse of equipment or appliances;
D. Chip/fat pan fires;
E. Playing with fire;
F. Careless handling of fire or hot substances;
G. Placing articles too close to heat;
H. Other accidental;
I. Unspecified

Figure 39: Causes of accidental fires for Dwellings and Other buildings, England

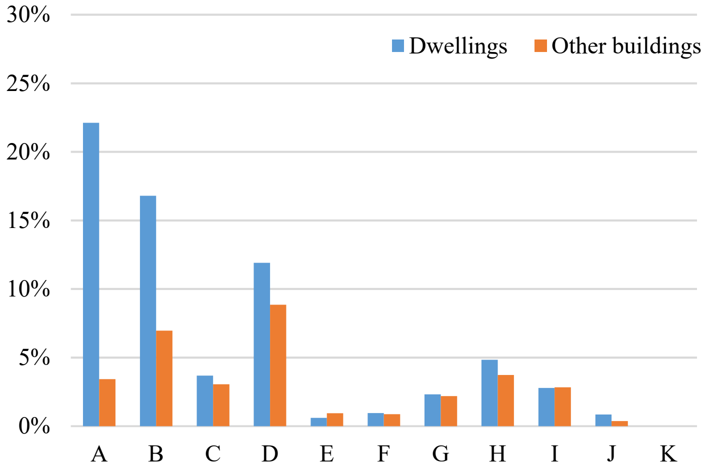
The sources of ignition considering accidental fires assume the highest values in cooking appliances 32.6%-4.9%, electrical distribution 7.7%-5.2% and other electrical appliances with 8% and 5% in *Dwellings* and *Other Buildings*, respectively. Other or unspecified source of ignition assume 13% in *Other buildings* and 6.1% in *Dwellings* while the other classes are lower than 5% (Figure 40).



A. Smokers' materials;
B. Cigarette lighters;
C. Matches;
D. Cooking appliances;
E. Space heating appliances;
F. Central and water heating appliances;
G. Blowlamps, welding & cutting equipment;
H. Electrical distribution;
I. Other electrical appliances;
J. Candles;
K. Other / Unspecified

Figure 40: Source of ignition accidental fires for Dwellings and Other building, England

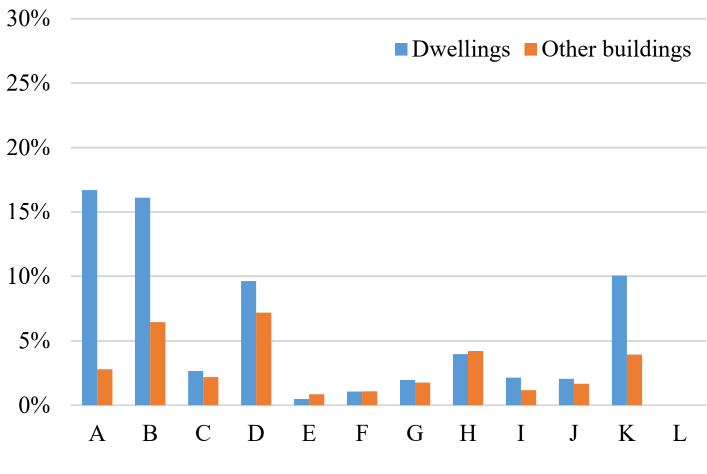
The fire statistics in England considers for the evaluation of the material or item first ignited the total fire incidents for *Dwellings* and *Other buildings*. As shown in Figure 41, the material or items first ignited are represented by food with 22.1%-3.4%, textiles, upholstery and furnishings with 16.8%-7% and structure and fittings with 11.9%-8.8% of the total fires respectively in *Dwellings* and *Other buildings* (Figure 41).



A. Food;
B. Textiles, upholstery and furnishings;
C. Paper, cardboard;
D. Structure and fittings;
E. Agricultural and forestry product;
F. Explosive Gases & Chemicals;
G. Rubbish/ Waste/ Recycling;
H. Other materials;
I. Not known;
J. None;
K. Unspecified

Figure 41: Material or item first ignited for total fires in Dwellings and Other buildings, England

There are analogies in the classifications of item and material first ignited and material mainly responsible for the development of fire. Both present similar classes and the estimates are obtained considering the total number of fire incidents. Again, the three classes with the highest percentages for *Dwellings* and *Other buildings* are those of food (16.7%-2.8%), textiles, upholstery and furnishings (16.1%-6.4%) and structure and fittings (9.6%-7.2%) as presented in Figure 42. In particular, when structure and fittings are analysed, they have been divided in internal and external and the internal ones are usually the responsible for the fire developments in both *Dwellings* and *Other buildings* with the 80.9% and 75.2%. It is, therefore, possible to affirm that generally the item first ignited coincides with the one mainly responsible for fire growth.

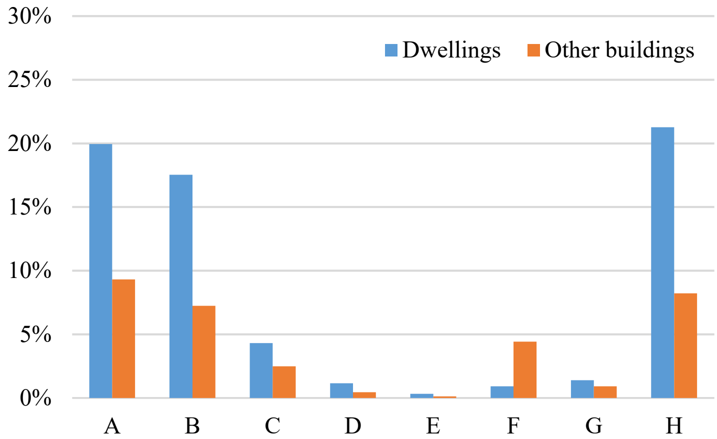


A. Food;
B. Textiles, upholstery and furnishings;
C. Paper, cardboard;
D. Structure and fittings;
E. Agricultural and forestry product;
F. Explosive Gases & Chemicals;
G. Rubbish/ Waste/Recycling;
H. Other materials;
I. Other;
J. Not known;
K. None;
L. Unspecified

Figure 42: Material mainly responsible for the development of fire in Dwellings and Other buildings, England

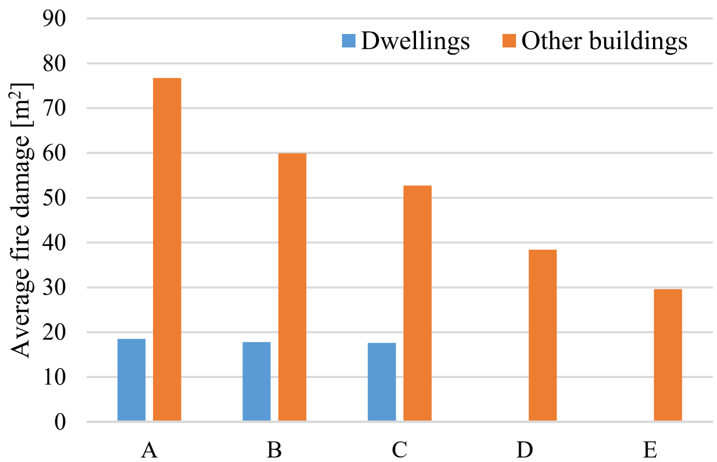
4.1.3 Fire growth and consequences

The data related to the fire growth are described by the recorded fire spread and according to eight classes going from fire limited to the item first ignited to fire affecting the whole building or roof. Moreover, a class where no fire damage occurred is also considered. As described in Figure 43, if the total number of fires is considered, the events appear to be limited to the item first ignited (20%-9.3%) and room of origin (17.5%-7.2%) in *Dwellings* and *Other buildings*, respectively. The class of fire affecting the whole buildings is equal to 4.4% in *Other buildings* while it is almost negligible for *Dwellings*. No fire damage is recorded for 21.3% in *Dwellings* and 8.2% in *Other buildings* showing a high number of fires causing negligible damage.



A. Limited to item 1st ignited;
B. Limited to room of origin;
C. Limited to floor of origin;
D. Limited to 2 floors;
E. Affecting more than 2 floors;
F. Whole building;
G. Roofs and roof spaces;
H. No fire damage

Figure 43: Spread of fire in Dwellings and Other buildings, England



A. Average;
B. Buildings excluding 10,000+ m^2;
C. Buildings excluding 5,000+ m^2;
D. Buildings excluding 2,000+ m^2;
E. Buildings excluding 1,000+ m^2

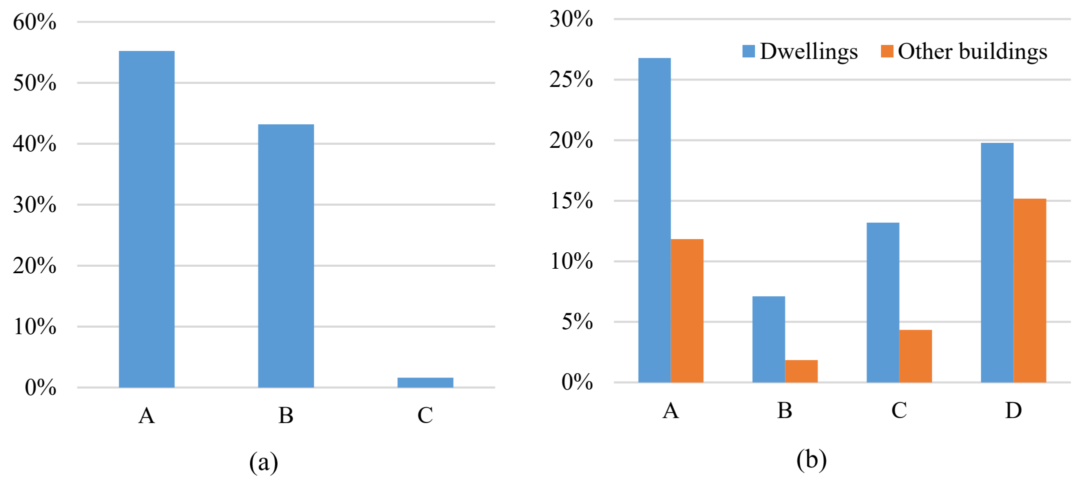
Figure 44: Average area of fire damage [m^2] in Dwellings and Other Buildings, England

For the quantification of damage, the average area of fire damage in m^2 is larger in *Other buildings* with 76.7 m^2 than in *Dwellings* 18.5 m^2. In *Other buildings*, classes consider buildings excluding more than 10,000, 5,000, 2,000 and 1,000 m^2 reducing the area from 59.9, 52.7, 38.4 and 29.6 m², respectively. For *Dwellings*, only buildings excluding more than 10,000 and 5,000 m² are considered with a small variation from 17.8 to 17.6 m² (Figure 44).

Only fire damage is quantified, without information on heat, smoke and water damage. It is important to highlight that no financial losses are provided by the Home Office but an evaluation is developed by the research of this thesis based on the newly released datasets explained in section 5.6.2 adopting the BVD formula (International Code Council, 2017) used in the USA fire statistics.

4.1.4 Fire safety measures

The fire statistics data published by the Home Office in 2014/2015 include only information for smoke alarms with no explanations about the performances of automatic extinguishing systems. In the data available, it is affirmed that 88% of households own working smoke alarms without specifying in which property types.

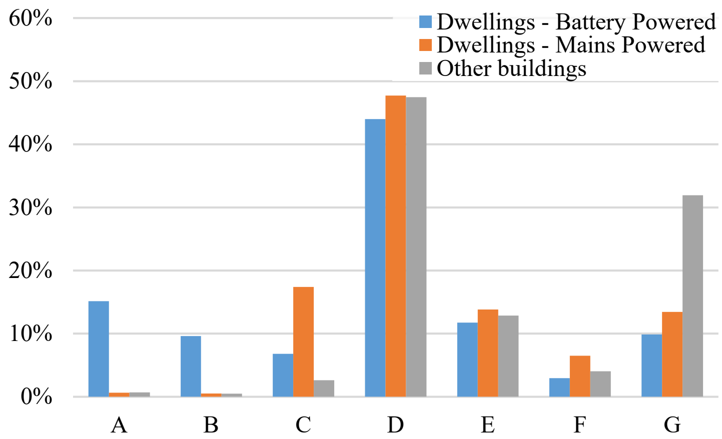


A. Battery powered;
B. Mains powered;
C. Other

A. Present, operated and raised the alarm;
B. Present, operated but did not raise the alarm;
C. Present but did not operate;
D. Absent

Figure 45: (a) Types of smoke alarm failures and (b) presence and operation of smoke alarms in Dwellings and Other buildings, England

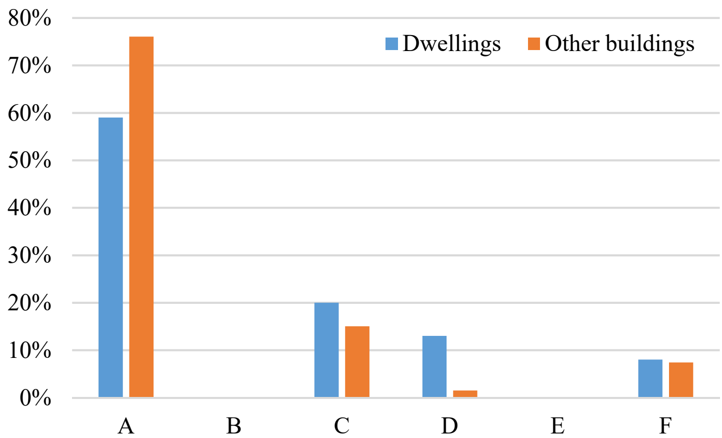
Failures are mainly showed by smoke alarms powered with battery with 55.2% followed by those mains powered with 43.2%. The class of other types is lower than 2%. However, in these statistics, a distinction between the property types is not specified as shown in Figure 45 (a). Presence and operation in *Dwellings* and *Other buildings* are described in Figure 45 (b). When the total number of fires is considered, 26.8%-11.8% are given when the smoke alarms were presented, operated and raised the alarm but 13.2%-4.3% are assumed when they were present but did not operate in *Dwellings* and *Other buildings*, respectively. Therefore, it is difficult to provide a general comment about the beneficial effects of their installation in buildings. Smoke alarms were absent for the 19.8% of fires in *Dwellings* and 15.2% in *Other buildings*.



A. Missing Battery;
B. Battery failure/flat;
C. Other act preventing alarm from operating;
D. Fire products did not reach detector(s);
E. Poor siting of detector(s);
F. Faulty system/ incorrectly installed;
G. Other

Figure 46: Reasons when smoke alarms did not operate in Dwellings and Other buildings, England

The reasons why smoke alarms did not operate or did not raise the alarm are explained in Figure 46 and Figure 47, respectively. However, in these two cases, only percentages for *Dwellings* with smoke alarms battery and mains powered, and *Other buildings* are available without the related total number of incidents. Starting with the description of Figure 46, data for the non-operation of smoke alarms seem to be concentrated in class related to fire products not reaching the detectors (44%-47.7%-47.5%) followed by the one of the poor siting of detectors (11.7%-13.8%-12.8%) in *Dwellings* battery powered and mains powered and *Other buildings*. For *Dwellings* with smoke alarms battery powered, the battery is missing for 15.1% and flat for 9.6%. When mains powered are investigated, 17.4% is reached when other act prevented alarm from operating in *Dwellings* and *Other buildings,* there is 31.9% for other reasons not specified.



A. Person raised the alarm before system operated;
B. Poor siting of detectors meant person raised alarm;
C. No person in earshot;
D. Occupants failed to respond;
E. Faulty system including incorrectly installed;
F. Other

Figure 47: Reasons when smoke alarms did not raise the alarm in Dwellings and Other buildings, England

When smoke alarms did not raise the alarms, valuable percentages are missing for the classes of poor siting of detectors meant person raised alarm and faulty system including incorrectly installed. However, for the other classes of Figure 47, peaks are assumed when the person raised the alarm before the system operated for 59% in *Dwellings* and 76% in *Other buildings*.

4.1.5 Fire response

The response time measures "the minutes and part minutes taken from the time of the call to the time of arrival at the scene of the first vehicle" (Home Office, 2017a). In Figure 48 and Figure 49, the total number of primary fires and the related response time is reported from 1994-95 to 2014-15 (Department for Communities and Local Government, 2015). If the trend in the total number of primary fires is evaluated, it shows an increase from 153,420 fires in 1994-95 till a maximum of 185,339 fires in 2001-02 after which a decreasing trend appears reaching 52,121 fires in 2014-15 (Figure 48).

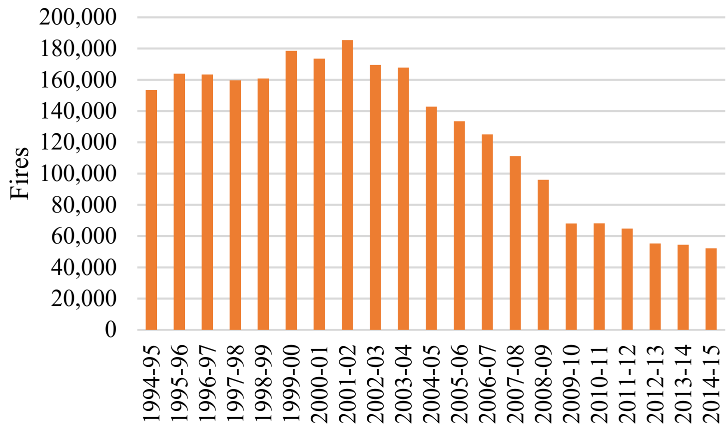


Figure 48: Primary fires number of incidents from 1994 to 2015, England

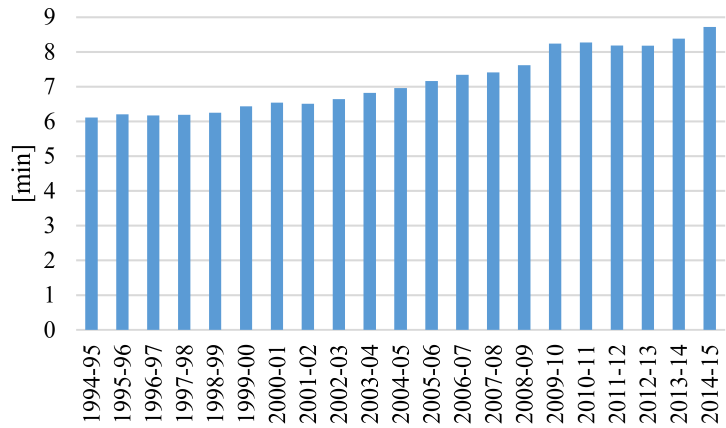


Figure 49: Primary fires response time [min] from 1994 to 2015, England

If the total number of fires assumes its minimum value in 2014-15, for the response time an opposite tendency is present with an increase from 6.1 minutes in 1994-95 to 8.7 minutes in 2014-15 (Figure 49). The difference in average response times between 2008-09 and 2009-10 is over half a minute. This is due to the discontinuity caused by shifting from a paper-based to a more comprehensive online data collection tool in 2009. Comparison over this time should be considered carefully (Department for Communities and Local Government, 2015).

In the English fire statistics for 2014/15, it is affirmed that the average response time is equal to 7.7 minutes in *Dwellings* and 8.5 minutes in *Other buildings*. Details about the fire service time of attendance are classified in 1 min bands in Figure 50. Peaks are reached from 5 to 8 minutes with the highest percentage of 11.6% in *Dwellings* and 5.3% in *Other buildings* from 6 to 7 minutes. After 10 minutes response, firefighters have usually already reached the place of the fire scene and started the rescue operations. This is the reason why trends for the two property types are less than 2% and tend to the null value after 11 minutes.

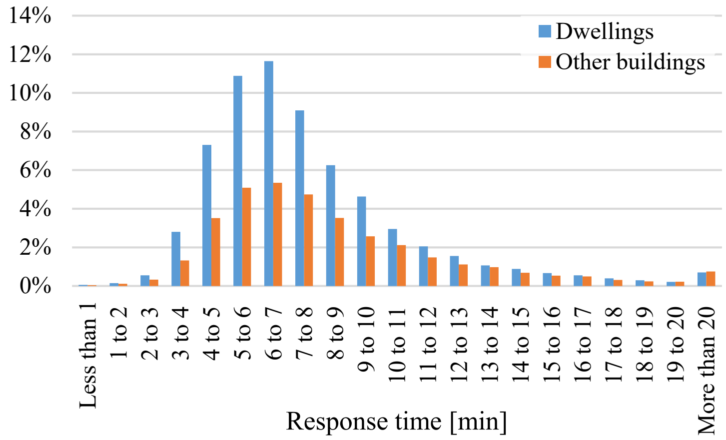


Figure 50: Incidents by 1-minute response bands in Dwellings and Other buildings, England

Further analyses about the response time in England and its implication on life safety and property protection are provided in Chapter 5 where several property types are evaluated according to fatality-casualty rates, fire spread and area damage.

4.1.6 Summary of key English statistics

The data of English statistics of 2014/15 demonstrate that amongst the calls received by the fire brigades, 31.2% are total fires, 43.5% are fire false alarms and 25.2% are non-fire incidents. Moreover, the total fire false alarms are mainly due to apparatus for 66.6% of cases. Fire incidents are mainly accidental with non-negligible deliberate fires in private non-residential buildings and other public buildings and services.

Fire causes are attributable to faulty of fuel supplies (5.8%-4%), faulty of appliances and leads (11.6%-7.4%) and misuse of equipment's or appliances (25.8%-4%); however, relevant percentages are represented by careless handling of fire or hot substances (6.4%-2.2%) and placing articles too close to heat (8.2%-7.2%) in *Dwellings* and *Other buildings*, respectively. The principal source of ignition is assumed by cooking appliances in *Dwellings* (32.6%) and electrical distribution in *Other buildings* (5.2%). Item and material mainly responsible for the development of fire are given by food; textiles, upholstery and fittings and paper and cardboard. Furthermore, fire is generally limited to the room of origin and the average area damage in *Dwellings* is equal to 18.5 m^2 which is approximately 4 times less than in *Other buildings* (76.7 m^2). Finally, alarms seem to be present, operated and raised alarm in 26.8% in *Dwellings* and 11.8% in *Other buildings* while present but did not operate in 13.2% and 4.3%, respectively. Information about sprinklers is not available in the data of 2014/15 but provided in the datasets published by the Home Office in 2017 which will be described and adopted in Chapter 5 and Chapter 6. The number of incidents has decreased from 1994/95 to 2014/15 while the response time of fire brigades increased. The average attendance time of fire service is evaluated as 7.7 minutes in *Dwellings* and 8.5 minutes in *Other buildings*.

4.2 Fire statistics in the USA (NFIRS)

The investigations on the USA statistics are developed considering two datasets from the US Fire Administration: one based on two publicly available datasets and the other one specifically provided for the development of this research.

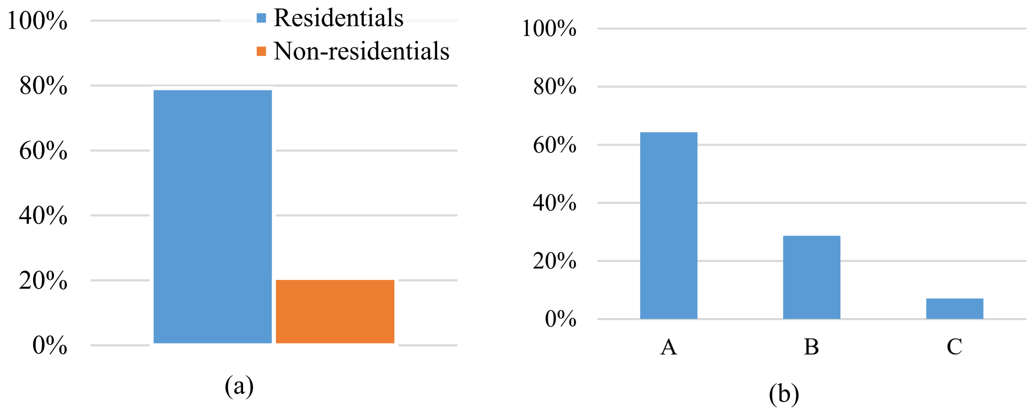
The two publicly available datasets from the US Fire Administration are named ‘residential non-residential fire loss estimates from 2003 to 2017’ for the analysis of the number of fires, property types and causes, and the ‘US fire loss data sets from 2005 to 2014’ for the economic losses. A total of 379,500 fires and US $6,9000,300 are related to *Residential* buildings while 99,500 fires and $2,628,000,000 in *Non-residential* ones in 2014.

The US Fire Administration provided the Fire Incidents dataset of 2014 for a complete evaluation of the building fires and fire characteristics (area of origin, item first ignited, cause of ignition, etc.) considering 596,521 fires in 2014. The information of the datasets examined is explained below according to fire causes, growth and consequences, safety measures and response as for section 4.1. However, there could be a different nomenclature adopted than the one for the English statistics for example *Residential* and *Non-residential buildings* instead of Dwellings and Other buildings.

4.2.1 Spreadsheets US Fire Administration

4.2.1.1 Fire incidents

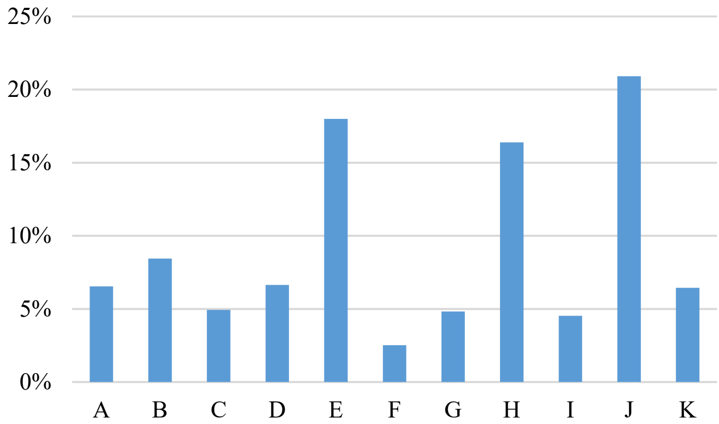
In 2014, the total number of fires was equal to 479,000 considering 79.2% in *Residential* and 20.8% in *Non-residential buildings* as shown in Figure 51 (a). When *Residential* fires are investigated, 64.3% are found in One and two families, 28.6% in Multifamily and 7.1% in Other residential buildings (Figure 51 (b)).



A. One and two families; **B**. Multifamily; **C**. Other

Figure 51: (a) Residential and Non-residential fires and (b) fires in Residential properties, USA

In *Non-residential* fires, the highest percentages are assumed in Stores and Offices 18%, Storage 16.4% and Outside or special property buildings 20.9%. The other property types are less than 10% where Eating and drinking establishment assumes 8.4%, Institutional buildings 6.6% and Assembly 6.5% (Figure 52). The class of Retail premises was the one showing a high number of fires also in England as shown in Figure 38.



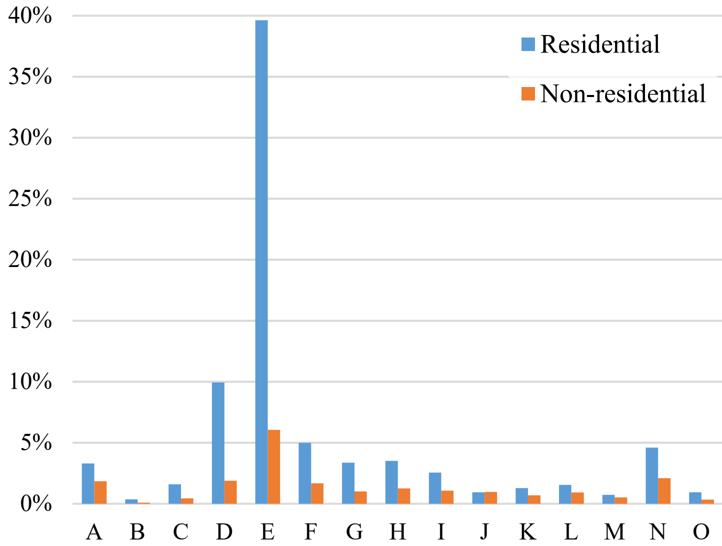
A. Assembly;
B. Eating & Drinking Establishments;
C. Educational;
D. Institutional;
E. Stores and Offices;
F. Basic Industry;
G. Manufacturing;
H. Storage;
I. Detached Garages;
J. Outside or Special Property Buildings;
K. Other

Figure 52: Fire in Non-residential buildings, USA

4.2.1.2 Fire causes

When fire causes are investigated considering the total number of fires, the main reason for fire incidents is due to cooking 39.6%-6.1% followed by heating 9.9%-1.9% and electrical malfunction with 5%-1.7% and other unintentional 4.6%-2.1%, respectively in *Residential* and *Non-residential* buildings. In *Non-residential* buildings, intentional causes present 1.8% while all the other classes are less than this value as represented in Figure 53.

As described in section 4.1.2, despite the different countries, it appears that in England and the USA the main causes for fire incidents are due to the malfunction of electrical appliances or due to heat sources as cooking or placing the item too close to the heat.



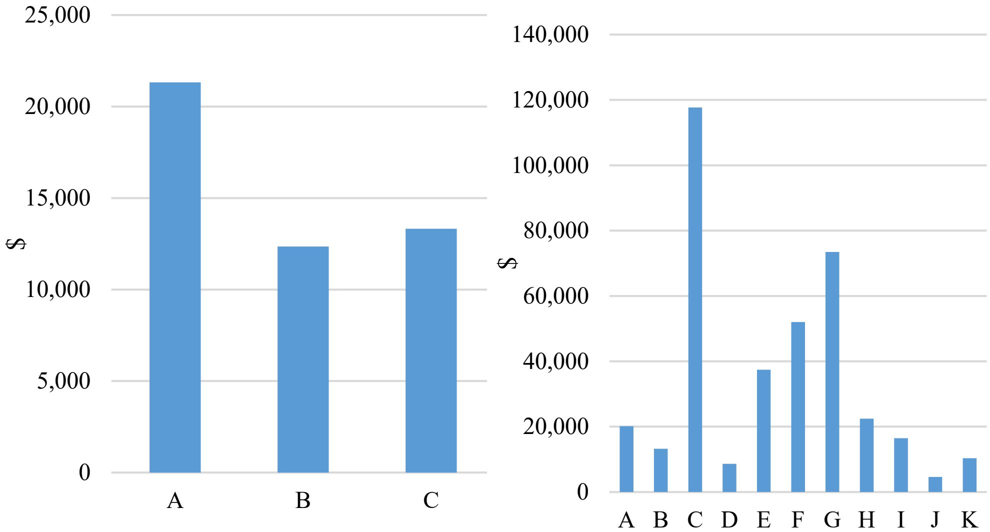
A. Intentional;
B. Playing with Heat Source;
C. Smoking;
D. Heating;
E. Cooking;
F. Electrical Malfunction;
G. Appliances;
H. Open Flame;
I. Other Heat;
J. Other Equipment;
K. Natural;
L. Exposure;
M. Equipment Malfunction;
N. Other Unintentional, Careless;
O. Cause Under Investigation

Figure 53: Fire causes in Residential and Non-residential fires, USA

4.2.1.3 Fire financial losses

A total fire loss of $6,900,300,000 in *Residential* and $2,628,000,000 *Non-residential* buildings are recorded in 2014 by the US Fire Administration. Considering now the sub-properties, an estimate is evaluated by this research calculating the dollar loss per fire. In *Residential* buildings, a fire incident costs $21,317 in One and two families, $12,346 in Multifamily and $13,321 in Other residential buildings (Figure 54 (a)) with an average of $15,661 per fire. In Figure 54 (b), when *Non-residential* buildings are analysed, fire incidents reach $117,673 in Educational buildings, $73,438 in Manufacturing, $52,000 in Basic Industry and $37,397 in Stores and offices. The remaining properties have values approximately less than $20,000 and more comparable to those found in *Residential* buildings.

Dollar losses per fire per cause are also evaluated for *Residential* and *Non-residential* buildings. In particular, according to Figure 55, the peaks of economic losses per fire for *Residential* buildings are in different causes than the one for *Non-residential* buildings. The highest values of $79,410 are assumed for natural causes and $79,978 for cause under investigation followed by $53,324 of exposure and $49,914 of other unintentional causes in *Residential*. Despite the high number of fires explained in Figure 53 due to cooking, heating and electrical malfunction, in the analysis of the dollar loss per fire per cause, they have values less than \$40,000. In *Non-residential* buildings, \$160,950 are due to open flame and \$55,600 to equipment malfunction. A value of \$89,688 is also available for cause under investigation and this is similar to the one in *Residential* buildings (Figure 55).



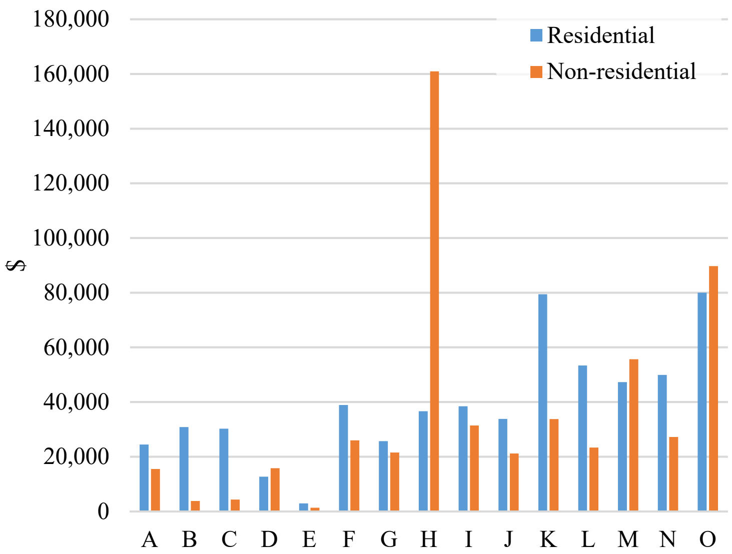
(a)

(b)

A. One and two-family; **B**. Multifamily; **C**. Other

A. Assembly; **B**. Eating & Drinking Establishments; **C**. Educational; **D**. Institutional; **E**. Stores and Offices; **F**. Basic Industry; **G**. Manufacturing; **H**. Storage; **I**. Detached Garages; **J**. Outside or Special Property Buildings; **K**. Other

Figure 54: Dollar loss per fire in (a) Residential and (b) Non-residential buildings, USA



A. Intentional;
B. Playing with Heat Source;
C. Smoking;
D. Heating;
E. Cooking;
F. Electrical Malfunction;
G. Appliances;
H. Open Flame;
I. Other Heat;
J. Other Equipment;
K. Natural;
L. Exposure;
M. Equipment Malfunction;
N. Other Unintentional, Careless;
O. Cause Under Investigation

Figure 55: Dollar loss per fire per cause in Residential and Non-residential buildings, USA

Once the fire incidents, causes and economic losses have been evaluated based on the data of the spreadsheets, the fire incidents dataset provided by the US Fire Administration is deeply analysed in the following section.

4.2.2 Database US Fire Administration

The dataset provided by the US Fire Administration for 2014 is composed of different parts such as *Basic Incidents* in which all calls attended are reported, *Fire Incidents* where only fire incidents and their description are present and *Cause* with the reasons for fires. However, fire causes and financial losses have been already studied in section 4.2.1.2 and section 4.2.1.3, therefore, the analysis is now focused on the explanations of fire incidents, other causes (i.e. factors contributing to ignition), growth and consequences, safety measures and response.

4.2.2.1 Fire incidents

If in the dataset the part of *Fire Incidents* is investigated, a total of 596,521 rows are available where each of them indicates a fire event attended. The percentages of fires in *Residential* and *Non-residential* buildings are different than those expressed in section 4.2.1.1. In this case, there is a 48.6% in *Residential* and 51.4% in *Non-residential* where *Non-residential* building fires appear to have a higher frequency than the one evaluated before in Figure 51.

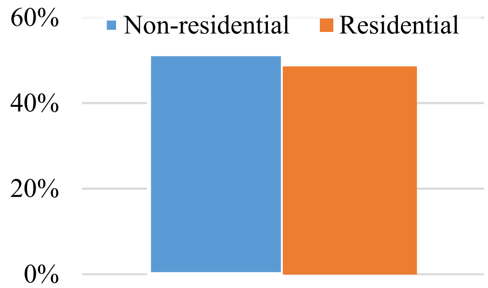
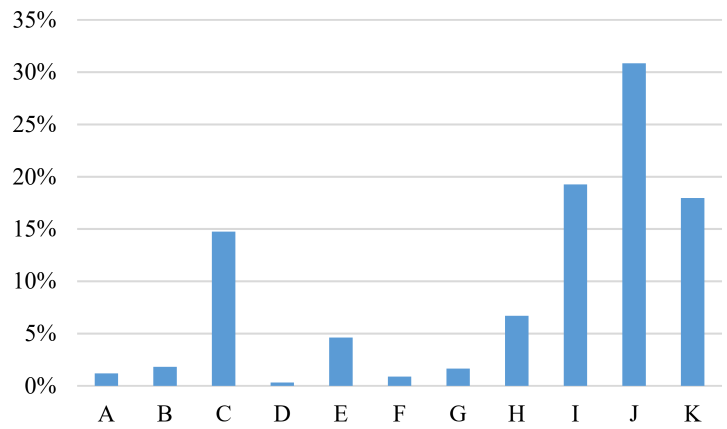


Figure 56: Fires in Residential and Non-residential buildings, USA

In this dataset, there is also information about the structure type and based on the data available, 88.7% of fire occurred in enclosed buildings including subways terminals and underground buildings. The remaining 11.3% is distributed in all the other structure types for example, open structures, fixed or mobile structures or open platform. Moreover, it is affirmed that 83% of fires are in a structure in normal use. This class includes properties closed or unoccupied for a brief time as business closed over the weekend or a house when no occupants are present. Furthermore, 4.1% and 5.5% are found when the structure is vacant and secure and vacant and unsecured, respectively.

Other fields related to the characteristics of the building are the number of storeys above and below the ground floor, the main floor length and width, the total ft^2 of the building and the storey of fire origin. The data describing the building dimensions are used in Chapter 5 when the fire frequency is evaluated according to the total floor area of the building.

The area of origin described in Figure 57, has the four highest peaks for 30.8% in Outside areas, 19.3% in Transportation, vehicles areas, 18% in Other area of fire origin and finally 14.8% in Function areas. Other relevant percentages are 6.7% in Structural areas and 4.6% in Storage areas while the remaining areas of origin are less than 2% (Figure 57).



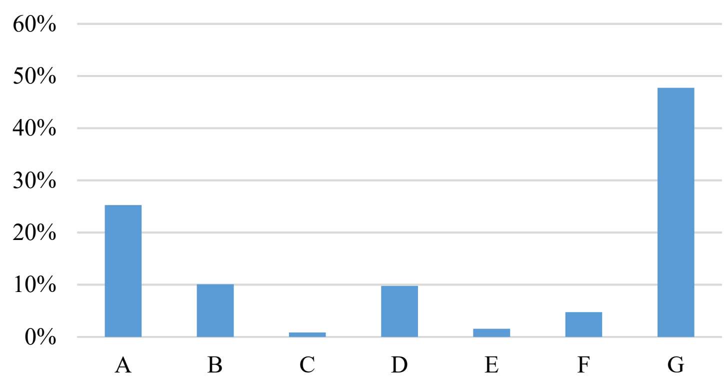
A. Means of egress;
B. Assembly or Sales Areas;
C. Function Areas;
D. Technical Processing Areas;
E. Storage Areas;
F. Service Areas;
G. Service or Equipment Areas;
H. Structural Areas;
I. Transportation, Vehicle Areas;
J. Outside Areas;
K. Other Area of Fire Origin

Figure 57: Area of origin, USA

4.2.2.2 Fire causes

Fire causes have already been described in section 4.2.1.2; this section is focused on the evaluation of other factors causing the fire incidents.

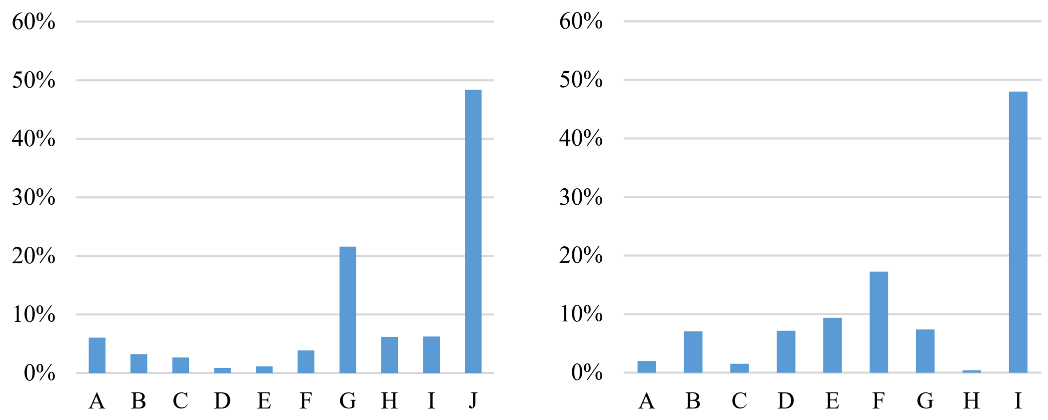
The major heat sources that caused ignition are represented by Operating equipment with 25.3%, hot or smouldering objects with 10.1% and other open flame or smoking materials with 9.8%. Moreover, the class of other heat sources not present in the classification of Figure 58 present the 47.7% implying that further classes should be added to better investigate this value and its sub-components.



A. Operating Equipment;
B. Hot or Smoldering Object;
C. Explosives, Fireworks;
D. Other Open Flame or Smoking Materials;
E. Chemical, Natural Heat Sources;
F. Heat Spread From Another Fire. Excludes operating equipment;
G. Other heat Source

Figure 58: Heat source, USA

While for English statistics, the item and material first ignited have the same classification as described in section 4.1.2, in the NFIRS of USA they present different classes and this is the reason why they are described separately. The item first ignited is usually given for the 21.6% by organic materials, for 6.2% by General materials (this is subdivided into two classes including different items) and for 6% by structural components and finish. The other classes are all below 4% as shown in Figure 59 (a). For the material first ignited, 17.3% is associated with wood or paper, 9.4% with a natural product, 7.4% with fabric, textiles, fur, 7.1% with plastic and 7% with flammable or combustible liquids (Figure 59 (b)). However, the class of Others represents the highest peak of 48.3% and 48% for item and material first ignited, respectively.



(a)

A. Structural Component, Finish; **B**. Furniture, Utensils. Includes built-in furniture; **C**. Soft Goods, Wearing Apparel; **D**. Adornment, Recreational Material, Signs; **E**. Storage Supplies; **F**. Liquids, Piping, Filters; **G**. Organic Materials; **H**. General Materials; **I**. General Materials Continued; **J**. Other Items First Ignited

(b)

A. Flammable Gas; **B**. Flammable or Combustible Liquid; **C**. Volatile Solid or Chemical; **D**. Plastic; **E**. Natural Product; **F**. Wood or Paper – Processed; **G**. Fabric, Textiles, Fur; **H**. Material Compounded With Oil; **I**. Other Material

Figure 59: (a) Item and (b) material first ignited, USA

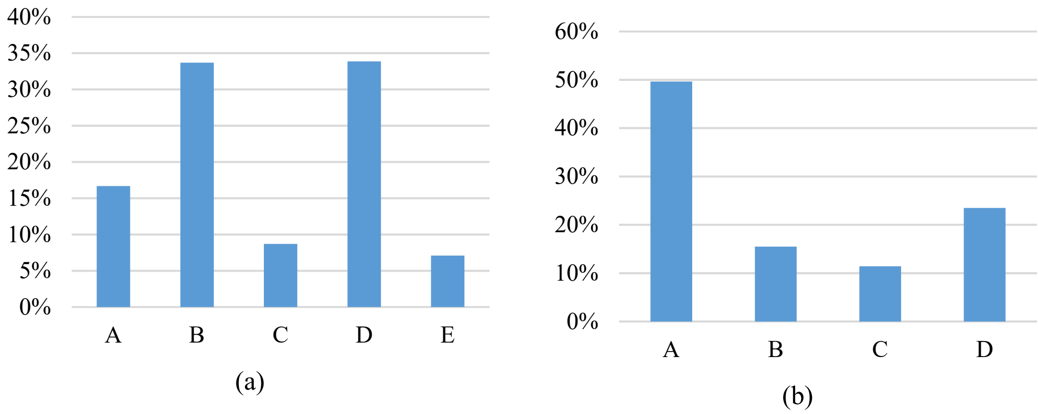
4.2.2.3 Fire growth and consequences

For the factors contributing to the fire growth, item and material contributing most to flame are recoded in the dataset of the NFIRS. However, since they can coincide in some cases with the item or material first ignited already discussed in section 4.2.2.2, this section is focused on how the fire affects the buildings in terms of spread and building damage.

For the fire spread, the classes are classified from fire confined to object of origin to the one of fire confined to the building of origin and fire which spreads beyond the building of origin as described in Figure 60 (a). The spread of fire is confined for the 16.7% to the object of origin, for the 33.7% to the room of origin, for the 8.7% to the floor of origin, for 33.9%

confined to the building of origin and for the 7.0% of incidents fires spread beyond the building of origin. Figure 60 (a) shows that compartmentation works well. However, a significant number of fires affecting area outside the room of origin are recorded.

The data for area damaged is divided into four categories: Minor, Significantly, Heavy and Extreme damaged. For each class, the fire departments must specify the number of floors subjected to fire according to Minor (1% to 24%), Significantly (25% to 49%), Heavy (50% to 74%) and Extreme (75% to 100%) damage.



A. Confined to object of origin; **B**. Confined to room of origin; **C**. Confined to floor of origin; **D**. Confined to building of origin; **E**. Beyond building of origin

A. Minor; **B**. Significantly; **C**. Heavy; **D**. Extreme

Figure 60: (a) Fire spread and (b) building damage, USA

The percentage of fires within these four categories are described in Figure 60 (b) with 49.6% of all the fires causing Minor damage, 15.5% Significantly damage, 11.4% Heavy damage and 23.5% Extreme damage which also represents the second-highest peak.

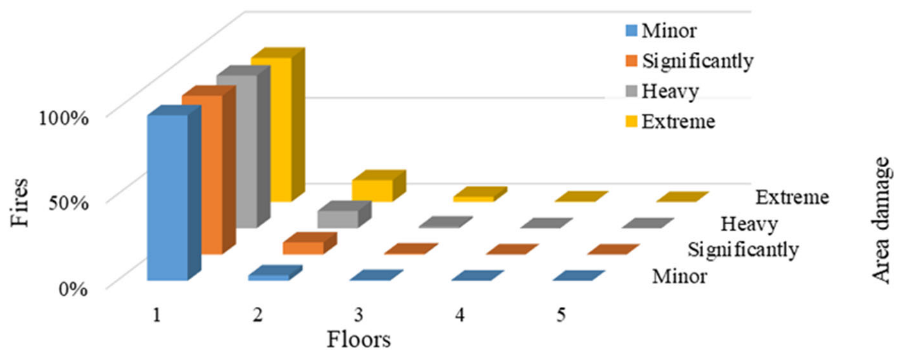
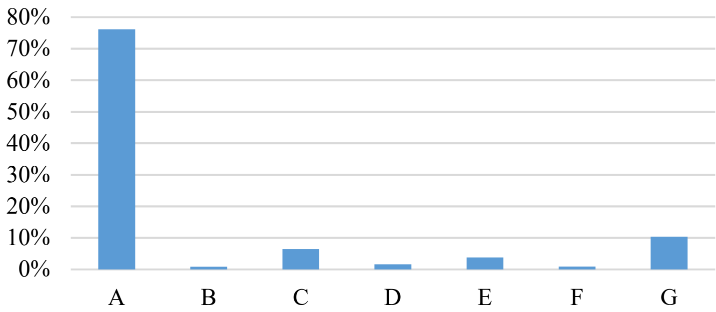


Figure 61: Area damage and number of floors, USA

Figure 61 plots the same data in relation to the number of floors affected by the fires and shows that from 83.9% (Extreme damage) to 96.3% (Minor damage) of these fires are limited to a single floor. The values drastically decrease from 3.2% (Minor damage) to 12.7% (Extreme damage) when fires involved two floors with values, in general, less than 3% when 3 floors are affected. Therefore, there is a high number of fires with various percentages of damage which usually creates damage on one floor while a small number of large fires causes spread in two or more floors.

4.2.2.4 Fire safety measures - detectors

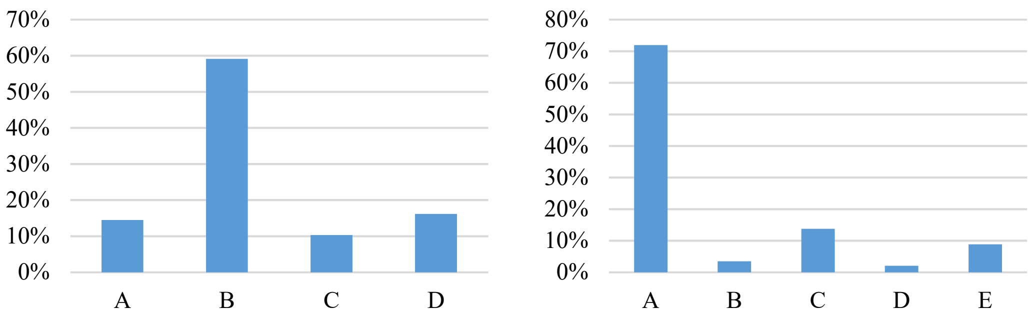
For the analysis of fire safety measures, information about detectors and automatic extinguishing systems are available in the dataset provided by the US fire administration while in English statistics only the one for alarms are present.



A. Smoke;
B. Heat;
C. Combination smoke and heat in a single unit;
D. Sprinkler, water flow detection;
E. More than one type present;
F. Detector type, other;
G. Undetermined

Figure 62: Types of detectors, USA

In the USA, detectors are present for 39.7%, absent for 32.9% and undetermined for 27.5% of total fires. The most common detector type is the smoke detector for 76.1% while the remaining types are composed of 6.4% of detector combined for smoke and heat unit, 3.8% when more than one type is installed and 10.3% for undetermined detectors as shown in Figure 62. For the detector power supply classes, the most relevant are given by the 38.8% of battery only, 25.7% of hardwire with battery backup and 10.8% with hardwire only. The other power supplies are less than 3% with 19% in the case of undetermined supply.



(a)

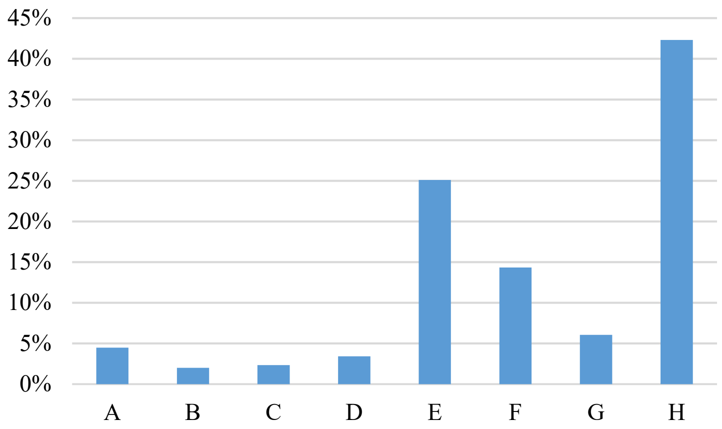
A. Fire too small to activate detector; **B**. Detector operated; **C**. Detector failed to operate; **D**. Undetermined

(b)

A. Detector alerted occupants, occupants responded; **B**. Detector alerted occupants, occupants failed to respond; **C**. There were no occupants; **D**. Detector failed to alert occupants; **E**. Undetermined

Figure 63: Detector (a) operation and (b) effectiveness, USA

In the USA, almost 60% of detectors operated while 10.3% failed to operate. In the 14.5% of cases, fires were too small to activate detectors and in the 16.1% of fires, the detector operation is undetermined as shown in Figure 63 (a). Figure 63 (b) presents the detector effectiveness and in 71.9% of fires, detectors alerted occupants and occupants responded. There is a 13.8% in which no occupants were present at the time of the incident. Again, the class of undetermined effectiveness assumes 8.8%. In general, detectors seem to operate and efficiently alert occupants but reasons for failure are described in Figure 64.



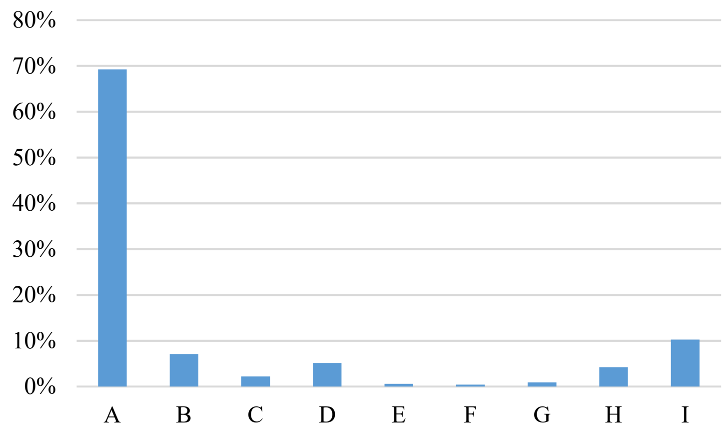
A. Power failure or hardwired detector shut off or disconnected;
B. Improper installation or placement of detector;
C. Defective detector;
D. Lack of maintenance. Includes not cleaning;
E. Battery missing or disconnected;
F. Battery discharged or dead;
G. Detector failure reason, other;
H. Undetermined

Figure 64: Reasons for detector failures, USA

The main reason for the detector failure is due for 25.1% to battery missing or disconnected, followed by 14.3% of battery discharged or dead and 6.1% for other detector failure reasons. In 4.5% of fires, the detector failed because there was a power failure or hardwire shut off or disconnected (Figure 64). As for the previous analyses, the reasons for failures are undetermined for 42.3% of cases and this aspect needs further investigation.

4.2.2.5 Fire safety measures – automatic extinguishing systems

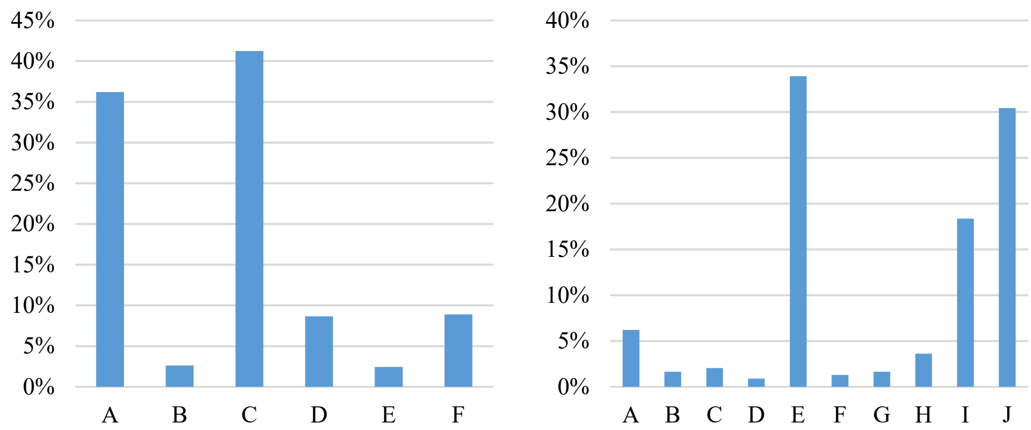
According to the data present in the analysed dataset, the automatic extinguishing systems are mainly absent for 83.6% and present for 6.9% of fires. Being present only for 6.9%, data on automatic extinguishing systems need to be considered carefully. The USA NFIRS records also the case in which partial systems are present (0.3%) while the remaining 9.1% are for undetermined automatic extinguishing systems. The main type of automatic extinguishing systems is represented by 69.2% of wet-pipe sprinkles systems and the second and third class are given for 7.1% and 5.1% by dry-pipe sprinklers and dry-chemical systems, respectively. Special hazard systems are described by 4.2% and other undetermined types by 10.3% (Figure 65). Therefore, based on the data of Figure 65, this research named the automatic extinguishing systems as sprinklers because they represent the major type in case of their presence.



A. Wet-pipe sprinkler system; **B**. Dry-pipe sprinkler system; **C**. Other sprinkler system. Includes deluge sprinkler systems and pre-action sprinkler systems; **D**. Dry chemical system; **E**. Foam system; **F**. Halogen-type system. Includes non-halogenated suppression systems that operate on the same principle; **G**. Carbon dioxide system; **H**. Special hazard system, other; **I**. Undetermined

Figure 65: Types of automatic extinguishing systems, USA

For the automatic extinguishing systems operation and effectiveness are described within the same field. As shown in Figure 66 (a), there is a 36.2% of fires in which the system operated and was effective and 41.2% in which fire was too small to activate the systems. The system did not operate for 8.6% and the operation is undetermined for 8.9%. The classes of the system operated and was not effective, or other operations assume 2.6% and 2.4%, respectively.



(a)

A. The system operated and was effective; **B**. System operated and was not effective; **C**. Fire too small to activate the system; **D**. System did not operate; **E**. Operation of AES, other; **F**. Undetermined

(b)

A. System shut off; **B**. Not enough agent discharged to control the fire; **C**. Agent discharged, but did not reach the fire; **D**. Inappropriate system for the type of fire; **E**. Fire not in area protected by the system; **F**. System components damaged; **G**. Lack of maintenance. Includes corrosion or heads painted; **H**. Manual intervention defeated the system; **I**. Reason system not effective, other; **J**. Undetermined

Figure 66: Automatic extinguishing system (a) operation and (b) failure, USA

The main reasons for the failure of automatic extinguishing systems are due for 33.9% when a fire was not in the area protected by the system followed by the 18.3% when the system was not effective, 6.2% for system shut off and 3.6% when a manual intervention defeated the systems. Again, in 30.4% of cases, the reasons for the system failure are undetermined. The data related to cases of fires located in a different area than the one equipped with automatic extinguishing systems, clearly introduce questions if fire safety design considers real fire scenarios occurring in the current building stock with the presence of various safety measures. This aspect is deeply analysed in Chapter 6.

4.2.2.6 Fire response

In the USA, time of alarm, arrival, controlled and last unit cleared are recorded according to the actual month, day, year, and time of the day. Their definitions in the NFIRS are the following: '*alarm time* when the alarm was received by the fire department, *arrival time* when the first responding unit arrived at the incident scene, the *controlled time* when the fire is brought under control or the incident is stabilized and does not require additional emergency resources where "Controlled" is the time when the incident commander determines that the fire will not escape from its containment perimeter, and the *last unit cleared time* when the last unit cleared the incident scene' (USFA, 2014). Response time is usually defined as the time from the alarm to the first unit of fire brigade arriving at the fire scene and it is introduced here to create a direct comparison with the one obtained for England. In the dataset of *Basic Incidents*, this information can be evaluated considering the *time of alarm* and the *time of arrival* of firefighters. The values obtained are those related only to fire incidents without considering hazardous conditions, service or good intent calls. The datasets contain 557,260 incidents where only fire calls are analysed.

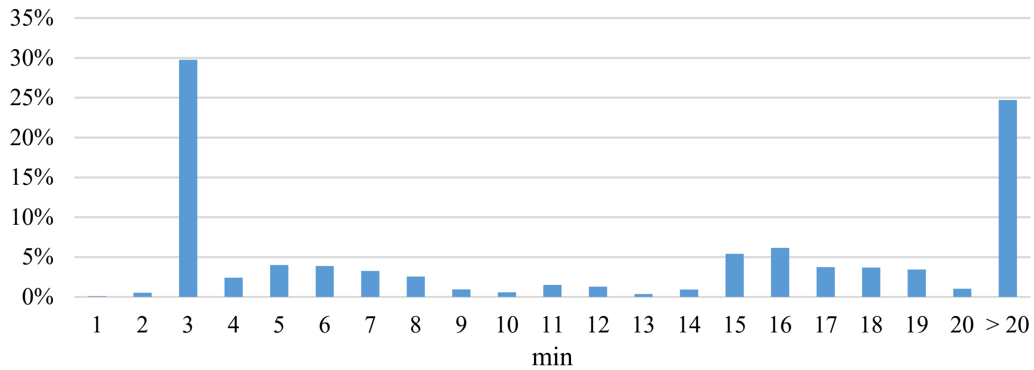


Figure 67: Response time [min], USA

The response time in the USA is described in Figure 67 and it seems that usually, fire brigades arrive in 3 minutes after the call for 29.7% of cases. For the other values, approximately 4% of fire incidents present 5 and 6 minutes. After 8 minutes, the fire brigades have usually reached the scene and started the rescue operations. However, for 15-16 minutes attendance, there is 5.4% and 6.1% of fires recorded and a peak of 24.7% is present for a time greater than

20 minutes. Excluding 20 minutes, the average response time is of 8.5 minutes which is comparable to those found in England of 8.7 minutes in 2014-15 explained in section 4.1.5.

If the time from alarm to the last unit cleared is investigated, the peaks are usually reached between 11-15 minutes with 10.1% and 16-20 minutes with 9.2%. When the time from arrival to last unite cleared is considered, the highest values are assumed in lower time ranges as 6-10 minutes for 12.5% and 11-15 minutes for 10.3% of incidents. However, both fields present an average of 28% for a time greater than 60 minutes (Figure 68).

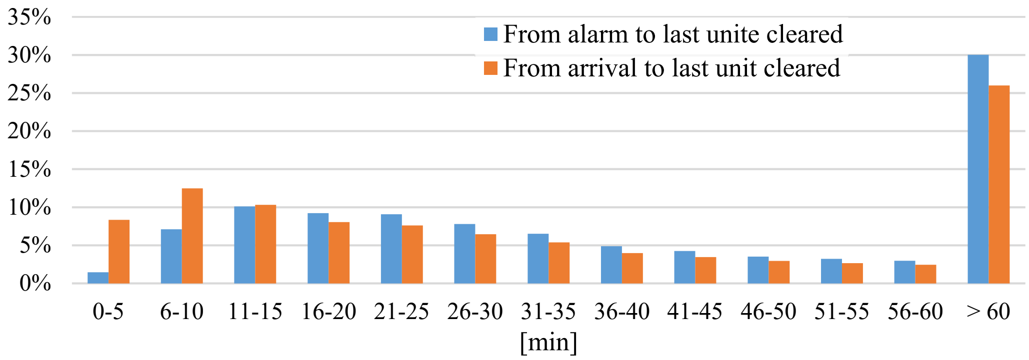


Figure 68: Time from alarm to the last unit cleared and from arrival to last unite cleared, USA

4.2.3 Summary of key USA statistics

In the USA publicly available datasets, 79.2% of fires affect *Residential* and 20.8% *Non-residential* buildings where the main property types are represented by Stores and Offices, Storage and Outside and special properties. The main fire causes for *Residential* and *Non-residential* buildings are attributable to cooking, heating and electrical malfunction. Total fire losses of $6,900,300,000 and $2,628,000,000 are recorded in *Residential* and *Non-residential* buildings with a peak of $21,317 losses per fire in One and two-family and $117,673 losses per fire in Educational buildings.

In the USA databases provided by the US Fire Administration, 48.6% of fires are recorded in *Non-residential* buildings. The heat source is mainly represented by operating equipment (25.3%) and other heat source (47.7%), the item ignited by organic material (21.6%) and the material ignited by wood or paper (17.3%). However, for item and material ignited a 48% is recorded for the class of others.

Fire spread is predominately confined to the object of origin (16.7%) and room of origin (33.7%) with a 33.9% assumed for fire confined to the building of origin. The class of damage is usually represented by Minor damage (49.6%) followed by Significantly damage (15.5%) with a non-negligible 23.5% of Extreme damage. The fire usually affects only the floor origin.

Smoke detectors are the type present for more than 75% of cases where detectors appear to operate in 59.1%, alerted occupants and occupants responded in 71.9%. The main detector failures are given by battery missing or disconnected and battery discharged or dead with 42.3% of cases undetermined. The automatic extinguishing systems mainly collected are wet pipe sprinkler system (69.2%) where the system operation and effectiveness are recorded for 36.2% with a 41.2% in which fire was too small to activate the system. The reason for the automatic extinguishing system failure is due to the presence of fire in an area not protected by the system (33.9%) with 18.3% and 30.4% for other reasons for the system not effective and undetermined failures, respectively. Fire response time presents a peak in 3 minutes (29.7%) and 15-16 minutes (approximately 6%). However, the average response time is estimated at 8.5 minutes.

4.3 Analogies and differences in English and USA fire statistics

The analyses developed for the two fire statistics present a similar collection system for the information recorded in which the fire brigades fill in an online form in the aftermath of an event. The data are merged in a dataset which is updated and yearly released by the Home Office or kindly provided by the US Fire Administration. While at the beginning of the research of this thesis, only specific spreadsheets were published by the Home Office, from 2017 it is possible to access two datasets for *Dwellings* and *Other buildings*. However, not all fire safety fields are publicly available.

The first difference found in the USA statistics is its geographical focus which considers the entire country while for the Home Office only England. Moreover, the nomenclature adopted in the various classifications is different (e.g. *Dwellings* and *Other buildings* in England, *Residential* and *Non-residential* buildings in the USA).

Causes and description of the fire incident including the area of origin, item and material first ignited or affecting the fire, are present and similar in the two fire statistics while a significant difference is provided when the consequences of fire are estimated. Despite the fire spread classes seem to approximately have a correspondence in the two fire statistics, the damage is recorded as fire and total damage in England and fire damage in the USA. Furthermore, the damage is quantified as m^2 of area damage in England and percentage of property damage according to four damage classes (Minor, Significantly, Heavy, Extreme) in the USA.

Concerning safety systems, the dataset of the Home Office adopted in section 4.1.4 presents only information about smoke detectors while the one published in 2017 contains also data on the presence of sprinklers and will be investigated in Chapter 5. In the USA, detectors are classified according to type, operation, effectiveness and failure while the automatic extinguishing systems to type, operation and failure.

Finally, in the USA a methodology to evaluate the direct economic losses due to fire incidents in various property types is provided while in England no evaluation of financial losses are present.

It is, therefore, clear how improvements could be applied in each of the two fire statistics and that the best approach could be to establish a unified methodology of collection of the data based on a universal glossary. It would be also very important to understand the variables necessary for a correct fire safety design which are currently missing in the statistics. For example, it would be relevant to insert a field related to the fuel load, construction techniques and building materials and presence of façade.

In section 4.3.1, key comparisons of the two fire statistics examined in this Chapter are introduced and in section 4.3.2 the IRS is studied considering possible changes and improvements in the data collection based on the previous analysis of the USA datasets and fire safety fields currently missing.

4.3.1 Key comparisons of fire statistics

In the two fire statistics, *Residential* fire incidents assume 66.8% and 79.2% while in *Non-residential* 33.2% and 20.8% in England and the USA, respectively as described in Figure 69. In England, fire causes are attributable to faulty of fuel supplies, faulty of appliances and leads and misuse of equipment's or appliances and similar causes have been found in the USA with heating, electrical malfunction and cooking.

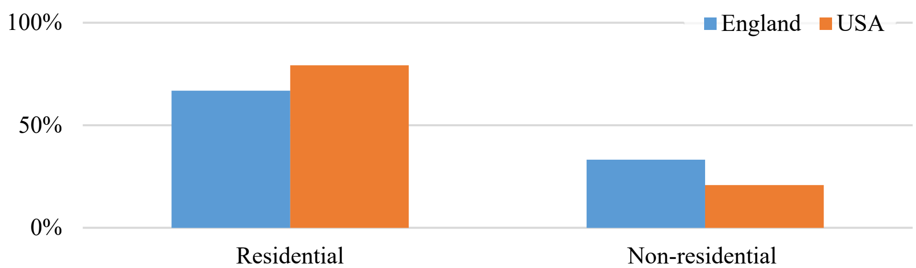


Figure 69: Fire incidents in Residential and Non-residential buildings in England and the USA

The principal source of ignition is given by cooking appliances in *Dwellings* and electrical distribution in *Other buildings* in England; operating equipment and other heat source in the USA. Item first ignited for the development of fire are given by food; textiles, upholstery and fittings and paper and cardboard in England and results are similar for the material mainly responsible for the fire in England. In the USA, due to a different classification, the item ignited is mainly represented by organic material and the material ignited by wood or paper.

The fire spread in the two fire statistics appears generally limited to the room of origin with average area damage in *Dwellings* of 18.5 m^2 and *Other buildings* of 76.7 m^2 in England. In the USA, the four classes of damage assume the following percentages: Minor damage 49.6%, Significantly damage 15.5%, Heavy damage 11.4% and Extreme damage 23.5%. Therefore, the two statistics represent a high number of small damage fire and a small number of high damage ones. Financial fire losses are available only in the USA where total fire losses of US $6,900,300,000 and $2,628,000,000 are recorded in *Residential* and *Non-residential* buildings.

Finally, when alarms are examined they appear to be mainly present, operating and raising alarm during the fire incident in 26.8% in *Dwellings* and 11.8% in *Other buildings* in England. In the USA, smoke detectors are recorded for more than 75% of cases and detectors operate in 59.1%, alerted occupants and occupants responded in 71.9% of fire incidents. The data when alarms are present but did not operate are 13.2% and 4.3% in *Dwellings* and *Other buildings* in England, respectively. In the USA, detector failures are attributable to battery missing or disconnected and battery discharged or dead with 42.3% of cases undetermined.

Information about sprinklers is not available in England statistics while in the USA, the main type recorded in the statistics is wet pipe sprinkler system where operation and effectiveness are recorded for 36.2%. The reason for the automatic extinguishing system failure in the USA is represented by the presence of fire in an area not protected by the system with 33.9% and this arises potential questions about the location of sprinklers.

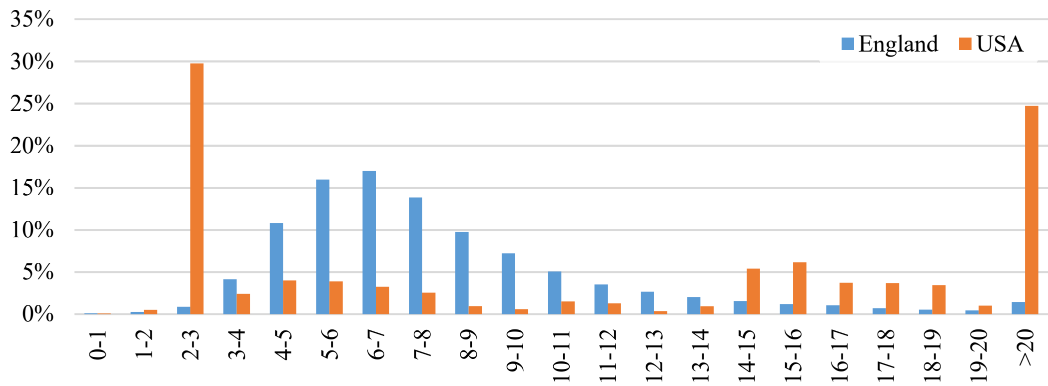


Figure 70: Response time in England and USA for 1-minute bands in 2014-2015

The average attendance time of fire service is evaluated as 7.7 minutes in *Dwellings* and 8.5 minutes in *Other buildings* in England, and 8.5 minutes in the USA. If the response time of the two fire statistics is investigated according to 1-minute bands up to more than 20 minutes, the three highest peaks are reached in 6-7 minutes (17%), 5-6 minutes (16%) and 7-8 minutes (13.8%) in England, and 2-3 minutes (29.7%), 15-16 minutes (6.1) and over 20 minutes (24.7%) in the USA as shown in Figure 70.

4.3.2 Possible changes in the Home Office IRS

Incident Reporting System (IRS) (Home Office, 2017a) has been introduced in section 2.3.2 and it is filled in by the fire departments after attending a fire event. The analysis developed in this section is focused on the building damage after the fire and fire safety aspects related to fire incidents. It highlights the possible changes or additions that could be applied to the IRS form to fulfil the constantly increasing demand in understanding the response of buildings subjected to a real fire, cover the missing aspects related to structural fire safety and better formulate some questions, which could be investigated more in detail. Below, some of the IRS questions (Q) are listed with the original number and section in the IRS and investigated to provide comments about possible improvements.

EVENT DESCRIPTION

Q 3.2 (What type of Property was involved?) is recorded for all incidents and specifies the property type in which the event occurred. The list considers both *Dwellings* and *Other buildings* and an improvement could be applied to insert an additional question to understand: a) the number of living units, and b) if the building is a mixed-use property. This would allow the designer to adopt appropriate building dimensions and consider the specific characteristics of various property types.

Q 8.18 (Was there any special method of building construction involved?) describes if new methods of building construction are adapted to the property affected. The full list reported in Table 18 comprehends the major fields of interest in the whole international fire safety community. Essential is the addition of further investigations according to the specified special method of construction chosen as the answer. For example, the description of the location, dimensions, materials and construction method used in claddings and sandwich panels present in the façade as well as the insulation and the presence of fire breakage to avoid fire spread are necessary to gain a comprehensive view of modern techniques. For timber buildings, the orientation, glue used to attach the different layers and the thickness consumed by the charring layer need to be inserted in the form. Moreover, an additional class for Table 18 could be the presence of photovoltaic panels and their fire response. Therefore, structural materials of the building should always be reported to facilitate the analysis of the fire incident to those who have only access to fire statistics datasets and were not present during the investigation.

Finally, the analysis of fire incidents in specific construction type could determine the evaluation of common problems or understanding of performances.

Table 18: Special methods of building construction list in the IRS

Special Building construction involved	
None	Thatch
Timber framed	Large single storey retail premises
Cladding	Other
Sandwich panels	Not known
Atria	

Q 5.1 (Did the fire have multiple seats?) is fundamental for fire description because it could reveal arson fires but needs to be specified more in detail since it is not clear if the IRS form is referred to the principal fire location or the whole building. Other questions could be added to understand where were fire seats and the description of each of them if some of them merged and the presence of travelling fires enabling the evaluation of the fire front and direction necessary in computational analysis about fire dynamics.

FIRE SAFETY MEASURES

If fire safety regulations are applicable (Q 5.5 – Do fire safety regulations apply? (Consider if the incident is not located in domestic premises)), the questions about means of escape (Q 5.6 – Means of Escape) and compartmentation (Q 5.7 - Compartmentation) appear. It would be interesting to estimate the dimension of the compartment in m^2 and also its openings or ventilation systems where applicable to apply fire modelling techniques to evaluate fire development in combination with the information related to the fire ignition and causes.

In the Additional Information section, questions related to the presence of alarms are present while those for safety systems are in Action. It would be suggested to reorganize the IRS form in a way that the alarms and safety systems fields are in the same section since they could be considered as belonging to the safety devices class. Even if operation and failure reasons are fundamental to verify the correct appliance installation, the effectiveness of fire detection in alerting occupants could be added to understand the impact of active fire safety measures on alerting people (e.g. Detector alerted occupants, occupants responded; Detector alerted occupants, occupants failed to respond; There were no occupants; Detector failed to alert occupants; Undetermined – as in the NFIRS (USFA, 2014)). This information is also necessary to optimize evacuation strategies and understand human response to fire.

DAMAGE

The damage section includes the description of fire consequences according to four aspects: flame, heat, smoke and water damage. Usually, the IRS questions are formulated grouping flame-heat damage and heat-smoke damage (no fire). In Q 8.19 (Was there heat and/or smoke damage only (no fire)?), the answer of the fire department is only binary (Yes-No). The damage quantification in m^2, once the fire is extinguished, is considered according to flame-heat damage in Q 8.24 (What is the horizontal area damaged by flame and/or heat in m^2 (at the stop)?) and total damage in Q 8.25 (What is the total horizontal area damaged (by flame and/or heat and/or smoke and/or water etc.) in m^2 at stop?). It would be better to estimate the m^2 of each damage type and consequently evaluate the total value. This would enable the evaluation of the damage caused by fire and by the fire brigade intervention to extinguish the fire. Even if the spread involving more than two floors is specified, the horizontal or total area damage does not explain the damage in each floor and it is important to add additional questions related to the damage evaluation in each building part affected by the fire to understand not only the horizontal spread but also the vertical one.

Q. 8.27 (What is the approximate size of the floor of the fire's origin (sq. m.)?), Q 8.28 (Number of floors/decks above ground level/main deck (e.g. 1 for a bungalow)), Q 8.29 (Number of floors/decks below ground level/main deck (e.g. 1)) and Q 8.30 (Which floor/deck did the fire originate upon?) should always be available in the public dataset released by the Home Office to facilitate researchers scaling the fire in relation to the total building area or floor size.

Other aspects that could be covered are those investigating if fire damage affects only building contents or structure for the damage evaluation, building accessibility for the analysis of the access points for fire brigades and escape routes for occupants and firefighters, structural stability for the description of building performance in fire conditions and considerations about the need of reparations or demolition for the estimate of fire financial losses and potential life continuity after the incident. Furthermore, academic research could be oriented to create a damage scale, able to qualify the structural damage depending on different severity classes (i.e. Minor; Significantly; Heavy; Extreme as in the NFIRS (USFA, 2014)).

Although the presence of hazardous materials is investigated, the approximated fuel load evaluation, at least in the room of origin, is important to understand the spread and evolution of fire in the aftermath of the incident by fire safety engineers who are consequently able to apply heat transfer models and time-temperature curves once this information is known. The evaluation of fuel loads after the fire incident is very difficult so households or occupants could be involved in the explanations of the furniture composition and items in the room of origin.

Q 8.21 (If any adjacent properties were affected at the time that you arrived, how far away were they?) and Q 8.22 (If any adjacent properties were affected at the stop, how far away were they (m)?) consider the spread of fire beyond the building of origin according to the distance of the building in m^2. It is not specified if the related buildings affected were more than one and the level of damage shown by each of them. It is important to highlight also these aspects to quantify the exact spread and specify the m^2 of fire, heat, water and smoke damage necessary for a correct fire investigation and analysis.

Another field of interest could be the analysis of potential travelling fires. This is partially already estimated thanks to Q 8.20 (What was the extent of flame and heat damage on arrival?) and Q 8.22 (What was the extent of flame and heat damage (at the stop)?) only considering the spread and not the area damaged. The extension of these questions would enable the definition of the quantification of fire damage and spread fundamental in the analysis of fire dynamics, material response and structural performances of elements exposed to fires.

HAZARDOUS MATERIAL

Q 5.18 (Were there any hazardous materials involved?), Q 5.19 (What hazardous materials were involved?), Q 5.20 (What is the Emergency Action Code for this material?) and Q 5.21 (What is the Hazard Identification Number for this material?) describe if and what kind of hazardous materials were involved and the emergency actions are taken. As reported in the NFIRS (USFA, 2014), other aspects could be described such as the container type and capacity, the estimated amount of hazardous material released, the physical state when released, the area affected and the one evacuated, the cause and factors contributing to release. All these fields improve future mitigation actions that could be taken into account and could be used in combination with the description of the fuel loads present in the buildings and in particular in the room of origin.

WILDLAND FIRE

Even if the focus of this research is about the structural behaviour during fire incidents, some comments are provided about the questions related to wildfires as Q 5.17 (If grassland/woodland, was the fire in an area designated as a National Park?), Q 8.35a (Please specify the fire damage area in hectares?) and Q 8.36 (Did the fire occur in an area designated as a National Park?). An improvement could be to fully describe the fire incident in this area reporting also weather information (especially wind direction), the primary crops burned, fire elevation, relative position on slope and rate of speed as deeply evaluated in the NFIRS (USFA, 2014) to support experts in wildfires to create strategic plans to prevent the fire spread, protect plant and animal life, and learn from previous incidents.

FINANCIAL LOSSES

No fire financial loss questions are available in the IRS while they could provide a fundamental parameter that quantifies the intensity and effects of fires. If considering the NFIRS (USFA, 2014), the estimation of the direct financial losses due to fires are evaluated according to the Building Valuation Data (BVD) formula expressed in Eq. 1. The ft^2 construction costs per different property types are listed in the BVD but do not consider levels of damage (according to a developed damage scale) or types (flame, heat, smoke and water). The previous considerations could be parts of future works related to the economic fire impact on buildings. Indirect fire losses are usually not directly considered in the fire statistics of the various countries but they could explain not only fire consequences for families and business interruptions but also for society and governments as described in section 2.4.2. Moreover, their evaluation could support the effectiveness of buildings fire resilience assessments and prevention. People and companies involved in fire incidents should be contacted by groups in charge of the fire investigation after a couple of months from the incident and asked to answer surveys to assess fire impact on their lives and jobs and how governments and public organizations have helped them return to their normal habits. The evaluation of direct and indirect financial losses is fundamental in understanding the economic impact of fire incidents on families, business and society and could be used as a tool to support governments in the creation of supporting schemes for people affected by fire incidents to return to normal life in the shortest time possible.

In this Chapter, two fire statistics datasets of England and USA have been investigated to understand the fire safety variables available and information related to fire incidents. The data introduced in Chapter 4 will be adopted in the rest of the thesis. Chapter 4 provides an overall description of the current fire statistics and the data it is based on are then subsequently reprocessed in Chapter 5 and Chapter 6. In particular, Chapter 5 and Chapter 6 consider the USA datasets and the fields of the English statistics introduced in Chapter 4 as inputs for the analyses developed. The only aspect to highlight is that for the English statistics, an extended dataset and data covering a wider time range, kindly provided by the Home Office, are adopted in Chapter 5 and Chapter 6. While Chapter 5 assumes the data of Chapter 4 to evaluate fire frequency, consequences, response time and life safety and compare them with the trends of PD 7974-7:2003, Chapter 6 is focused on the evaluation of alarm and automatic extinguishing systems where the event trees are created for the English and USA statistics to evaluate the fire response of occupants and fire brigades for presence and absence of alarms.

Chapter 5. Evaluation of BS PD 7974-7:2003 based on USA and English statistics

"The probability of fire in a building can only be estimated from an examination of fire incidents in the past."

- R. Rutstein

5.1 Updates to BS PD 7974-7:2003 and databases adopted

As discussed in section 2.5, the data of British Standard PD 7974-7:2003 (BSI PD 7974-7, 2003) vary between 1966 to 1987 (except Table 2 with data from 1995) and could be no longer representative of the current situation regarding fire statistics. Therefore, in this Chapter, a critical evolution of the British Standard PD 7974-7:2003 (named herein as PD 7974-7) (BSI PD 7974-7, 2003) is developed based on English and USA statistics to recreate the PD 7974-7 Tables A.1, A.2, A.4, A.5, A.6, A.7, A.8, A.12, A.13 described in Table 12. In Table A.12, a methodology for the valuation of the financial losses is not provided and thus, they have been evaluated by the author applying the BVD formula of Eq. 1 to current English fire statistics to create the comparison. Instead, Table A.13 has been updated and expanded considering English statistics for the response time affecting fatalities, casualties, fire spread and area damaged. Tables A.3 and A.16 are not well specified in PD 7974-7:2003, and Table A.9 and A.15 are not objects of this thesis. Table A.14 describes the frequency distribution of the number of deaths. However, in the English statistics, fatalities and casualties are recorded in a combined field. Table A.17 presents some reliability data adopted in the design.

Description of the fire statistics analysed is provided in section 2.5.2. In particular, the research used for the USA statistics, the National Fire Incident Reporting System (NFIRS) (USFA, 2014) investigating approximately 600,000 fire incidents already introduced in section 2.3.3 and described in section 4.2 and applying the BVD formula of Eq. 1 to evaluate fire financial losses. As explained in section 2.3.2, in September 2017 a new database has been released for *Other building* fires dataset examining data from 2010/11 to 2016/17 including 121,558 fire incidents (Home Office, 2017b) which have been adopted for all the analyses of this Chapter except for the evaluation of fire frequency in relation to the total floor space of the building of Table A.1 of PD 7974-7:2003 due to the total floor area of the building not included in the published dataset. The Home Office kindly provided the author with an additional database with information about the building dimension. In the provided database, the data of 2014/15 have been considered cleaned of potential errors as entries in which the building room or floor of origin are equal to 0 m^2, the number of floors above or below ground/main level is recorded as 99 or 999, and fires where the fire damage is greater than the total damage reducing the dataset from 15,561 to 11,168 fire incidents. The datasets adopted are summarized in Table 5.

The Tables of PD 7974-7 have been updated based on English and USA statistics considering similarities and differences. The comparison between fire safety data of PD 7974-7:2003 and those of USA fire statistics (Manes & Rush, 2018) has been referenced in Annex B Table B.3

of the PD 7974-7 published in 2019 for the overall probability of a fire starting in various types of occupancy. Finally, the comparison between PD 7974-7:2003 and English fire statistics has been created in 2019 (Manes & Rush, 2020).

5.1.1 Building stocks in England and the USA

In order to recreate the fire frequency in Table A.1 and the overall probability of a fire starting in Table A.2 of PD 7974-7:2003 for various occupancy types with more updated fire safety data in Chapter 5, it is necessary to identify the total number of buildings at risk respectively in England and USA.

In the UK, the building stock for various property types according to specific total floor space has been examined based on the Valuation Office Agency (VOA) of the 2017 rating list compiled on April 2017 for England and Wales. The entries in the rating list include a rateable value with 80% supported by the regular site and building survey and 20% by specialised surveys or based on construction costs or annual accounts. Moreover, bulk class properties are recorded as a particular use of the property at the time of the valuation (Valuation Office Agency, 2016). The research has considered only data recorded as still valid and with a rateable value greater than zero and the bulk class buildings distributed according to specific total space.

In the USA, two datasets have been considered from the US Energy Information Administration (EIA) (U.S. Energy Information Administration, 2019b) namely:

- commercial buildings energy consumption survey (CBECS) (U.S. Energy Information Administration, 2019a), and
- manufacturing energy consumption survey (MECS) (U.S. Energy Information Administration, 2019c).

The two abovementioned databases are national sample surveys collecting the number of commercial and manufacturing buildings in the US stock with the related energy characteristics and energy usage data (consumption and expenditures). CBECS databases categorise buildings according to their total floor space and present the number of buildings within a banded range of total floor space from 1,001 ft^2 to over 500,000 ft^2. In the MECS databases, the average floor space per ft^2 is evaluated based on the average enclosed floor space per establishment divided by the average number of buildings onsite per establishment. The MECS values have been consequently reclassified to have a homogenous classification with the one available in the CBECS databases.

The most updated CBECS data from 2012 reports 5.6 million commercial buildings in the U.S. Moreover, it is stated that in commercial buildings at least half of the floor space is used for a purpose that is not residential, industrial, or agricultural such as traditional commercial buildings (stores, restaurants, warehouses, and office buildings), schools, hospitals, correctional institutions, and buildings used for religious worship. The Energy Information EIA used a stratified statistical sample of over 12,000 buildings completed surveys to represent the entire population of the sample. The sampling technique ensures that all types and sizes of commercial buildings have a chance to be selected where the energy consumption is highly related to the footage and the variance is minimized due to time and budget constraints.

The MECS sample size of 2014 includes approximately 15,000 establishments considered as a nationally representative sample of 97-98% of the manufacturing payroll. The EIA reports separate estimates of energy use for 21 3-digit industry subsectors, and 50 industry groups and industries according to the North American Industry Classification System (NAICS) (Executive office of the President & Office of Management and Budget, 2017).

In the analyses of section 5.3 for the fire frequency in various occupancy types, the assumption assumed is that the fire frequencies are represented in a point of the bands evaluated as an average of the total floor space for that band divided by the total number of buildings. This choice does not consider the average of the general floor space band but the average floor space of all the buildings attributable to that band. Certainly, this will influence the evaluation of the developed relationships.

The data of CBECS and MECS determining the number of non-residential buildings in the USA classified according to the different building sizes have been grouped according to the USA NFIRS classification to enable a direct comparison between numbers of fires per type of buildings according to the building size.

5.2 Overall probability of fire starting

Table A.2 of the PD 7974-7:2003 regards the overall probability of a fire starting in various occupancy types and it has been compared to 2014/15 English and the USA statistics considering the total number of fires divided by the total number of buildings at risk. The latter has been found in the VOA and the US Census Bureau. Table A.2 of PD 7974-7:2003 has been first updated based on the comparison between PD 7974-7 and USA statistics in 2018 (Manes & Rush, 2018) and fire probabilities found have been referenced in the new version of PD 7974-7 published in 2019. The analysis has been further developed in 2019 when the new released fire statistics datasets of the Home Office have been available (Manes & Rush, 2020). The updated values are shown in Table 19 for non-residential buildings and the classes are those presented in the PD 7974-7 with the exception for *Storage* in the USA and *Assembly non-residential* in English and USA where a comparison has not been possible.

Table 19: Table A.2 in PD 7974-7, USA and English statistics [fires·y^{-1}]

Occupancy types	PD 7974-7:2003	PD 7974-7:2019	USA	England
Industrial	4.4×10^{-2}	0.9×10^{-2}	1.121×10^{-2}	0.953×10^{-2}
Storage	1.3×10^{-2}	N/A	N/A	0.132×10^{-2}
Offices	0.62×10^{-2}	0.4×10^{-2}	0.423×10^{-2}	0.166×10^{-2}
Assembly entertainment	12×10^{-2}	0.7×10^{-2}	5.446×10^{-2}	0.868×10^{-2}
Assembly non-residential	2.0×10^{-2}	N/A	N/A	N/A
Hospitals	30×10^{-2}	2.6×10^{-2}	0.363×10^{-2}	5.856×10^{-2}
Schools	4.0×10^{-2}	1.4×10^{-2}	5.512×10^{-2}	1.362×10^{-2}

Frequencies in the PD 7974-7:2003 are in general always higher than those obtained from current fire statistics in particular for *Assembly entertainment* (12×10^{-2}) and *Hospitals* (30×10^{-2}). As shown in Table 19, PD 7974-7:2003 presents values for *Industrial* 4 times, *Assembly entertainment* approximately 2 times and *Hospitals* 5 times greater than the maximum value in the other two statistics. PD 7974-7:2003 underestimates the probability in *Schools* where in USA statistics 5.512×10^{-2} and England 1.362×10^{-2} are estimated (Table 19).

All the fire frequencies in the USA and English statistics are in the same order of magnitude with the exceptions of *Assembly entertainment* (5.446×10^{-2}) and *Schools* (5.512×10^{-2}) in USA and *Hospitals* (5.856×10^{-2}) in England which present higher peaks than the other classes.

In England, the probabilities of fire starting have slightly different values than those of PD 7974-7:2019 for two property types: *Offices* where, in PD 7974-7:2019, also includes retail premises and *Hospitals* where the new evaluation considers the *Other buildings* dataset not previously available. In general, trends appear uniform where PD 7974-7 generally overestimates the overall probability of fire starting showing a reduction of fires in current fire statistics probably due to an improvement of fire safety measures in buildings.

5.3 Frequency of fire starting in various occupancy types

Table A.1 in PD 7974-7:2003 (named PD 7974-7) presents the probability of fire starting *F* as a function of the total area of the building according to Eq. 7 which is reported below:

$$F = aA^b \qquad \text{Eq. 7}$$

The coefficients *a* and *b*, explained in section 2.5.1, are calculated with the fire incidents and building stock datasets, described in section 5.1.1 and summarized in Table 20.

Table 20: Datasets adopted for the coefficient a and b of Eq. 7

	a			b	
	USA	England		USA	England
Tot number of fires	NFIRS	IRS	Tot number of fires	NFIRS	IRS
Tot number of buildings at risk	CBECS MECS	VOA	Building maximum floor area	NFIRS	IRS

The analysis developed in this section for the USA considers the number of fires from the NFIRS fire database, and the number of buildings at risk from the CBECS and MECS. Fire incidents in various property types have been evaluated and the area of the buildings obtained based on the fields of building floors above and below ground level and the average size of the floor in ft^2 of the NFIRS summing the number of building below and the building above to obtain the total number of floors and multiplying them by the average size of floor. Values obtained in ft^2 have been converted in m^2 to create a comparison with those of PD 7974-7.

As already explained in section 2.5.1, the evaluations developed by Rutstein (1979b) assumed the term probability. However, the frequentistic definition is considered to be adopted where probability is defined as the relative frequency of occurrence of an event given by the number of times that it occurs divided by the number of experiments if it approaches infinity (Faber, 2012). The author believes that Rutstein obtained relative frequencies due to the presence of increasing but finite total floor spaces and consequently the term frequency instead of probability should be adopted. Therefore, there is a difference in the terminology used.

Table A.1 in PD 7974-7 is subdivided into two mains parts: the first one for *Industrial and manufacturing buildings* and the second one for *Other occupancies* excluding residential buildings. One important aspect to consider is that in Table A.1, the frequency period is not specified while in this research a yearly frequency is assumed.

The property types considered in both countries are only those which provide more than 3 data points. All the others are not fitted such as *Mechanical engineering and other metal goods* and *Electrical engineering* in USA and *Vehicle*, *Other manufacturing* and *Hotels* in England. The areas ranges are classified differently for USA and England because they are based on those present in the related building stock. For example, they vary from approximately 1,000 to 500,000 ft^2 (from 93 to 46,452 m^2) in USA while from 0 to over 50,000 m^2 in England.

Table 21 compares the values of Table A.1 of PD 7974-7 with those obtained by the analyses created with the USA and English statistics. Unfortunately, it has been possible to recreate only 5 industry or manufacturing subclasses for the USA and none of them for England. In the

USA for *Other occupancies*, *Shops* and *Offices* have been represented as *Mercantile, Business* and *Hospitals* as *Health care, Detention and Correction.* Despite these representations to recreate the property types are not perfect, they appear appropriate for the comparison.

The positive exponent power law [*Power (Rutstein)*] adopted by Rutstein to evaluate the coefficients does not often guarantee good agreement with the current dataset, therefore, better fitting relationships for the fire statistics have been investigated and two functions named *[Power (Improved)]* for the power law with positive or negative exponent and *[Poly. (Improved)]* for a polynomial function have been considered. The fire frequency relationships are based on various occupancy types and grouping fire incidents according to floor area bands of the building in which they occurred and relating them to the fire frequency defined as fires divided by a total number of buildings at risk per floor area band. While [*Power (Rutstein)]* is calculated according to the definitions for the coefficient *a* and *b* and always assumes a positive exponent, the improved functions *[Power (USA-improved)]* and *[Poly (USA-improved)* are based on the dot plots deduced by the analysis with the associated R-squared values to understand how well the trends describes the fire datasets.

In England, the data points obtained are 12 for *Shops* and *Offices*, 11 for *Industry and manufacturing* and *Miscellaneous*, 10 for *Storage*, *Schools* and *Leisure* and 9 for *Hospitals* while in the USA no more than 8 data points are available for the property types with only 4 points present in the class of *Overall Industry*.

The limited number of data points provide a high degree of uncertainty as proved by the analysis of the residuals (Lovric, 2011) which in the USA usually assumes a "not random" distribution and suggests a poor fit for the two improved laws. In England, residuals provide a random distribution showing that the models fit the data well with some exception stated below. Moreover, in England, the Spearman's correlation (Rebekić et al., 2015) has been evaluated investigating the total floor areas and fire frequencies and it usually provides a positive correlation with values varying from 0.503 to 0.930 in the occupancy types examined with the only exception of -0.209, -0.248 and -0.164 in *Industry and manufacturing*, *Storage* and *Miscellaneous*, respectively. Future research and an increased number of data points would better validate the analysis developed.

Table 21: Frequency of fire starting in different occupancy types in USA and England

Industrial buildings	PD 7974-7		USA Fire Statistics						
			According to dots graph frequency of fire – tot floor space						
	[Power (PD)]		[Power (USA-Rutstein)]		[Power (USA-Improved)]			[Poly (USA-Improved)]	
	a	b	a	b	a	b	R^2	Law	R^2
Overall Industry and Manufacturing	0.0017	0.53	0.003920	0.1464	1.7584	-0.831	0.482	N/A	N/A
Food, drink and tobacco	0.0011	0.60					Not applicable		
Chemical and allied	0.0069	0.46	0.000249	0.0028	0.00003	0.2447	0.047	N/A	N/A
Mechanical engineering and other metal goods	0.00086	0.56	0.000245	0.0027				Only 2 points	
Electrical engineering	0.0061	0.59	0.002537	0.0041				Only 2 points	
Vehicles	0.00012	0.86					Not applicable		
Textiles	0.0075	0.35					Not applicable		
Timber, Furniture	0.00037	0.77					Only 1 point		
Paper, printing and publishing	0.000069	0.91					Not applicable		
Other manufacturing	0.0084	0.41	0.012748	0.0474	0.0018	0.1523	0.010	$2.28*10^{-9}A^2-1.95*10^{-5}A+4.23*10^{-2}$	1

Other Occupancies	PD 7974-7		USA Fire Statistics						
	[Power(PD)]		[Power (USA-Rutstein)]		[Power (USA-Improved)]			[Poly (USA-Improved)]	
	a	b	a	b	a	b	R^2	Law	R^2
Storage	0.00067	0.5	0.0023	0.0392	0.0001	0.349	0.405	$-3.75*10^{-17}A^3+7.26*10^{-12}A^2-9.90*10^{-8}A+0.0019$	0.993
Shops	0.000066	1	0.0010	0.0589	0.00005	0.4514	0.927	$4.88*10^{-17}A^3-4.61*10^{-12}A^2+2.25*10^{-7}A+0.0008$	0.997
Offices	0.000059	0.9							
Hotels	0.00008	1	0.0037	0.0125	0.0003	0.366	0.673	$-1.10*10^{-16}A^3+1.13*10^{-11}A^2+9.35*10^{-8}A+0.0031$	0.991
Hospitals	0.0007	0.75	0.0029	0.0115	0.0001	0.4867	0.839	$-2.37*10^{-12}A^2+4.71*10^{-7}A+0.004$	0.742
Schools	0.0002	0.75	0.0012	0.0101	0.0002	0.2179	0.768	$2.92*10^{-16}A^3-7.76*10^{-12}A^2+1.04*10^{-7}A+0.0010$	0.983

Occupancy types	PD 7974-7		English fire statistics						
			According to data points frequency of fire – total floor space						
	[Power(PD)]		[Power (Eng-Rutstein)]		[Power (Eng-Improved)]			[Poly (Eng-Improved)]	
	a	b	a	b	a	b	R^2	Law	R^2
Industry manufacturing	0.0017	0.53	0.0029	0.0736	0.0044	-0.137	0.055	$4\times10^{-15}A^3-9\times10^{-11}A^2+3\times10^{-7}A+0.003$	0.155
Storage	0.00067	0.5	0.0253	0.3187	0.0439	-0.237	0.101	$-7\times10^{-10}A^2+3\times10^{-6}A+0.0177$	0.205
Shops	0.000066	1	0.0027	0.0515	0.0014	0.164	0.262	$1\times10^{-11}A^2-2\times10^{-7}A+0.0049$	0.449
Offices	0.000059	0.9	0.0009	0.0128	0.00007	0.518	0.835	$-2\times10^{-11}A^2+1\times10^{-6}A+0.0017$	0.588
Hospitals	0.0007	0.75	0.0117	0.1183	0.0002	0.764	0.442	$-4\times10^{-12}A^3+8\times10^{-8}A^2-5\times10^{-5}A+0.0157$	0.999
Schools	0.0002	0.75	0.0246	0.0544	0.0047	0.340	0.178	$-5\times10^{-12}A^3+4\times10^{-8}A^2-4\times10^{-5}A+0.0473$	0.718
Leisure	N/A	N/A	0.0079	0.0563	0.0012	0.321	0.228	$-3\times10^{-13}A^3+2\times10^{-9}A^2+5\times10^{-6}A+0.0059$	0.861
Miscellaneous	N/A	N/A	0.068	0.068	0.053	-0.01	0.0005	$-2\times10^{-10}A^2+9\times10^{-7}A+0.0684$	0.068

Figure 71 (a) shows for *Overall Industry and Manufacturing* the fire frequency based on three functions: the function presented in PD 7974-7 *[Power (PD)]*, the USA power law positive exponent *[Power (USA-Rutstein)]* and the one based on fires per area band *[Power (USA-improved)]*. Figure 71 (b) is focused only on the USA dots distribution and related functions. In Figure 71, the positive exponent power law from PD 7974-7 and the law generated using USA data with the positive exponent constraint appear to not represent the data well because the graph presents a reduction in fire frequency with an increase of the total floor area determining a negative exponent. This tendency could be attributable to the fact that larger buildings could have better fire safety measures able to prevent the fire ignition or detect fires in their early stages. However, for small floor areas, a negative exponent power law produces high fire frequencies (e.g. for a floor area of 10 m^2 fire frequency is equal to 26%) and there is a need to identify the potential limits of the relationships incorporating small building areas.

For *Chemical and allied*, buildings are distributed from 464.4 to 9,290.3 m^2 total floor space with no buildings recorded between 2,323 and 4,645 m^2 and this data point has been neglected in the analysis. In Figure 72 (a), neither of the laws ([*Power (USA-improved)*] and [*Power (USA-Rutstein)*]) are accurate due to large data dispersion. The difference from the analysis developed for *Overall Industry and Manufacturing* is that fire frequency according to the building area assumes a positive exponent in the power law of *Other manufacturing* (Figure 72 (b)). Again, a great dispersion of data leads to a very low correlation ($R^2 = 0.010$) for [*Power (USA-improved)*] possibly associated with the classification of the area adopted for the buildings. Higher fidelity in the building stock could improve the relationships further.

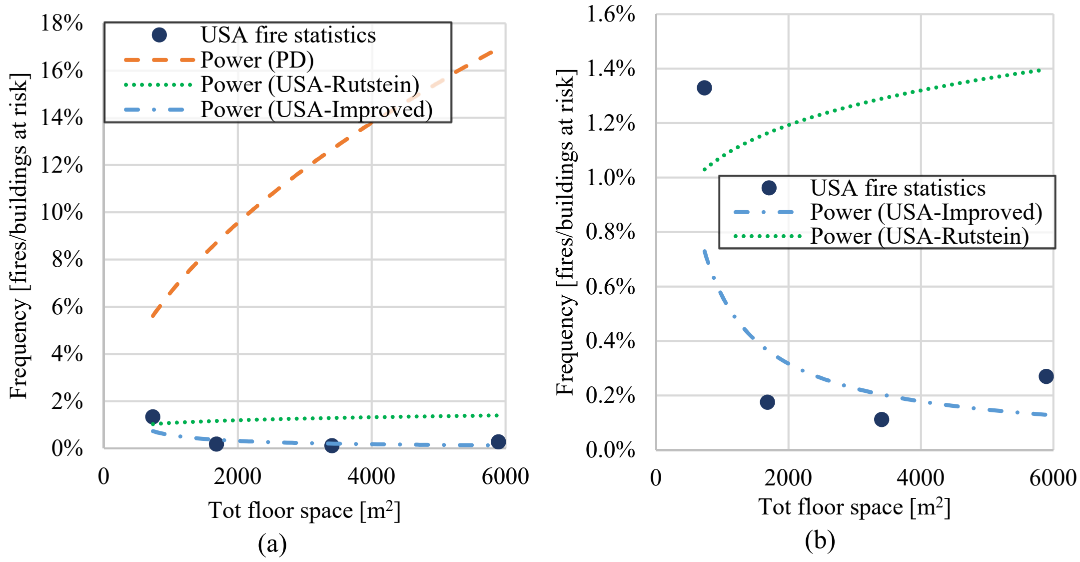


Figure 71: Frequency of fire starting in Industry and manufacturing (a) PD 7974-7 and USA statistics; and (b) only USA

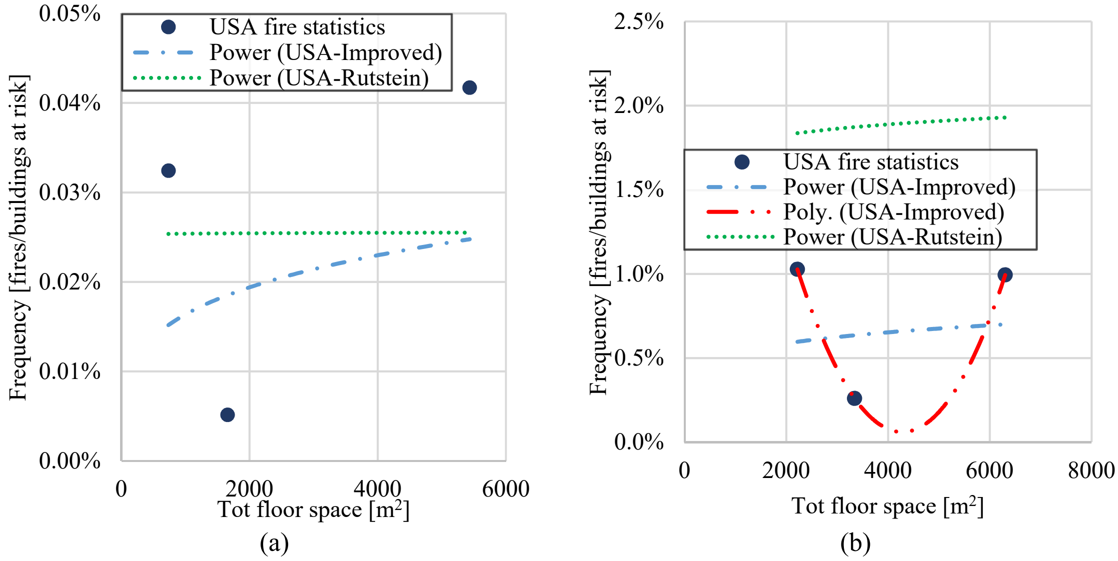


Figure 72: Frequency of fire starting of USA fire statistics in (a) Chemical and allied industry; and (b) Other manufacturing

In England *Industry and manufacturing*, PD 7974-7 appears to overestimate the trends obtained in English and the USA statistics where the [*Power (Eng-Improved)*] for both countries shows a negative exponent providing an R^2 equal to 0.055 in England and 0.482 in USA (Table 21). The polynomial function of third order seems to better describe the data distribution in England, although still poorly with an R^2 of 0.155 (Figure 73).

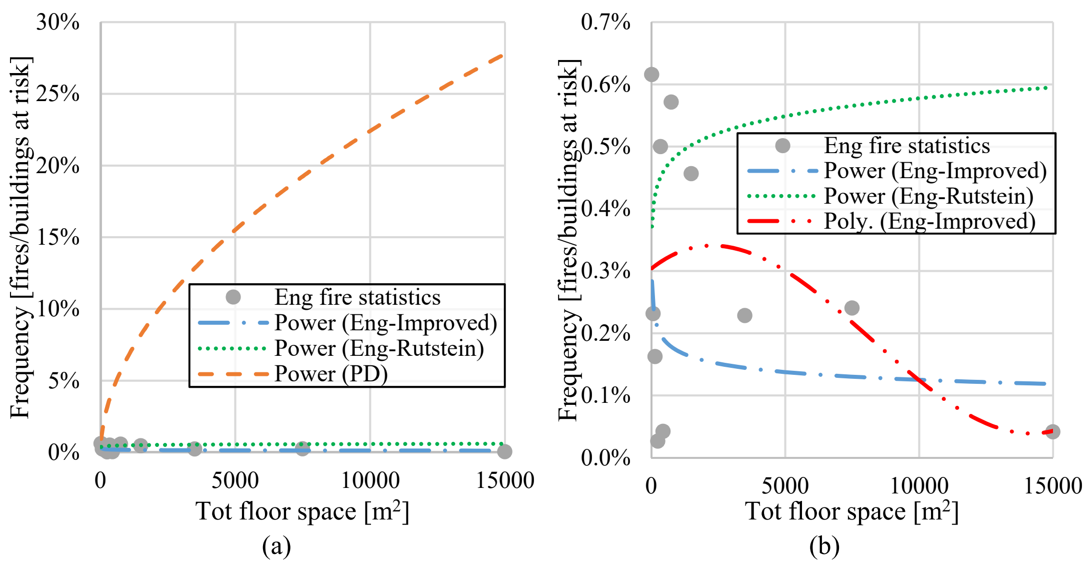


Figure 73: Frequency of fire starting Industry and manufacturing (a) PD 7974-7 and English statistics, (b) only in England

The second part of Table A.1 is characterised by *Other Occupancies* not considering residential buildings. Generally, there is a consistent trend in which fire frequency increases with floor areas but the function suggested by Rutstein's appears to not describe well the distribution. Indeed, the evaluated power law with positive exponent [*Power (Rutstein)*] significantly underestimates the fire frequency according to the building size. R^2 values for the curve fitting power law usually vary in the USA between 0.405 and 0.927 and England between 0.101 and 0.835 but the most consistently accurate function examined appears to be assumed by a polynomial function of second or third order which regularly produced R^2 values in the USA from 0.742 to 0.997 and in England from 0.155 to 0.999 (Table 21).

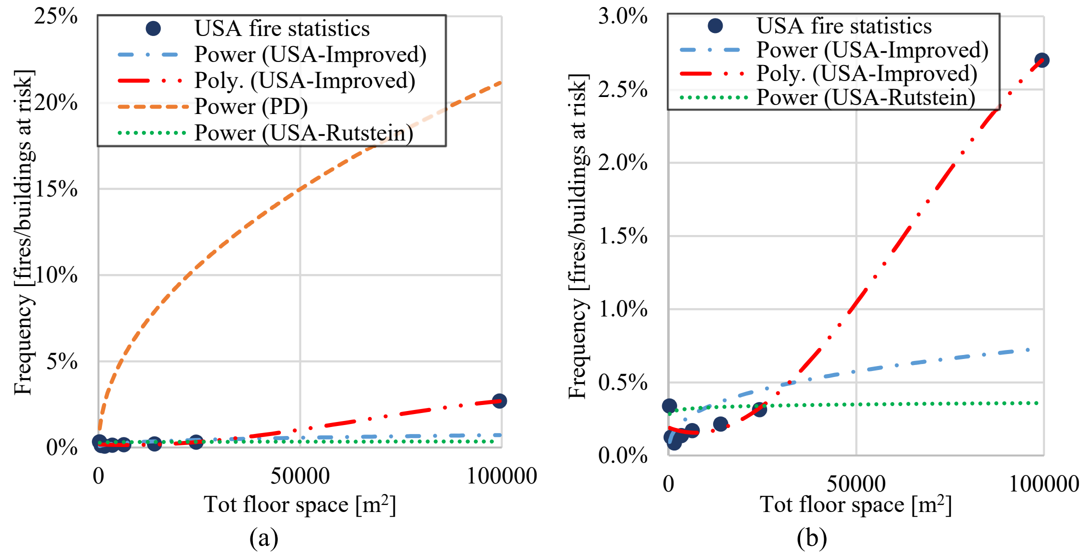


Figure 74: Frequency of fire starting in Storage (a) PD 7974-7 and USA fire statistics; and (b) the only USA

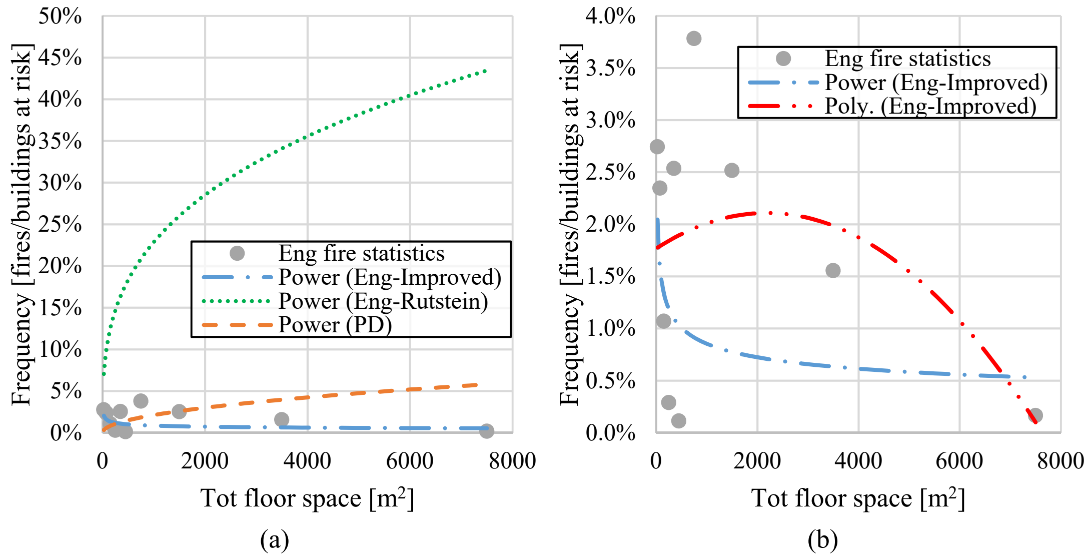


Figure 75: Frequency of fire starting Storage (a) PD 7974-7 and English statistics, (b) only in England

Figure 74 shows for *Storage* in USA three functions: the PD 7974-7 relationship, the [*Power (USA-Rutstein)*], and the [*Poly. (USA-Improved)*] functions considering a total area greater than 92.99 m^2. PD 7974-7 adopts a conservative approach if compared to the trends seen in NFIRS data. When Figure 74 (b) is considered, the positive exponent power law describes the increasing fire frequency with increasing total building area but R^2 is equal to 0.405. When the cubic polynomial function is adopted, the R^2 value increases to 0.993. In England *Storage*, [*Power (Eng-Rutstein)*] with positive exponent represents the highest curve while the function of PD 7974-7 assumes higher values than those described by the data distribution of English statistics which are well approximated by a second order polynomial function of R^2 = 0.205 (Figure 75). However, the polynomial functions found in the USA and England should be considered carefully because they could be not a physically representative relationship and difficult to justify. They could describe the influence of how the design has different criteria as buildings get larger/taller and future research will provide further explanations.

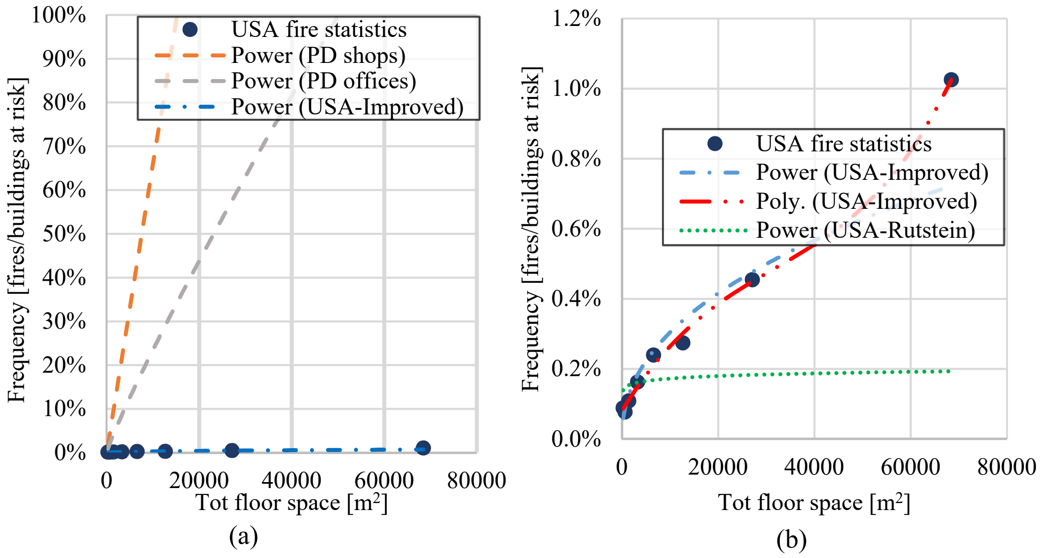


Figure 76: Frequency of fire starting in Shops and Offices (a) PD 7974-7 and USA statistics, (b) the only USA

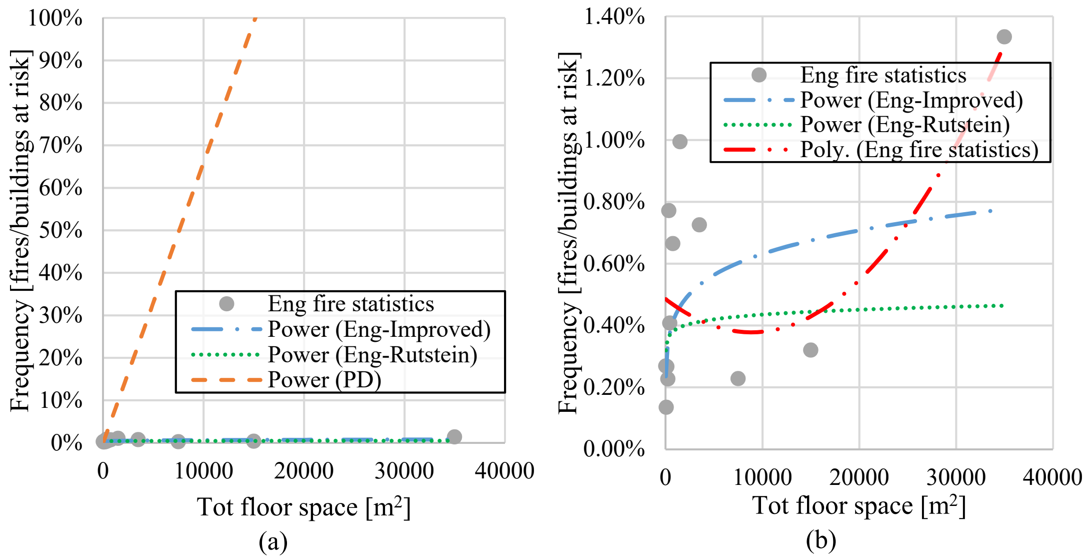
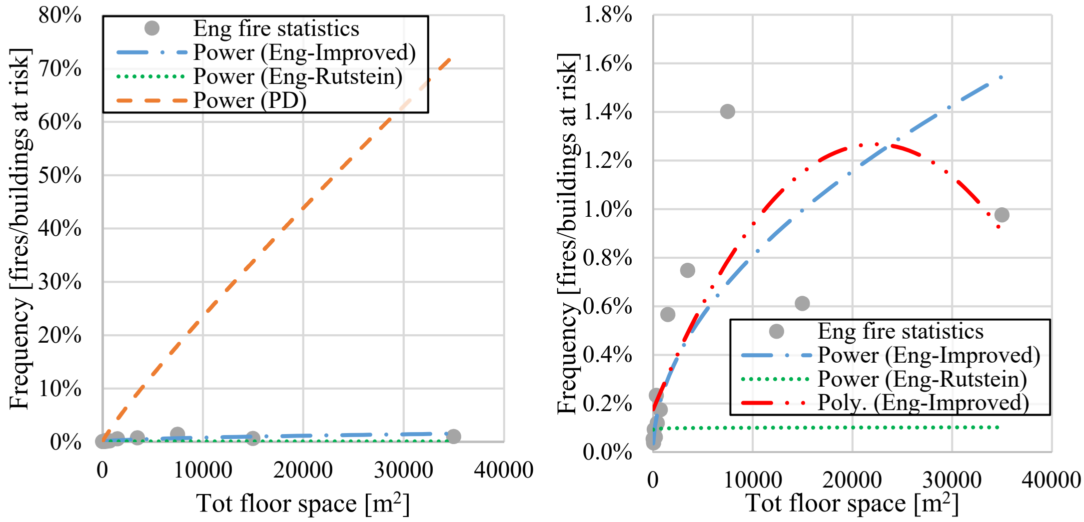


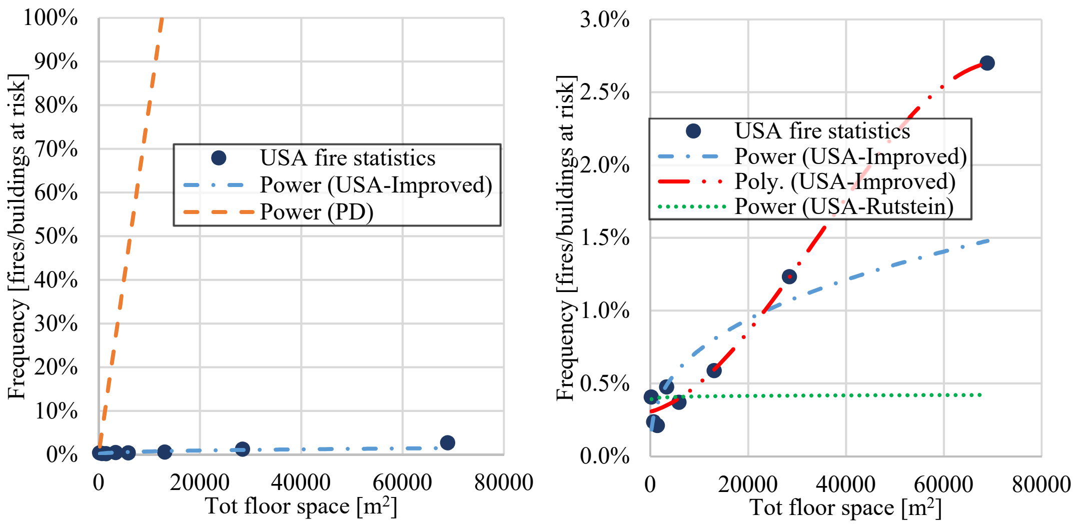
Figure 77: Frequency of fire starting Shops (a) PD 7974-7 and English statistics, (b) only in England

While in PD 7974-7 *Shops and Offices* are two distinct categories which are separately investigated in England, they are compared in the USA to the closest class of the NFIRS which is *Mercantile, Business* (Figure 76). The power law for *Shops* and *Offices* in PD 7974-7 seems to not represent well the data distribution of the two statistics. In fact, according to the PD 7974-7 laws, one fire per year could ignite in a *Shop* or *Office* if they have a total floor area greater than 15,000 m^2 and 50,000 m^2, respectively. The power law in the USA provides an R^2 value of 0.927 and the accuracy is improved with a cubic polynomial approximation with an R^2 of 0.997 (Table 21). In *Shops* in England, the power law with positive exponent and a second order polynomial assume an $R^2 = 0.262$ and $R^2 = 0.449$, respectively (Figure 77).



(a) (b)

Figure 78: Frequency of fire starting Offices (a) PD 7974-7 and English statistics, (b) only in England



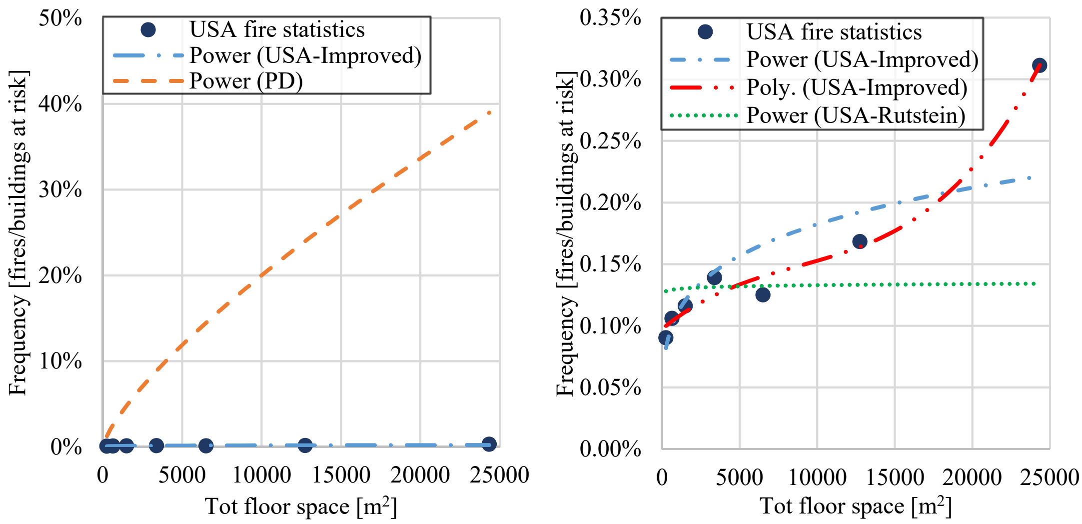
(a) (b)

Figure 79: Frequency of fire starting in Hotels (a) PD 7974-7 and USA statistics; and (b) the only USA

In *Offices* in England, PD 7974-7 power law assumes fire frequency greater than 70% for 35,000 m^2. The second order polynomial is less accurate ($R^2 = 0.588$) while the power law ($R^2 = 0.835$) better describes the data. [*Power (Eng-Rutstein)*] with positive exponent shows values lower than 0.2% as shown in Figure 78.

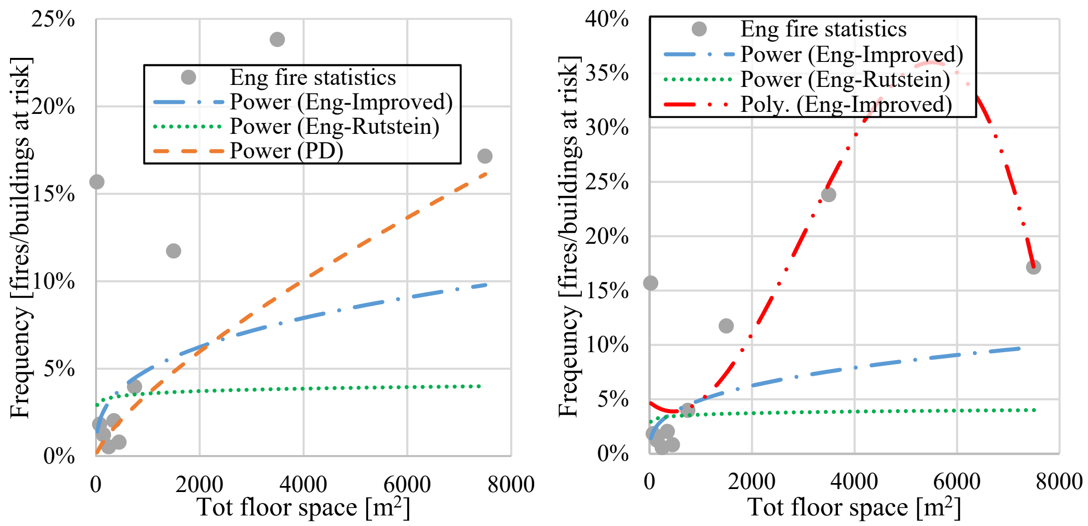
Hotels have been recreated only in the USA. PD 7974-7 law presents a fire frequency of 100% while in the USA statistics fire frequency is equal to 0.6% considering for both a total area greater than 12,500 m^2 (Figure 79). The cubic function provides better approximation than the power law with a positive exponent (R^2 = 0.991 and R^2 = 0.673, respectively).

For *Schools,* PD 7974-7 appears conservative if compared to the USA fire statistics distribution as represented in Figure 80. The two improved laws, power and a cubic functions in the USA present R^2 values of 0.768 and 0.983, respectively, as reported in Table 21. Similarities are shown in English statistics and PD 7974-7 for *Schools* in particular for the range of fire frequencies up to 2,000 m^2 (Figure 81 (a)). In England, the data are well represented by a polynomial function of third order with R^2 equals to 0.718 (Figure 81).



(a) (b)

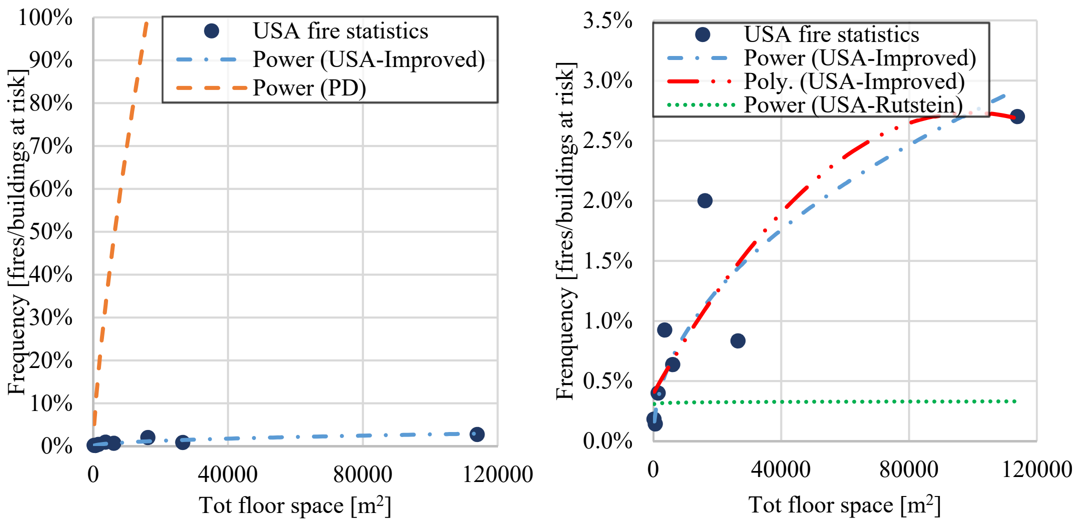
Figure 80: Frequency of fire starting in Schools (a) PD 7974-7 and USA statistics; and (b) the only USA



(a) (b)

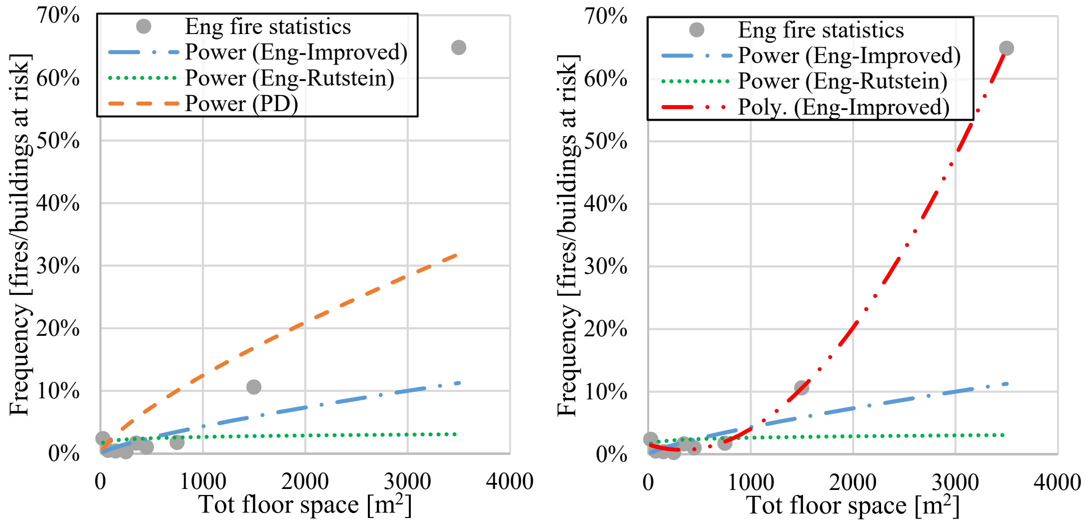
Figure 81: Frequency of fire starting Schools (a) PD 7974-7 and English statistics, (b) only in England

Hospitals are recreated in the USA investigating the class of *Health Care, Detention and Correction* in NFIRS considered its nearest comparator. According to what stated in Table A.2 of PD 7974-7 for *Hospitals*, a fire will occur yearly if the hospital has a total area greater than 16,000 m^2 as shown in Figure 82. Again the data do not support this trend, where fire frequency is approximately 2% for a similar area in *Health Care, Detention and Correction* in the USA. Plotting the two USA-Improved functions both a power law and a second order polynomial function present a good R^2 of 0.839 and 0.742, respectively. However, the great dispersion of data suggests considering this evaluation carefully.



(a) (b)

Figure 82: Frequency of fire starting (a) comparing PD 7974-7 Hospitals and USA fire statistics Health Care, Detention and Correction; and (b) focussing on USA Health Care, Detention and Correction fire statistics



(a) (b)

Figure 83: Frequency of fire starting Hospitals (a) PD 7974-7 and English statistics, (b) only in England

PD 7974-7 overestimates English statistics in the majority of the property types but in *Hospitals,* this is not as obvious as in the other classes as shown in Figure 83. Plotting English statistics trends, the best fit is represented by a third order polynomial (R^2 = 0.999) and by a power law with a positive exponent (R^2 = 0.442). The above-mentioned power law provides a systematic pattern of the residuals and the model does not represent the data well. The analysis of the residuals for the improved laws in English *Hospitals* and *Schools* show a pattern and the models appear as a poor fit.

The analysis for the fire frequency starting in several property types has demonstrated that PD 7974-7 generally overestimates current fire trends. Moreover, according to the results obtained in Table 21, the power law with positive exponent suggested by Rutstein does not always provide the best approximation for the data. In *Industrial manufacturing* of USA and England, a negative exponent is assumed by the power law as well as in *Storage* in English statistics. Despite the polynomial fitted function of second or third order seems to be more accurate in the USA, this is not always the case in England (Table 21). A common data distribution form is found in the two statistics characterized by a frequency which usually decreases to a minimum and consequently gradually increases. The difference obtained for the USA and English statistics could be attributed to various factors such as the presence of a high number of buildings with a small floor area, the different safety measures adopted in large buildings and the difference in the regulatory requirements as the size of building increases. In England, the majority of the power or polynomial relationships gives R^2 lower than 0.4 while in the USA R^2 is often above 0.99. Extreme data points are less dense than those of smaller total floor areas and non-uniform data scatter is usually present. Uncertainties due to the fitting of the data with the curves need to be treated carefully.

5.4 Area damage and percentage of fires per fire spread category

The area damage in m^2 according to various classes of fire spread and the related percentage of fires in *Textile industry* and *Pubs, clubs and restaurant* with different fire origin locations are described in Table A.4 and Table A.5 of PD 7974-7:2003, respectively. The data in PD 7974-7 are referred to the UK Fire Statistics of 1984-86. These tables have been updated using the *Other buildings* dataset of the Home Office in England and the NFIRS datasets in the USA.

Textile industry in PD 7974-7 has been recreated using *Manufacturing, Processing* in the USA and *Industrial manufacturing* (not including Factory) in England. In Table A.4, the fire origin locations investigated in USA and English statistics are respectively: <u>Production area</u> as Processing/manufacturing area, workroom, assembly area - Process/Production room; <u>Storage area</u> as Storage Areas - Store room/Laundry room/Cloakroom, Refuse store; <u>Other areas</u> as all the other fire origin locations excluding those previously considered.

For the comparison in Table A.5, within the property type of *Assembly* in USA fire statistics the following subclasses have been considered: Athletic or health club (includes YMCA or YWCA, lodge, swimming, and baths); Clubhouse associated with country club that includes golf, tennis, hunting, fishing, and riding activities; Yacht club (includes boating and yacht club facilities; excludes marinas, boat mooring facilities; boat repair/refuelling facilities; or boat sales, services, and repairs); Casino, gambling clubs (includes bingo halls - use only where the primary use is for gambling); Clubs, others; Restaurant or cafeteria, places specializing in on-premises consumption of food (includes carryout and drive-through restaurants); Bar, nightclub, saloon, tavern, pub; Eating, drinking places, others. For England, *Pub, wine bar, bar; Casino, club, nightclub; Restaurant, cafe and Takeaway, fast food* are analysed.

The data are classified according to sprinklered and un-sprinklered buildings and while in the USA, only *fire damage* is recorded which does not include areas receiving only heat, smoke, or water damage; in England statistics, data are available for *fire* and *total damage* where *fire damage* is defined as the total horizontal area damaged by the flame and heat in m^2 at the stop of the fire; and *total damage* as the area damaged by the flame, heat, smoke and water in m^2. Moreover, the damage is recorded in m^2 of area damage in England while it is expressed as banded percentage ranges of the area in the USA in which the median of each band has been considered.

PD 7974-7 distinction in the class of fire confined to the room of origin affecting only contents or involving the structure is not present in current fire incident datasets and usually, current fire statistics of England and USA present more classes of fire spreading beyond the room of origin. Unfortunately, a total number of fires in PD 7974-7 is not provided for Table A.4 and Table A.5 while it is available for England and the USA where in the USA, previous studies have analysed fire frequency considering fires and unclassified events (Manes & Rush, 2018).

5.4.1 Textile industry

Table A.4 of PD 7974-7 considers three fire origin locations of <u>Production areas</u>, <u>Storage areas</u> and <u>Other areas</u> for what concerns the area damage and fire frequency and they have been recreated adopting the USA and English statistics as described in 5.4.

In the **USA**, <u>Production areas</u> based on NFIRS data presents a total of 54 fires recorded for the presence of sprinklers and 29 for their absence (Table 22). Moreover, for sprinklered buildings, 7 fire incidents are available for spread confined to floor, 14 for spread confined to building and 2 for the one beyond building while for un-sprinklered buildings, 4 incidents are related to fire confined to the floor and 2 for spreads beyond the building of origin. The research of this thesis has neglected one value in which the spread confined to building shows median damage of 85,935 m^2, not comparable with the other results.

Fire frequency not confined to the room of origin is given by 4% for sprinklered and 12% for un-sprinklered in PD 7974-7 while the spread beyond the room of origin in USA statistics equals to 24.07% for sprinklered and 51.73% for un-sprinklered (Table 23). PD 7974-7 shows similar areas of damage for sprinklered and un-sprinklered buildings while in the USA the damage for the presence of sprinklers shows greater values than the one in un-sprinklered buildings. The reason for these trends could be due to the very limited number of fires.

For Storage areas in the PD 7974-7, the area damage confined to the room, for contents only and structure involved in sprinklered buildings, presents for two times 19 m^2 of damage and 24% of frequency. This is considered as a potential error because if these values are both counted, the total frequency would be greater than 100%. Therefore, this research has combined the two classes assigning 19 m^2 of area damage and 24% of fire frequency. A potential typo is assumed in the average area damage for buildings without automatic extinguishing systems in PD 7974-7 equals to 539 m^2 while it should be of 533 m^2 (Table 22).

In the USA Storage areas, 29 and 31 fire incidents are recorded for the presence and absence of sprinklers, respectively. The analysis developed neglects one fire recorded because its median area damaged is considered too high if compared to the other values. In NFIRS, no data are available for fire spread beyond the building of origin for sprinklered buildings, and only 5 fires for spread confined to floor and 7 for spread confined to the building. Fire frequency in PD 7974-7 tends to decrease with the increase of fire spread class with an increase of area damage. In the USA, fire frequency for spread within the room of origin is 68.97%-19.35% for buildings equipped and not equipped with sprinklers, respectively. A significant 58.06% represents spread confined to building in un-sprinklered buildings. Fires spread beyond the room of origin is 31% in sprinklers and 80% for their absence (Table 23). Average damage in un-sprinklered buildings is 1.49% greater than for sprinklered ones (Table 22).

In Other areas in the USA, 123 and 107 fire incidents are available for presence or absence of sprinklers, respectively. In PD 7974-7, fire frequency decreases and the area damage increases when the spread of fire affects greater areas. In the USA sprinklered buildings, 6 fire incidents present fire beyond the building of origin and the spread within the room of origin is 66.67% for the presence of sprinklers and 40.19% for their absence. 43.93% of fires are recorded for spread confined to the building of origin for un-sprinklered buildings (Table 23). The spread beyond the room of origin is 33.33% in sprinklered buildings and 59.82% in un-sprinklered ones. However, future research should investigate the causes of the difference in trends.

Table 22: Table A.4 Area damage for each category of fire spread in the textile industry, PD 7974-7 vs USA fire statistics

		Area damage [m²]											
		Production areas				**Storage areas**				**Other areas**			
		Sprinklers		No Sprinklers		Sprinklers		No Sprinklers		Sprinklers		No Sprinklers	
		PD	USA	PD	USA	PD	USA	PD	USA	PD	USA	PD	USA
B		5	292.13	5	22.38	4	38.32	10	3.62	2	228.11	2	99.35
C	C1	13	499.52	17	14.38	19	170.71	17	16.41	11	428.92	4	71.11
	C2	113		475				262		68		68	
D	D1		198.32		39.25		75.45		84.89		62.64		31.91
	D5	694	429.16	694	379.08	1712	137.05	1712	161.70	1007	472.93	1007	1004.24
	D6		768.00		164.68		-		1176.10		89.72		86.14
Average		40	425.67	153	177.62	76	124.38	533	185.81	49	322.24	165	482.80
Total fires			54		29		29		31		123		107

A. No fire damage; **B**. Confined to item ignited; **C**. Confined to origin room; **C1**. Contents only; **C2**. Structure involved; **D**. Spread beyond room; **D1**. Confined to origin floor; **D2**. Confined to two floors; **D3**. Whole building; **D4**. Roofs/Roof spaces; **D5**. Confined to building; **D6**. Beyond building of origin; **Red**: Corrected value

Table 23: Table A.4 Percentage of fire for each category of fire spread in the textile industry, PD 7974-7 vs USA fire statistics

		Area damage [m²]											
		Production areas				**Storage areas**				**Other areas**			
		Sprinklers		No Sprinklers		Sprinklers		No Sprinklers		Sprinklers		No Sprinklers	
		PD	USA	PD	USA	PD	USA	PD	USA	PD	USA	PD	USA
B		72%	22.22%	43%	13.79%	72%	20.69%	19%	6.45%	66%	32.52%	42%	15.89%
C	C1	18%	53.70%	32%	34.48%	24%	48.28%	18%	12.90%	22%	34.15%	25%	24.30%
	C2	6%		13%				38%		8%		18%	
D	D1		7.41%		3.45%		13.79%		16.13%		11.38%		9.35%
	D5	4%	14.81%	12%	41.38%	4%	17.24%	25%	58.06%	4%	19.51%	15%	43.93%
	D6		1.85%		6.90%		0%		6.45%		2.44%		6.54%

A. No fire damage; **B**. Confined to item ignited; **C**. Confined to origin room; **C1**. Contents only; **C2**. Structure involved; **D**. Spread beyond room; **D1**. Confined to origin floor; **D2**. Confined to two floors; **D3**. Whole building; **D4**. Roofs/Roof spaces; **D5**. Confined to building; **D6**. Beyond building of origin; **Red**: corrected values

Table 24: Table A.4 Area damage for each category of fire spread in the textile industry, PD 7974-7 vs English fire statistics [F=Fire, T=Total]

		Area damage [m^2]																	
		Production areas						**Storage areas**						**Other areas**					
		Sprinklers			No Sprinklers			Sprinklers			No Sprinklers			Sprinklers			No Sprinklers		
		PD	Eng F	Eng T	PD	Eng F	Eng T	PD	Eng F	Eng T	PD	Eng F	Eng T	PD	Eng F	Eng T	PD	Eng F	Eng T
A		/	2.91	12.28	/	9.16	23.90	/	0.00	0.00	/	4.65	18.50	/	2.43	4.65	/	4.64	16.57
B		5	7.26	45.06	5	3.37	33.07	4	4.33	129.50	10	2.53	12.25	2	2.64	6.44	2	5.43	16.67
C	C1	13	39.67	163.34	17	21.24	98.65	19	39.00	176.50	17	16.58	36.23	11	7.18	33.20	4	17.84	59.85
	C2	113			475						262			68			68		
D	D1	694	15.79	185.32	694	80.04	163.25	1712	21.75	79.25	1712	80.83	171.36	1007	45.50	130.94	1007	53.41	136.20
	D2		97.50	207.50		87.80	228.11		75.50	150.50		199.25	301.75		35.50	55.50		86.54	156.43
	D3		1000.00	1000.00		350.23	401.41		750.50	750.50		420.85	457.54		504.00	504.00		354.41	389.03
	D4		212.30	225.80		38.89	46.75		/	/		328.15	455.10		37.83	62.83		69.12	92.33
Average		40	29	100.20	153	29	72.43	76	87	163.73	533	101	137.97	49	21	39.89	165	47	77.86
Total fires			198	198		2124	2124		11	11		172	172		94	94		1800	1800

A. No fire damage; **B**. Confined to item ignited; **C**. Confined to origin room; **C1**. Contents only; **C2**. Structure involved; **D**. Spread beyond room; **D1**. Confined to origin floor; **D2**. Confined to two floors; **D3**. Whole building; **D4**. Roofs/Roof spaces; **D5**. Confined to building; **D6**. Beyond building of origin; **Red**: Corrected values

Table 25: Table A.4 Percentage of fire for each category of fire spread in the textile industry, PD 7974-7 vs UK fire statistics

		Frequency											
		Production areas				**Storage areas**				**Other areas**			
		Sprinklers		No Sprinklers		Sprinklers		No Sprinklers		Sprinklers		No Sprinklers	
		PD	Eng	PD	Eng	PD	Eng	PD	Eng	PD	Eng	PD	Eng
A		/	19.70%	/	24.86%	/	18.18%	/	20.93%	/	24.47%	/	22.50%
B		72%	35.86%	43%	38.94%	72%	27.27%	19%	17.44%	66%	26.60%	42%	30.61%
C	C1	18%	29.29%	32%	22.36%	24%	18.18%	18%	26.74%	22%	31.91%	25%	18.50%
	C2	6%		13%				38%		8%		18%	
D	D1	4%	9.60%	12%	8.00%	4%	18.18%	25%	10.47%	4%	9.57%	15%	13.72%
	D2		2.53%		1.51%		9.09%		4.65%		2.13%		2.33%
	D3		0.51%		3.67%		9.09%		13.95%		2.13%		8.17%
	D4		2.53%		0.66%		0.00%		5.81%		3.19%		4.17%

A. No fire damage; **B**. Confined to item ignited; **C**. Confined to origin room; **C1**. Contents only; **C2**. Structure involved; **D**. Spread beyond room; **D1**. Confined to origin floor; **D2**. Confined to two floors; **D3**. Whole building; **D4**. Roofs/Roof spaces; **D5**. Confined to building; **D6**. Beyond building of origin; **Red**: Corrected values

When **English** statistics is investigated, in Production areas, the total number of fires is 198 and 2,124 for sprinklers and no sprinklers, respectively. It is already clear that, for Production areas, the number of fires usually recorded in England is greater than the one in the USA and this enables more accurate comparisons. Moreover, in English statistics, the damage is classified according to *fire* and *total damage* as explained in section 5.4. For the average area damaged in Table 24, 40 m^2 and *fire damage* of 29 m^2 are found for the presence of sprinklers in PD 7974-7 and English statistics, respectively. One fire with 1,000 m^2 affecting the whole building in England, is recorded and may not be representative of the fire scenario for the presence of sprinklers (Table 24). Fire frequency presents more than 80% of cases in which it is confined up to the room of origin for the presence and absence of sprinklers (Table 25).

In England Storage areas, 11 fires for sprinklers and 172 for their absence are available. Therefore, the focus will be only on the buildings not equipped with sprinklers. The *total damage* in England is 137.97 m^2 for the absence of sprinklers which is four times lower than those found in PD 7974-7 equals to 533 m^2 (not 539 m^2 as explained above) and there is a small difference between *fire* and *total damage* (Table 24). Fire frequency in England for spread confined to the room of origin for buildings without sprinklers is recorded in 65% of incidents showing a relevant 13.95% of spread affecting the whole building (Table 25).

In Other areas in England, the total number of fires recorded is 94 for sprinklers and 1,800 for no sprinklers. For the absence of sprinklers, if the average area damage in PD 7974-7 is compared to the one of English statistics, it is two times bigger being English *total damage* equals to 77.86 m^2 (Table 24) while the values are similar in the case of presence of sprinklers. In England, approximately 80% and 70% are the fire frequencies confined within the room of origin in sprinklered and un-sprinklered buildings with a 13.72% of spread limited to the floor of origin for the absence of sprinklers (Table 25).

5.4.2 Pubs, clubs and restaurants

Table A.5 of *Pubs, clubs and restaurants* has been recreated evaluating area damage and fire frequency for presence or absence of sprinklers in all fire origin locations, described in section 5.4, where extending the fire spread, fire frequency decreases and area damage increases.

In **USA** fire statistics, only 7 fires are recorded for fire beyond the building of origin in sprinklered buildings. Fire frequency in the USA is equal to 70.23% and 50.38% for spread limited to the room of origin in the presence or absence of sprinklers, respectively (Table 26). For PD 7974-7 and USA, the average area damage assumes lower values when sprinklers are available, approximately 5 times lower in PD 7974-7 and 2.5 times in USA statistics.

Table 26: Table A.5 Area damage and percentage of fire for each category of fire spread in Pubs, Clubs and Restaurants, PD 7974-7 vs USA fire statistics

		Area damage [m²]				Frequency			
		Sprinklers		No Sprinklers		Sprinklers		No Sprinklers	
		PD	USA	PD	USA	PD	USA	PD	USA
B		1	31.30	1	4.19	59%	25.58%	26%	20.38%
C	C1	1	24.11	2	13.81	15%	44.65%	12%	30.00%
	C2	4		15		19%		45%	
D	D1	50	2.18	101	8.20	7%	4.19%	17%	7.69%
	D5		11.95		126.67		24.19%		37.31%
	D6		1.02		79.05		1.40%		4.62%
Average		5	21.77	24	56.54				
Total fires			215		260				

A. No fire damage; **B**. Confined to item ignited; **C**. Confined to origin room; **C1**. Contents only; **C2**. Structure involved; **D**. Spread beyond room; **D1**. Confined to origin floor; **D2**. Confined to two floors; **D3**. Whole building; **D4**. Roofs/Roof spaces; **D5**. Confined to building; **D6**. Beyond building of origin

Table 27: Table A.5 Area damage and percentage of fire for each category of fire spread in Pubs, Clubs and Restaurants, PD 7974-7 vs English fire statistics [F=Fire, T=Total]

		Area damaged [m²]						Frequency			
		Sprinklers			No Sprinklers			Sprinklers		No Sprinklers	
		PD	Eng F	Eng T	PD	Eng F	Eng T	PD	Eng	PD	Eng
A		/	2.24	16.26	/	3.92	12.43	/	28.13%	/	22.85%
B		1	3.48	93.82	1	2.21	9.11	59%	31.25%	26%	32.71%
C	C1	1	7.27	34.50	2	8.08	44.50	15%	27.08%	12%	22.94%
	C2	4			15			19%		45%	
D	D1	50	1.88	188.88	101	25.72	73.53	7%	4.17%	17%	10.02%
	D2		12.13	388.00		52.24	121.93		4.17%		4.10%
	D3		255.50	255.50		181.01	237.27		3.13%		3.57%
	D4		41.75	93.00		69.07	114.97		2.08%		3.81%
Average		5	13	77.19	24	17	41.25				
Total fires			96	96		11429	11429				

A. No fire damage; **B**. Confined to item ignited; **C**. Confined to origin room; **C1**. Contents only; **C2**. Structure involved; **D**. Spread beyond room; **D1**. Confined to origin floor; **D2**. Confined to two floors; **D3**. Whole building; **D4**. Roofs/Roof spaces; **D5**. Confined to building; **D6**. Beyond building of origin

In *Pubs, clubs, restaurants* in England, 96 and 11,429 fires are reported for presence or absence of sprinklers. Comments are focused on fires for building not equipped with sprinklers. The average area damaged for PD 7974-7 of 24 m^2 is almost half of those derived in English statistics for the *total damage* (41.25 m^2) in the absence of sprinklers. *Total damage* appears three times bigger than *fire damage* in the absence of sprinklers when the various fire spread classes are investigated. Therefore, firefighting activities to extinguishing the fire have a non-negligible impact. When fire spreads beyond the room of origin in absence of sprinklers, fire frequency results in 17% and 21.5% for PD 7974-7 and English statistics, respectively. Moreover, the frequency appears to be confined to the item first ignited for approximately 30% and presents no fire damage for 25% in English fire statistics for presence and absence of sprinklers (Table 27).

In USA statistics, the number of fires recorded is very limited and never exceeds 50 incidents while in English statistics, only fires when sprinklers are present are limited in number. Therefore, general comments on the results found for USA statistics and those of English statistics in the presence of sprinklers need to be treated carefully considering a high degree of uncertainty. Moreover, the area damage for both statistics seems to increase extending the spread of fire and in English statistics, the *total damage* is generally greater than *fire damage*. Fire frequency appears well confined for the majority of cases within the room of origin with relevant peaks of fires affecting the whole building.

Since Tables A.4-5 consider only two property types this study has examined all occupancy types available in USA and English fire statistics to extend the analysis to building types not investigated previously and improve the available fire safety data based on current fire statistics. The fields recorded in the USA and English fire statistics have been investigated and adopted to create more detailed data on fire spread and area damage in the case of presence or absence of safety systems.

5.4.3 Area damage and percentage of fires in USA fire statistics

While Table A.4-5 considers only the *Textile industry* and *Pubs, clubs, restaurants*, in USA fire statistics more property types are available and are investigated in this section. In the NFIRS, the damage is represented by the number of stories damaged by flame spread where fire damage is expressed as banded percentage ranges of the area instead of m^2 of area damage as shown in section 4.2.2.3. These percentage bands present a range and the median of each band is evaluated with error bars for the upper and lower bands (i.e. for Minor damage, the median is 12% damaged area, with lower and upper bounds of 0% and 24%, respectively).

The total weighted area damaged is calculated from the number of stories damaged, average floor area, and damage class involved per building based on the presence or absence of automatic extinguishing systems. Finally, the fire frequency for each fire spread class has been classified according to fires and unclassified events.

Generally in the USA, the influence of sprinklers reduces the fire spread with fires 10-30% more likely to be confined to object or room of origin and limits the damage to the damage bands of Minor and Significantly rather than to the Heavy and Extreme ones. However, several fires are recorded for which a level of fire spread is provided but no damage class is assigned and these fires have been named as unclassified (U) (from Table 49 to Table 56 in Annex). Table 49 - Table 56 in the Annex present: number of fires for each fire spread level for each damage class, percentages of fire spread per damage class (%F-S, percentages sum horizontally for the specific spread class) and percentages of damage per spread class (%F-D, percentages sum vertically for the specific damage class). For instance in Table 49 in the Annex, in sprinklered *Assembly* buildings, for fire spread limited to the object of origin, the likelihood of Minor damage is 97.01% (%F-S) and Significant damage is 2.99% (percentages sum horizontally); for the damage being classed as Minor damage (%F-D) the probability of fire spread confined to object is 29.41% and being confined to floor of origin is 4.52% (percentages sum vertically).

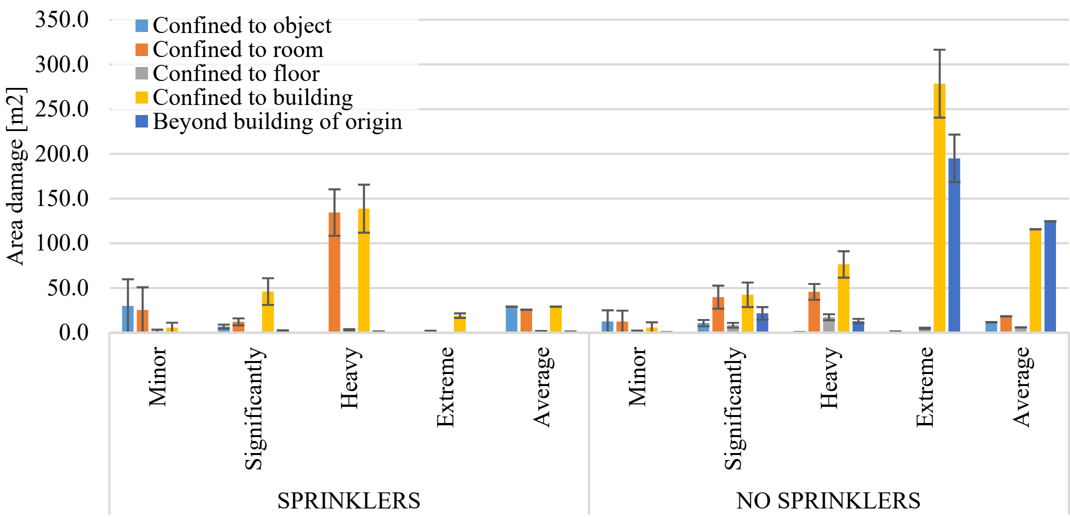


Figure 84: Area damage in Assembly for different spread of fire and damage classes, including weighted average area damage in USA statistics

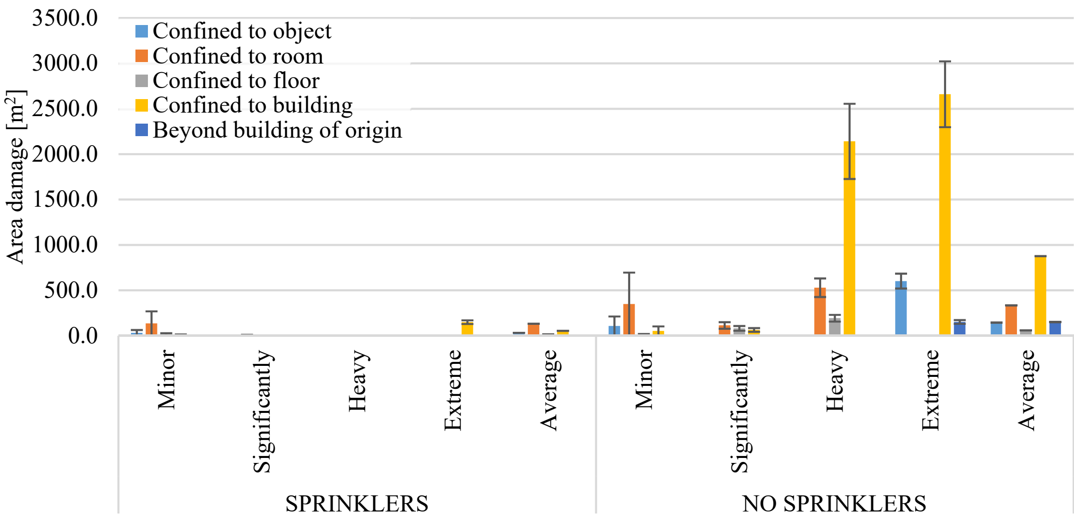


Figure 85: Area damage in Educational for the different spread of fire and damage classes, including weighted average area damage in USA statistics

Starting with *Assembly*, data have been classified according to the presence or absence of safety systems and for each condition, the average damaged area is expressed as a median value within the damage range with error magnitude based on the upper and lower limits of each band. Note, a single fire (no sprinklers, confined to floor, Significant damage) has been removed from the analysis as the area damaged (in the range of 145,161 to 284,516 m^2; 25%-49%, respectively) is significantly higher than the others and it appears to skew the data to unrepresentative values.

Table 49 in Annex and Figure *84* show that in *Assembly* in the USA, the damage is predominantly Minor damage in sprinklered buildings, whereas Extreme damage in un-sprinklered ones. This consideration supports the idea that automatic extinguishing systems have an impact on the reduction of fire spread. When the fire is confined to the item or room of origin, the area damaged by flame is higher for the presence of sprinklers than for their absence probably due to larger spread for unsprinklered fires not confined to the mentioned damage classes. However, when the fire spreads beyond the room of origin, un-sprinklered buildings experience higher damage and the frequency of fires which spreads beyond the room of origin in un-sprinklered buildings assumes 51%, compared to 29% in the sprinklered ones. Moreover, fires are frequently confined within the room of origin with 71% and 49% of fires and associated damage of 85% and 68% when including unclassified fires for buildings equipped and not equipped with sprinklers. The data also indicates when fires are extended beyond the room of origin, they are likely to spread to the whole building with sprinklers and no automatic extinguishing systems having 24.61% and 43.85% of fires spreading past the floor of origin, respectively. The total weighted area in *Assembly* is 25.96 m^2 and 59.50 m^2 of damage in the presence or absence of sprinklers, respectively (Table 49 in Annex).

Table 50 and Figure 85 show the analysis for *Educational buildings*, and it appears that the presence of sprinkler systems have a significant impact on the spread of fire and the amount of damage these fires cause, with approximately 85% of fires confined to the room of origin and characterized mainly by the Minor damage class. For the absence of sprinklers, there is more than 30% chance of fires spreading beyond the room of origin. Investigating spread beyond the building of origin, no fires are reported in sprinklered buildings while this occurs in 3% of the fires for un-sprinklered ones. The average area damaged is of almost 87 m^2 for presence, compared to approximately 390 m^2 for the absence of sprinklers.

In *Health Care, Detention and Correction*, for the presence of sprinklers no data are available for the class of fire spread beyond the building of origin. Since its median area damaged is 89,186 m^2, one fire incident has not been neglected for spread confined to object first ignited. Fire spread is well confined to the room of origin for sprinklered buildings (86.02%), however for un-sprinklered a significant percentage (41.18%) of fires will spread beyond the room of origin (Table 51 and Figure 86). Sprinklers, again are shown to reduce the area damaged with average damage being 70.70 m^2 and 94.51 m^2 for sprinklered and un-sprinklered buildings, respectively.

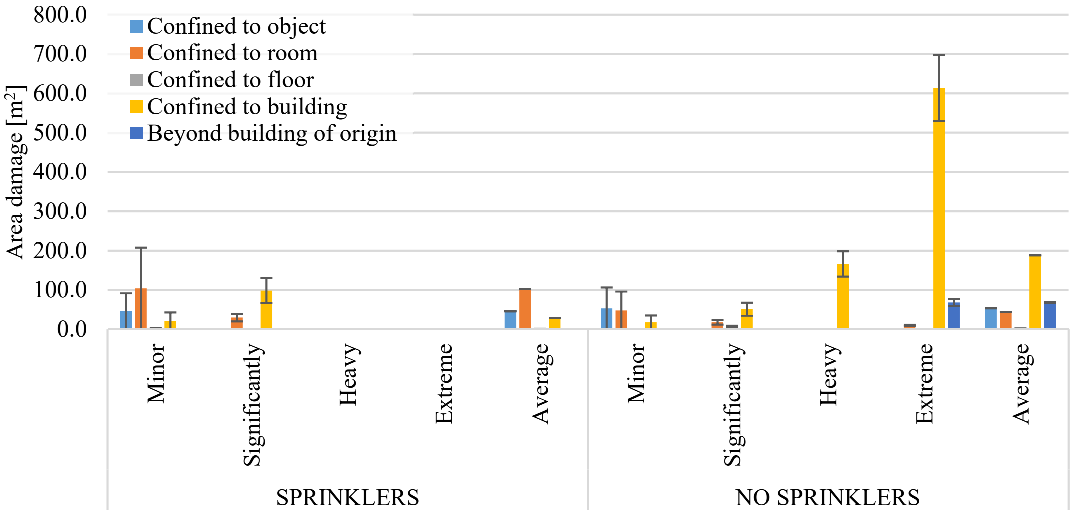


Figure 86: Area damage in Health Care, Detection and Correction for the different spread of fire and damage classes, including weighted average area damage in USA statistics

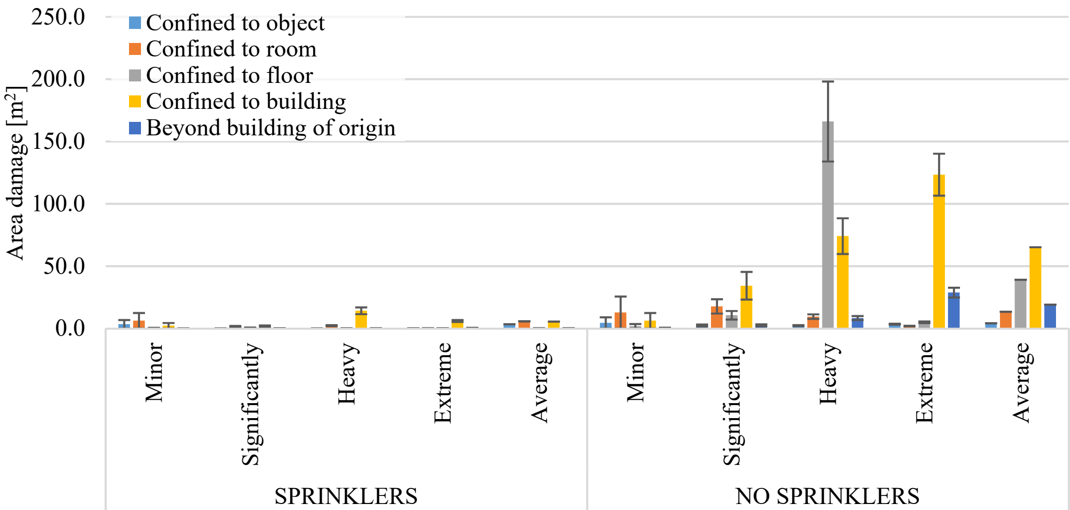


Figure 87: Area damage in Residential for the different spread of fire and damage classes, including weighted average area damage

In *Residential buildings*, sprinkler systems significantly reduce the fire spread, with 70.79% of fire being confined to the room of origin, compared to 44.41% in the un-sprinklered case (Table 52 and Figure 87) with the average damage being 4.92 m^2 for the presence of automatic extinguishing systems compared to 35.69 m^2 for their absence.

In *Mercantile, Business*, one sprinklered fire incident (confined to floor of origin, significant damage) has been neglected since its median value (103,122 m^2) was higher than the others.

For fire frequency, sprinklers again limit fire spread to the room of origin in 74.62% of fires, compared to 46.28% in un-sprinklered buildings (Table 53 and Figure 88). In un-sprinklered fires, there is a 42.41% chance that the fire will spread to the whole building and cause an average of 191.41 m^2 of damage. When sprinklers are absent, the average damage recorded in the Heavy and Extreme class is equal to 300.41 m^2 and 341.46 m^2, respectively.

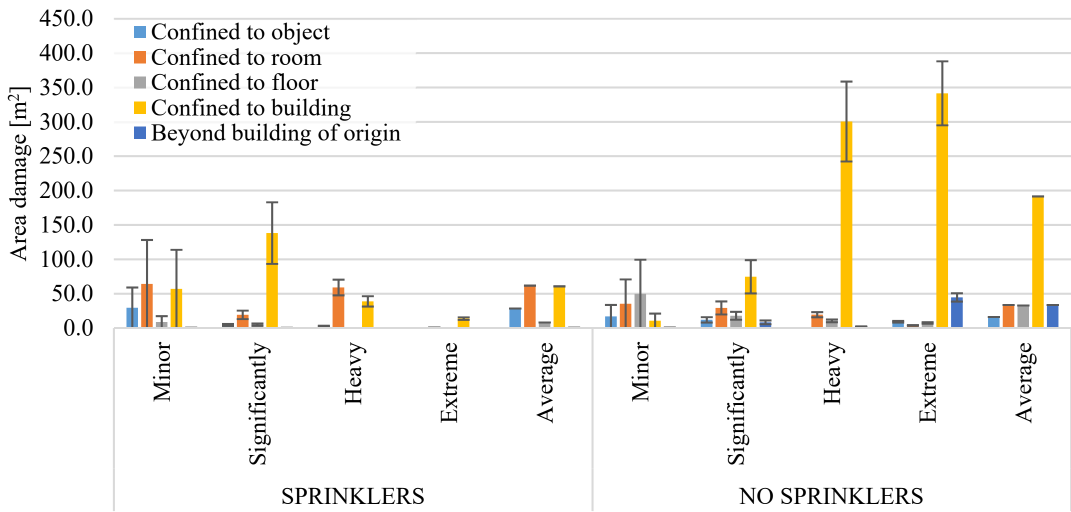


Figure 88: Area damage in Mercantile, Business for the different spread of fire and damage classes, including weighted average area damage in USA statistics

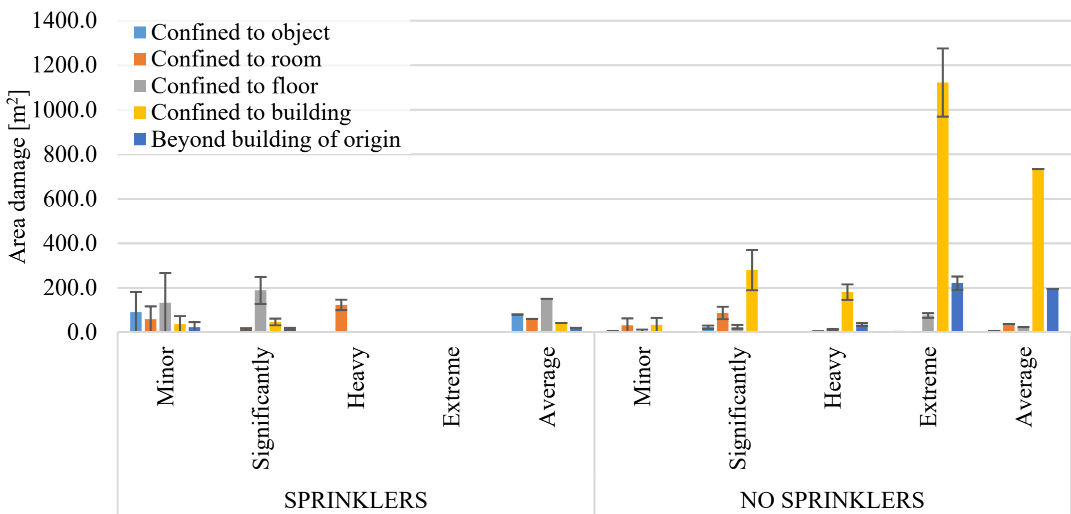


Figure 89: Area damage in Industrial, Utility, Defence, Agricultural, and Mining for the different spread of fire and damage classes, including weighted average area damage in USA statistics

In *Industrial, Utility, Defence, Agricultural, Mining*, 4 fire incidents for spread confined to floor, 5 for spread confined to building and 3 for spread beyond the building of origin in the presence of sprinklers are recorded and consequently, considerations are focused on the data when sprinklers are absent. For un-sprinklered buildings, in 54.73% of cases (Table *54* and Figure 89) fire affects the whole buildings with related average area damage of 734.02 m^2

mainly in the realm of Extreme damage (1,122.31 m^2 related to the spread confined to the building).

In *Manufacturing, Processing*, 69% of fires are confined to the room of origin when sprinklers are present and 37% when they are absent (Table 55 and Figure 90). For sprinklered and un-sprinklered buildings, the damage class is usually Minor, however, peaks are seen for Significantly damage of 2,856.61 m^2 of area damage confined to building for sprinklers and Extreme damage of 2,007.78 m^2 confined to building for the absence of sprinklers. For sprinklered and un-sprinklered buildings, the highest average area damage is reached for spread confined to building with 843.41 m^2 and 839.56 m^2, respectively.

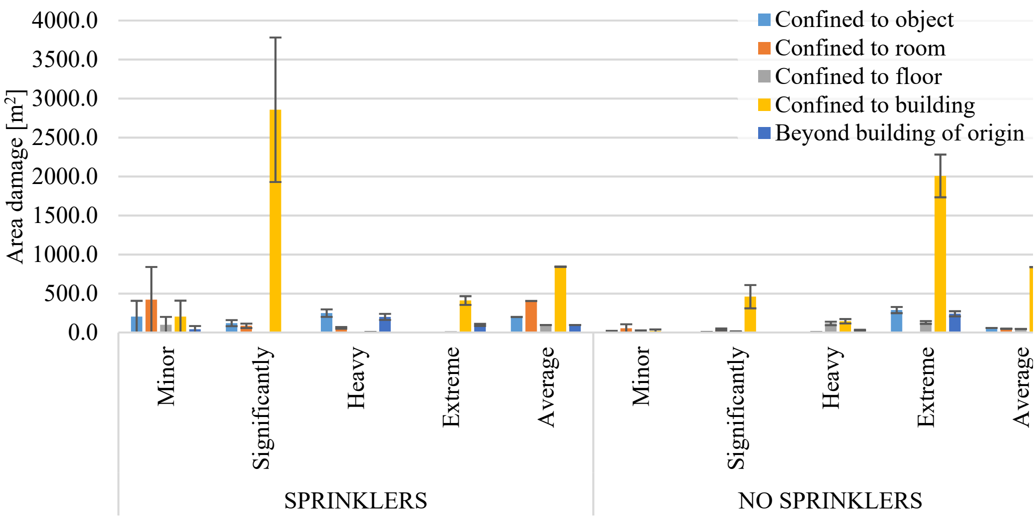


Figure 90: Area damage in Manufacturing, Processing for the different spread of fire and damage classes, including weighted average area damage in USA statistics

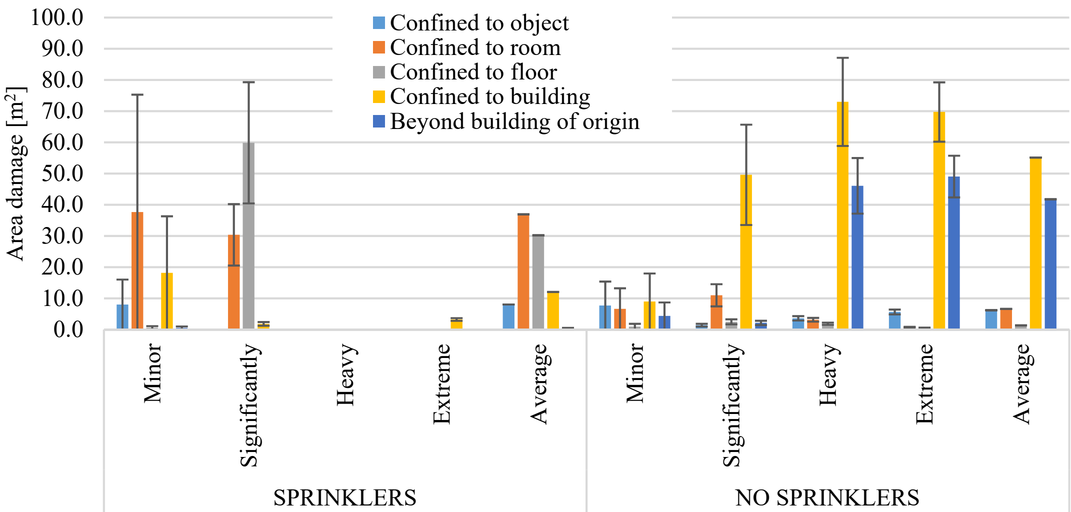


Figure 91: Area damage in Storage for the different spread of fire and damage classes, including weighted average area damage in USA statistics

Finally, *Storage* has limited data for sprinklers so comments are focused on un-sprinklered ones. When the building is not equipped with sprinklers, almost 79% of fires spread beyond the floor of origin and are more likely to cause Heavy or Extreme damage (Table 56 and Figure 91). The average area of damage for un-sprinklered Storage building is 41.30 m^2.

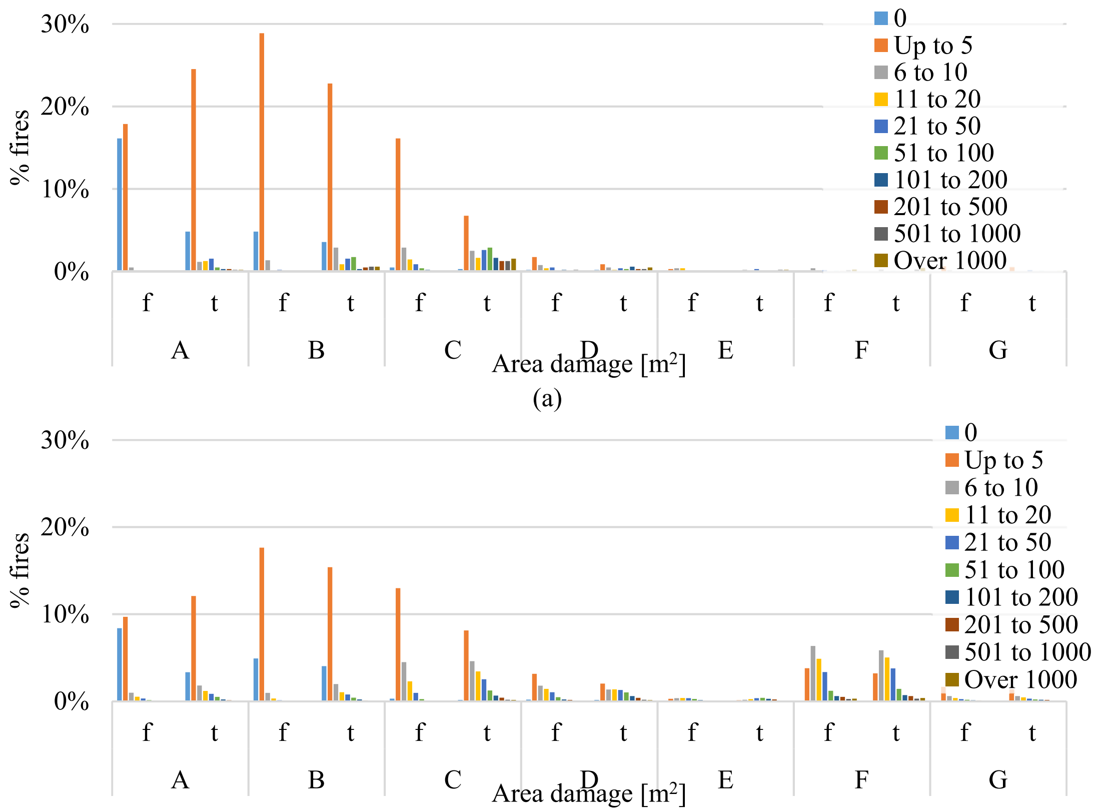
The evaluation developed in this section represents an extension of Table A.4-5 of PD 7974-7 considering other property types. From the analysis developed in this section and based on the considerations affirmed above, the property types for which sprinklers are effective and their action limits fire and spread, are *Educational*; *Health care, Detention and Correction*; *Industrial, Utility, Defence, Agricultural, Mining*; and *Storage*. Automatic extinguishing systems appear to limit the damage but not the spread in *Assembly*; *Residential*; and *Mercantile, Business*. However, only flame damage is recorded and no indication is provided about the damage caused by the sprinkler systems, firefighting activities or smoke. The limited number of fires recorded for fire incidents in the presence of sprinklers creates a high degree of uncertainty in the analysis and future implemented fire incident datasets could validate these trends.

5.4.4 Area damage and percentage of fires in English fire statistics

For the analyses of the area damage and percentage of fire in English statistics, the *Other buildings* dataset with data from 2010/11 to 2016/17 has been investigated and it is described in detail in section 5.1. The property types available have been reclassified according to six general classes of *Commercial*, *Educational*, *Industrial*, *Utility*, *Leisure* and *Miscellaneous*.

Table A.4 and A.5 of PD 7974-7 have been improved considering other property types and classifying the area damage in banded classes of m^2 according to various fire spread classes and presence or absence of sprinklers while other safety systems have not been considered. In English dataset, not only *fire damage* is recorded but also *total damage* and their definition have been introduced in section 5.4. For each fire spread class, the percentages of fires are shown in terms of *fire* and *total damage* and m^2 of area damage providing a more detailed analysis than the one developed for USA statistics. The class of fire spread of 'No fire damage' should indicate negligible fire spread. However, in the fire statistics dataset, m^2 of area damage are often available and usually up to 10 m^2 for *fire damage* and involving greater m^2 of *total damage*. 'No fire damage' class could be interpreted as the damage caused only by smoke, heat or water, however, this is not specified in the dataset. This field should be better explained in the future versions of the IRS. The related results obtained have not been removed to guarantee a complete description of the information of the database, however, it is suggested to consider the data cautiously and associating a high degree of uncertainty. The total number of fires is considered to evaluate the percentages in the fire spread classes and not the number of fires of a specific class.

Starting with *Commercial*, this general property type class includes those of Shed/Garage/Greenhouse/Summer house; Petrol station; Hotel/Motel; Pub/Wine bar/Bar; Retail; Offices and call centres; Temporary office; Bank/Building Society; Restaurant/Café; Takeaway/Fast food; Shopping Centre; Warehouses and bulk storage; Vehicle Repair. The total number of fires recorded are 1,036 and 58,154 for presence or absence of sprinklers, respectively. According to Figure 92, the distribution of fires appears similar in the smaller classes of fire spread where peaks are different in values but usually characterized by the majority of fires represented by the area damage of 0 m^2 or up to 5 m^2 for both *fire* and *total damage*. The highest peak is reached in the class of spread limited to the item first ignited where fire damage assumes 28.86% and 17.63% for sprinklers or no sprinklers, respectively. The difference between presence and absence of sprinklers is when automatic extinguishing systems are absent, fires are more likely to affect the whole buildings or more than two floors where the area damage between 21 and 50 m^2 presents approximately 3.5%.

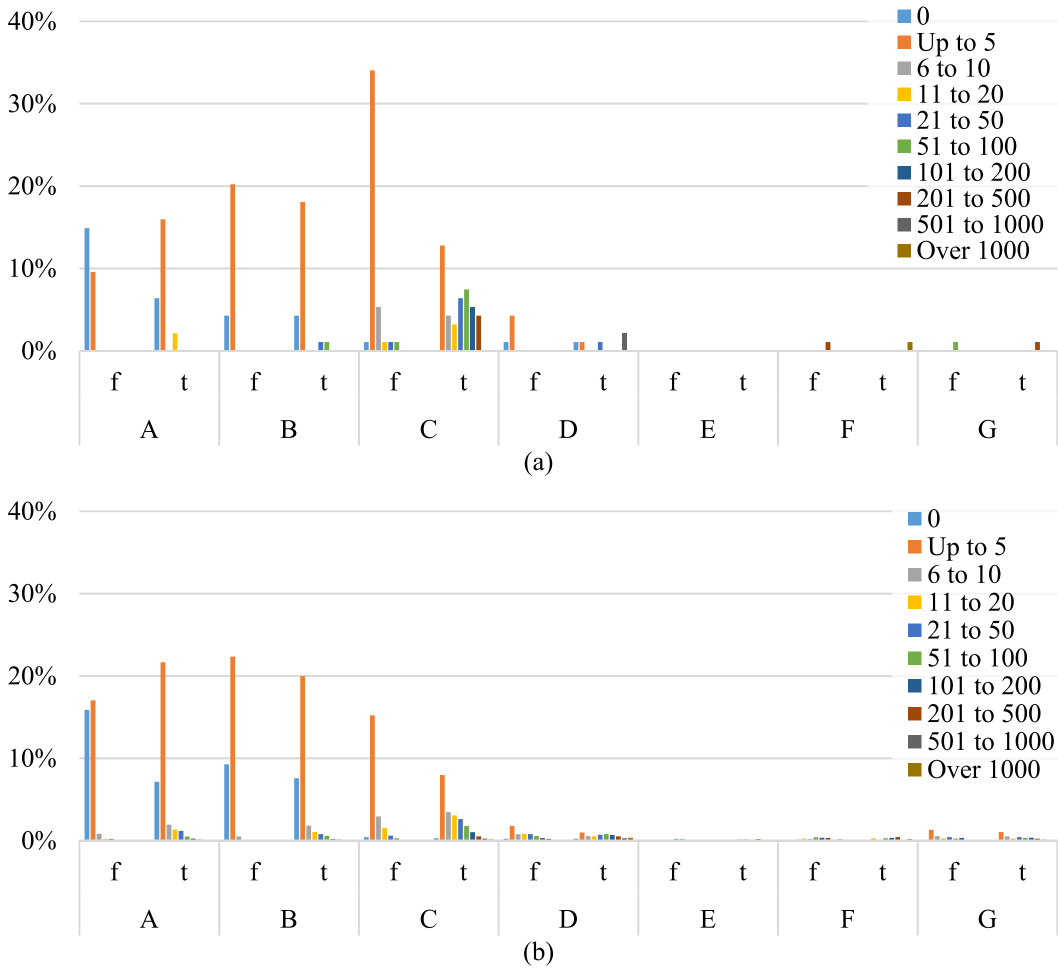


(b)

A. No fire damage; **B**. Limited to item ignited; **C**. Limited to room of origin; **D**. Limited to floor of origin; **E**. Limited to two floors; **F**. Whole building/ more than two floors; **G**. Roofs/Roof spaces; **f**. Fire damage; **t**. Total damage

Figure 92: Area damage in Commercial for the different spread of fire and damage classes in (a) sprinklers, (b) no sprinklers in English statistics

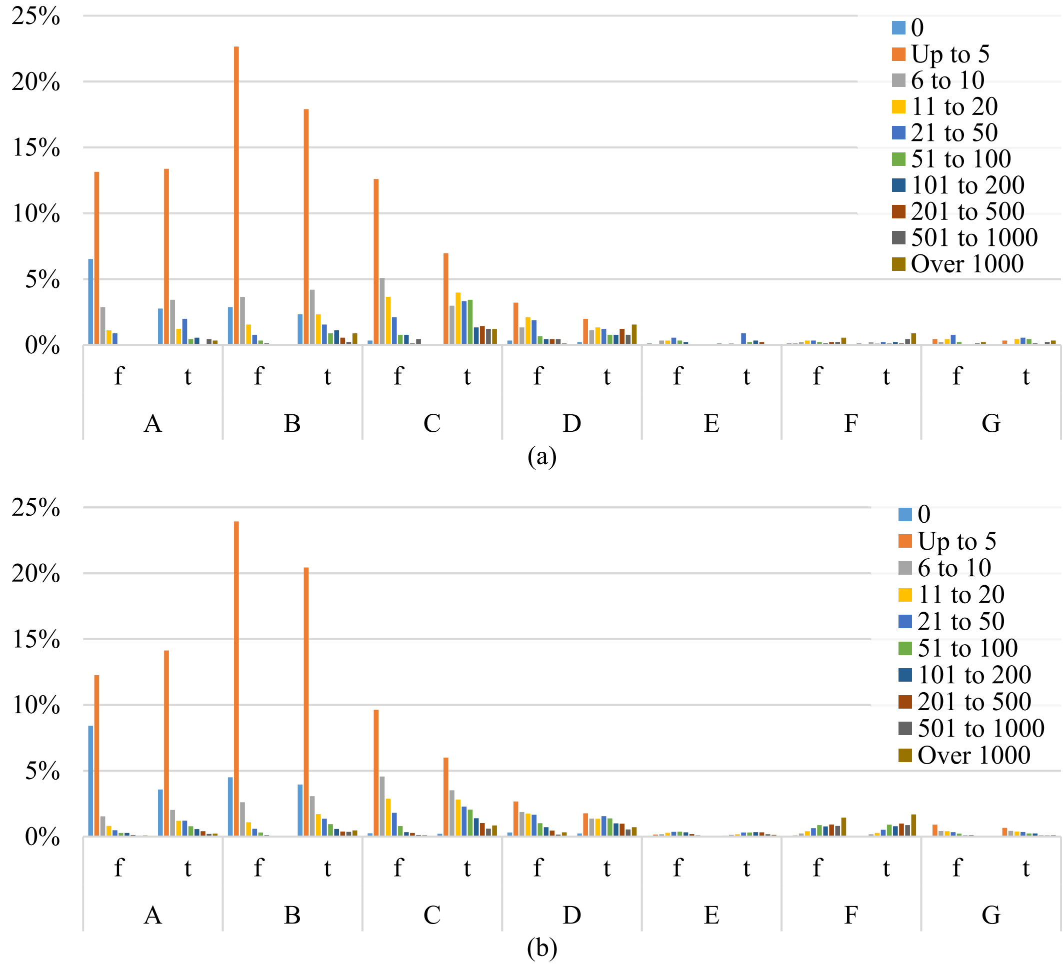
In *Educational* buildings, the property types of Pre-school, Nursery, Infant and primary schools; Secondary schools; College/Universities and Other Educational Establishment of the Home Office dataset are included. While 4,990 fires are collected for the absence of sprinklers, for buildings equipped with sprinklers only 94 fires are recorded. When sprinklers are investigated, a peak of 34.04% of fires is shown for *fire damage* up to 5 m^2 considering spread limited to the room of origin while when sprinklers are absent in the same class, *total damage* assumes percentages greater than 4% for area damage exceeding 20 m^2. Due to the limited number of fires recorded, the results need to be considered with a high degree of uncertainty. In no sprinklers, moving towards greater fire spread classes, greater m^2 of area damage appear to be relevant reaching approximately 3% for 11 to 20 m^2 when the spread is limited to the room of origin (Figure 93).



A. No fire damage; **B**. Limited to item ignited; **C**. Limited to room of origin; **D**. Limited to floor of origin; **E**. Limited to two floors; **F**. Whole building/ more than two floors; **G**. Roofs/Roof spaces; **f**. Fire damage; **t**. Total damage

Figure 93: Area damage in Educational for the different spread of fire and damage classes in (a) sprinklers, (b) no sprinklers in English statistics

The class of *Industrial buildings* is composed of four property types present in the Home Office fire statistics which are: Factory, Industrial manufacturing (not including factory), Industrial processing (not including recycling centre) and Recycling centre. The fires recorded are 905 for the presence of sprinklers and 9,346 for their absence and despite the difference in numbers, results appear similarly distributed with a peak of approximately 23% in *fire damage* and 19% in *total damage* in spread limited to the item first ignited (Figure 94) considering sprinklers and no sprinklers. The main difference is given by the spread involving the whole building or more than two floors that while for the presence of sprinklers is negligible, it assumes approximately a 1.5% for area damage over 1,000 m^2 for no sprinklers (Figure 94).

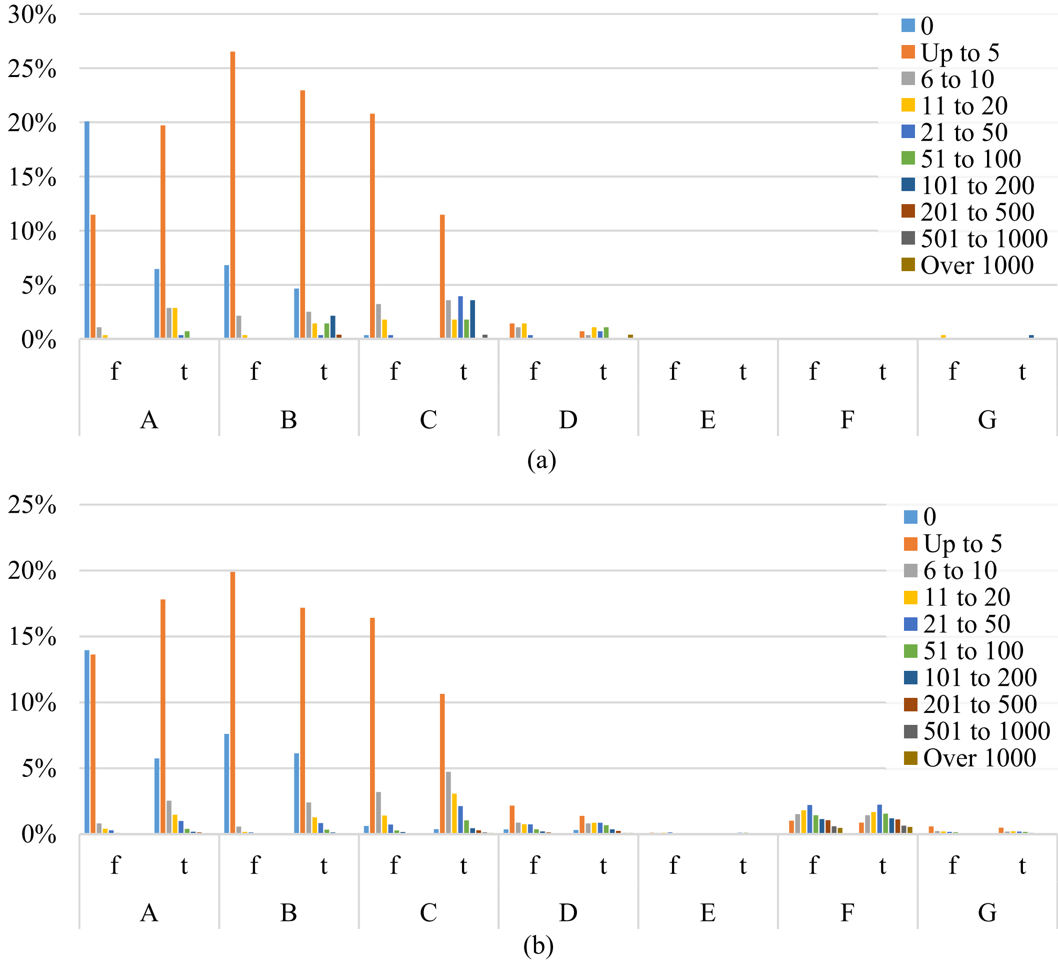


A. No fire damage; **B**. Limited to item ignited; **C**. Limited to room of origin; **D**. Limited to floor of origin; **E**. Limited to two floors; **F**. Whole building/ more than two floors; **G**. Roofs/Roof spaces; **f**. Fire damage; **t**. Total damage

Figure 94: Area damage in Industrial for the different spread of fire and damage classes in (a) sprinklers, (b) no sprinklers in English statistics

In *Miscellaneous* the following property types are grouped: Hospital; Retirement Care Home; Medical care (not including Hospital); Nursing/Care Home; Public admin, security and safety; Public Utilities; Prison / Young Offenders Unit; Hostel; Residential (not a dwelling); Sheltered

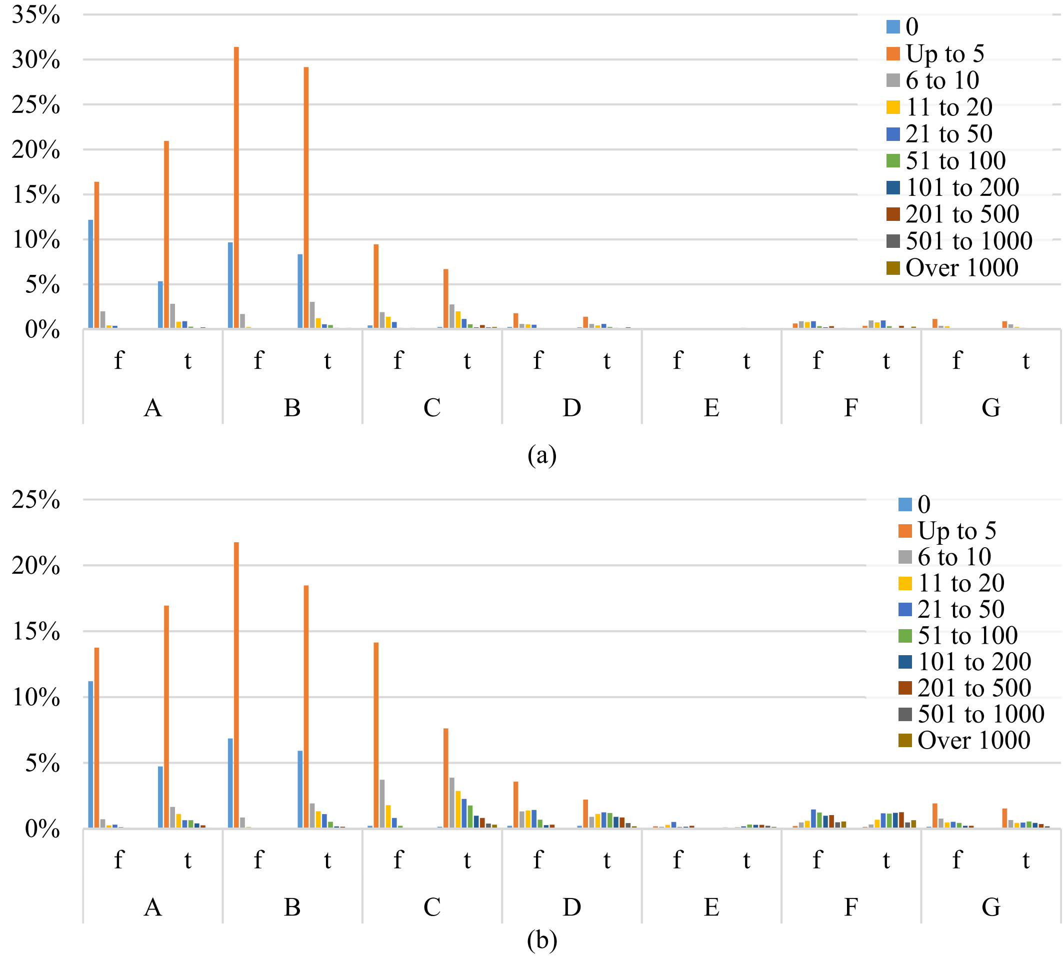
Housing - not self-contained; Other Residential Home; Permanent Agricultural and Others. The number of fires recorded is 279 for the presence of sprinklers and 36,178 when sprinklers are absent. When buildings are not equipped with sprinklers, no fires are recorded which spread beyond the floor of origin with peaks greater than 22% in the class of fire limited to the item first ignited for *fire* and *total damage* (Figure 95 (a)). For the absence of sprinklers, it appears that relevant percentages of fires affect the whole building or more than two floors with an approximately 2% for area damage from 21 to 50 m^2 (Figure 95 (b)).



A. No fire damage; **B**. Limited to item ignited; **C**. Limited to room of origin; **D**. Limited to floor of origin; **E**. Limited to two floors; **F**. Whole building/ more than two floors; **G**. Roofs/Roof spaces; **f**. Fire damage; **t**. Total damage

Figure 95: Area damage in Miscellaneous for the different spread of fire and damage classes in (a) sprinklers, (b) no sprinklers in English statistics

The general property types of *Utilities* includes Transport buildings while the one of *Leisure* considers Entertainment and Culture; Casino/Club/Nightclub; Student Hall of Residence; Church/Chapel/Cathedral; Temple; Mosque; Synagogue; Other Religious; Sporting venues. The fires are 61 and 2,360 in *Utilities* and 49 and 5,886 in *Leisure* for presence and absence of sprinklers, respectively. Due to the limited number of data present for the presence of sprinklers, the analysis is focused on the results for their absence as shown in Figure 96. The distribution of up to 5 m^2 of area damage in the various fire spread classes appears similar for the two property types with values approximately less than 10% in *Leisure* than those found for *Utilities*. The main difference appears in the classes of spread limited to the room of origin and floor of origin where relevant percentages of area damage greater than 6 m^2 are present in *Leisure* while for *Utilities* they are negligible.



A. No fire damage; **B**. Limited to item ignited; **C**. Limited to room of origin; **D**. Limited to floor of origin; **E**. Limited to two floors; **F**. Whole building/ more than two floors; **G**. Roofs/Roof spaces; **f**. Fire damage; **t**. Total damage

Figure 96: Area damage for the different spread of fire and damage classes only for no sprinklers in (a) Utilities and (b) Leisure in English statistics

While the distribution of fire percentages appears similar in small classes of fire damage for presence and absence of automatic extinguishing systems, when buildings are not equipped with sprinklers, a relevant number of fires is recorded affecting more than the floor of origin with area damage greater than 50 m^2. Therefore, in English fire statistics, as for USA fire statistics, the presence of sprinklers appears to limit fire spread, however, data need to be treated carefully considering the uncertainties due to the limited number of fires recorded.

5.5 Frequency distribution of area damage

Tables A.6, A.7 and A.8 in PD 7974-7 describe the frequency distribution of area damage in terms of the number of fires and percentage of fires exceeding banded area damage according to specific fire origins of *Offices*, *Retail premises* and *Hotels*. The area damage classes vary from 1 m^2 and under to 1,000 m^2 and above. Even in these tables, values are classified according to the presence or absence of sprinklers and the data of PD 7974-7 are based on UK Fire Statistics from 1979 and 1984 to 1987. It is not clear if the data for the 5 years are grouped.

Table 28: Fire origin locations of Table A.6-7-8 recreated with USA and English statistics

		Fire origin locations	
Tables	PD 7974-7	USA	England
A.6	Office rooms	Office	Meeting room/Office
	Other rooms	All other fire origins	All the other fire origins
A.7	Assembly areas	Assembly or Sales Areas (Group of people)	Meeting room/Office; Corridor/Hall/Open Plan Area/Reception area
	Storage areas	Storage areas	Store room/Laundry room/Cloakroom; Refuse store
	Other areas	All other fire origins	All other fire origins
A.8	Assembly areas	Assembly or sales Areas (Group of people)	Corridor/Hall/Open Plan Area/Reception Area; Meeting Room/Office
	Bedrooms	Bedroom for less than five people (includes jail or prison cells, lockups, patient rooms, sleeping areas); Bedroom for more than five people (includes barracks, dormitories, patient wards)	Bedroom/Bedsitting room
	Storage and other areas	All the other fire origins	Store room/Laundry room/Cloakroom; Refuse store

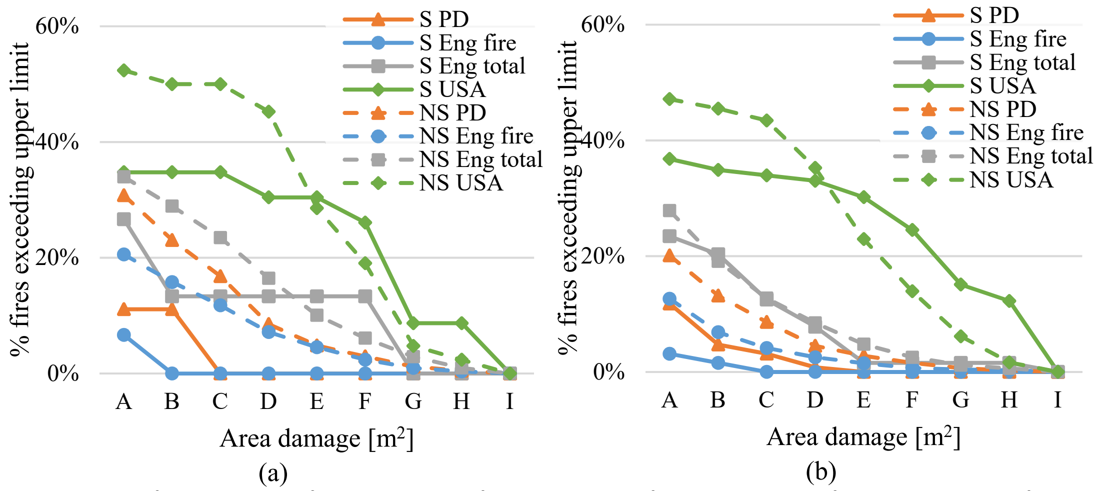
The property types in Tables A.6-7-8 of PD 7974-7 have been recreated adopting USA and English statistics respectively as follows: *Offices* as Business office – Offices and call centres; *Retail premises* as Mercantile, Business - Retails; and *Hotels* as Hotel/Motel, commercial and Boarding/Rooming house (including residential hotels and shelters) – Hotel/Motel. The fire origin locations adopted for the two statistics are summarized in Table 28.

While in USA fire statistics only *fire damage* is present, in English fire statistics there is a distinction between *fire* and *total damage* which are both considered in the following analysis. Unfortunately, in PD 7974-7 it is not specified if the values are referred to *fire* or *total damage*.

5.5.1 Office buildings

Table A.6 of PD 7974-7 considers *Office buildings* according to the fire origin locations of <u>Office rooms</u> and <u>Other rooms</u> recreated adopting Office and Meeting rooms for the first location and all the other fire origins in the second one for USA and English statistics, respectively (as explained in section 5.5).

Table 57 in the Annex for the presence of sprinklers in Other rooms, fires exceeding 1 m^2 of damage are equal to 25.2% in PD 7974-7 and 37.74% in the **USA** statistics. However, a non-negligible 12.26% fires are exceeding 999 m^2 of damage in the NFIRS. In Other rooms with the absence of sprinklers, fires with 1 m^2 or less of area damage correspond to 59.2% in PD 7974-7 and 51.64% in the USA. USA fire statistics show 24.18% for damage greater than 50 m^2 while PD 7974-7 provide only 2.8%.



A. Up to 5 m^2; **B**. 6 to 10 m^2; **C**. 11 to 20 m^2; **D**. 21 to 50 m^2; **E**. 51 to 100 m^2; **F**. 101 to 200 m^2; **G**. 201 to 500 m^2; **H**. 501 to 1000 m^2; **I**. Over 1000 m^2

Figure 97: Frequency distribution of area damage in Office buildings in (a) Office rooms and (b) Other rooms [S=Sprinklers; NS=No sprinklers] for PD 7974-7, English and USA statistics

For **England** Office rooms, there are 18 and 1,860 fires in PD 7974-7 while in English statistics 15 and 1,342 fires for presence and absence of sprinklers, respectively. In Other rooms, PD 7974-7 collects 127 and 4,369 while English statistics 64 and 3,051 for buildings equipped and not equipped with sprinklers, correspondingly (Table 58 in the Annex). In Office rooms, no consideration is expressed for the presence of sprinklers due to the limited number of fires recorded while for the absence of sprinklers, percentages of fires exceeding upper limits are similar for PD 7974-7 and English *fire damage* and slightly different for English *total damage*. In Other rooms for the presence of sprinklers, while for PD 7974-7 fires never exceed 50 m^2, when *total damage* is evaluated in England 7.81% is found for the same area damage class. When sprinklers are absent, fires determine higher fire damage reaching the possibility of exceeding 999 m^2 of 0.3% in PD 7974-7 and approximately 0.5% in England (Table 58 in Annex).

According to Figure 97, for both fire origin locations, similar consideration can be affirmed as English *fire damage* is lower and *total damage* is greater than the tendency found for PD 7974-7*,* where the frequency of fire exceeding the damage bands upper limit for sprinklers is usually less than 30%. USA statistics trend appears far from the prediction provided by PD 7974-7 which is similar to the one described by the English *fire* and *total damage*.

5.5.2 Retail premises

Table A.7 of PD 7974-7 presents *Retail premises* according to three fire origin locations as Assembly areas, Storage areas and Other areas reproduced with current fire statistics as explained in section 5.5.

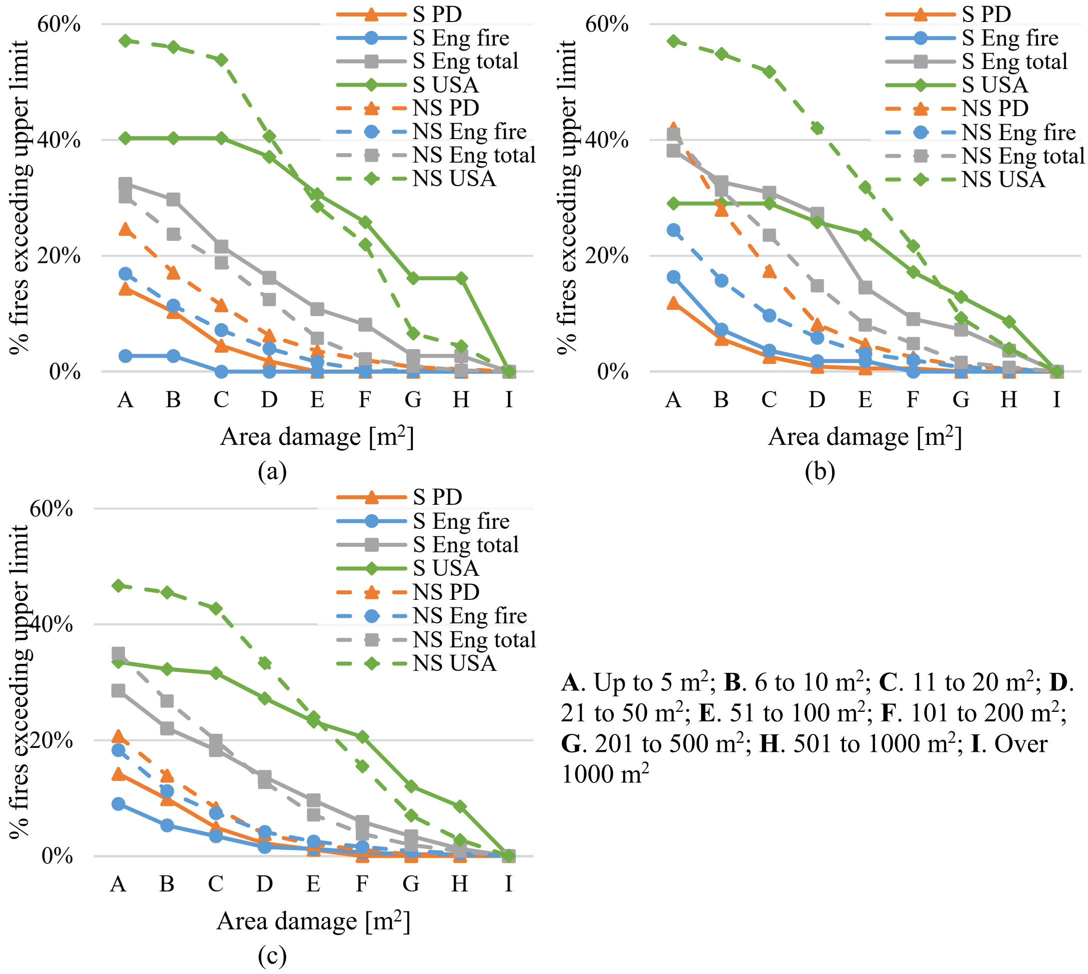


Figure 98: Frequency distribution of area damage in Retail premises in (a) Assembly areas, (b) Storage areas and (c) Other areas [S=Sprinklers; NS=No sprinklers] for PD 7974-7, English and USA statistics

For **USA** Assembly areas, the total number of fires for sprinklers is 223 (not 224 as incorrectly stated in PD 7974-7) and 62 fires and for no sprinklers 8,207 and 91 fires in PD 7974-7 and USA, respectively. When sprinklers are present in the fire origin of Assembly areas, in the NFIRS 16.13% of fires cause 999 m^2 or more of damage while PD 7974-7 never exceeds the upper limit of the damaged area of 99 m^2. In un-sprinklered Assembly areas, the two statistics present around 50% of fires characterized by damage lower than 1 m^2. Moreover, percentages of fires exceeding the upper limit of 50 m^2 are greater in the USA (28.57%) than in PD 7974-7 28.57% (3.5%) as described in Table 59 in the Annex.

The number of fires for Storage areas is 354 in PD 7974-7 and 93 in the USA for sprinklers and 5,144 in PD 7974-7 and 226 in the USA for unsprinklered (Table 59 in the Annex). Relevant fires exceeding 999 m^2 of the area damaged are recorded in the USA data (8.60%), whereas the area damage in PD 7974-7 is limited to 499 m^2 for the presence of sprinklers. For un-sprinklered Storage areas, more than 50% of fires cause damage greater than 1 m^2 for PD 7974-7 and USA. PD 7974-7 provides 8.1% of fires exceeding 49 m^2 while USA 42.48% for no sprinkles. For incidents causing more than 999 m^2, 3.98% and 0.5% of fires are found in the USA and PD 7974-7, respectively.

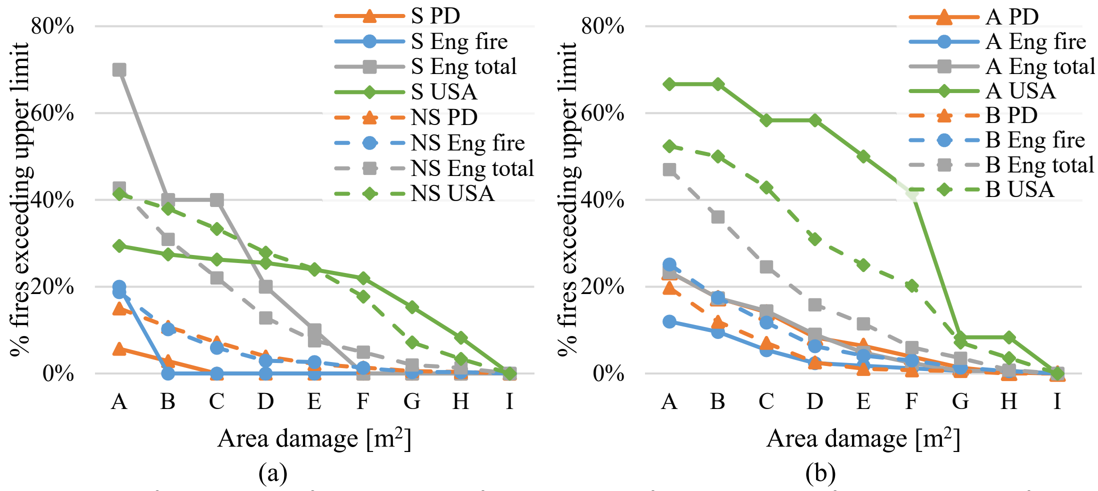
In Other areas, when sprinklers are present, 183 and 7,194 fires are recorded in PD 7974-7 while 573 and 1,542 in the USA for presence and absence of sprinklers, respectively (Table 60 in Annex). For the presence of sprinklers, USA shows 8.6% of fires for area damage exceeding 999 m^2 while fires for PD 7974-7 never exceed 200 m^2. Trends obtained for the absence of sprinklers are similar to those for their presence with higher percentages of damage registered for USA fire statistics with approximately 3% of fires causing more than 999 m^2 compared to 0.1% of PD 7974-7.

In the **England**, when buildings are equipped with sprinklers, 223 and 37 fires in Assembly areas, 354 and 55 in Storage areas and 183 and 322 in Other areas, respectively for PD 7974-7 and English fire statistics. When building with no sprinklers are considered, 8,207 and 851 are the fires in Assembly areas, 5,144 and 1,672 in Storage areas and 7,194 and 9,378 for Other areas in PD 7974-7 and English statistics, respectively. Comments on the fire origin locations are focused on the fields of the absence of sprinklers because they are characterized by a higher number of incidents recorded. In Assembly areas, for PD 7974-7 and English *fire* and *total damage*, there is approximately 18% of fires exceeding 10 m^2 of damage. More fires exceeding 1,000 m^2 are recorded for PD 7974-7 (34) than in England (2 for *total damage* and none for *fire damage*) as shown in Table 61 in the Annex. In Storage areas, values of fires exceeding 50 m^2 are equal to 8.1% for PD 7974-7, 5.86% in English *fire damage* and 14.83% in English *total damage*. Percentages result higher in English *total damage* than those for the other two categories considered (Table 61 in the Annex). For Other areas, there is an approximately 1% in PD 7974-7, 1.5% in English *fire damage* and 4% for English *total damage* of fires exceeding 200 m^2 of area damage as shown in Table 61 in Annex.

The trends for the three fire origin locations are similar where usually the presence of sprinklers has lower values than those for no sprinklers except for *total damage* which provides an opposite trend. As for *Offices*, PD 7974-7 values are generally between the English *fire damage* and the English *total damage*. Greater values are obtained for USA statistics than those for PD 7974-7 and England (Figure 98).

5.5.3 Hotels

The *Hotels* are analysed in Table A.8 of PD 7974-7 according to the fire origin locations of Assembly areas, Bedrooms and Storage and Other areas as described in section 5.5. For Assembly and Bedrooms areas in PD 7974-7, only buildings without sprinklers are considered.



A. Up to 5 m^2; **B**. 6 to 10 m^2; **C**. 11 to 20 m^2; **D**. 21 to 50 m^2; **E**. 51 to 100 m^2; **F**. 101 to 200 m^2; **G**. 201 to 500 m^2; **H**. 501 to 1000 m^2; **I**. Over 1000 m^2

Figure 99: Frequency distribution of area damage in Hotels in (a) Storage and other areas [S=Sprinklers, NS=No Sprinklers] and (b) Assembly areas (A) and Bedrooms (B) only for no sprinklers in PD 7974-7, English and USA statistics

In the analysis based on **USA** statistics for Assembly areas, when sprinklers are absent only 518 and 12 fires are recorded, for Bedrooms 1,196 (not 1,205 as wrongly stated) and 84 fires and for Storage and Other areas, 3,821 and 237 for PD 7974-7 and USA, respectively. Similar results as those obtained for previous analyses are found for buildings not equipped with sprinklers with USA fires more often causing greater area damage than those of PD 7974-7. Indeed, 8.33% in Assembly and 3.57% fires in Bedrooms cause more than 999 m^2 of damage in the USA while for PD 7974-7 the values are approximately null (Table 63 in Annex). In sprinklered Storage areas and other areas, fires recorded in PD 7974-7 never exceed 19 m^2 where 26.27% of fires are recorded in the USA for the same area damage band while when sprinklers are absent, the damage exceeding 999 m^2 is 3.38% in the USA compared to 0.4% in PD 7974-7 (Table 64 in Annex).

In *Hotels* in **English** statistics, in the case of absence of sprinklers, 518 and 167 in Assembly areas and 1,196 and 366 fires in Bedrooms are recorded for PD 7974-7 and English statistics, respectively. In Storage areas, 35 and 10 for the presence of sprinklers and 3,821 and 304 fires in absence of sprinklers are recorded for PD 7974-7 and USA statistics, correspondingly. In the analysis for the absence of sprinklers, the percentages of fires exceeding 10 m^2 are similar for PD 7974-7 and English *total damage* and approximately equal to 17% in Assembly areas (Table 65 in Annex). In Bedrooms, in England, there is a 25% of cases in which fires exceed 20 m^2 for English *total damage* compared to 7% predicted by PD 7974-7 (Table 65 in Annex). In Storage areas, for the presence of sprinklers a limited number of fires is recorded and for buildings without sprinklers fires exceeding 50 m^2 are equal to 4% in PD 7974-7, 2.96% in English *fire damage* and 12.83% in English *total damage* (Table 66 in Annex).

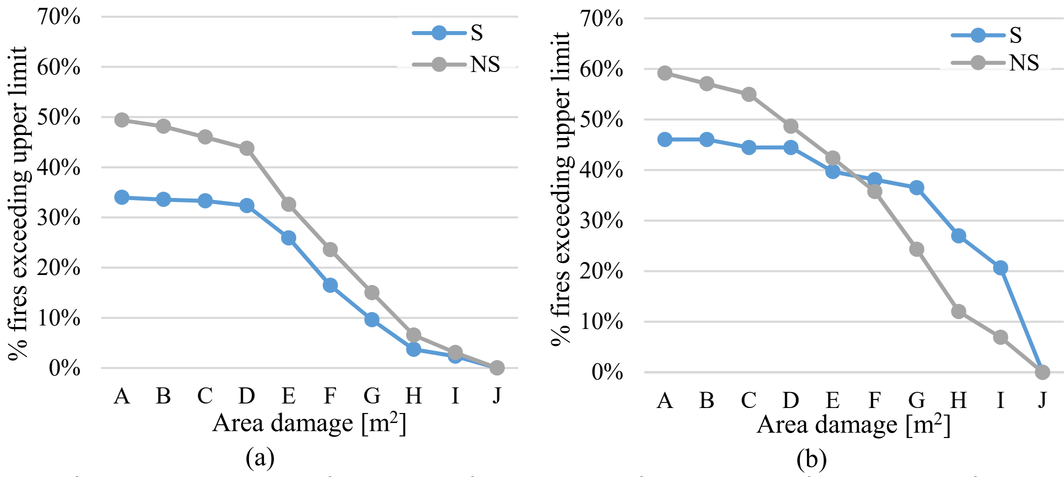
When *Hotels* are analysed in English statistics, similar comments can be affirmed as those found for *Offices* and *Retail premises* with the only difference that Storage areas assumed higher percentage when sprinklers are present than when they are absent and this tendency is possibly due to the limited number of fires recorded. In the three fire origin locations, the percentage of fire exceeding 100 m^2 damage is approximately less than 10%. In this case, USA statistics prediction is similar to the one obtained using English statistics shown in Figure 99.

The results obtained recreating Table A.6-7-8 with USA and English statistics has provided similar results. In general, USA statistics present higher percentages of fires exceeding the upper limit of area damage than those obtained for PD 7974-7 and English statistics which show closer predictions. Usually, PD 7974-7 trend is greater than the one of English *fire damage* and less than the one of English *total damage*. Moreover, PD 7974-7 seems to overestimate the USA statistics.

5.5.4 Frequency distribution of area damage in USA fire statistics

The analysis of Table A.6-7-8 of PD 7974-7 has been extended investigating all the occupancies available in the USA statistics. The various building types show two different tendencies which are represented by *Assembly* and *Industrial, Utility, Defence, Agricultural and Mining* when the presence and absence of sprinklers are investigated.

For *Assembly*, the absence of sprinklers determines an increase in the percentages of fires that cause higher area damage. The prediction for the absence of safety systems (Figure 100 (a) and Table 67 in the annex) is greater than approximately 15% for 1 m^2 and 3% for 200 to 499 m^2 than the one for the presence of sprinklers. However, the trend for the presence of automatic extinguishing systems is always less than the one for their absence. This tendency is also assumed by the property type of *Educational* (Figure 139 and Table 68 in Annex) and *Health Care, Detention and Correction* (Figure 139 and Table 69 in Annex).



A. 1 m^2 and under; **B**. 2 to 4 m^2; **C**. 5 to 9 m^2; **D**. 10 to 19 m^2; **E**. 20 to 49 m^2; **F**. 50 to 99 m^2; **G**. 100 to 199 m^2; **H**. 200 to 499 m^2; **I**. 500 to 999 m^2; **J**. 1000 m^2 and above

Figure 100: Frequency distribution of area damage in (a) Assembly and (b) Industrial, Utility, Defence, agricultural and Mining [S=Sprinklers; NS=No sprinklers] in USA statistics

In *Industrial, Utility, Defence, Agricultural and Mining*, the prediction is similar to those present in *Assembly* where percentages of fire exceeding upper limit for the absence of sprinklers are greater than the one for their presence up to 49 m^2. From the class of area damage from 50 to 99 m^2, the tendency reverses and values of fires exceeding upper limits reached a maximum of approximately 15% greater in sprinklered than in un-sprinklered buildings (Figure 100 (b) and Table 72 in Annex). Similar tendencies are seen in *Residential* (Figure 139 and Table 70 in Annex), *Mercantile, Business* (Figure 139 and Table 71 in Annex), *Manufacturing and Processing* (Figure 139 and Table 73 in Annex) and *Storage* (Figure 139 and Table 74 in Annex). In the above-mentioned property types, the trend reverses in the class of area damage from 100 to 199 m^2 except for *Mercantile, Business* for which it starts from 50 to 99 m^2 and *Storage* from 10 to 19 m^2. The less rapid decrease towards greater classes of area damage in the presence of automatic extinguishing systems could be due to sprinklers not effective or to the limit number of fires recorded.

5.5.5 Frequency distribution of area damage in English fire statistics

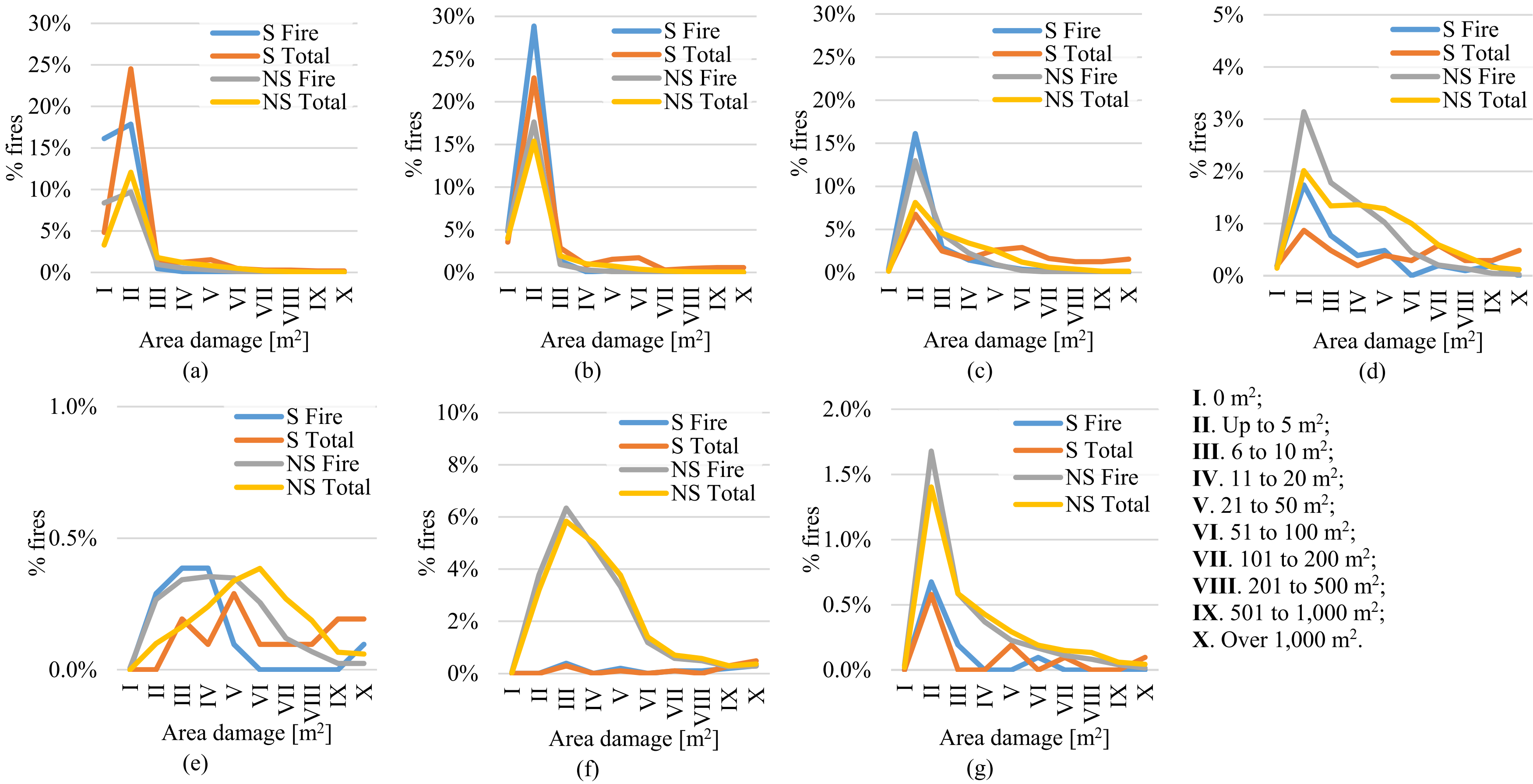
Table A.6, A.7 and A.8 of the PD 7974-7 have been implemented adopting English fire statistics considering not only percentages of fire according to area damage in m^2 but also based on the classes of fire spread. Due to the increased complexity of the analysis, percentages of fires for each class are considered instead of percentages of fire exceeding the upper limit of the area damage bands (from 0 m^2 to over 1,000 m^2) for presence and absence of sprinklers. The percentages of *fire damage* in the various fire spread classes are obtained considering the total number of fires and the same approach has been adopted for those of *total damage*. As discussed in section 5.4.4, ‘No fire damage’ should indicate negligible fire spread but it presents m^2 of area damage up to 10 m^2 for *fire damage* and involves greater m^2 of *total damage*. The 'No fire damage' class is not specified in the dataset and could be interpreted as the damage caused only by smoke, heat or water. The results obtained have not been removed to guarantee a complete description of the database but it is suggested to treat the data carefully. This field should be better explained in the future versions of the IRS questions.

The *Other buildings* dataset with data from 2010/11 to 2016/17 has been examined and it is described in detail in section 5.1. The property types available in English statistics have been reclassified according to six general classes of *Commercial*, *Educational*, *Industrial*, *Utility*, *Leisure* and *Miscellaneous* as explained in section 5.4.4. The total number of fires recorded for each general property type mentioned above are summarized in Table 29 for sprinklers and no sprinklers. The analysis in this section is focused on *Commercial* and *Industrial* while for *Educational*, *Utilities* and *Miscellaneous*, the graphs for these property types are introduced in Figure 140, Figure 141, Figure 142 and Figure 143 in Annex, due to the limited number of fires for the presence of sprinklers recorded.

Table 29: Fire incidents in the general property types of English statistics

	Fire incidents	
Property types	Sprinklers	No sprinklers
Commercial	1,036	58,154
Educational	94	4,990
Industrial	905	9,346
Utilities	61	2,360
Leisure	49	5,886
Miscellaneous	279	36,178

For *Commercial* buildings, in the class of spread limited to the item first ignited the percentages of fires are mainly confined up to 10 m^2 with a peak of approximately 25% for area damage up to 5 m^2 (Figure 101 (b)) for both *fire* and *total damage* despite the presence or absence of sprinklers. In the class of spread limited to the room of origin (Figure 101 (c)), the highest values are assumed by *fire damage* for presence and absence of automatic extinguishing systems with a value of approximately 15% which is lower than the one found for the previous fire spread class. The tails of the prediction have higher values and consequently, the area under the curves becomes greater showing higher area damage recorded. This area tends to increase, moving towards fires affecting more than two floors (Figure 101 (e)). When fire affects the whole buildings (Figure 101 (f)), the relevant percentages of fires recorded are only those for the absence of sprinklers with a peak of approximately 6% for 6 to 10 m^2 of damage. Therefore, the presence of sprinklers appears to reduce the fire spread and the area damage. However, usually, *fire damage* assumes slightly greater values than those available for *total damage*.



a. No fire damage; **b**. Limited to item ignited; **c**. Limited to room of origin; **d**. Limited to floor of origin; **e**. Limited to two floors; **f**. Whole building/ more than two floors; **g**. Roofs/Roof spaces; **S**. Sprinklers; **NS**. No Sprinklers; **Fire**. Fire damage; **Total**. Total damage

Figure 101: Frequency distribution of area damage in Commercial [S=Sprinklers; NS=No sprinklers] in English statistics

I. 0 m^2;
II. Up to 5 m^2;
III. 6 to 10 m^2;
IV. 11 to 20 m^2;
V. 21 to 50 m^2;
VI. 51 to 100 m^2;
VII. 101 to 200 m^2;
VIII. 201 to 500 m^2;
IX. 501 to 1,000 m^2;
X. Over 1,000 m^2.

a. No fire damage; **b**. Limited to item ignited; **c**. Limited to the room of origin; **d**. Limited to the floor of origin; **e**. Limited to two floors; **f**. Whole building/ more than two floors; **g**. Roofs/Roof spaces; **S**. Sprinklers; **NS**. No Sprinklers; **Fire**. Fire damage; **Total**. Total damage

Figure 102: Frequency distribution of area damage in Industrial [S=Sprinklers; NS=No sprinklers] in English statistics

In *Industrial*, the same considerations found for *Commercial* can be applied where *fire* and *total damage* assume similar trends for presence or absence of sprinklers with area damage well confined up to 20 m^2 and peaks on average equal to 22% in fire limited to the item first ignited (Figure 102 (b)) and 9% in spread limited to the room of origin (Figure 102 (c). When the analysis considers greater fire spread classes, the tails of the predictions involve greater area damage and percentages continue to appear similar for *fire* and *total damage* for buildings equipped and not equipped with sprinklers with values below 3% in spread limited to the floor of origin and below 1% in spread limited to two floors (Figure 102 (d) and (e)). Finally, when a fire affects the whole building (Figure 102 (f)), percentages of *fire* and *total damage* for the absence of sprinklers are almost 1% greater than the one for their presence for area damage from 201 to 501 m^2 showing relevant percentages of fires significantly affecting the building.

In general, *fire* and *total damage* for presence and absence of sprinklers assume similar values in classes of fire spread confined to item or room of origin. Moving towards higher fire spread classes, the percentages for the absence of sprinklers are greater than the one for their presence and the area damage under the curve increases towards classes of greater m^2 of damage.

5.6 Average financial loss per fire

Table A.12 of PD 7974-7 describes the average loss per fire in 1966 for different property types. The conversion from the pounds of 1966 in PD 7974-7 to those of 2014 has been evaluated using the Historical UK inflation rate equals to £1:£16.64 (Bank of England Inflation Calculator, 2018). The methodology for the evaluation of the financial losses is not specified in Table A.12 and this research considers the one adopted by the NFRIS to evaluate the fire loss based on the International Code Council's Building Valuation Data (BVD) formula (International Code Council, 2017) and explained in section 2.3.3. Average construction costs per ft^2 are listed for various occupancy types and the total economic loss per fire evaluated thanks to Eq. 1 reported below for clarity:

$$\$\, loss = Total\ ft^2\ of\ damage\ x\ ft^2\ construction\ cost \qquad \text{Eq. 1}$$

Since in English fire statistics no economic losses are available, the average construction costs per ft^2 indicated by the BVD are applied to the damage recorded in the Home Office datasets considering several property types. It is important to specify that the evaluations developed regard the direct financial loss, defined in section 2.4.1, and do not consider the indirect losses as explained in section 2.4.2.

5.6.1 Average loss per fire in the USA

The values present in Table A.12 are compared to USA fire loss data, where the USD to GBP conversion is based on December 2014 exchange rate of $1 - USD=£ 0.607353 - GBP (OFX International Money Transfer and Exchange, 2018).

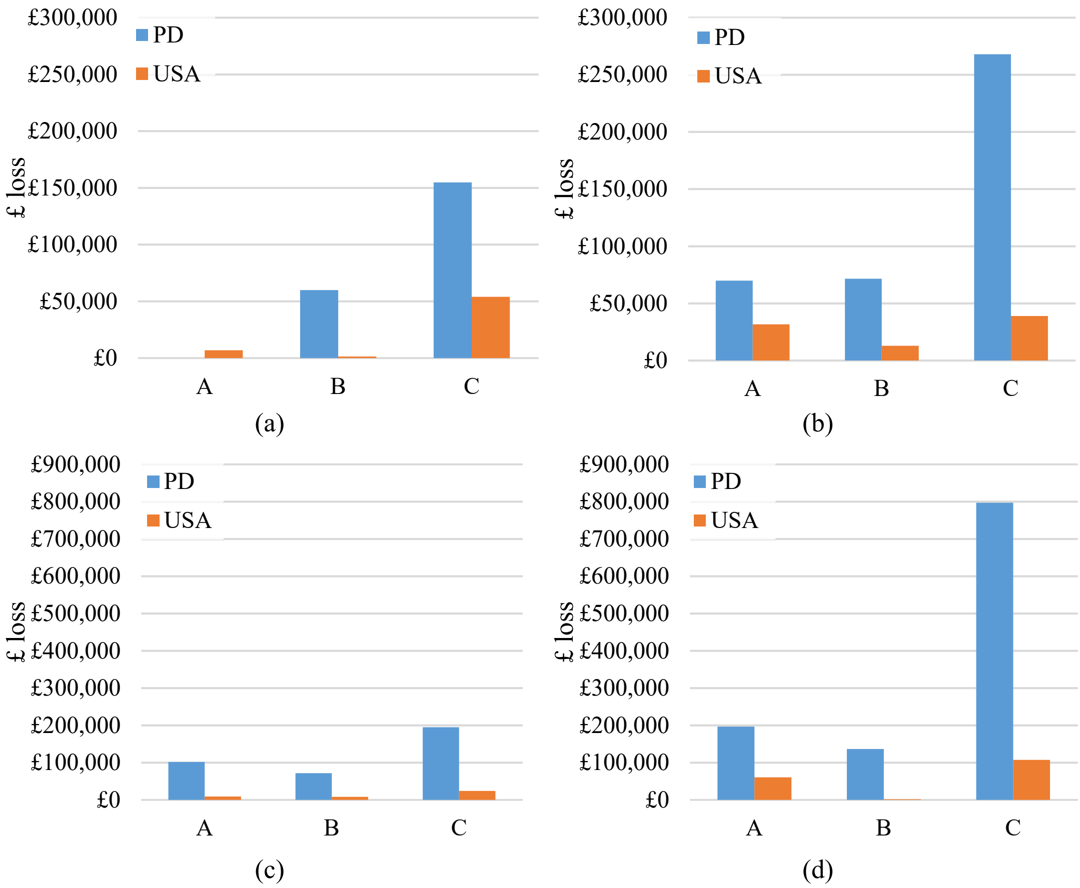
Some property types considered in Table A.12 of PD 7974-7 have been grouped to create a comparison with the closest ones available in the USA fire statistics. Based on the classifications of Table A.12, the property types considered in the NFIRS are described in Table 30. The class of Laboratory or science laboratory in the USA includes chemical, medical, biological, physical materials testing, psychological, electronics, general research laboratories, classrooms and offices incidental to laboratory facilities where minor laboratory areas incidental to operations in another property are considered part of the predominating property.

Table 30: Property types of Table A.12 of PD 7974-7 considered with those of USA statistics

PD 7974-7	USA
Wholesale distributive trades Retail distributive trades	Mercantile, Business
Chemical and allied	Laboratory or science laboratory Gas distribution, gas pipeline Flammable liquid distribution system, flammable liquid pipeline
Timber and furniture Textiles Paper, printing and publishing	Manufacturing and Processing

Focused on the comparisons between the common property types of PD 7974-7 and USA statistics introduced in Table 30, the analysis considers single and multi-storey buildings for the presence or absence of automatic extinguishing systems. According to Figure 103 (a) and (b), for single storey buildings, higher values for financial loss are available in the PD 7974-7 than those provided for the USA fire statistics while, despite the difference in values, in both cases, data indicate that sprinklers appear to reduce the damage recorded and therefore directly the cost. The exception is represented for *Timber and furniture; Textile; Paper, printing and publishing* where the economic losses evaluated for buildings without sprinklers (£38,868.58) are less than those for buildings equipped with sprinklers (£54,014.98) in the USA.

For multi-storeys as for the single storey, the presence of sprinkler systems reduces the financial loss per fire evaluated as shown in Figure 103 (c) and (d) for the three property types considered in Table 30. The difference in values is greater than the one found in the analysis of single-storey and the estimate obtained is approximately up to 4 times greater when sprinklers are absent.



A. Wholesale distributive trades; Retail distributive trades; **B**. Chemical and allied; **C**. Timber and furniture; Textiles; Paper, printing and publishing

Figure 103: Average loss per fire for (a) single storey-sprinklers; (b) single storey-no sprinklers; (c) multy storey-sprinklers; (d) multy storey-no sprinklers in PD 7974-7 and USA fire statistics

The analysis developed in this section considers not only the property types listed in the PD 7974-7 but also those available in the USA statistics as introduced in Table 31. According to Table 31, the presence of sprinklers appears to reduce the direct financial loss per fire. However, some exceptions are present, for single storey buildings in *Outside and special property* (£11,915.87 sprinklered and £7,917.65 in un-sprinklered) and multi-storey in *Industrial, Utility, defence, Agricultural and Mining* (£887,731.46 sprinklered and £45,585.02 un-sprinklered) in USA statistics. Table 31 shows a positive influence of sprinklers in reducing the average loss per fire in the majority of the property types.

The question that arises with these data is that being the reduction for the presence of sprinklers relatively small in some occupancy types, for instance, *Residential* properties where sprinklers reduce the cost of fires by between £4,000 and £8,000 approximately, the cost to benefit ratio of installing sprinkler systems needs to consider whether the benefit of sprinkler systems would outweigh the cost of installation. The analysis developed in this section has been also applied to English statistics to evaluate if similarities are found.

Table 31: Average loss per fire at 1966 for PD 7974-7 converted in 2014 prices and compared to those of USA statistics

	PD 7974-7				USA			
	Sprinklers		No Sprinklers		Sprinklers		No Sprinklers	
floor	Single	Multi	Single	Multi	Single	Multi	Single	Multi
A	/	/	/	/	£9,380.83	£37,035.08	£45,145.31	£58,493.41
B	/	/	/	/	£3,717.46	£8,196.74	£1,485,019.68	£24,578.62
C	/	/	/	/	£1,424.77	£6,724.44	£20,998.87	£46,013.53
D	/	/	/	/	£5,066.74	£19,196.93	£13,701.75	£23,173.02
E								
F	/	£78,208	£63,232	£156,416	£6,795.31	£8,986.39	£31,633.99	£60,274.06
G	/	£23,296	£6,656	£39,936				
H					£9,430.67	£887,731.46	£43,717.78	£45,585.02
I	£59,904	£71,552	£71,552	£136,448	£1,396.91	£8,098.04	£12,893.24	£1,518.38
J								
K	£19,968	£53,248	£39,936	£108,160	£54,014.98	£23,969.37	£38,868.58	£107,086.46
L	£48,256	£58,240	£109,824	£419,328				
M	£86,528	£83,200	£118,144	£269,568				
N	/	/	/	/	£7,792.25	£3,155.40	£11,661.23	£19,487.70
O					£11,915.87	£89,265.71	£7,917.65	£251,522.73

A. Assembly: **B**. Educational; **C**. Health care, detection and correction; **D**. Residential; **E**. Mercantile, Business; **F**. Wholesale and distributive trades; **G**. Retail distributive trades; **H**. Industrial, Utility; Defence; Agricultural and Mining; **I**. Chemical and allied; **J**. Manufacturing, processing; **K**. Timber and furniture; **L**. Textiles; **M**. Paper, printing and publishing; **N**. Storage; **O**. Outside or special property.

5.6.2 Average loss per fire in England

Since no evaluations of financial losses are available in the *Other buildings* dataset in England, the BVD formula of Eq. 1, adopted in the USA fire statistics, has been applied to the fire statistics database published by the Home Office. The conversion between USD to GBP has been realized based on 31st December 2015 in which 1 - USD = 0.674809366 GBP (Bank of England GBP to USD exchange rates, 2019) and the average construction cost in \$ USD/ft^2 transformed in £ GBP/m^2. In the public *Other buildings* dataset with data from 2010/11 to 2016/17, described in detail in section 5.1, only data of 2014/15 have been investigated removing potential errors as inputs where *total damage* is greater than *fire damage*, building floors above the ground level are equal to 0 (e.g. 1 is recorded for a bungalow) or 999 and building floors below the ground level recorded as 999. The property types available in English statistics have been reclassified according to six general classes of *Commercial*, *Educational*, *Industrial*, *Utility*, *Leisure* and *Miscellaneous* as explained in section 5.4.4 and compared to the closest occupancy present in the BVD. Moreover, the area damage is usually listed according to the classification specified in section 5.5.5 from 0 m^2 to over 1,000 m^2 and an average value has been associated with each class. For the evaluation of the area damage for *fire* and *total damage*, the tolerance interval plots for each general property type have been calculated to cover at least the 95% of fires recorded obtaining the lower and upper limits of the area damage which are consequently multiplied by the average cost in £/m^2 to calculate the total direct financial losses. The fires collected in the Home Office dataset have been evaluated considering all fires and according to buildings equipped with or without sprinklers.

In Table 32, similar lower limits for the *fire damage* are found for presence and absence of sprinklers while when upper limits are considered usually in presence of sprinklers values are less than 20 m^2 and for their absence, they reach up to 750.5 m^2. The only two property types in which the upper limit *fire damage* for sprinklers is greater up to 2 times than for no sprinklers are *Commercial* and *Industrial*. However, the limited number of fires recorded when automatic extinguishing systems are present introduce uncertainties in the analysis developed and results need to be treated considering the related uncertainties.

Table 32: Financial losses considering tolerance intervals for fire damage in English statistics

Fire damage						
Property types	fires	Damage [m^2] Lower	Damage [m^2] Upper	£/m^2	Financial loss [£] Lower	Financial loss [£] Upper
General						
Commercial	4888	2.5	150.5	879.50	2,198.74	132,364.36
Educational, Training and cultural	318	2.5	350.5	1,199.40	2,998.50	420,390.04
Utilities	163	2.5	750.5	447.48	1,118.70	335,833.11
Industrial	970	2.5	350.5	639.20	1,597.99	224,038.19
Leisure	404	2.5	350.5	1,313.68	3,284.21	460,446.57
Miscellaneous	2759	2.5	350.5	1,014.81	2,537.03	355,692.29
Sprinklers						
Commercial	81	2.5	350.5	879.50	2,198.74	308,263.84
Educational, Training and cultural	11	2.5	8	1,199.40	2,998.50	9,595.21
Utilities	6	2.5	15.5	447.48	1,118.70	6,935.93
Industrial	81	2.5	750.5	639.20	1,597.99	479,716.58
Leisure	4	2.5		1,313.68	3,284.21	
Miscellaneous	24	2.5	15.5	1,014.81	2,537.03	15,729.62
No sprinklers						
Commercial	4748	2.5	150.5	879.50	2,198.74	132,364.36
Educational, Training and cultural	305	2.5	350.5	1,199.40	2,998.50	420,390.04
Utilities	152	2.5	750.5	447.48	1,118.70	335,833.11
Industrial	839	2.5	350.5	639.20	1,597.99	224,038.19
Leisure	394	2.5	350.5	1,313.68	3,284.21	460,446.57
Miscellaneous	2669	2.5	350.5	1,014.81	2,537.03	355,692.29

In Table 33, the tolerance intervals for *total damage* have been evaluated determining lower and upper limits of damage in m^2 for general classes of property types. If the values for the presence of sprinklers are compared to the one for their absence, usually the estimates of *total damage* are similar. The only exception in which the area for the presence of sprinklers is greater than the one for their absence is found for the upper limits in which in *Commercial* is equal to 750.5 m^2 compared to 350.5 m^2 for buildings with or without sprinklers, respectively. Moreover, upper limits of *total damage* are greater for the absence of safety systems and equal to 750.5 m^2 and 350.5 m^2 compared to 150.5 m^2 for their presence in the property types of *Utilities* and *Miscellaneous*, correspondingly. The reason for this relevant difference is probably attributable to the small number of fires recorded when buildings are equipped with sprinklers which leads to a small population for the analysis.

Table 33: Financial losses considering tolerance intervals for total damage in English statistics

Total damage						
Property types	fires	Damage [m²]		£/m²	Financial loss [£]	
		Lower	Upper		Lower	Upper
General						
Commercial	5,154	2.5	350.5	879.50	2,198.74	308,263.84
Educational, Training and cultural	356	2.5	750.5	1,199.40	2,998.50	900,150.43
Utilities	176	2.5	750.5	447.48	1,118.70	335,833.11
Industrial	1,006	2.5	750.5	639.20	1,597.99	479,716.58
Leisure	429	2.5	750.5	1,313.68	3,284.21	985,920.55
Miscellaneous	3,091	2.5	350.5	1,014.81	2,537.03	355,692.29
Sprinklers						
Commercial	92	2.5	750.5	879.50	2,198.74	660,062.80
Educational, Training and cultural	12	2.5	750.5	1,199.40	2,998.50	900,150.43
Utilities	7	2.5	150.5	447.48	1,118.70	67,345.61
Industrial	84	2.5	750.5	639.20	1,597.99	479,716.58
Leisure	4	2.5	750.5	1,313.68	3,284.21	985,920.55
Miscellaneous	33	2.5	150.5	1,014.81	2,537.03	152,729.50
No sprinklers						
Commercial	5,001	2.5	350.5	879.50	2,198.74	308,263.84
Educational, Training and cultural	341	2.5	750.5	1,199.40	2,998.50	900,150.43
Utilities	163	2.5	750.5	447.48	1,118.70	335,833.11
Industrial	871	2.5	750.5	639.20	1,597.99	479,716.58
Leisure	419	2.5	750.5	1,313.68	3,284.21	985,920.55
Miscellaneous	2,983	2.5	350.5	1,014.81	2,537.03	355,692.29

In English statistics, only in *fire damage,* the financial losses for the presence of sprinklers are less than those found for their absence while this difference is generally not as relevant for *total damage* where results appear similar for the various property types investigated.

5.7 Fatality and casualty rate

Table A.13 of PD 7974-7 describes the discovery time and fatal casualties based on the data of the Fire Statistics of the United Kingdom of 1978-1991 classified according to *Single* and *Multiple occupancy* dwellings. The number of deaths, fires and the fatality rate per fire defined as the number of deaths divided by the number of fires, are evaluated according to the discovery time (Ramachandran, 1993). The classes of discovery times in the PD 7974-7 Table A.13 are listed such as discovery at ignition, under 5 minutes, between 5 and 30 minutes and more than 30 minutes after ignition. The fatality rate is assumed to increase with time-based on a linear relationship according to a constant λ (called increase rate per minute) defined relating the fatality rate to the discovery time. Since usually a high number of fatalities are found in the fire room of origin at ignition and the class of discovery time over 30 minutes (usually approximated to 45 minutes) presents a very wide range, λ is calculated considering only the discovery time under 5 minutes and between 5 and 30 minutes. Detection systems are not considered in the analysis even if they could reduce the fatality rate (Rasbash et al., 2004). Based on a linear relation, the coefficient k is defined as the intercept of the vertical axis as shown in Eq. 11 where P_d is the overall fatality rate and Δt_{det} is the average discovery time.

$$P_d = k + \lambda \cdot \Delta t_{det} \qquad \text{Eq. 11}$$

Table 34: Discovery time, number of fatalities and casualties and fires in PD 7974-7 and English statistics

	Fatality	Fatality/Casualty	Fires		Fatality rate	Fatality/Casualty rate
	PD	Eng	PD	Eng	PD	Eng
Single occupancy						
Immediately	445	3251	76243	25714	0.005837	0.126429
Under 5 mins	686	8052	212519	56274	0.003228	0.143086
5 to 30 mins	2156	7707	141462	46390	0.015241	0.166135
30 mins up to 2 h	2766	1127	53677	8393	0.051530	0.134279
Over 2 h		563		4709		0.119558
Not known	/	1180	/	8135	/	0.145052
Total	6053	21880	483901	149615	0.012509	0.146242
Multiple occupancies						
Immediately	204	1251	27805	9689	0.007337	0.129115
Under 5 mins	334	3802	123648	24449	0.002701	0.155507
5 to 30 mins	1281	3924	110078	21700	0.011637	0.180829
30 mins up to 2 h	1703	497	28125	3100	0.060551	0.160323
Over 2 h		154		1209		0.127378
Not known	/	458	/	2917	/	0.157011
Total	3522	10086	289656	63064	0.012159	0.159933
Other occupancies						
Immediately	/	476	/	3480	/	0.136782
Under 5 mins	/	1429	/	8590	/	0.410632
5 to 30 mins	/	779	/	4076	/	0.223851
30 mins up to 2 h	/	72	/	402	/	0.020690
Over 2 hours		28		159		0.008046
Not known	/	135	/	819	/	0.038793
Total	/	2919	/	17526	/	0.166553

The England Home Office dataset for *Dwellings* published in 2017 with data from 2010/11 to 2016/17, is described in section 2.3.2 and has been adopted for the analysis developed in this section considering *Single* and *Multiple occupancy* dwellings. The general class of *Single occupancy* dwellings includes those of House – single occupancy; Bungalow – single occupancy; Converted flat/Maisonette – single occupancy. In *Multiple occupancies*, Dwelling – multiple occupancy; Purpose built low rise (1-3) Flats/Maisonette; Purpose built medium rise (4-9) Flat and Purpose built high rise (10+) Flat classes are considered. Moreover, the class of *Other occupancies* in the *Dwellings* fires datasets has been considered in the analysis. The classification adopted for English statistics for the discovery time is similar to the one presented in Table A.13 of the PD 7974-7 with the only exception of two classes which are discovery time over 30 minutes and up to 2 hours and the one of discovery time over 2 hours which are summed together. However, while for the PD 7974-7 the fatality rate is evaluated, in the Home Office datasets fatalities and casualties are recorded as a combined value and the fatality/casualty rate is obtained for the *Dwellings* fires dataset.

The comparisons for PD 7974-7 and English statistics are summarized in Table 34 in which the number of fatality for PD 7974-7 or fatality and casualty for English statistics, fires and the related rate are calculated. In general, the number of fires recorded in English statistics is approximately 3.2 and 4.6 times less while the number of fatalities and casualties is 3.6 and 2.9 times greater than those of PD 7974-7 in *Single* and *Multiple occupancies*, respectively.

Figure 104 plots the fatality rates for PD 7974-7 and the fatality/casualty rates for English statistics obtained for *Single* and *Multiple occupancy* according to the classes of discovery times present in PD 7974-7 and English statistics. The trend for *Single* and *Multiple occupancy* in PD 7974-7 and English statistics have similar values and a great difference between the two statistics is not present. However, the fatality/casualty rate in English statistics is usually at least 10 times greater than those available in PD 7974-7. This could be due to the fact that fatalities and casualties are recorded together in English statistics providing a greater numerator in the rate.

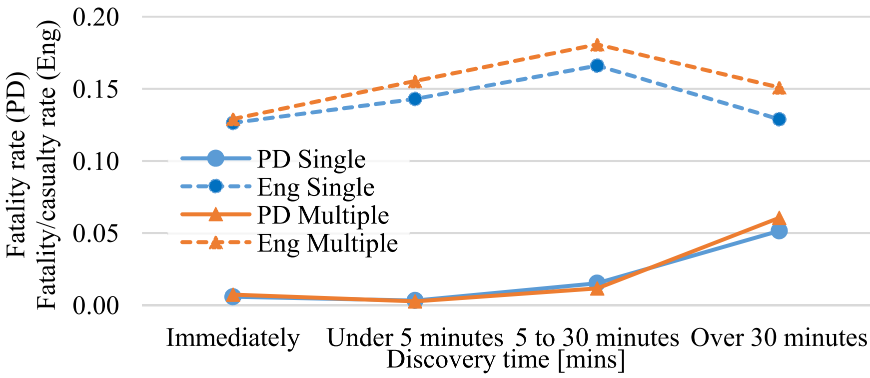


Figure 104: Fatality and fatality/casualty rate for Single and Multiple occupancies in PD 7974-7 and English statistics

In Table 35, the discovery time classes are those available in Table A.13 of the PD 7974-7 and approximated to 0, 2, 17 and 45 minutes. According to Eq. 11, the total fatality rate in PD 7974-7 and fatality/casualty rate in English statistics are obtained considering the total number of fatality or fatality/casualty and the total number of fires, respectively. The coefficient λ is evaluated considering the difference between the rate for 17 and 2 minutes and dividing the value by the time range of 15 minutes. Once λ is known, the coefficient k is evaluated inverting the formula of Eq. 11 applying the overall rate and discovery time for 2 minutes. The average discovery time Δt_{det} is calculated considering the total rate and the coefficients λ and k. As stated in section 6.2.5 (life risk) of PD 7974-7, Δt_{det} is equal to 13 minutes for *Single* and *Multiple occupancies*. The analysis developed in this research obtained Δt_{det} of 17.9 minutes for *Multiple occupancy* and a coefficient k of 0.001510 instead of 0.001509 for the data provided. Furthermore, the average discovery time for *Single* and *Multiple occupancy* are of 4.1 and 4.6 minutes in English statistics, respectively.

Table 35: Total fatality and fatality/casualty rate and the coefficient λ and k for Single and Multiple occupancy in PD 7974-7 and English statistics

Single occupancy	[min]	Fatality rate	Fatality/Causality rate
		PD	Eng
Immediately	0	0.005837	0.126429
Under 5 minutes	2	0.003228	0.143086
5 to 30 minutes	17	0.015241	0.166135
Over 30 minutes	45	0.051530	0.128988
Not known	/	/	0.145052
P_d		0.012509	0.146242
λ		0.000801	0.001537
k		0.001626	0.140012
Δt_{det}		13.6	4.1
Multiple occupancy	[min]	Fatality rate	Fatality/Causality rate
		PD	Eng
Immediately	0	0.007337	0.129115
Under 5 minutes	2	0.002701	0.155507
5 to 30 minutes	17	0.011637	0.180829
Over 30 minutes	45	0.060551	0.151079
Not known	/	/	0.157011
P_d		0.012159	0.159933
λ		0.000596	0.001688
k		0.001510	0.152131
Δt_{det}		17.9	4.6
Red: Corrected values			

Table A.13 of PD 7974-7 considers only the fatality rate and the values are derived from research developed by Ramachandran (1993). However, in Ramachandran's study, not only the fatalities are present but also the non-fatal casualties for the same fires recorded by the Fire Statistics United Kingdom in the period 1978-1991. Therefore, the analysis developed in this section has summed the number of fatalities and non-fatal casualties to evaluate the fatality/casualty rates based on the data presented by Ramachandran to obtain a direct comparison with the results found for English statistics.

As for Table 35, the data recorded in English statistics have been grouped according to the discovery classes available for Ramachandran's data. In Table 36 and Figure 105, the fatality/casualty rates according to Ramachandran's study and English statistics appear similar without the great difference found in Figure 104. Indeed, the values of the fatality/casualty rate of Figure 105 vary from 0.10 to 0.20 in *Single occupancy* and from 0.12 to 0.27 in *Multiple occupancies*. The average fatality/casualty rate for both statistics could be approximated in 0.14 in *Single occupancy* and 0.17 in *Multiple occupancies*. Moreover, applying the same methodology adopted for Table 35 considering the overall fatality/casualty rate P_d and the coefficients λ and k, the average discovery time Δt_{det} is equal to 9.7 and 11.5 minutes which appear to be 4 and 6 minutes less than those obtained for the analysis of fatalities of PD 7974-7 in Table 35 in *Single* and *Multiple occupancies*, respectively.

Table 36: Total fatality/casualty rate and the coefficient λ and k for Single and Multiple occupancy in Ramachandran (Ramachandran, 1993) *and English statistics*

Single occupancy	[min]	Fatality/Casualty rate per fire	
		PD	Eng
Immediately	0	0,152093	0,126429
Under 5 minutes	2	0,105355	0,143086
5 to 30 minutes	17	0,180013	0,166135
Over 30 minutes	45	0,189653	0,128988
Not known	/	/	0,145052
P_d		0,143895	0,146242
λ		0,004977	0,001537
k		0,095401	0,140012
Δt_{det}		9,7	4,1
Multiple occupancy	[min]	Fatality/Casualty rate per fire	
		PD	Eng
Immediately	0	0,181119	0,129115
Under 5 minutes	2	0,121280	0,155507
5 to 30 minutes	17	0,200594	0,180829
Over 30 minutes	45	0,267591	0,151079
Not known	/	/	0,157011
P_d		0,171372	0,159933
λ		0,005288	0,001688
k		0,110705	0,152131
Δt_{det}		11,5	4,6

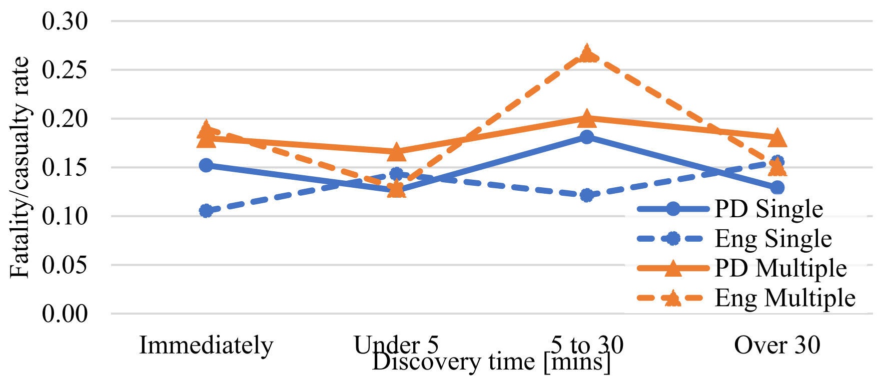


Figure 105: Fatality/casualty rate for Single and Multiple occupancy in Ramachandran (Ramachandran, 1993) *and English statistics*

The Tables of PD 7974-7 have been recreated, extended and improved based on the fields available for USA and English statistics to understand if the prediction of the British Standard document is still applicable to current fire incidents in buildings. The fatality rates of PD 7974-7 are less than the fatality/casualty rates of England. However, the PD 7974-7 data are based on the study of Ramachandran which also includes the number of casualties. Therefore, fatality/casualty rates derived from Ramachandran's study are similar to those of English statistics. The following section will now be based on the evaluation of the response time in terms of life and property losses considering English statistics. In particular, the fatality/casualty rate, the fire spread and the *fire* and *total damage* will be investigated based on the response time of fire brigade in *Dwellings* and property types in *Other buildings*.

5.8 Response time and impacts on losses

Response time is defined as the time interval between the notification of the incident and the first fire vehicle attending the scene (Home Office, 2017b) and it is evaluated as the sum of dispatch preparation and travel time. As introduced in section 2.5.2, the response time appears as one of the most relevant factors affecting the occupant rescues and property protection.

The Fire incidents response time published by the Home Office (Home Office, 2018) affirmed that the overall response times over the past 20 years has increased from less than 6 minutes in 1994/95 to almost 8 and 9 minutes in 2016/17 for *Dwellings* and *Other buildings*, respectively. This is potentially attributable to several factors such as the increased traffic level, changes in the health and safety policy of fire brigades asking more questions to better address the fire risk. From 2015/16 to 2016/17, a decrease of 6% and 5% have been recorded for fire-related fatalities and non-fatal casualties in *Dwellings* while for the average area damage an increase of 1% and a decrease of 1% is evaluated for *Dwellings* and *Other buildings* (Home Office, 2018). It is, therefore, clear that fire risk changes over time.

The analysis developed in this section and the following ones, consider the *Dwellings* and *Other buildings* datasets of the Home Office with data from 2010/11 to 2016/17, as described in section 2.3.2 for various property types as specified in section 5.7, to evaluate the average response time and the influence that it can have on property and lives. The classes of response time are usually recorded with a time range of 1 minute up to 10 minutes, of 5 minutes from 10 to 20 minutes and 40 minutes from 20 to 60 minutes. The time ranges have been reclassified according to the 1-minute band and the fire frequency evaluated based on the number of fires for a specific response time divided by the total fires.

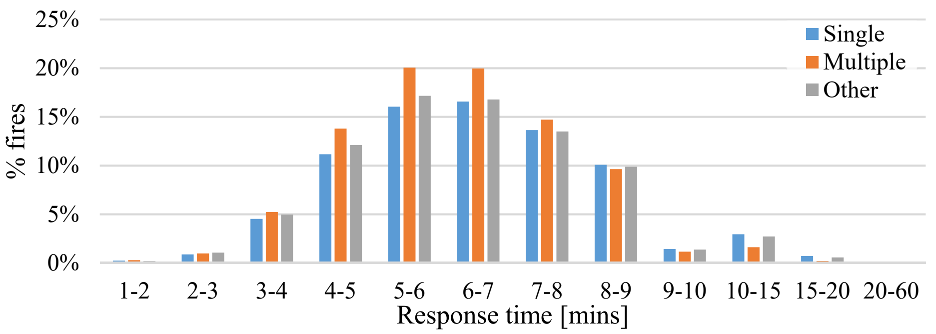


Figure 106: Response time of Dwellings for Single, Multiple and Other occupancies in English statistics

When the percentage of fires is evaluated according to the related response time in *Dwellings* for the three occupancy types considered, it shows percentages over 15% for 5-6 and 6-7 minutes followed by percentages greater than 10% in 4-5 and 7-8 minutes where the average response time is equal to 8.27 in *Single occupancy*, 7.10 in *Multiple occupancy* and 7.94 minutes in *Other occupancies* as described in Figure 106.

In *Other buildings*, the property types are subdivided into two groups according to similar trends where the first one is represented by *Commercial, Educational* and *Miscellaneous* with an average response time of 8.02, 8.19 and 9.14 minutes while the second one by *Utilities, Industrial* and *Leisure* with an average response time of 9.24, 9.07 and 7.98 minutes, respectively. The highest percentages of fires for *Commercial, Educational* and *Miscellaneous* are equal to 16.33%, 16.42% and 14.72% in 5-6 minutes followed by 16.17%, 16.12% and 14.39% in 6-7 minutes and 13.65%, 14.81% and 11.96% in 7-8 minutes. As described in Figure 109, in *Utilities, Industrial* and *Leisure* the highest peak is reached by 13.73%, 14.41% and 16.52% in 6-7 minutes while the second-highest value in 5-6 minutes in *Utilities* and *Leisure* (12.24% and 16.11%) and 7-8 minutes in *Industrial* (14.20%).

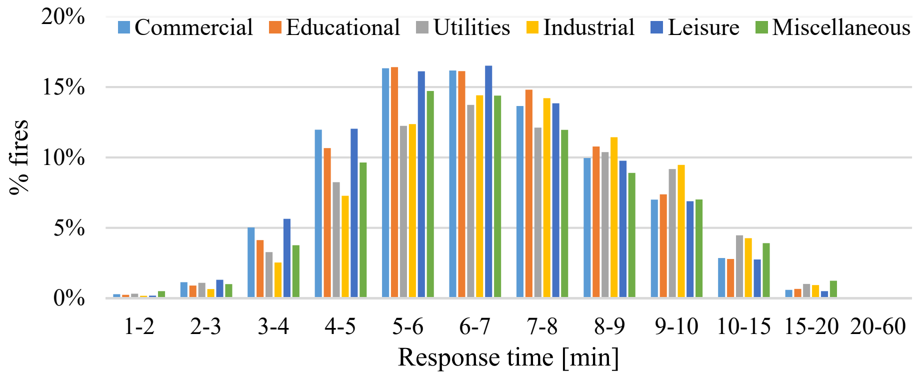


Figure 107: Response times of Other buildings in English statistics

Similar trends are found in *Dwellings* and *Other buildings* where the peaks are confined from 4-5 to 7-8 minutes response time. The main difference is given in the class of response time of 9-10 minutes where fire frequency is usually below 2% in *Dwellings* while it is greater than 7% in *Other buildings*.

5.8.1 Response time and fatality/casualty rate

As already evaluated in section 5.7, the fatality/casualty rate is calculated considering the total number of fatalities and casualties divided by the total number of fire incidents where fatalities and casualties are recorded as a unique value in the dataset. While in section 5.7, the discovery time has been considered, in this section the response time is analysed for *Dwellings* considering *Single*, *Multiple* and *Other occupancy* and *Other buildings*, where the property types have been grouped in six general classes such as *Commercial*, *Educational*, *Utilities*, *Industrial*, *Leisure* and *Miscellaneous*.

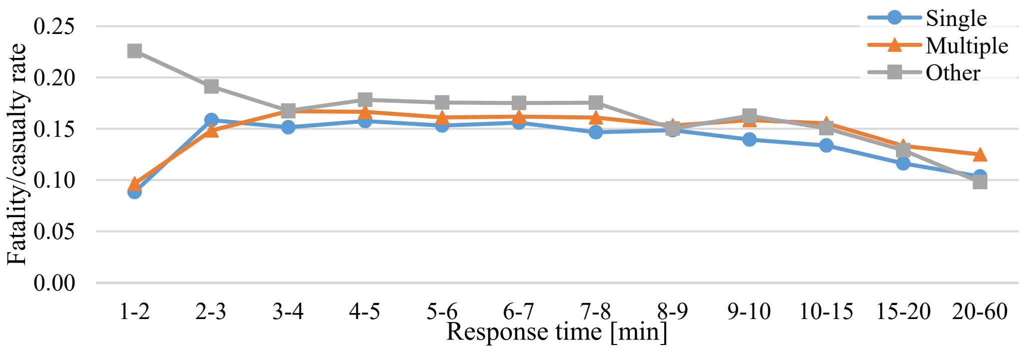


Figure 108: Fatality/casualty rate and response time of Dwellings for Single, Multiple and Other occupancies in English statistics

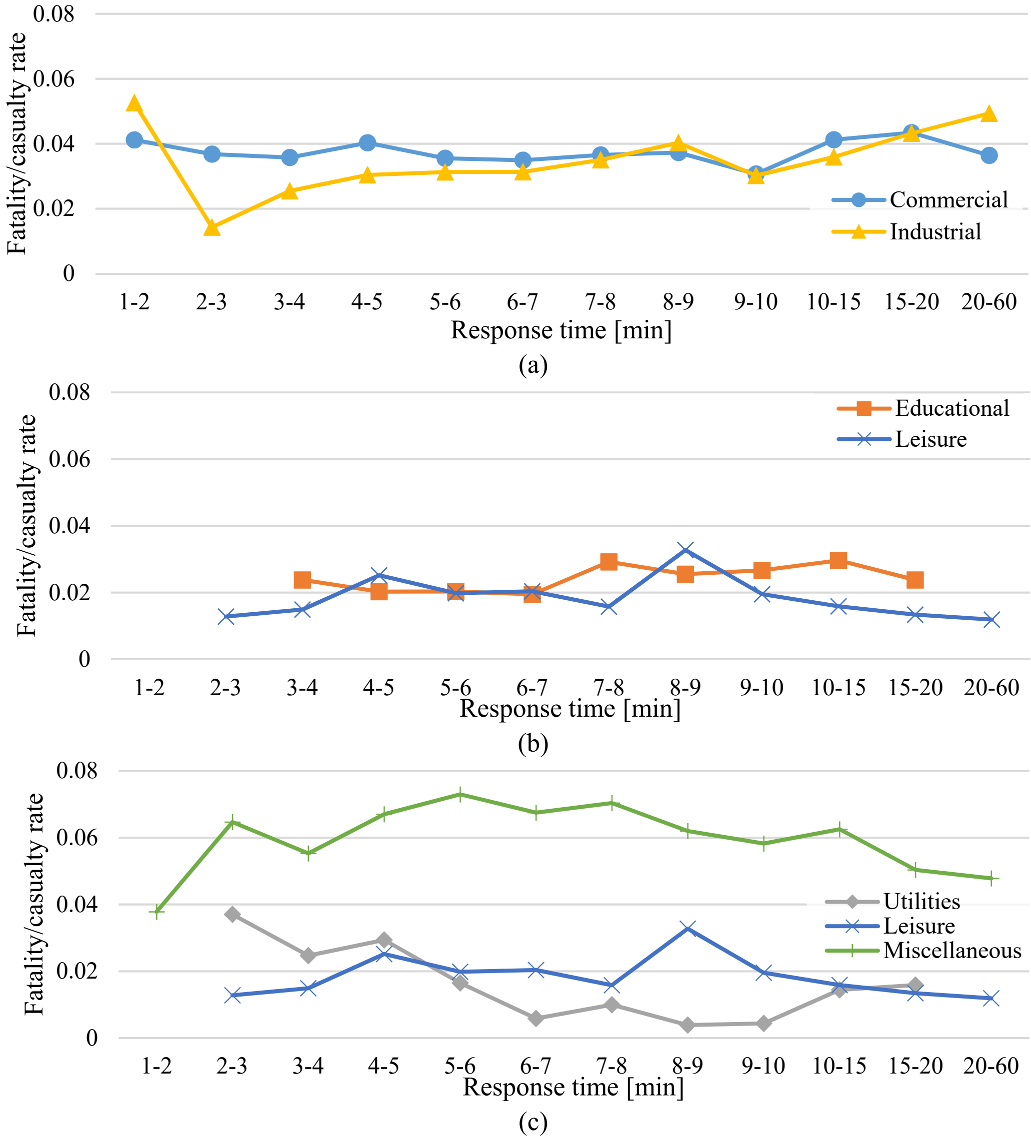


Figure 109: Fatality/casualty rate and response time of Other buildings for (a) Commercial and Industrial, (b) Educational and Leisure and (c) Utilities, Leisure and Miscellaneous in English statistics

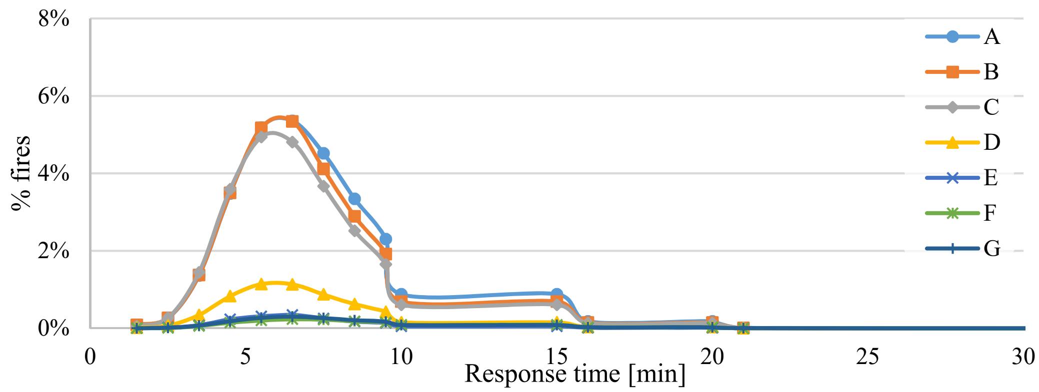
In *Dwellings*, the fatality/casualty rate for 1-2 minutes response time assumes an approximated value of 0.10 in *Single* and *Multiple occupancy* and 0.23 in *Other occupancies*. Despite the difference value for few minutes response time, from 3-4 to 7-8 minutes a plateau of 0.16 fatality/casualty rate is reached for the three occupancy types demonstrating that the response time has a great impact especially in the first minutes after the notification of the incident. Moreover, the fatality/casualty rate usually decreases after 9-10 minutes due to the arrival of the fire brigade and the beginning of the occupant rescue operations (Figure 108). This could be also attributable to the small number of fires recorded for a response time of 9 minutes or greater as shown in Figure 106.

Generally, the fatality/casualty rate in *Other buildings* assumes values between 1/4 and 1/3 of those found in *Dwellings*. The occupancy types of *Other buildings* can be described according to their tendency in three main groups represented by *Commercial* and *Industrial*, *Educational* and *Leisure* and *Utilities* and *Miscellaneous*. *Commercial* and *Industrial* present similar fatality/casualty rates between 0.03 and 0.04 from 4-5 to 8-9 minutes response time and while *Commercial* rates fluctuate around 0.04, in *Industrial,* there is a minimum of 0.01 for 2-3 minutes response time (Figure 109 (a)). Fatalities and casualties are not available for some response times and this is the reason why the trend of *Leisure* starts from 2-3 minutes and the one of *Educational* from 3-4 minutes and ends in 15-20 minutes. *Educational* and *Leisure* present similar fatality/casualty rates of 0.02 from 5 to 7 minutes of attendance time. The other rates show a wide scatter distribution; however, they vary from 0.01 and 0.03. Finally, *Miscellaneous* represents the highest trend reaching 0.07 for 5-6 minutes and *Utilities* the lowest one with a minimum of 0.004 from 8 to 10 minutes. *Leisure* and *Utilities* assume similar values of 0.02 from 4 to 6 and from 10 to 20 minutes as shown in Figure 109 (c).

The response time appears to influence the fatality/casualty rates of various property types in the first minutes and is less influential after 4 minutes. The occupancy types in *Dwellings* present similar tendency while in *Other buildings* is difficult to deduce common comments.

5.8.2 Response time, fire spread and damage

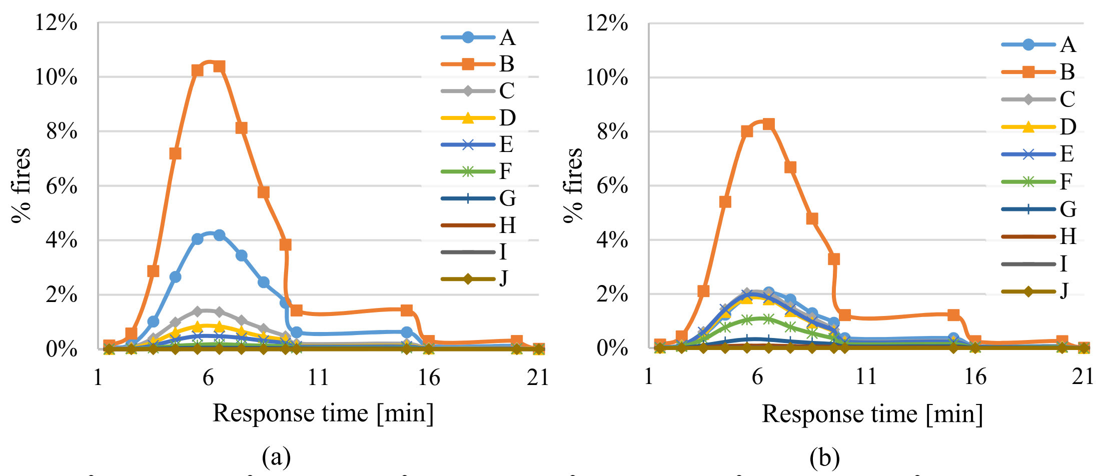
This section investigates the fire scenarios faced by fire brigades in terms of fire spread and damage according to 1 minute band response time evaluating the percentages of fires. As described in section 2.3.2, in English statistics, the damage is recorded according to *fire* and *total damage* where *fire damage* is the total horizontal area damaged by the flame and/or heat while the total damage also includes smoke and water and the *total damage* is the area damaged by the flame, heat, smoke and water at the stop of the fire in m^2 (Home Office, 2017b). For *Dwellings* and *Other buildings*, fire frequency increases for the various classes of spread and damage with a maximum around approximately 7 minutes and then it gradually decreases reaching a zero value for a response time greater than 20 minutes.



A. No fire damage; **B**. Limited to 1st ignited; **C**. Limited to room of origin; **D**. Limited to floor of origin (not whole building); **E**. Limited to 2 floors; **F**. Whole building/Affecting more than 2 floors; **G**. Roofs/Roof spaces

Figure 110: Response time and fire spread of Dwellings in English statistics

In *Dwellings*, the evaluation of fire spread and response time shows peaks in fire frequency for 6-7 minutes response time in the class of no fire damage and limited to the item first ignited (5.36%-5.34%) and for 5-6 minutes when the fire is confined to the room of origin (4.94%). Therefore, fires are usually confined to the floor of origin with the higher classes of fire spread assuming fire frequencies less than 2% (Figure 110).

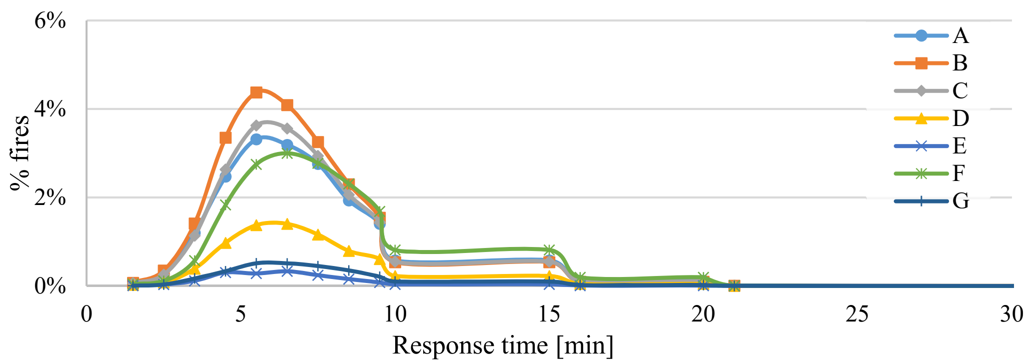


A. 0 m^2; **B**. Up to 5 m^2; **C**. 6 to 10 m^2; **D**. 11 to 20 m^2; **E**. 21 to 50 m^2; **F**. 51 to 100 m^2; **G**. 101 to 200 m^2; **H**. 201 to 500 m^2; **I**. 501 to 1000 m^2; **J**. Over 1000 m^2

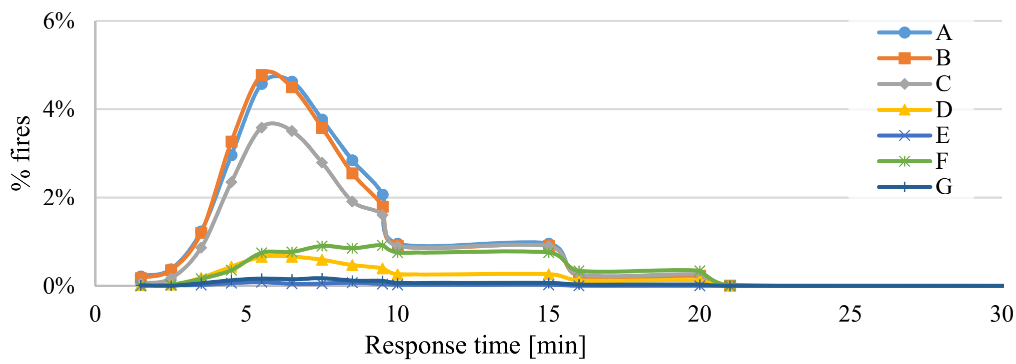
Figure 111: Response time and (a) fire and (b) total damage of Dwellings in English statistics

The analysis of damage with the related response time in *Dwellings* presents a maximum for 5-6 and 6-7 minutes response time with damage confined to 0 and 5 m^2 with fire percentages greater than 10% and 4% when *fire damage* is considered (Figure 111 (a)). Even if peaks are reached between 5 and 7 minutes, when *total damage* is investigated, the highest curve is represented by 0 m^2 of *total damage* while all the other classes assume values less than 2% with the consequence that greater m^2 of damage appear relevant and not negligible as in the case of *fire damage* (Figure 111 (b)).

In *Other buildings,* the trends found for the fire spread in relation to the response time are similar to those obtained for *Dwellings* where the highest fire percentages are presented in the classes of the item first ignited, no fire damage and spread limited to the room of origin while greater classes of fire spread are usually negligible. The only exception is given in *Commercial* and *Miscellaneous* where the fourth-highest curve is described by fire affecting the whole building or more than two floors as represented by Figure 112. Generally, peaks for the various property types in *Other buildings* are obtained for a maximum of 6% corresponding to response time from 5 to 7 minutes. The fire spread and response time for *Educational*, *Utilities*, *Industrial* and *Leisure* are available in Figure 144 in the Annex.



(a)



(b)

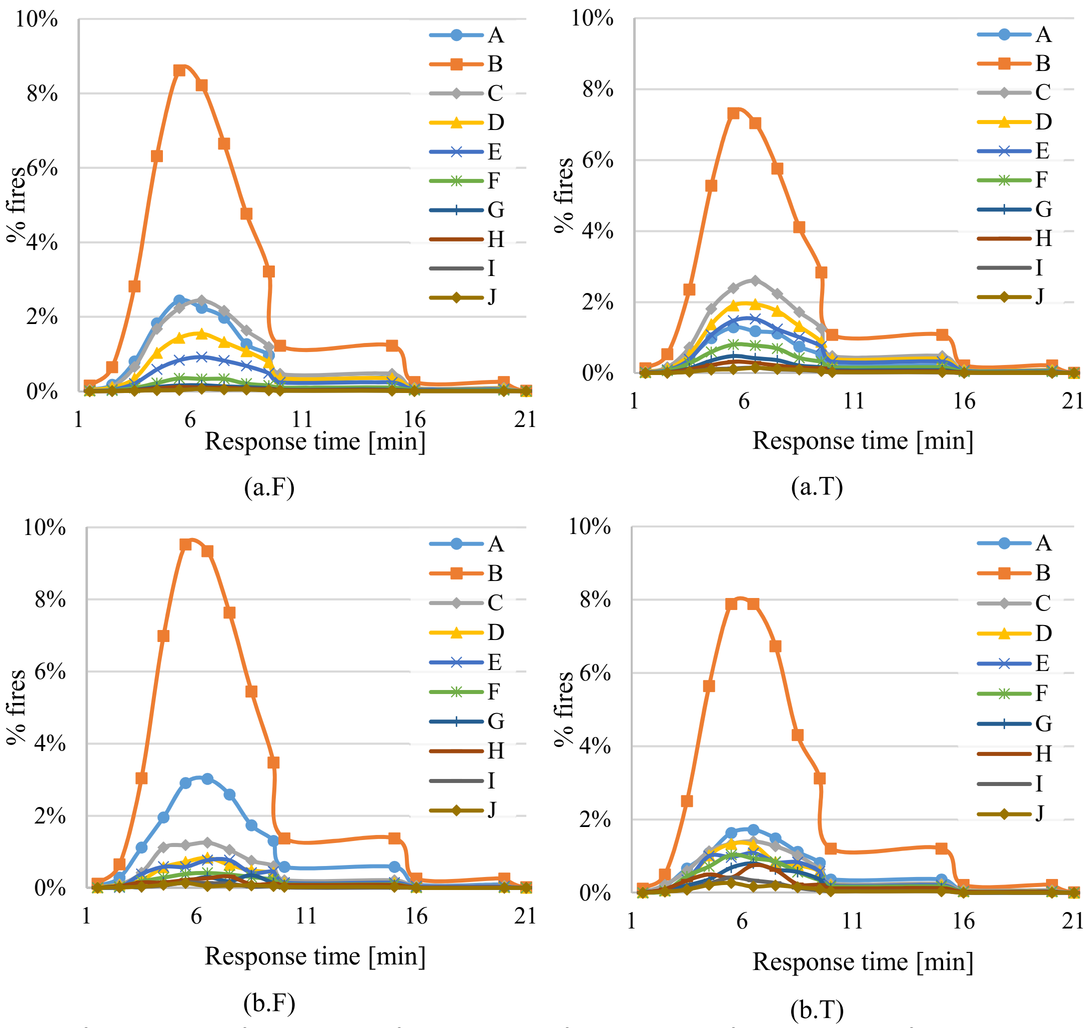
A. No fire damage; **B**. Limited to 1st ignited; **C**. Limited to room of origin; **D**. Limited to floor of origin (not whole building); **E**. Limited to 2 floors; **F**. Whole building/Affecting more than 2 floors; **G**. Roofs/Roof spaces

Figure 112: Response time and fire spread of (a) Commercial and (b) Miscellaneous in English statistics

In *Other buildings*, when fire and total damage are evaluated according to the response time of fire brigades, the maximum values are always less than 10% in *fire damage* and less than 9% in *total damage*. Moreover, the distribution is usually right-skewed where the highest curves are provided by damage up to 5 m^2 and 0 m^2. As for *Dwellings*, while the other classes of damage appear almost negligible for *fire damage*, they increase in value in *total damage* tending towards to the second-highest curve represented by 0 m^2.

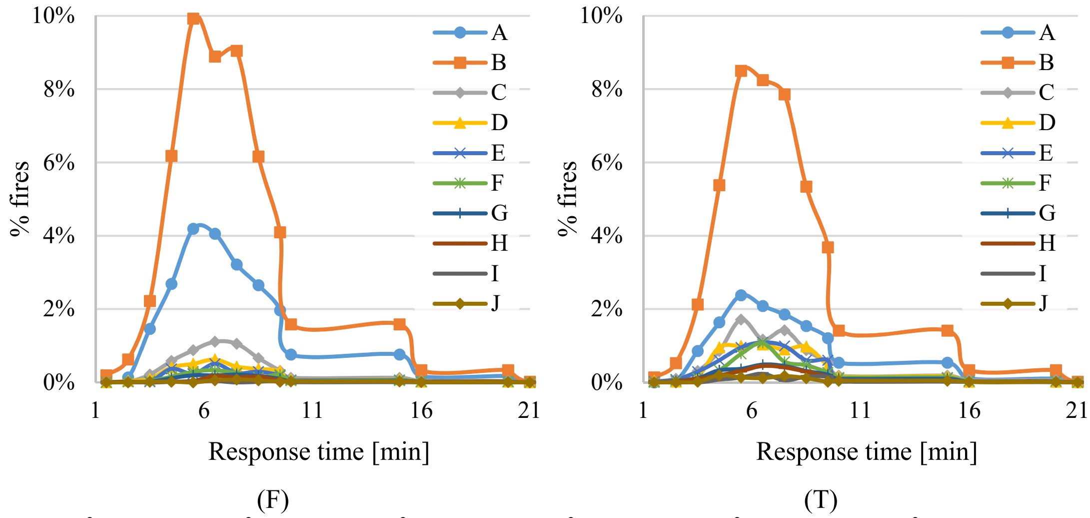
The property types in *Other buildings* are described according to three groups based on similar trends: *Commercial* and *Leisure*, *Educational*, *Utilities* and *Industrial*, and *Miscellaneous*.

In *Commercial* and *Leisure*, the highest peaks in fire percentage are reached when damage is up to 5m^2 with an average of 8.42% and 9.43% in *fire damage* and 7.18% and 7.89% in *total damage*, respectively. In *Commercial*, the second-highest curve is given by 6 to 10 m^2 of damage and in *total damage* the highest m^2 of damage increase if compared to those of *fire damage*, with a value of approximately 1% for the class of 51 to 100 m^2 in 5-6 minutes (Figure 113 (a)). In *Leisure*, the percentages of fires are greater in 0 m^2 than in the curve up to 5 m^2 where again greater damage areas are usually less than 2% for 6-7 minutes (Figure 113 (b)).



A. 0 m^2; **B**. Up to 5 m^2; **C**. 6 to 10 m^2; **D**. 11 to 20 m^2; **E**. 21 to 50 m^2; **F**. 51 to 100 m^2; **G**. 101 to 200 m^2; **H**. 201 to 500 m^2; **I**. 501 to 1000 m^2; **J**. Over 1000 m^2

Figure 113: Response and fire (F) and total (T) damage of (a) Commercial and (b) Leisure in English statistics



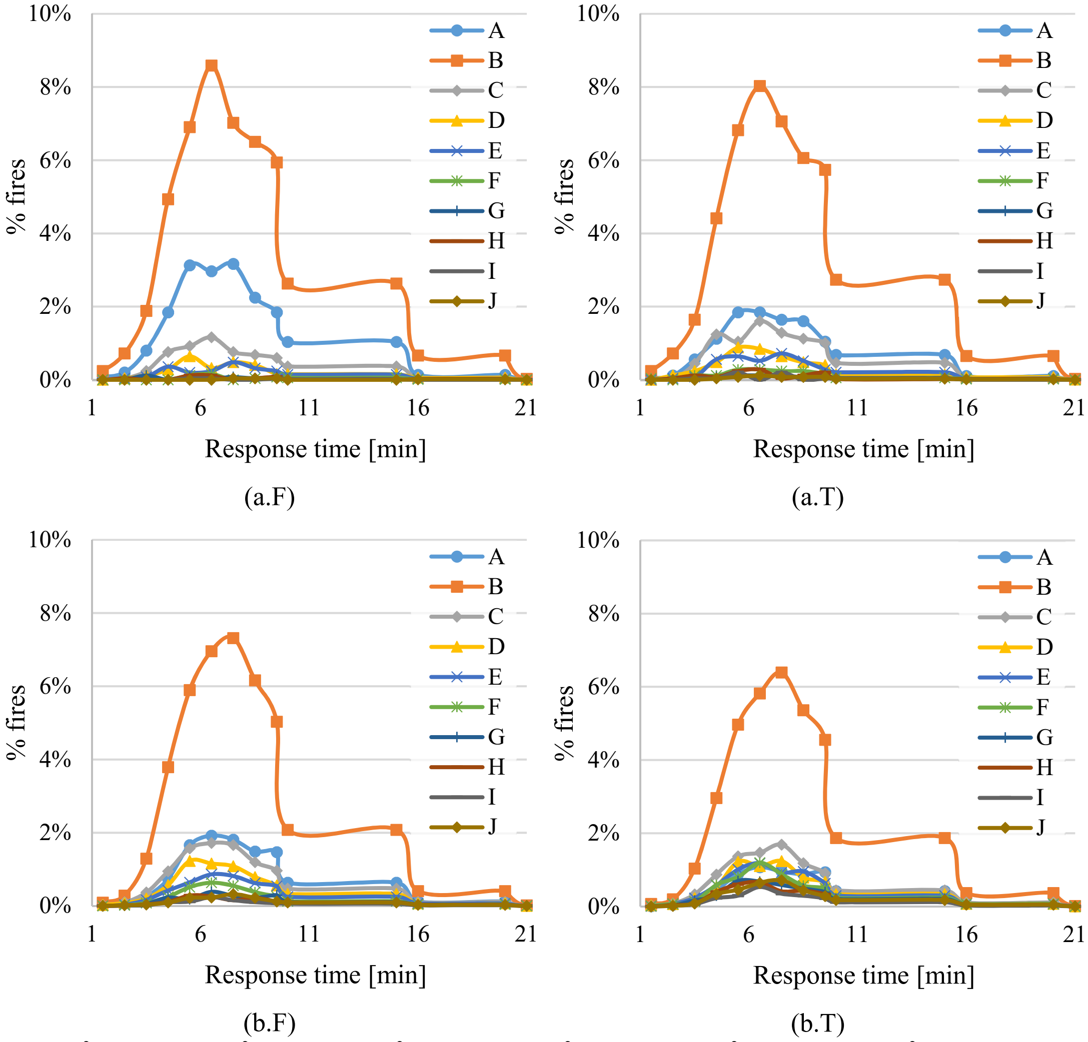
A. 0 m²; **B**. Up to 5 m²; **C**. 6 to 10 m²; **D**. 11 to 20 m²; **E**. 21 to 50 m²; **F**. 51 to 100 m²; **G**. 101 to 200 m²; **H**. 201 to 500 m²; **I**. 501 to 1000 m²; **J**. Over 1000 m²

Figure 114: Response and fire (F) and total (T) damage of Educational in English statistics

In *Educational*, the three highest fire percentages are reached when damage is up to 5 m² from 5 to 8 minutes response time with an average value of 9.29% in *fire damage* and 8.20% in *total damage*. For fire and total damage, the second-highest curve is represented by the one describing null damage and all the other classes of area damage slightly increase if total damage is investigated (Figure 114).

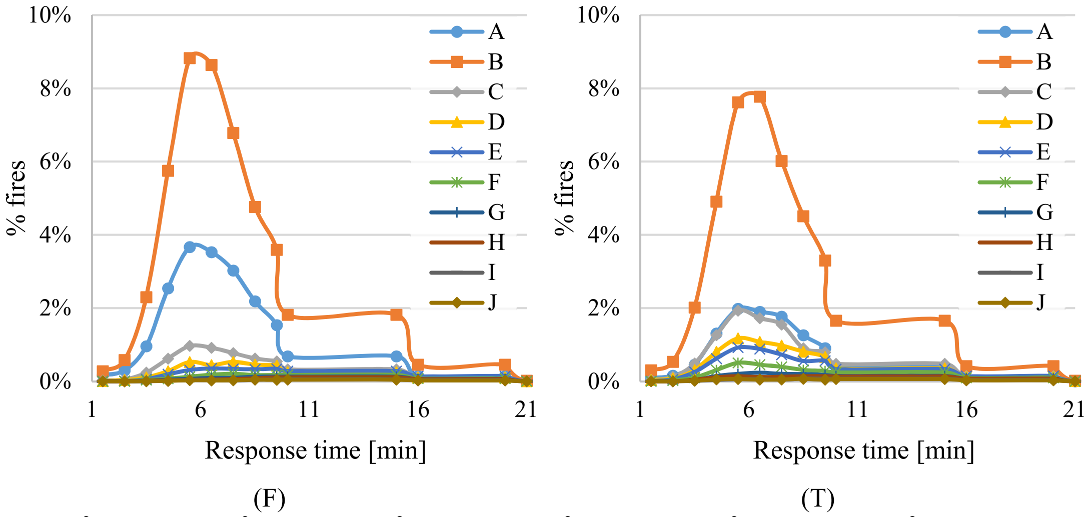
In *Utilities* for damage up to 5 m², despite the peak is reached for damage in 6-7 minutes response time, values greater than 6% are present for a response time between 5 and 10 minutes for *fire* and *total damage*. The second highest percentages of fires are found for 0 m² and in *total damage* the damage classes greater than 10 m² present values less than approximately 1% (Figure 115 (a)). The interval between 10 and 15 minutes response time usually presents values less than 2% for damage up to 5 m² while in Figure 115 assumes 2.63% and 2.74% in *Utilities* and 2.08% and 1.87% in *Industrial* for *fire* and *total damage*, respectively. In *Industrial*, a significant increase in greater damage areas in *total damage* compared to the *fire damage* is not found and in both cases, damage greater than 10 m² present percentages of fires greater than 1% for 6-7 minutes (Figure 115 (b)).

Finally, in *Miscellaneous*, from 5 to 7 minutes response time in damage up to 5 m², two consequent peaks are found with a value of approximately 8.73% in *fire damage* and 7.70% in *total damage*. While in *fire damage* only the classes of 0 and up to 5 m² and in *total damage* only the one of damage up to 5 m² provide percentages greater than 2%, all the other damage classes have values less than 0.97% in *fire damage* and 1.93% in *total damage*.



A. 0 m^2; **B**. Up to 5 m^2; **C**. 6 to 10 m^2; **D**. 11 to 20 m^2; **E**. 21 to 50 m^2; **F**. 51 to 100 m^2; **G**. 101 to 200 m^2; **H**. 201 to 500 m^2; **I**. 501 to 1000 m^2; **J**. Over 1000 m^2

Figure 115: Response and fire (F) and total (T) damage of (a) Utilities and (b) Industrial in English statistics



A. 0 m^2; **B**. Up to 5 m^2; **C**. 6 to 10 m^2; **D**. 11 to 20 m^2; **E**. 21 to 50 m^2; **F**. 51 to 100 m^2; **G**. 101 to 200 m^2; **H**. 201 to 500 m^2; **I**. 501 to 1000 m^2; **J**. Over 1000 m^2

Figure 116: Response and fire (F) and total (T) damage of Miscellaneous in English statistics

Response time has an impact in the first 7-8 minutes where usually a peak in fire percentages is found. A large number of small fires and a small number of large fires are recorded where most severe damage classes are relevant when total damage is investigated.

5.9 Chapter Summary

The analyses developed in this Chapter to recreate the Tables present in the Annex of PD 7974-7 have the aim to understand if the predictions stated in the British Standard document with data from 1966 to 1987 related to fire frequency and damage according to presence or absence of automatic extinguishing systems and fatality rate based on the discovery time are still representative of the current fire incidents affecting buildings described by England and USA statistics. The analysis present in the PD 7974-7 has been extended considering various property types and other fire safety fields such as *fire* and *total damage* in England. Moreover, a critical evaluation of how the response time could have an impact on potential occupant rescues and property protection has been developed with English fire statistics.

The overall fire frequency of PD 7974-7 described in Table A.2 appears to usually overestimate those described by England and the USA statistics where values are in the same order of magnitude except for *Assembly entertainment* (5.446×10^{-2}) and *Schools* (5.512×10^{-2}) in USA and *Hospitals* (5.856×10^{-2}) in England.

The analysis of Table A.1 of PD 7974-7 describes the fire frequency and total floor area of the building according to a power law with a positive exponent as studied by Rutstein. However, when this function is applied to current fire safety data of England and USA statistics, it appears to not represent well the distribution. Therefore, two improved functions are obtained which are a power law with positive or negative exponent and a polynomial function of second or third order based on the related R^2 values. The improved power law in the two statistics generally assumes a positive exponent except for *Industrial* in USA and England and *Storage* in England. The evaluation of the residuals shows a pattern in the USA and *Hospitals* and *Schools* in England when the two improved functions are considered. Therefore, uncertainties due to the fitting of the data need to be considered carefully.

When Table A.4-5 of PD 7974-7 are recreated in PD 7974-7, the area damage increases while the fire frequency decreases with the extension of the fire spread classes. In England and the USA statistics, limited data are available for the presence of sprinklers. However, the absence of automatic extinguishing systems determines greater area damage recorded. Fire frequency in the two current statistics appears well confined to the room origin for the majority of cases.

The frequency distribution according to classes of area damage in m^2 is represented in Table A.6-7-8 of PD 7974-7 and the results show that the PD 7974-7 prediction underestimates the USA trend and is located between the *fire* and *total damage* in English statistics.

The evaluation of fire financial losses in PD 7974-7 are available in Table A.12 and they are generally greater than those of USA statistics. In England, the economic losses are obtained considering the BVD formula applied in the USA statistics and the obtained estimates are less for the presence of sprinklers than for their absence if *fire damage* is investigated while the difference in *total damage* is not as relevant.

The fatality rates of Table A.13 of PD 7974-7 are based on a study of Ramachandran which includes also the number of casualties not reported in the British Standard document. Since in English statistics fatalities and casualties are reported as a unique field, if the fatality/casualty rates of Ramachandran are compared to those of English statistics, they provide similar values.

The analysis of the response time in England appears relevant in the first 4 minutes when it is examined in terms of fatality/casualty rates. A large number of small fires and a small number of large fires are characterized by a response time within 7-8 minutes. Severe damage classes are recorded if the *total damage* is evaluated. The analysis of the response time is important to understand the potential scenario that fire brigades could face at the arrival at the fire scene and the effects that a reduction in response time could have in safety operations and the reduction of property damage.

Once the fire safety data have been investigated according to fire frequency, spread and damage in presence and absence of automatic extinguishing systems, it is now important to understand the impact that various safety measures could have in terms of fire response and damage. Therefore, Chapter 6 will investigate fire risk assessments in various property types based on event tree analyses and considering the success and failure of different safety measures such as detectors and automatic extinguishing systems.

Chapter 6. Probabilistic fire risk assessment

"The words of risk analysis have been, and continue to be, a problem."

- S. Keplan

In this Chapter, the considerations about probabilistic risk assessments expressed in section 2.6 will be now applied to event tree analysis as described in section 2.6.2.1. The event tree analyses realised in this Chapter have the aim to determine likelihood and consequences of fire risk in terms of fire response and damage based on operation and failure of various safety measures of several fire scenarios in the property types available in England and USA fire statistics as described in Chapter 4. The event tree analyses developed are automatic and modifying the fields requested for the success of the specific sub-events, they will automatically modify the risk evaluated in terms of probability and frequency of scenarios.

The English and USA databases adopted have already been introduced in section 2.3.2 and 2.3.3 and summarized in Table 5. The *Other buildings* dataset by the Home Office with 121,558 fire incidents from 2010/11 to 2016/17 has been evaluated in England and the 'basic incidents' dataset has been merged with the one of 'fire incidents' of NFIRS investigating 113,168 fires of 2014/2015 in the USA. Fire incidents are classified according to several property types grouped in general classes and the related frequency obtained considering the number of fires per building per year where fire incidents are derived by fire statistics and the number of buildings by national building stocks as explained in section 5.2.

For each property type, a probabilistic risk assessment is developed considering alarm operation and effectiveness on human response and fire notification, and evaluating the effects of automatic extinguishing systems on the reduction of fire spread and associated damage. Due to the differences in the fire safety data collected, different event tree analyses have been created for English and the USA fire statistics investigating fire response and damage. However, the analysis has tried to recreate event tree analyses as similar as possible to enable a comparison between the two fire statistics datasets.

Variables such as response time, or fields collected for the fire safety measures, have already been discussed in Chapter 4. Damage is considered as *fire* and *total damage* in England and fire damage in the USA defined in section 2.3.2 and 2.3.3, respectively. As explained in section 2.6.2.1, the overall probability of a specific scenario is given multiplying the probability obtained in each sub-event and the overall frequency of that scenario is obtained multiplying the overall probability by the frequency of the initiating event as shown in Figure 32. In event tree analyses, probabilities and frequencies are usually expressed with values between 0 and 1. Therefore, this is the assumption adopted in this Chapter to describe the results obtained.

The event trees developed in Chapter 6 are based on the suggestions provided by PD 7974-7:2003 (2003). For example, the event trees for the evaluation of damage follow the scheme presented in the above-mentioned document in which the following sub-events are considered:

- fire noticed at an early stage,
- fire extinguished using extinguishers,
- fire spread,
- fire controlled by the fire brigade, and
- evaluation of damage (less than £200,000).

In the analysis developed in Chapter 6 for damage, a similar pattern has been used:

- presence of automatic extinguishing systems,
- response time of fire brigade,
- fire size on arrival,
- fire spread,
- fire damage, and
- total damage.

Where the only difference is represented by the sub-event of response time moved at the beginning of the event tree because it is followed by the evaluation of fire size at arrival and at the end of the incident, quantification of fire damage and total damage in m^2. Moreover, presence and operation of automatic extinguishing systems are before the evaluation of fire spread and damage because these parameters are determined by the fire brigade after they arrive at the fire scene when usually safety systems should have already started their operation.

The event trees of fire response, have been subdivided into the following sub-events:

- presence of alarms and operation,
- time from ignition to discovery,
- time from discovery to call, and
- response time of fire brigades.

Despite the ignition happens before the alarm can operate, the operation of alarm could lead to the fire discovery for occupants. Therefore, this is the reason why the presence of alarm and operation are before the time between ignition and discovery in the event tree.

Even considering the differences present in the fields recorded in English and USA statistics, the event trees created logically follow from a preceding event in terms of a timeline.

The evaluation of English and USA statistics based on event tree analyses investigates how different safety measures and response time of occupants and fire brigades affect fire risks and consequences providing a general scheme to follow in a risk assessment and quantifying the effects of a series of sub-events in effectively respond to fire and in reducing property damage associating risk with specific fire scenarios. Moreover, the analyses developed appear to be representative of the available data of fires for buildings in English and the USA fire statistics. Based on the considerations obtained in this Chapter, future research could integrate cost-benefit and sensitivity analysis to assess the robustness of a decision based on probabilistic risk assessment facilitating the creation of impact and continuity plans for various buildings.

6.1 Event tree analysis of fire response

Event tree analysis has been developed adopting English and USA fire statistics to evaluate the fire response of occupants and fire brigades according to the presence or absence of fire alarms. The differences in the data and fire safety fields recorded in English and USA statistics have determined the creation of two separated event tree analyses.

In particular, as explained in section 2.5.2 and investigated in section 5.8, response time is defined as the attendance time to the fire scene of the fire brigades after the notification of the fire incidents measured in minutes. While response time defines the response of fire brigades, in England the response of occupants could be examined considering the time from ignition to discovery and the time from discovery to call in minutes. As described in Table 37, the research developed in this thesis has considered for England an ignition to discovery and discovery to call below 5 minutes and response time for both England and USA less than 9 minutes. The value of 5 minutes for the ignition to discovery and discovery to call has been assumed considering a prompt discovery of fire and notification of the incident to be effective in the consequential evacuation of occupants and suppression of fire while the 9 minutes response time has been based on the estimates provided by *Other Buildings* dataset of the Home Office (Home Office, 2018) in England and by the analysis developed in section 4.2.2.6 which has obtained an average response time of 8.5 minutes - approximated to 9 minutes in the USA. The event trees developed are automatic and changing the values assumed in Table 37 determines a variation of the overall probability and frequency for the scenarios evaluated.

Table 37: Fire response times in English and USA fire statistics

Fire response times		*Eng*	*USA*
Occupants	Ignition to discovery	Under 5 minutes	/
	Discovery to call	Under 5 minutes	/
Fire brigades	Response time	Under 9 minutes	Under 9 minutes

The data related to alarms present differences in how they are recorded in the two fire statistics. A unique field describing the presence, operation and effectiveness, is available in English statistics while the three fields and the one of occupant response are separated in USA fire statistics and they need to be answered in a sequential order only if the previous field has been filled in. For example in the USA, only if the fields related to detectors present, operated and alerted occupants are recorded, the field related to occupant response is available; otherwise, if detectors failed to operate, no other details need to be provided by the fire brigade and if detectors are absent, no other information is required. Therefore, the event tree in the USA has non-symmetric paths. In England, the data when alarms were not present, did not raise the alarm or did not operate have been grouped to simulate the absence of alarms (Table 38).

Table 38: Alarms in English and USA fire statistics

<table>
<tr><th colspan="5">Alarms</th></tr>
<tr><th>Eng</th><th colspan="4">USA</th></tr>
<tr><td>Alarm Present and raised the alarm</td><td rowspan="4">Present</td><td rowspan="2">Operated</td><td rowspan="2">Detector alerted</td><td>Occupants responded</td></tr>
<tr><td rowspan="4">Alarm Absent
Alarm Present but did not raise alarm
Alarm Present but did not operate</td><td>Occupants failed to respond</td></tr>
<tr><td colspan="3">Detectors failed to alert or no occupants</td></tr>
<tr><td colspan="3">Failed to operate or fire too small to activate</td></tr>
<tr><td colspan="4">None present</td></tr>
</table>

Fire response based on event tree analysis is now investigated considering the fire safety fields available of English and USA statistics in section 6.1.1 and 6.1.2. Overall probabilities and frequencies will also be investigated comparing the property types available.

6.1.1 Event tree analysis of fire response in English statistics

The analysis for the response time in English statistics has been developed considering six general property types of *Commercial*, *Educational*, *Utilities*, *Industrial*, *Leisure* and *Miscellaneous* according to the fire safety fields discussed in section 6.1 based on presence of alarms, ignition to discovery, discovery to call of occupants and response time of fire brigades.

The trends obtained for the properties could be subdivided into two main groups: alarms were absent for more than 0.60 represented by *Commercial*, *Utilities* and *Leisure* and the presence of alarms in 0.40 assumed by *Educational*, *Industrial* and *Miscellaneous*.

Considering *Commercial*, *Utilities* and *Leisure*, more than 0.2 of fire incidents are recorded for the presence of alarms and in this case, the ignition to discovery and discovery to call are mainly under 5 minutes, response time under 9 minutes except for *Utilities* where it is greater than 9 minutes for the scenario 110 (alarms present, ignition to discovery under 5 minutes, discovery to call greater than 5 minutes) and 100 (alarms present, ignition to discovery greater than 5 minutes, discovery to call greater than 5 minutes). Absence of alarms is recorded for more than 0.6 in the three property types analysed and while in *Commercial* and *Leisure* (Figure 117 and Figure 146 in Annex), the ignition to discovery is usually greater than 5 minutes for more than 0.5 of incidents, in *Utilities* this value is assumed by approximately 0.43 (Figure 145 in Annex). However, discovery to call is generally less than 5 minutes and response time is within 9 minutes. The absence of alarms generates a delay in the time between ignition and discovery while the fire brigades provide a prompt response after the notification.

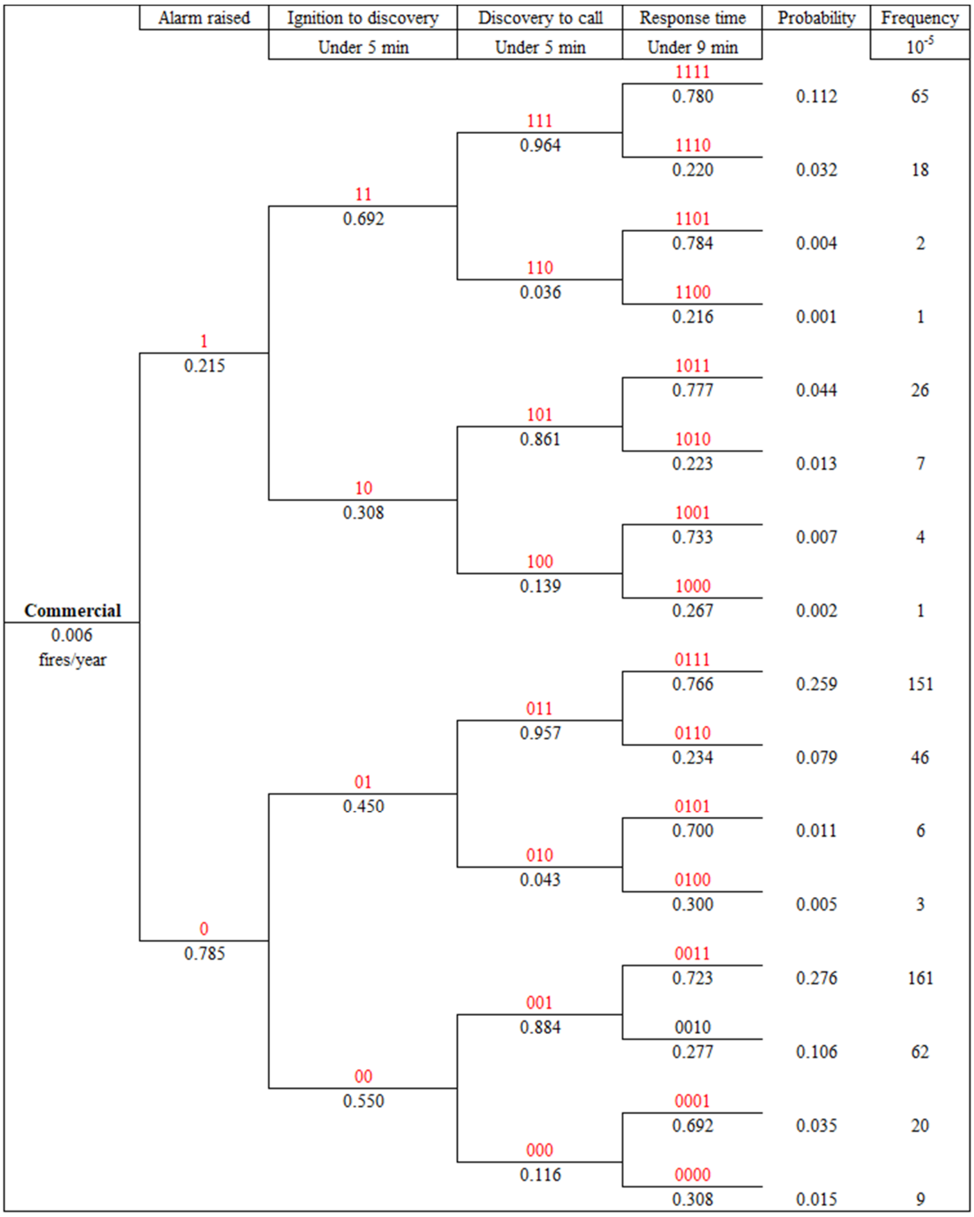


Figure 117: Event tree analysis fire response of Commercial in English statistics

In *Educational*, *Industrial* and *Miscellaneous,* alarms are recorded in more than 0.40 and not recorded in more than approximately 0.45 cases. The difference between presence and absence of alarms is not as relevant as in the three above mentioned property types. In general, ignition to discovery and discovery to call are under 5 minutes and response time is less than 9 minutes for *Educational*, *Industrial* and *Miscellaneous* (Figure 118, Figure 147 and Figure 148 in Annex). The only two exceptions are assumed in *Miscellaneous,* where, in the scenario 0000 (no alarms, ignition to discovery and discovery to call greater than 5 minutes), the response time is greater than 9 minutes for more than approximately 0.55.

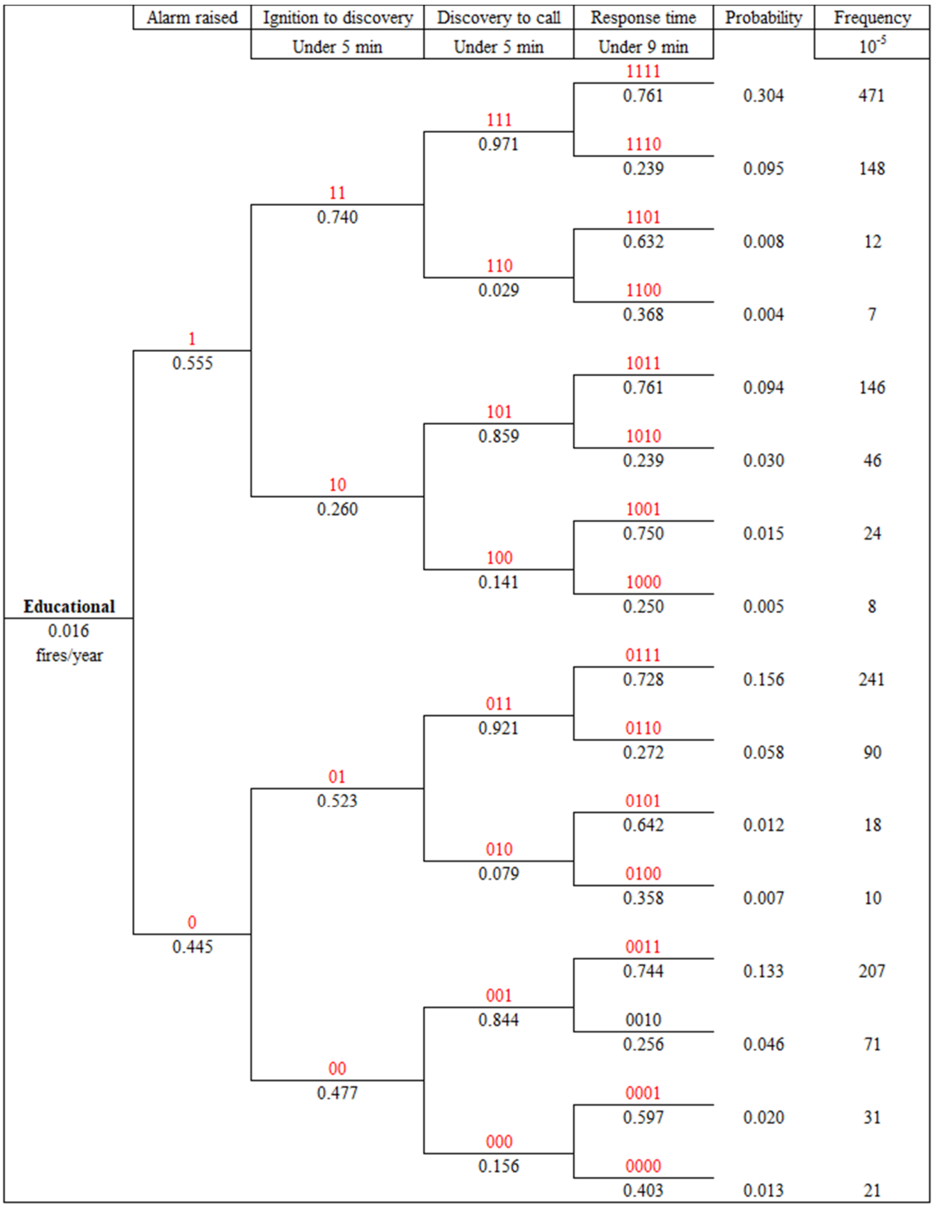


Figure 118: Event tree analysis fire response of Educational in English statistics

Table 39: Event tree for response in English statistics

Ignition to discovery [5 min]	**Discovery to call** [5 min]	**Response time** [9 min]	**Scenario**
Ignition to discovery <	Discovery to call <	Response time <	1
		Response time >	2
	Discovery to call >	Response time <	3
		Response time >	4
Ignition to discovery >	Discovery to call <	Response time <	5
		Response time >	6
	Discovery to call >	Response time <	7
		Response time >	8
Alarms present = a; No alarms = na			

When the probabilities and frequencies of the six property types are compared, in order to increase the clarity of the discussion, Table 39 renamed the scenarios from 1 to 8 for presence and absence of alarms named ‘a’ and ‘na’, respectively.

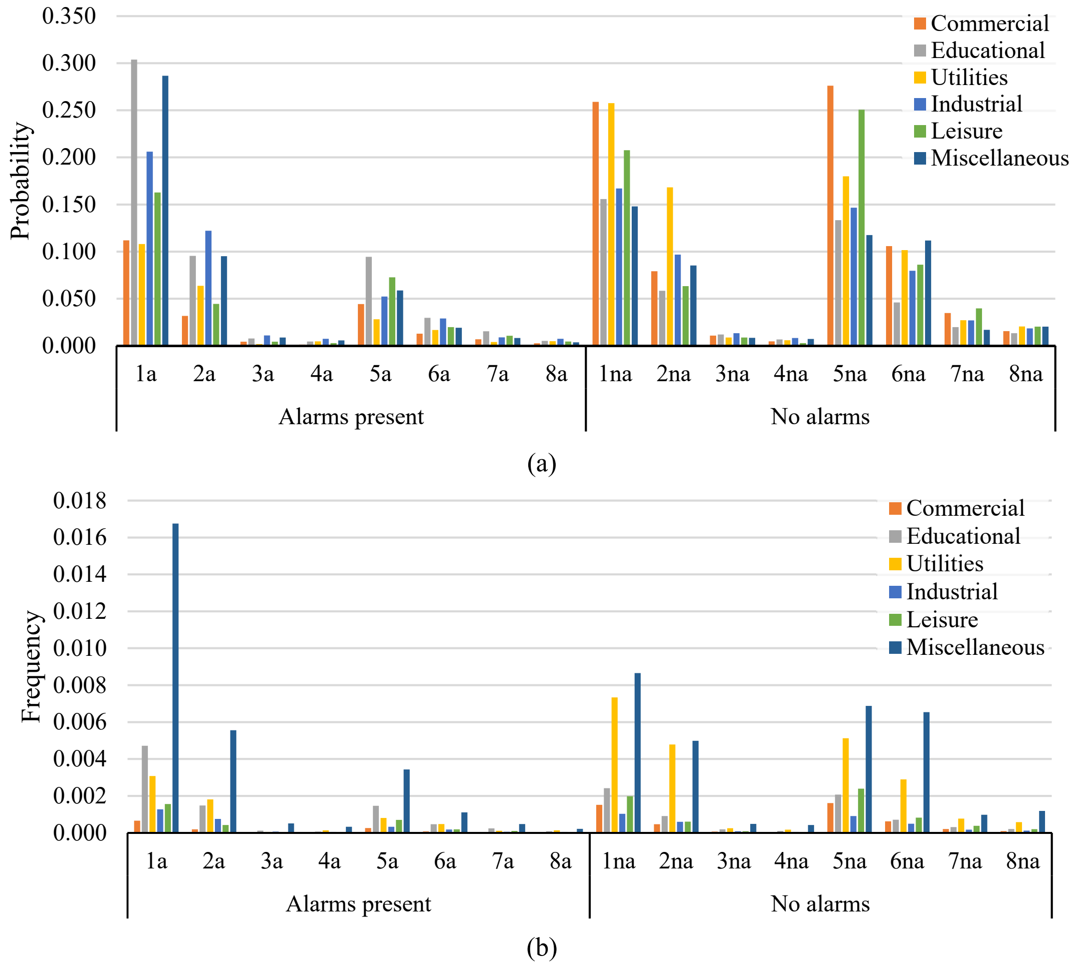


Figure 119: (a) Probability and (b) frequency in event tree analysis for fire response in English statistics

When probabilities are evaluated, the highest values for presence and absence of alarms characterized by ignition to discovery and discovery to call under 5 minutes and response time less than or more than 9 minutes, are assumed in scenario 1 and 2, respectively. The highest probabilities when alarms are present vary between 0.11 in *Commercial* and *Utilities* and approximately 0.30 in *Educational* and *Miscellaneous* in scenario 1a while 0.12 is assumed in *Industrial* in scenario 2a. When alarms are absent, values are assumed between approximately 0.16 in *Educational*, *Industrial* and *Miscellaneous* and 0.25 in *Commercial* and *Utilities* in scenario 1na and between 0.06 in *Educational* and 0.17 in *Utilities* in scenario 2na. Particular relevance is represented by scenario 5na and 6na for fire incidents with no alarms described by ignition to discovery greater than 5 minutes, discovery to call less than 5 minutes and response time less or greater than 9 minutes, respectively. In particular, probabilities assume values between 0.12 in *Miscellaneous* and 0.28 in *Commercial* in scenario 5na and between

0.05 in *Educational* and greater than 0.10 in *Commercial*, *Utilities* and *Miscellaneous* in scenario 6na (Figure 119 (a)).

As explained in section 6.1, frequency is obtained multiplying the overall probability of a particular scenario by the related frequency of the initiating event (fire incident). Figure 119 (b) presents the frequencies of the six property types considered in the analysis of this section for English fire statistics where the highest frequencies are assumed in *Educational* 0.0047-0.0015 and *Utilities* 0.0031-0.0018 in scenarios 1a and 2a, respectively. The scenarios in which frequencies assume the greatest influence when alarms are absent are 1na, 2na, 5na and 6na. If scenario 1na, 2na and 5na are evaluated, the highest peaks are represented by *Utilities* with approximately 0.0073-0.0048-0.0051 and *Educational* with 0.0024-0.0009-0.0021. *Miscellaneous* assumes the highest frequencies if the six property types are considered with 0.0168-0.00860 in scenario 1, 0.0056-0050 in scenario 2 for presence and absence of alarms, respectively.

Based on the considerations expressed for Figure 119, probabilities generally assume values about 10 times greater than those of frequencies characterized by a prompt response of occupants and fire brigades supported by a response time within 9 minutes. The response of occupants and fire brigade is very efficient in the first minutes after the ignition of the fire. Comments for presence and absence of alarms appear similar with small differences. The following section will consider fire response based on USA fire statistics.

6.1.2 Event tree analysis of fire response in USA statistics

In the USA, the analysis for the response time considering seven property types is divided into three main groups according to the properties in which there is no significant difference between the fire incidents for presence and absence of detectors, properties where fire incidents are mainly for the presence of detectors and where fire incidents are mainly referred to the absence of detectors.

The first group characterized by fire incidents almost equally recorded in terms of presence and absence of detectors is represented by *Assembly*, *Mercantile, Business* and *Industrial manufacturing* as shown in Figure 120, Figure 149 and Figure 150 in Annex, respectively. In these properties, values greater than 0.60 are found when detectors operated, alerted occupants and occupant responded. Moreover, response time is within 9 minutes for more than 0.60 in all 10 scenarios investigated.

Fire incidents are mainly recorded for the presence of detectors with values greater than 0.75 in *Educational* and *Health care, detention and correction* as described in Figure 121 and

Figure 151 in Annex, respectively. In the presence of detectors in these two property types, the scenarios appear successful with detectors operated, alerted occupants and occupants responded. For presence and absence of detectors, response time appears limited to 9 minutes showing an efficient response of fire brigades and values generally greater than 0.85.

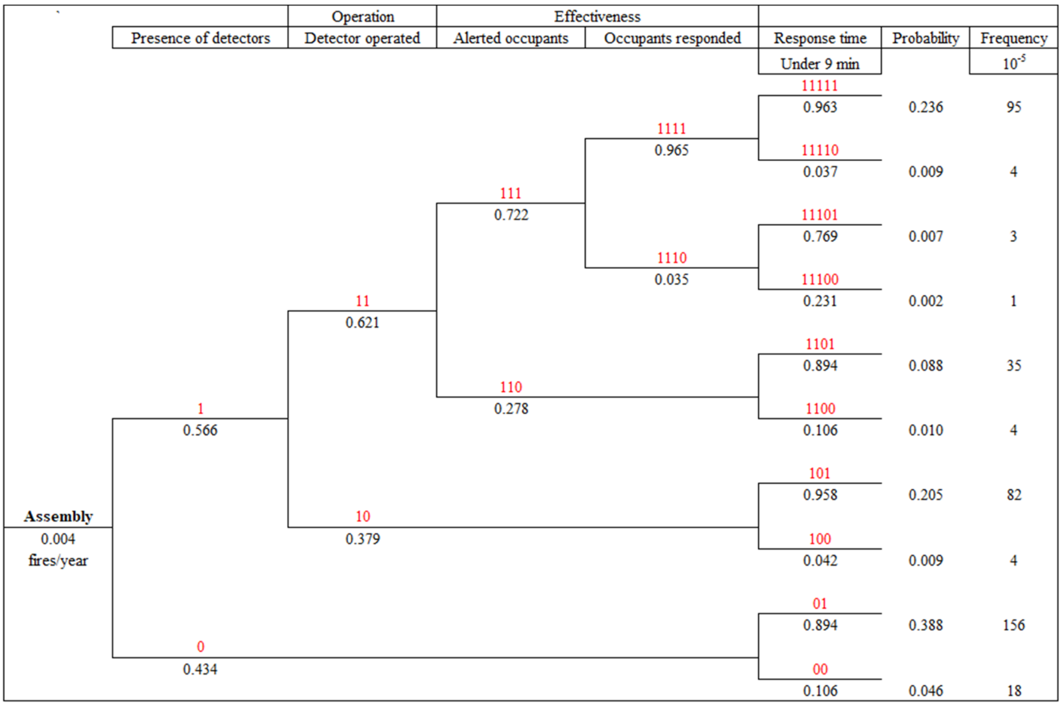


Figure 120: Event tree analysis fire response of Assembly in USA statistics

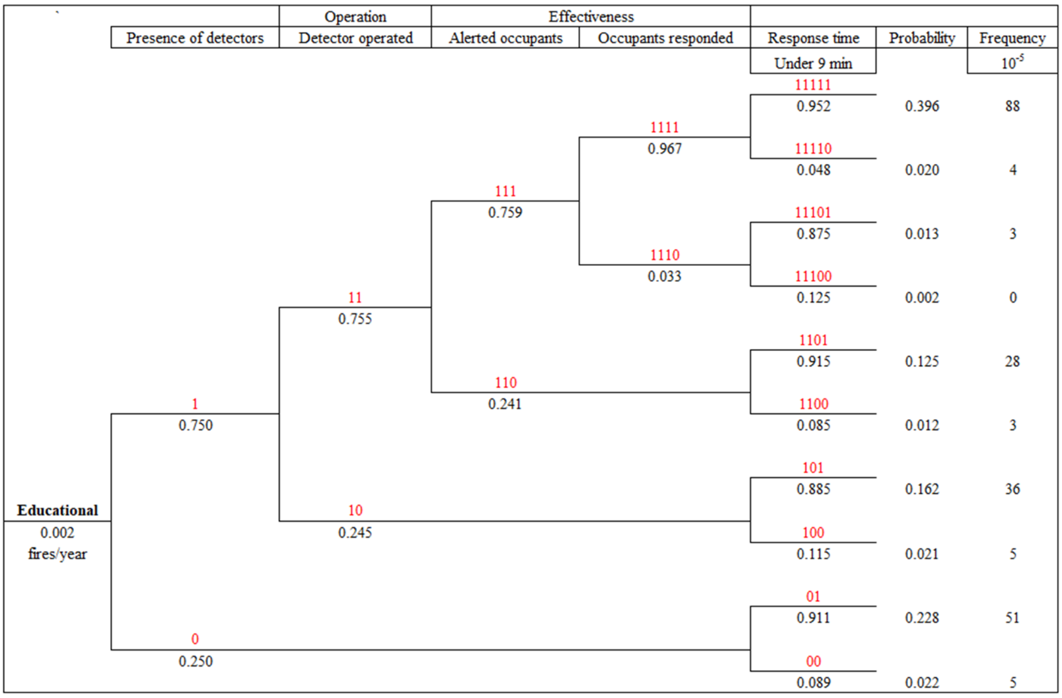


Figure 121: Event tree analysis fire response of Educational in USA statistics

Finally, in *Storage* and *Outside or special property* the fire incidents are mainly recorded when detectors are absent for approximately more than 0.90 with a response time less than 9 minutes for more than 0.70 as illustrated in Figure 122 and Figure 152 in Annex, respectively. Therefore, considerations about the presence of detectors are avoided. In *Outside or special property* of Figure 152 in Annex, scenario 1110 characterized by the presence, operation and effectiveness of detectors in terms of alert and occupants response, presents no data for the response time and this is the reason why scenarios 11101 and 11100 have empty cells.

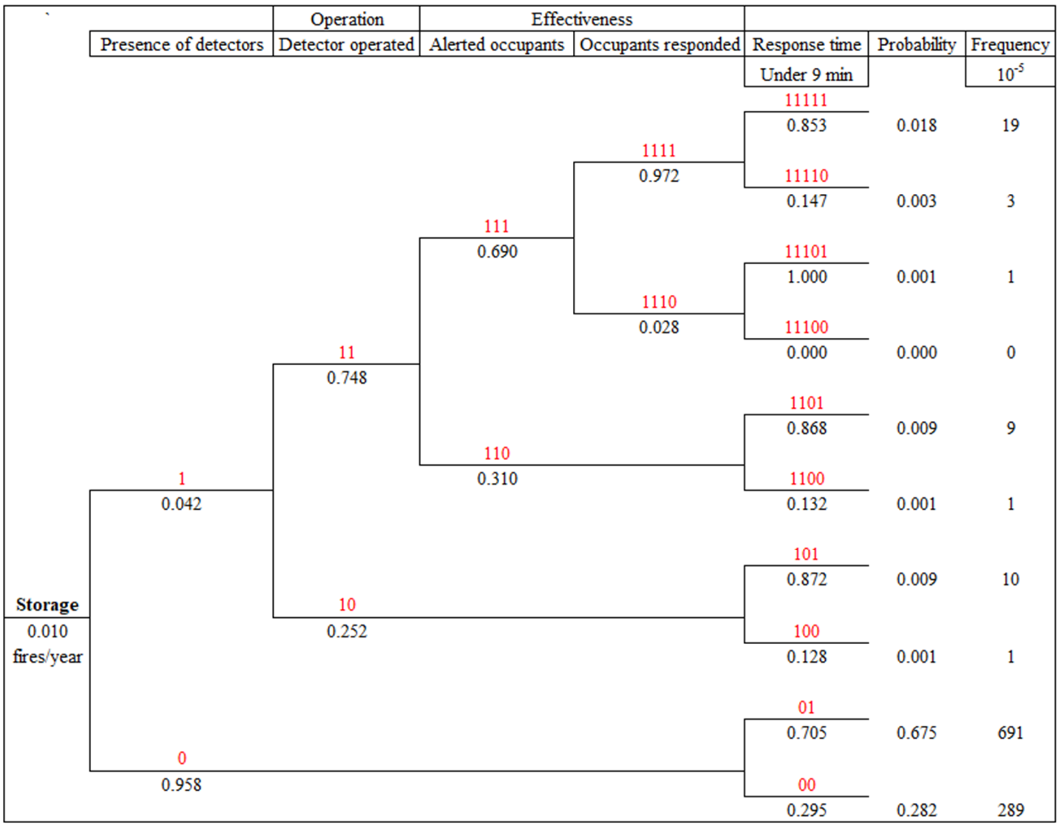


Figure 122: Event tree analysis fire response of Storage in USA statistics

Table 40: Event tree for fire response in the USA

Detector	Operation	Effectiveness		Response time [9 min]	Scenario
Present	Operated	Alerted occupants	Occupants responded	Response time <	1d
				Response time >	2d
			Occupants failed to respond	Response time <	3d
				Response time >	4d
		Failed to alert occupants or no occupants		Response time <	5d
				Response time >	6d
	Failed to operate or fire too small to activate			Response time <	7d
				Response time >	8d
Absent				Response time <	9nd
				Response time >	10nd
Detectors present = d; No detectors = nd					

Table 41 renames the 10 scenarios, 8 for the presence of detectors named 'd' and 2 for their absence named 'nd', to increase clarity in the discussion about overall probability and frequency in the 7 property types investigated.

Presence of detectors determines that the most likely scenarios are 1d, 7d and 5d according to decreasing values of probabilities (Figure 123 (a)). Scenario 1d is characterized by the detectors that operated, alerted occupants, occupants responded and response time within 9 minutes where probabilities vary from 0.19 in *Mercantile, Business* to 0.54 in *Health care, detention and correction*. Scenario 7d is referred to detectors failed to operate and response time less than 9 minutes where values assume probabilities between 0.09 in *Industrial, manufacturing* and approximately 0.20 in *Assembly* and *Health care, detention and correction*. In scenario 5d where detectors operated, failed to alert occupants and response time less than 9 minutes, the highest values are 0.09 in *Assembly* and 0.13 in *Educational*. Investigating the absence of detectors, response time appears generally within 9 minutes as shown in scenario 9nd with values from 0.14 in *Health care, detention and correction* to 0.68 in *Storage*. Finally, in Scenario 10nd with the absence of detectors and response time greater than 9 minutes, the highest probabilities are assumed in *Industrial, manufacturing*, *Storage* and *Outside or special property* (0.18-0.28-0.26%) while the other properties never exceed 0.06.

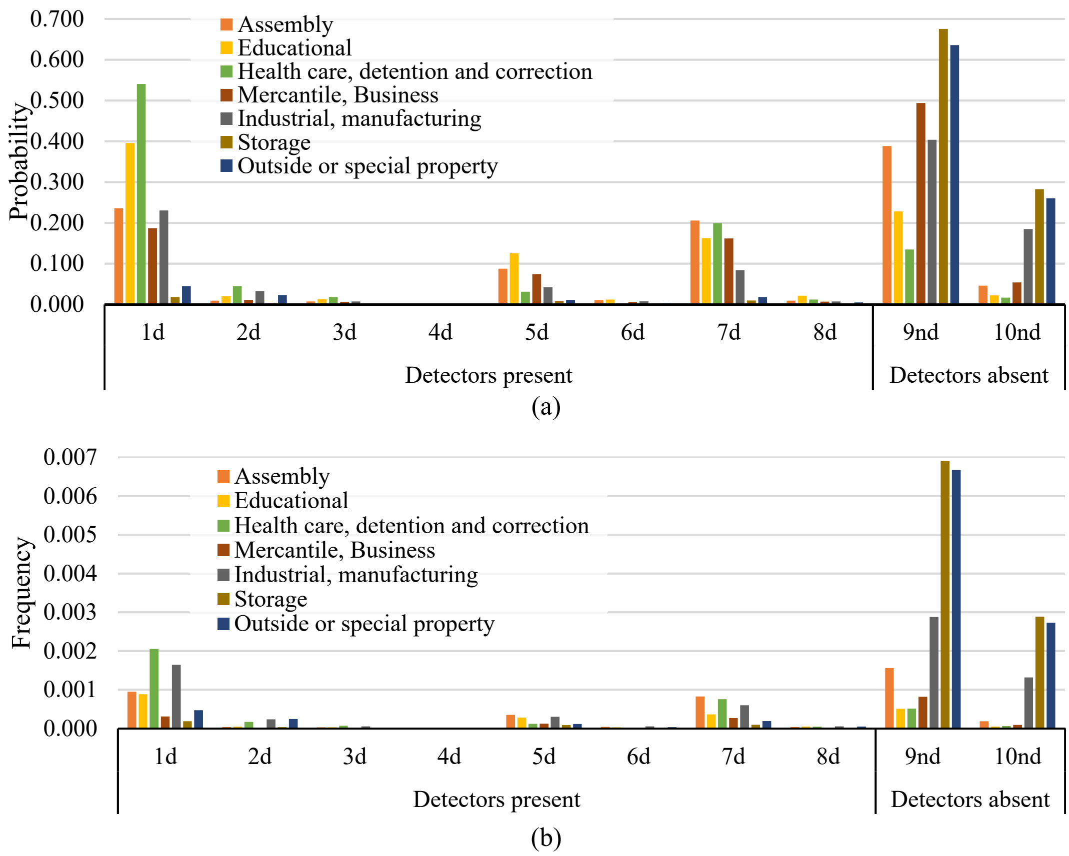


Figure 123: (a) Probability and (b) frequency in event tree analysis for fire response in USA statistics

Frequencies are summarized in Figure 123 (b) and when they are compared to the probabilities of Figure 123 (a), the difference is given by the values for frequencies approximately 10 times less than those for probabilities as already obtained for England in section 6.1.1. For fire incidents with the presence of detectors, frequencies are always less than 0.002 while for fire with the absence of detectors, the highest values are assumed in *Industrial, manufacturing* (0.0028-0.0013), in *Storage* and *Outside or special property* (approximately 0.0070-0.0030) in scenario 9nd and 10nd, respectively. Moreover, another peak is reached in *Assembly* with 0.0016 while the other properties of scenario 9nd present values less than 0.0010. Finally, in scenarios 10nd, the frequencies for the property types are usually null except for *Industrial, manufacturing*, *Storage* and *Outside or special property* as mentioned above.

The event tree analysis developed for the fire response in the USA shows that when detectors are present, they are effectively operating and affecting occupants. Furthermore, occupants appear to respond to alarms and the response time is within 9 minutes. The fire incidents with the absence of detectors seem to be characterized by a prompt response of fire brigades which is usually within 9 minutes.

6.2 Event tree analysis of fire damage

The second event tree analysis developed adopting English and USA fire statistics evaluates the damage due to fire incidents based on presence or absence of automatic extinguishing systems, response time, fire spread and damage. As in section 6.1, the differences in how the fire safety fields are recorded in English and USA statistics have determined two different event tree analyses.

Table 41: Automatic extinguishing systems in English and USA fire statistics

<table>
<tr><th colspan="4">Automatic extinguishing systems</th></tr>
<tr><th>Eng</th><th colspan="3">USA</th></tr>
<tr><td rowspan="3">Sprinklers present and raised the alarm
Sprinklers operated but did not raise alarm
Other System present and raised the alarm</td><td rowspan="3">Present or partially present</td><td rowspan="2">Operated</td><td>Operated and effective</td></tr>
<tr><td>Operated and not effective</td></tr>
<tr><td colspan="2">Fire too small to activate or Failed to operate, Other</td></tr>
<tr><td>Other System operated but did not raise alarm</td><td colspan="3">None present</td></tr>
<tr><td>No Safety System
Sprinklers present but did not operate
Other System present but did not operate</td><td colspan="3"></td></tr>
</table>

As for alarms in section 6.1, presence, operation and effectiveness are recorded as three separated fields in the USA while they appear as a unique one in England. Again in the USA, the three fields need to be filled in in sequential order and if the previous one present no data, no further information is required for the following ones. For example, if the fire is too small to activate or sprinklers failed to operate then information on how sprinkler performances were effective is not reported. For the automatic extinguishing systems in England, the class of no safety systems and sprinklers or other systems which did not operate are grouped to simulate the absence of safety systems while the other classes summed to represent their presence (Table 41). In future research and thanks to future potential extended datasets, these fields will be separated in England to have similarities with the USA fire statistics dataset.

The evaluation of damage induced by the fire incident in England is determined considering fire size on the arrival of the fire brigades if the fire had a rapid-fire growth, the fire spread and the quantification of damage in m^2 considering *fire* and *total damage* according to the definitions provided in section 2.3.2. The parameters assumed in the event tree analysis for England are fire size on arrival limited to the room of origin and fire spread limited to the floor of origin. Since generally fire room is assumed as a compartment, *fire* and *total damage* are limited to 50 m^2 to describe damage bigger than a room and smaller than a floor and support the above assumptions as indicated in Table 42.

In the USA, no fields are recorded for fire size on arrival and the evaluation of rapid-fire growth. However, the classification for fire spread is similar to the one of English statistics and assumed as confined to the floor of origin in this analysis. The number of stories damaged by fire in the USA is reported where the damage is referred to fire damage defined as the area (in ft^2) burned or charred not including areas receiving heat, smoke, water or damage (USFA, 2014). Fire damage is classified according to four classes as described in section 4.2.2.3 (Minor damage 0-24%, Significantly 25-49%, Heavy 50-74% and Extreme 75-100%) and each percentage has been multiplied by the related number of floors and converted in m^2. Fire damage is limited to 50 m^2 to compare results with English statistics (Table 42).

Table 42: Damage in English and USA fire statistics

Damage	*Eng*	*USA*
Fire size on arrival	Limited to room of origin	/
Rapid-fire growth	Yes / No	/
Fire spread	Limited to floor of origin	Confined to floor of origin
Fire damage	Up to 50 m^2	Minor (0-24%) Significantly (25-49%) Heavy (50-74%) Extreme (75-100%)
Total damage	Up to 50 m^2	/

Fire statistic parameters assumed in Table 42 have been considered in the event tree analysis developed for various property types to understand the likelihood and consequences of several scenarios based on English and USA statistics. The results obtained will increase awareness on the impact of safety systems and response time on structural damage. It could be considered as a tool to optimize evacuations measures and time of attendance of fire brigade investigating structural performance in terms of fire growth and spread during fire incidents.

6.2.1 Event tree analysis of fire damage in English statistics

The event tree analysis for the fire damage in English statistics has been applied to the property types of *Commercial*, *Educational*, *Utilities*, *Industrial*, *Leisure* and *Miscellaneous* as already introduced in section *6.1.1*. The analysis considers presence and absence of sprinklers, the response time assumed within 9 minutes, fire size on arrival limited to the room of origin, the spread of fire limited to the floor of origin and *fire* and *total damage* up to 50 m^2. The assumptions assumed for successful sub-events have been already discussed in section 6.2. A total of 128 scenarios are obtained. Due to the extended graphical dimensions, the event tree for each property type is divided into 4 parts representing 32 scenarios. Table 43 summarizes the main area covered by each of the four parts to improve clarity for readers.

Table 43: Parts of event tree analysis of fire damage in English statistics

	Sprinklers or other safety systems	Response
Part 1	Present and operated	< 9 min
Part 2	Present and operated	> 9 min
Part 3	Absent or did not operate	< 9 min
Part 4	Absent or did not operate	> 9 min

Generally, as represented by Table 44, the event tree analyses developed for the property types investigated are characterized predominantly by fire incidents in buildings not equipped with sprinklers. Moreover, for the presence of sprinklers, the majority of the property types present no data recorded providing several empty cells. Therefore, comments will be focused only on the analysis of the absence of sprinklers with the exceptions of *Commercial* and *Industrial* where consistent values for sprinklers are available.

Table 44: Probabilities of presence and absence of sprinklers in event tree analysis for fire damage for property types in English statistics

	Sprinklers	No Sprinklers
Commercial	0.0009	0.991
Educational	0.0013	0.987
Utilities	0.0022	0.978
Industrial	0.085	0.915
Leisure	0.007	0.993
Miscellaneous	0.017	0.983

The presence of sprinklers in *Commercial* and *Industrial* illustrated in Figure 124, Figure 125, Figure 153 and Figure 154 in Annex shows that the response time is within 9 minutes for more than 0.60, the fire size on arrival is limited to the room of origin, fire incidents are not characterised by a rapid-fire growth and fire spread is generally limited to the floor of origin. When the sub-events of *fire* and *total damage* are reached, data appear less dense in the datasets. In particular, while *fire damage* is confined to 50 m^2 for the majority of scenarios, *total damage* presents values greater when the area damage exceeds 50 m^2. However, the empty cells and the limited data suggest treating these results with a high degree of uncertainty.

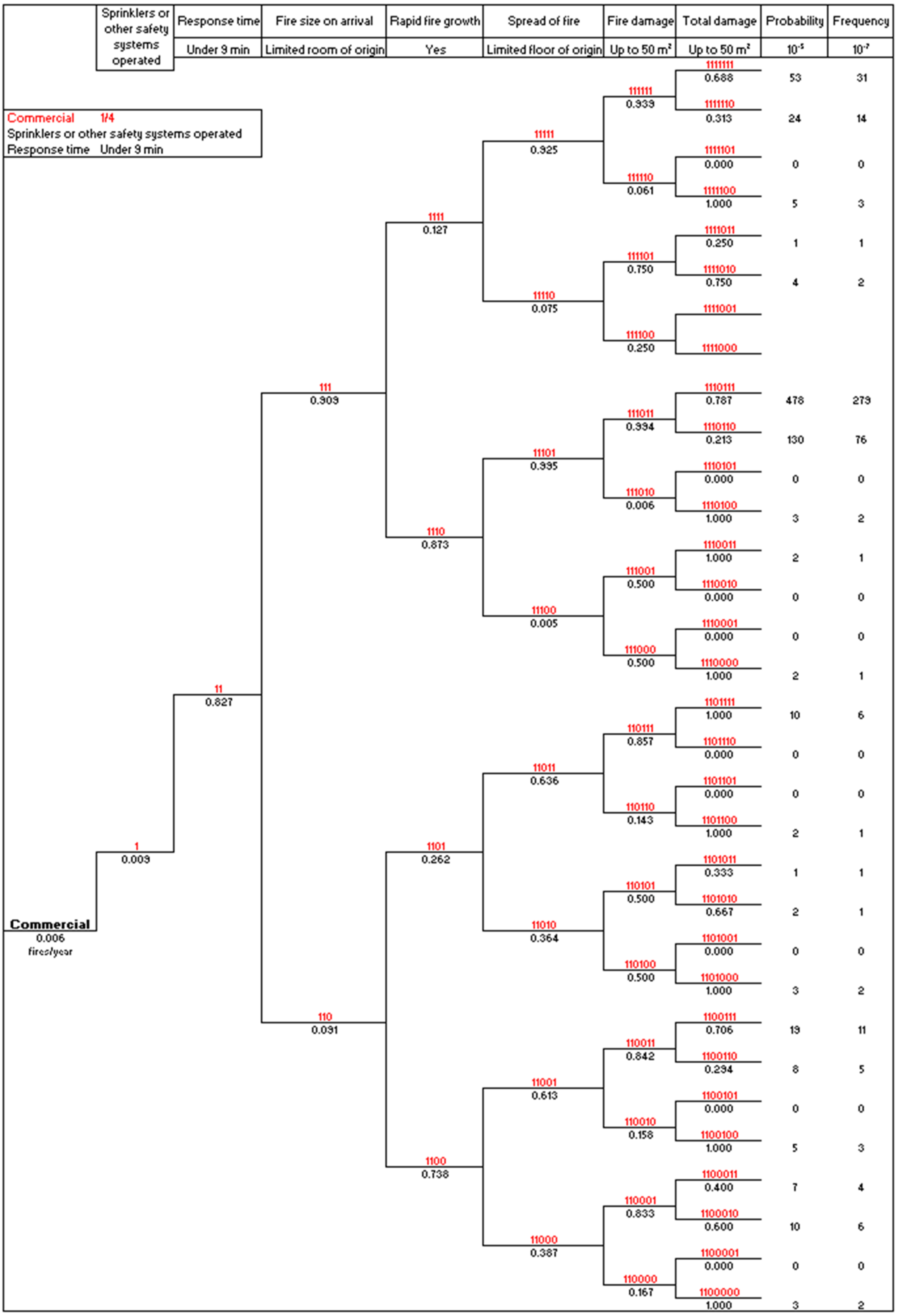


Figure 124: Event tree analysis fire damage of Commercial part 1/4 in English statistics

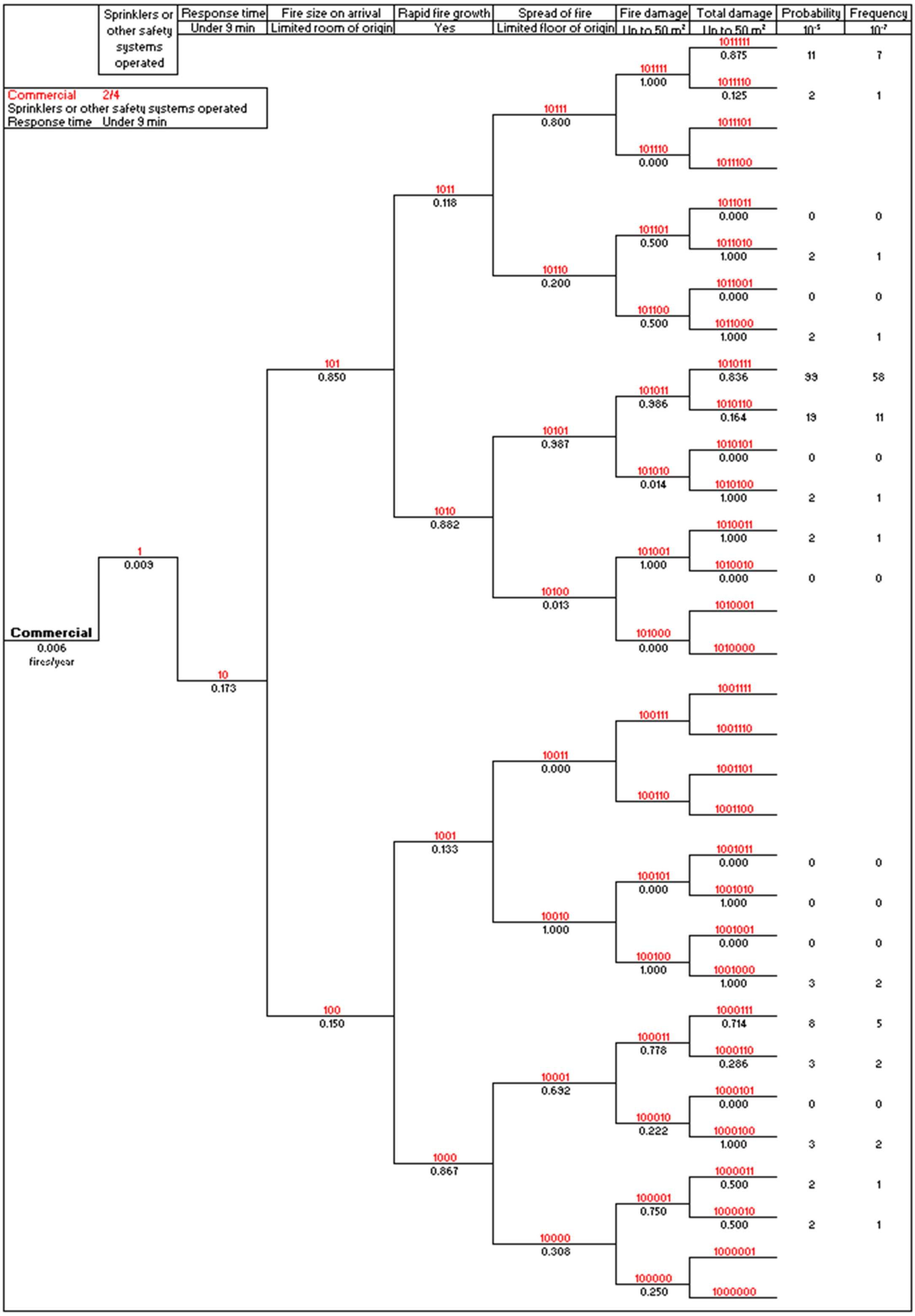


Figure 125: Event tree analysis fire damage of Commercial part 2/4 in English statistics

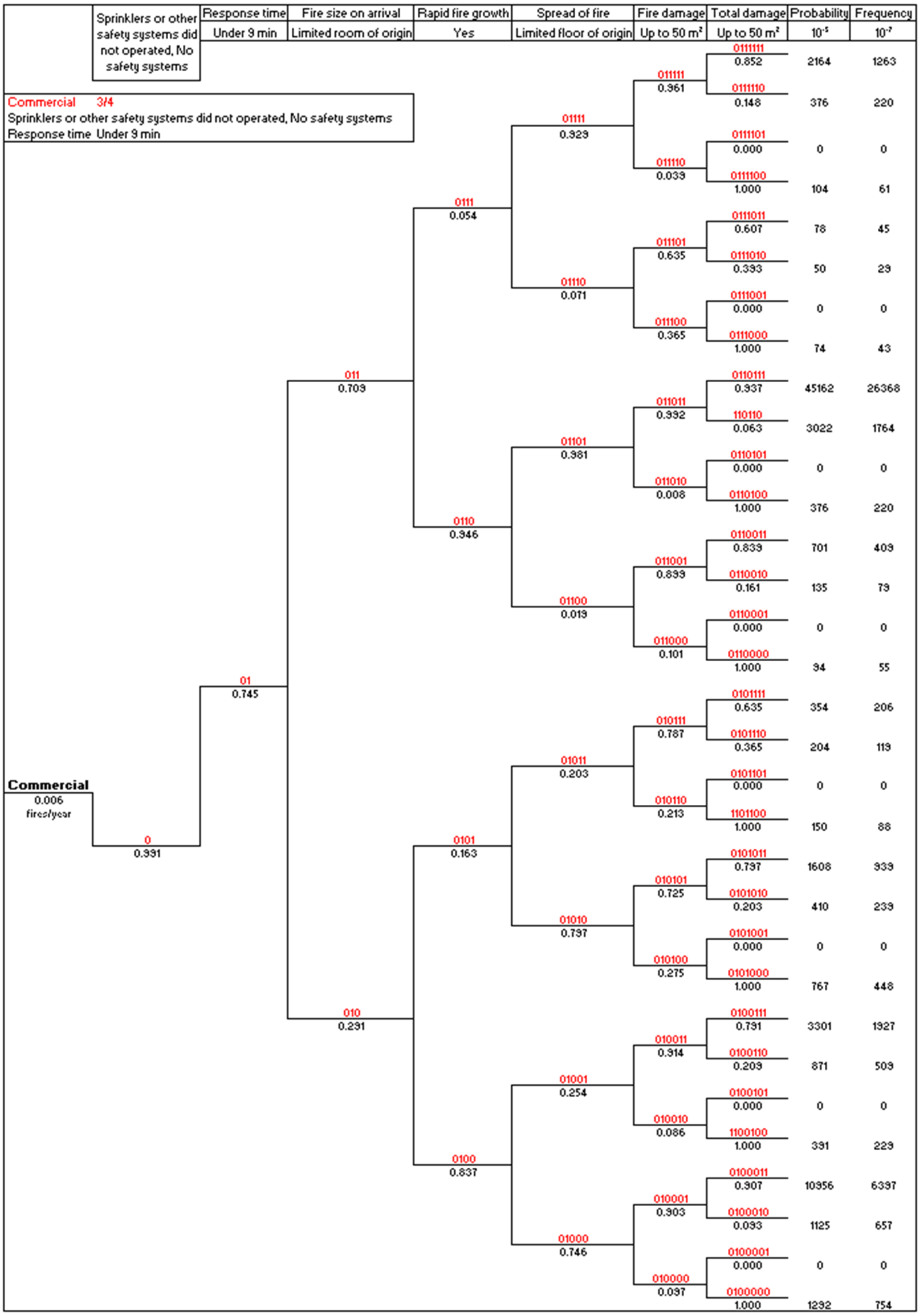


Figure 126: Event tree analysis fire damage of Commercial part 3/4 in English statistics

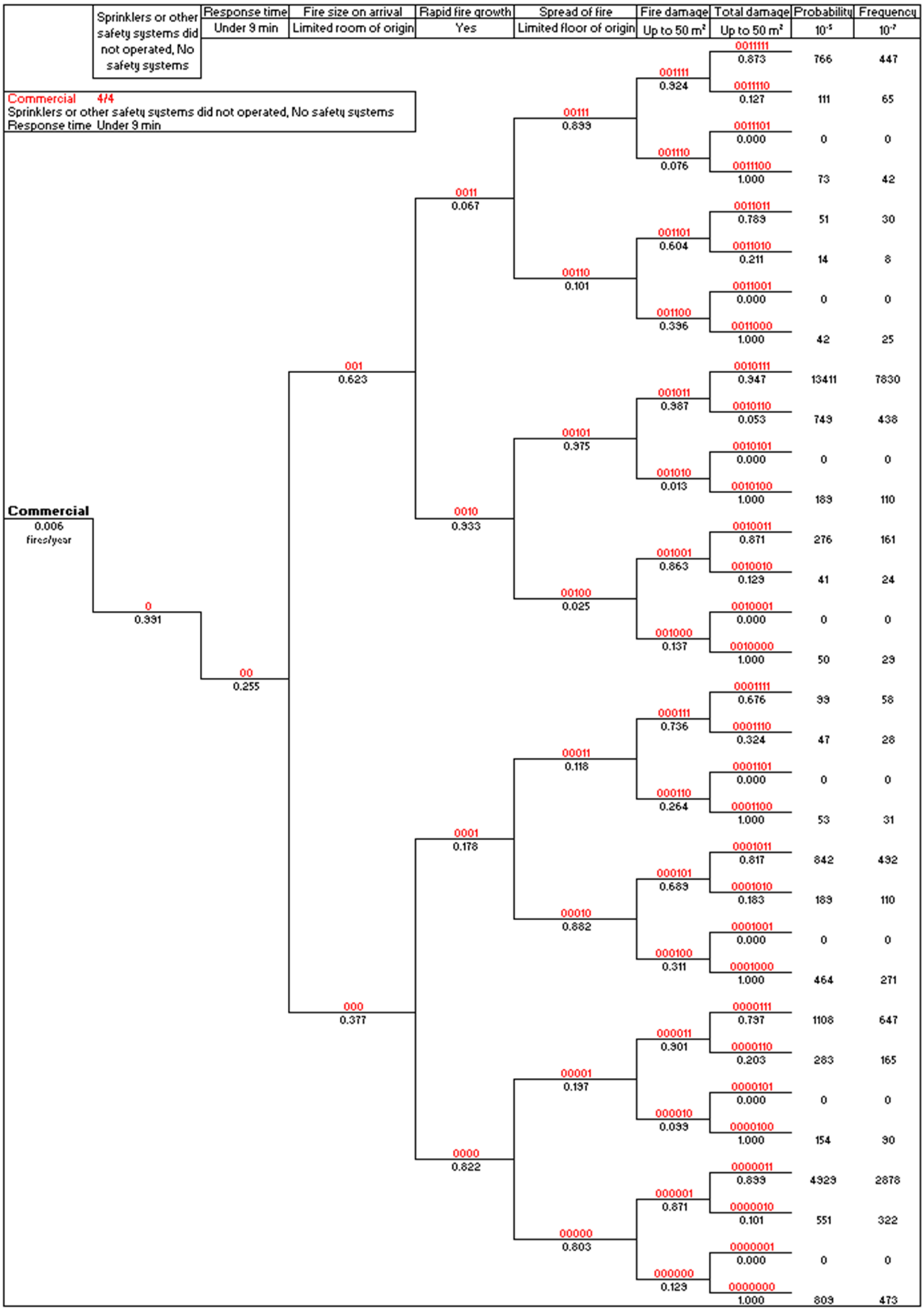


Figure 127: Event tree analysis fire damage of Commercial part 4/4 in English statistics

When absence of sprinklers is studied in Figure 126 and Figure 127 for *Commercial* and Figure 155 and Figure 156 in Annex for *Industrial*, the response is limited to 9 minutes for more than 0.60, fire size on arrival is limited to the room of origin with fires without a rapid-fire growth. In *Commercial*, the spread of fire appears limited to the floor of origin only in the scenarios where the fire size on arrival is limited to the room of origin while in the other ones overpasses the floor of origin for more than 0.70 (Figure 126 and Figure 127). In *Industrial,* the spread beyond the floor of origin is obtained only when fire size is not limited to room and rapid-fire growth for response time within and over 9 minutes (Figure 155 and Figure 156 in Annex). *Fire damage* appears limited to 50 m^2 in the majority of cases while *total damage* presents an area greater than 50 m^2 in 16 scenarios over the 64 investigated for the presence of sprinklers for both *Commercial* and *Industrial*. However, the majority of the 16 scenarios above mentioned is described by fires only recorded for *total damage* greater than 50 m^2 and could be not representative of the fire incident population.

Educational (from Figure 128 to Figure 131), *Utilities* (from Figure 157 to Figure 160 in Annex), *Leisure* (from Figure 161 to Figure 164 in Annex) and *Miscellaneous* (from Figure 165 to Figure 168 in Annex) are discussed only for what concerns the results obtained for the scenarios characterized by absence of safety systems due to the limited data available for their presence. For the four property types when sprinklers are not present, the response time of fire brigades is within 9 minutes with values greater than 0.60, fire size on arrival is mainly limited to the room of origin and fires do not present a rapid-fire growth. However, as described by Figure 130 and Figure 131 in *Educational* with trends similar to the other property types, the spread of fire appears limited to the floor of origin only when the fire size on arrival is limited to the room of origin while when it expands beyond the room of origin, the spread of fire is generally not limited to the floor of origin showing greater and high consequences fires affecting the building. Except for a few scenarios, *fire damage* is mainly confined up to 50 m^2 while *total damage* affects damage greater than 50 m^2 in the scenarios in which *fire damage* is greater than 50 m^2. However, when fire damage is not limited to 50 m^2, data appear scarce and results need to be considered with appropriate uncertainties.

According to the results shown by the event tree analysis developed for fire damage based on English statistics, the description of fire incidents demonstrates that buildings affected by the fire are mainly not equipped with sprinklers. If buildings without sprinklers are examined, the response time of fire brigades is usually within 9 minutes, fire size on arrival is limited to the room of origin and fires are not characterized by a rapid-fire growth. When fire size on arrival spread beyond the room of origin, is more likely to have a fire spread beyond the floor of origin. While *fire damage* is confined to 50 m^2, the *total damage* shows similar areas of damage; therefore, *fire* and *total damage* appear to be directly related. However, it is important to treat the results obtained in the event tree analyses of this section with the correct degree of uncertainties especially for the parts related to the presence of safety systems.

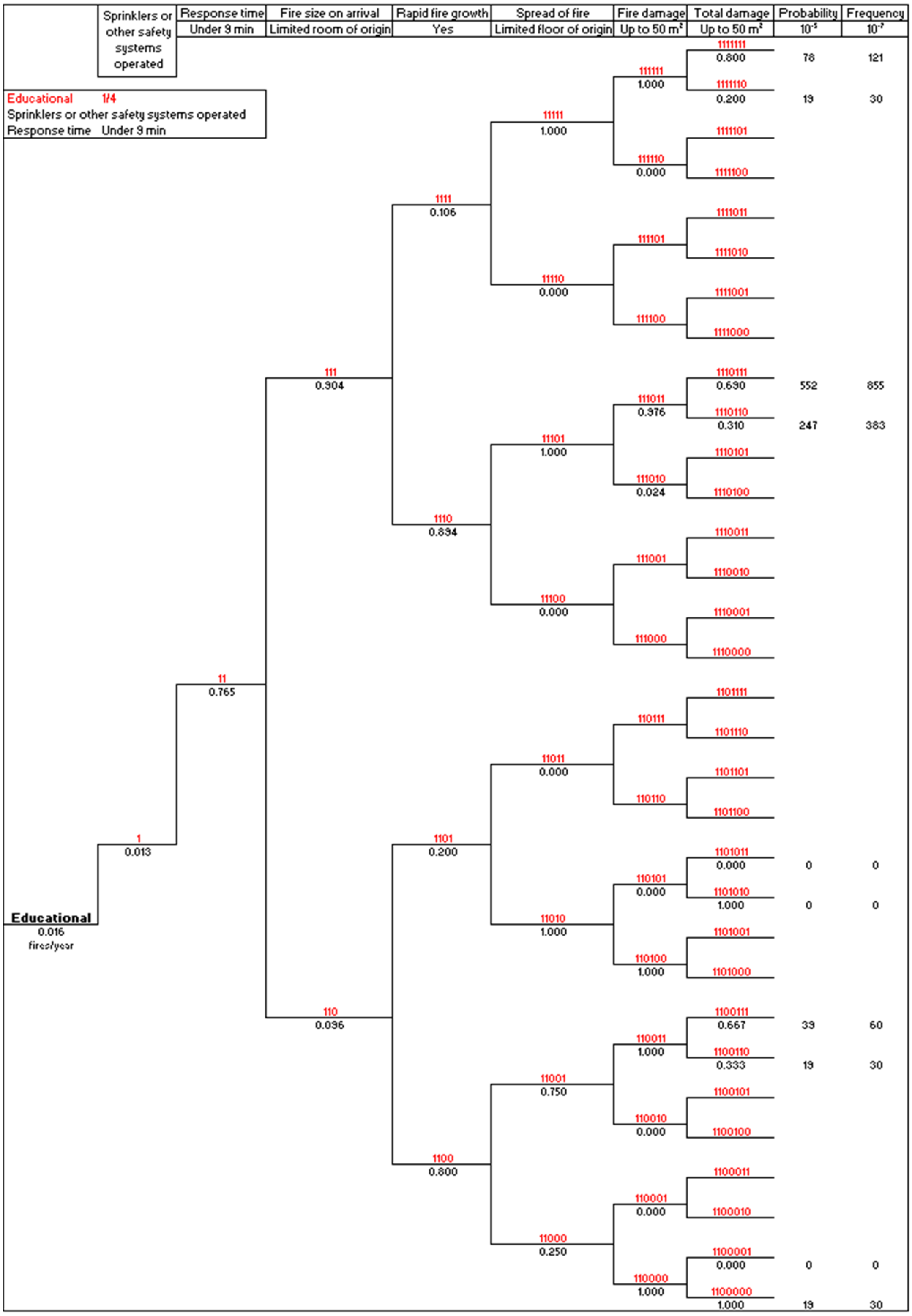


Figure 128: Event tree analysis fire damage of Educational part 1/4 in English statistics

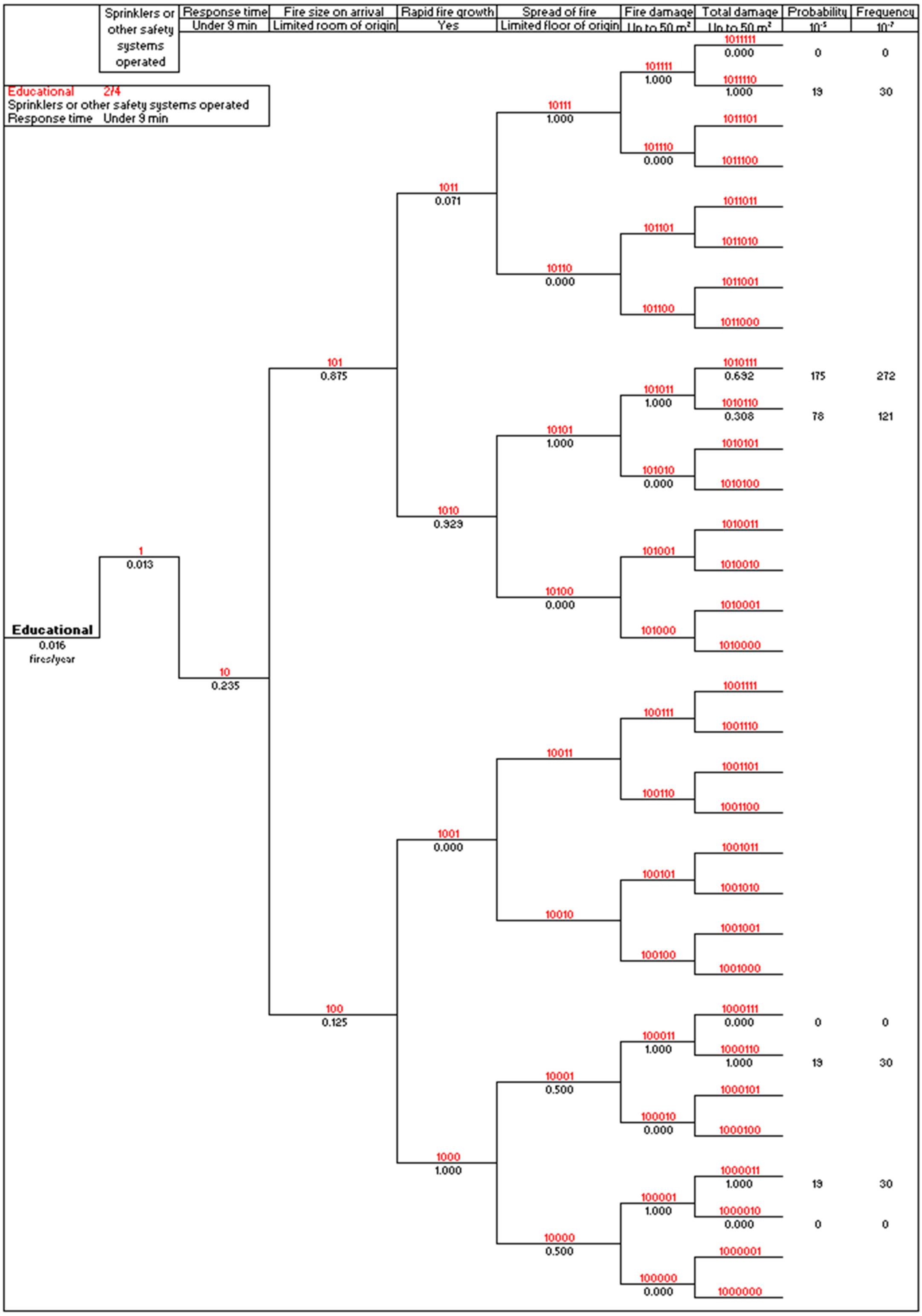


Figure 129: Event tree analysis fire damage of Educational part 2/4 in English statistics

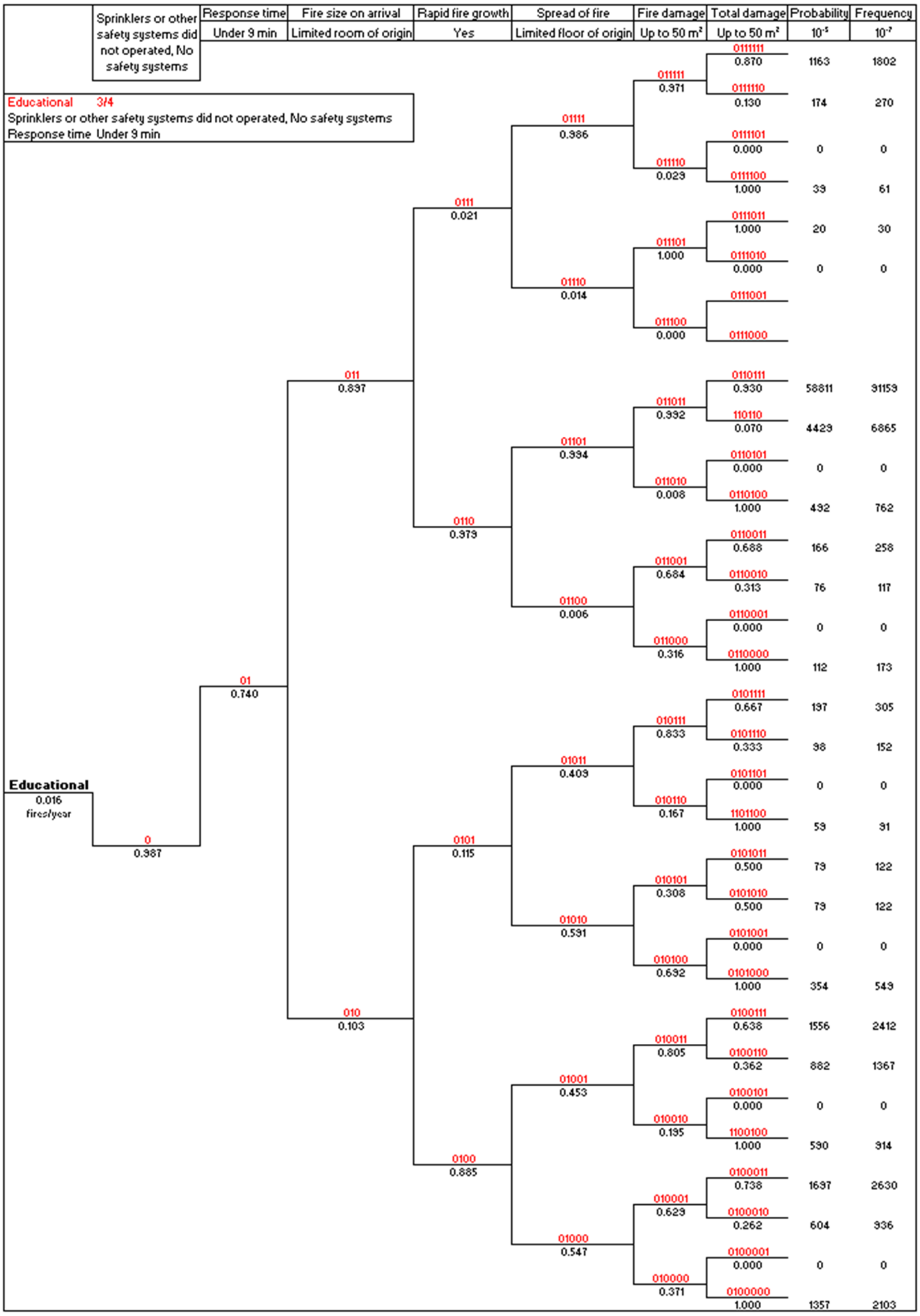


Figure 130: Event tree analysis fire damage of Educational part 3/4 in English statistics

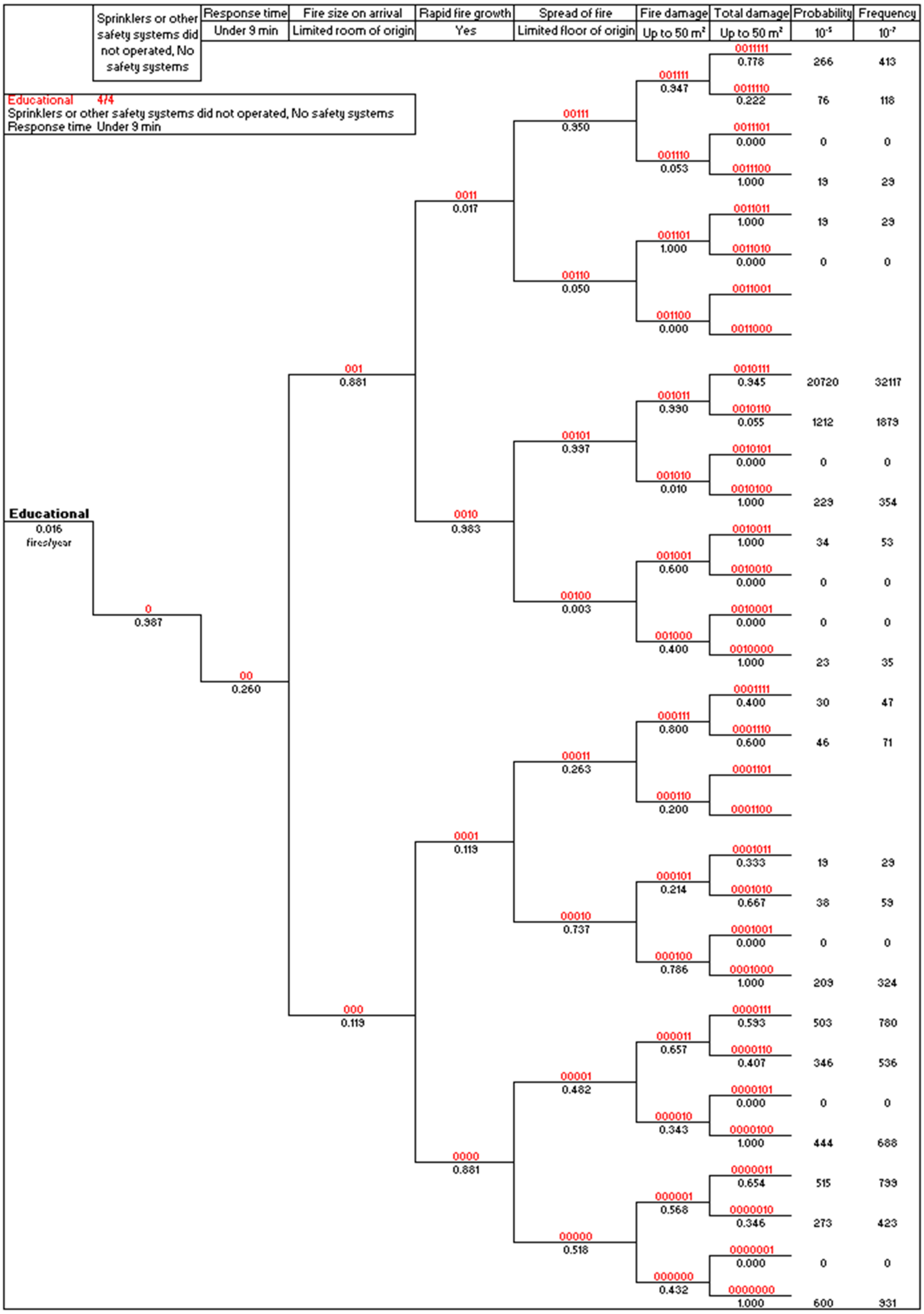


Figure 131: Event tree analysis fire damage of Educational part 4/4 in English statistics

The overall probability and frequencies have been obtained for the property types examined in English statistics and to increase the clarity of the discussion, the scenarios for each building type have been classified according to 64 scenarios for presence named 's' 64 for the absence of sprinklers named 'ns' for a total of 128 scenarios as investigated above. Due to data missing and values approximately null, amongst these 64 scenarios, only 8 (4 for sprinklers and 4 for no sprinklers) have been found as the most significant and are described and renamed in Table 45. The four damage scenarios provided in Table 45 present fire size on arrival limited to the room of origin, no rapid-fire growth, the spread of fire limited to the floor of origin and *fire damage* up to 50 m^2 where response time could be less (Scenario 9 and 10) or greater (Scenario 41 and 42) than 9 minutes and *total damage* greater than 50 m^2 in Scenario 10 and 42.

Table 45: Relevant fire scenarios for the event tree of fire damage in English statistics

Response time [9 min]	**Fire size on arrival** [Room of origin]	**Rapid growth**	**Spread of fire** [Floor of origin]	**Fire damage** [50 m^2]	**Total damage** [50 m^2]	**Scenario**
<	Limited	No	Limited	<	<	9
<	Limited	No	Limited	<	>	10
>	Limited	No	Limited	<	<	41
>	Limited	No	Limited	<	>	42

Sprinklers = s; No sprinklers = ns

When sprinklers are present, *Industrial* assumes the highest value with the probability of 0.03-0.01-0.02 respectively in 9s, 10s and 41s (Figure 132 (a)). *Utilities* and *Miscellaneous* represents the second and third peaks in 9s and 41s with an approximate value of 0.01. In 42s, excluding *Industrial*, all the other property types assume an almost null value. The analysis when sprinklers are absent provides similar probabilities for the six property types examined with a probability of around 0.50 in 9ns and 0.20 in 41ns as represented in Figure 132 (b). The highest values are reached in *Educational* with 0.59 in 9ns and *Utilities* with 0.32 in 41ns.

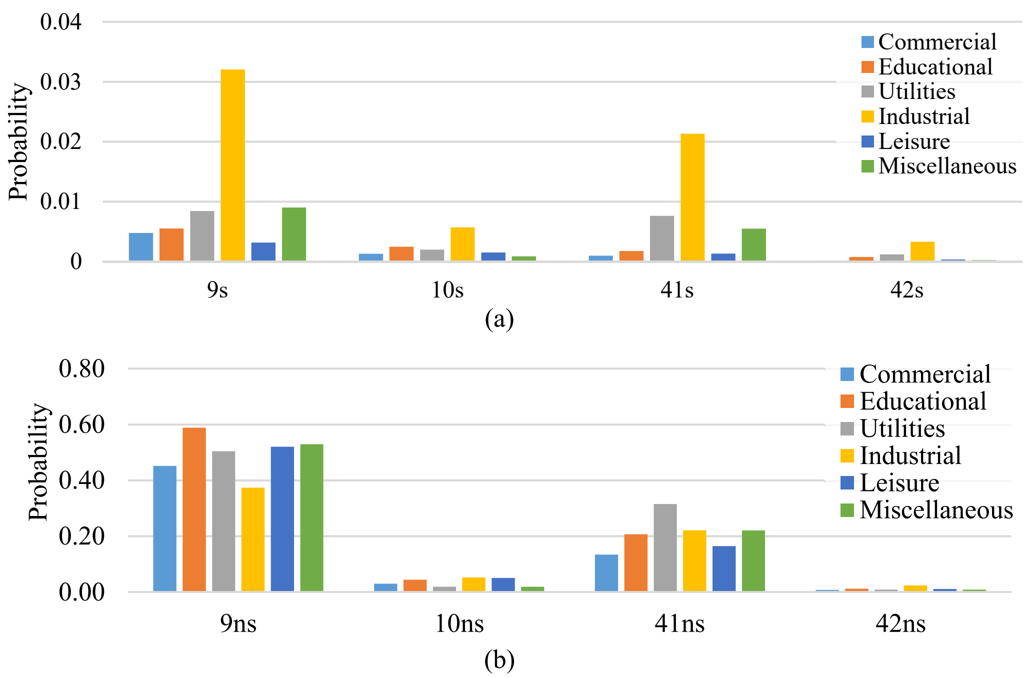


Figure 132: Probability in the most relevant damage scenarios (a) with and (b) without sprinklers in England

Frequencies examined for the absence of sprinklers present values greater than those available for their presence due to the paucity of data recorded for fires in buildings equipped with sprinklers. However, the trends appear similar to the highest peak reached by *Miscellaneous* with 0.0005-0.0309 in scenario 9 and 0.0003-0.0129 in scenario 41 for presence and absence of sprinklers, respectively. The difference in trends between Figure 133 (a) and (b) is attributable to scenario 41 where the second peak for both is given by *Utilities* (0.0002 in 41s and 0.0090 in 41ns) while the third one by *Industrial* with a value of 0.0001 in 41s and by *Educational* with 0.0032 in 41ns.

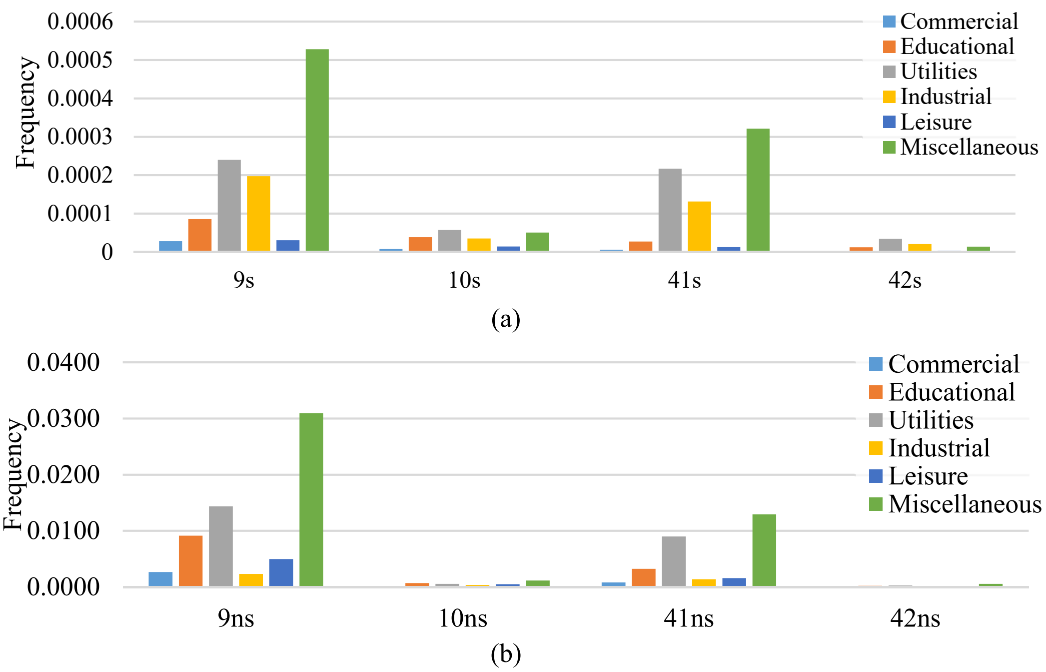


Figure 133: Frequency in the most relevant damage scenarios (a) with and (b) without sprinklers in England

The most likely scenarios according to the overall probability and frequencies support the considerations affirmed above for which the fire brigades provide a prompt response and usually within 9 minutes, fire size on arrival is limited to the room of origin, no rapid-fire growth and fire spread is limited to the room of origin. Moreover, *fire damage* is usually up to 50 m^2 while comments for *total damage* should be verified in future due to the high level of uncertainties. Limited data are available for the presence of sprinklers and the related results need to be considered carefully.

In the following section, the event tree analysis for fire damage is developed considering USA fire statistics. The research developed in this thesis recreates analyses as similar as possible to the one of England considering the differences in the fire safety fields recorded by the two fire statistics.

6.2.2 Event tree analysis of fire damage in USA statistics

In USA statistics, the event tree analysis for the fire damage considers seven property types as already discussed in section 6.2.2. The analysis developed examines not only the presence and absence of safety systems as in English statistics but also their operation and effectiveness and these fields need to be evaluated in sequential order. For example, if sprinklers are not present, no information about operation and effectiveness is available while if they are present and operated, the field related to their effectiveness appears in the dataset. Moreover, the other fields investigated are: response time under 9 minutes, the fire spread limited to the floor of origin and fire damage up to 50 m^2. The assumptions for successful sub-events have been already discussed in section 6.2. When USA statistics is investigated, a non-symmetric event tree analysis is obtained. A total of 32 scenarios is considered where 24 scenarios are available for the presence of sprinklers and 8 for absence.

The property types present a probability for sprinklers and no sprinklers summarized in Table 46 and they are described in this section according to four groups based on similar trends composed of: *Health care, detention and correction* where there is a majority of fire incidents recorded in presence of safety systems; *Assembly* and *Educational* where fires are mainly in buildings not equipped with safety systems and there are 12 scenarios for sprinklers with empty values; *Mercantile, business* and *Industrial, manufacturing* where fires are mainly in buildings without safety systems and there are 8 scenarios for sprinklers with empty values and *Storage* and *Outside and special property* where more than 0.90 fire incidents are recorded for the absence of safety systems.

Table 46: Probabilities of presence and absence of sprinklers in event tree analysis for fire damage for property types in USA statistics

	Sprinklers	No Sprinklers
Assembly	0.429	0.571
Educational	0.373	0.627
Health care, detention and correction	0.597	0.403
Mercantile, business	0.271	0.729
Industrial, manufacturing	0.410	0.590
Storage	0.027	0.973
Outside or special property	0.0034	0.966

In Figure 134 of *Health care, detention and correction*, the majority of fire incidents are recorded in buildings equipped with safety systems for 0.597 of cases. Sprinklers did not operate for high than 0.70 of cases showing not reliable safety systems. However, when they operated, almost the total was effective. For presence or absence of sprinklers, response time is within 9 minutes, the fire spread confined to floor of origin and fire damage up to 50 m^2.

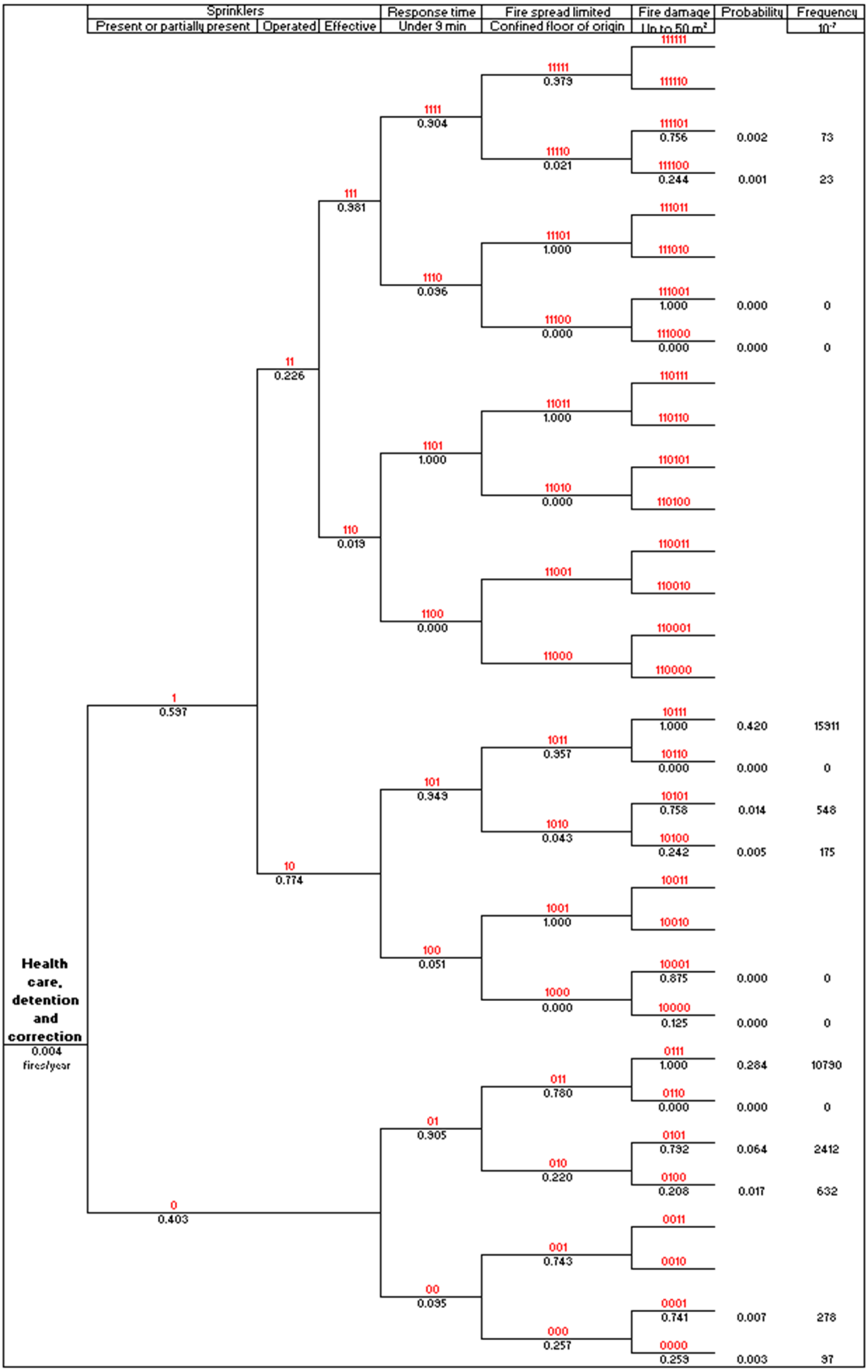


Figure 134: Event tree analysis fire damage of Health care, detention and correction in USA statistics

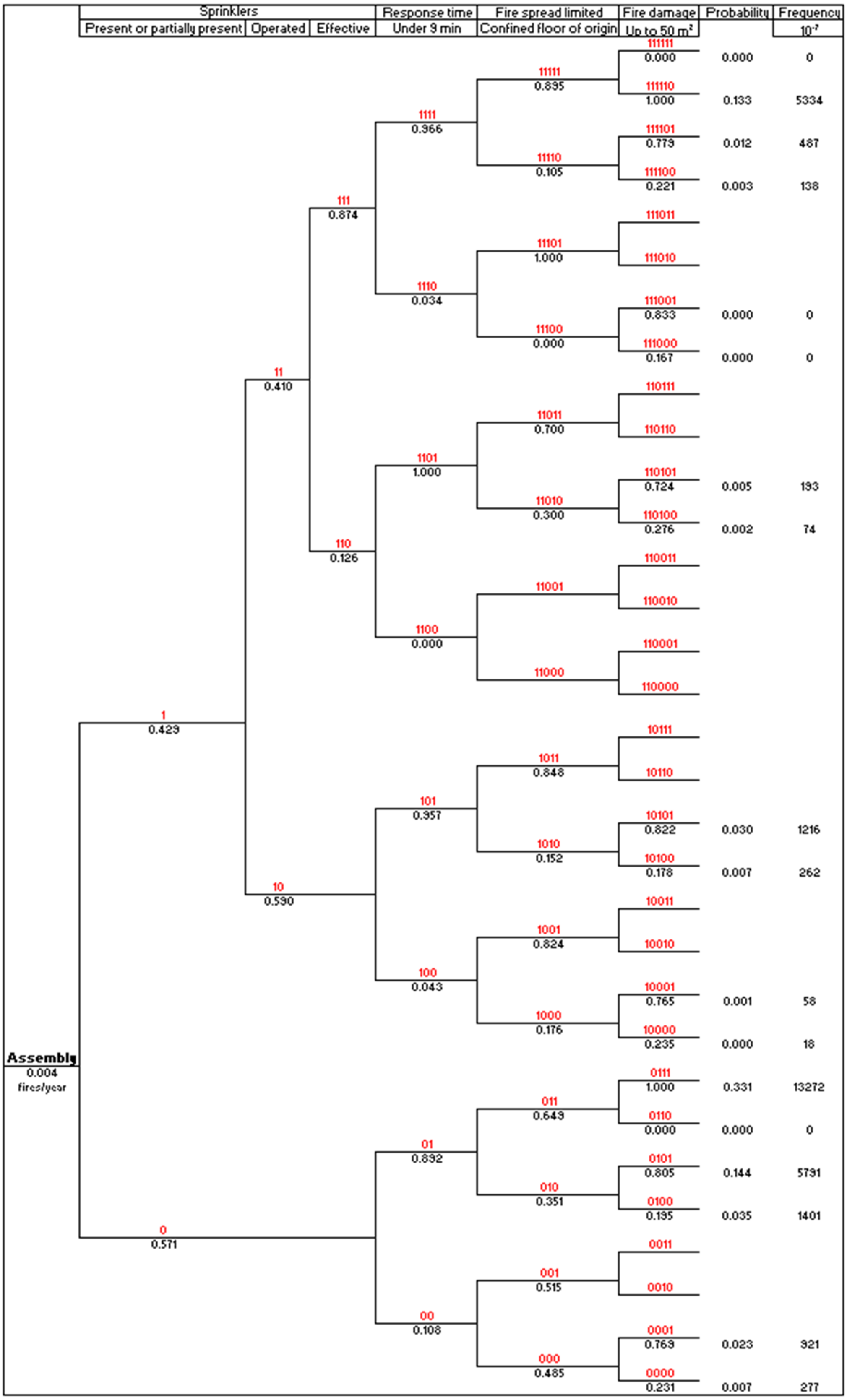


Figure 135: Event tree analysis fire damage of Assembly in USA statistics

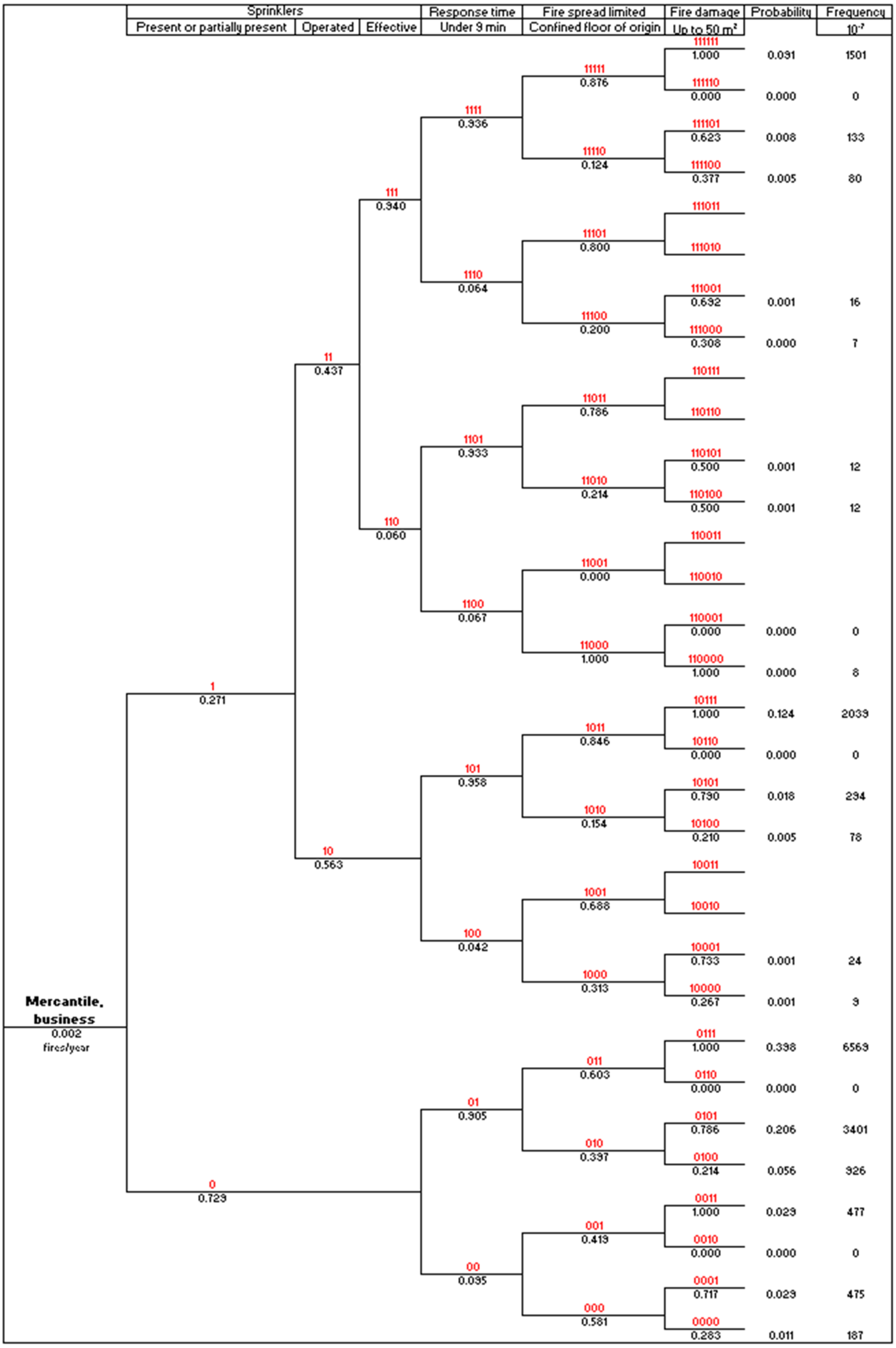


Figure 136: Event tree analysis fire damage of Mercantile, business in USA statistics

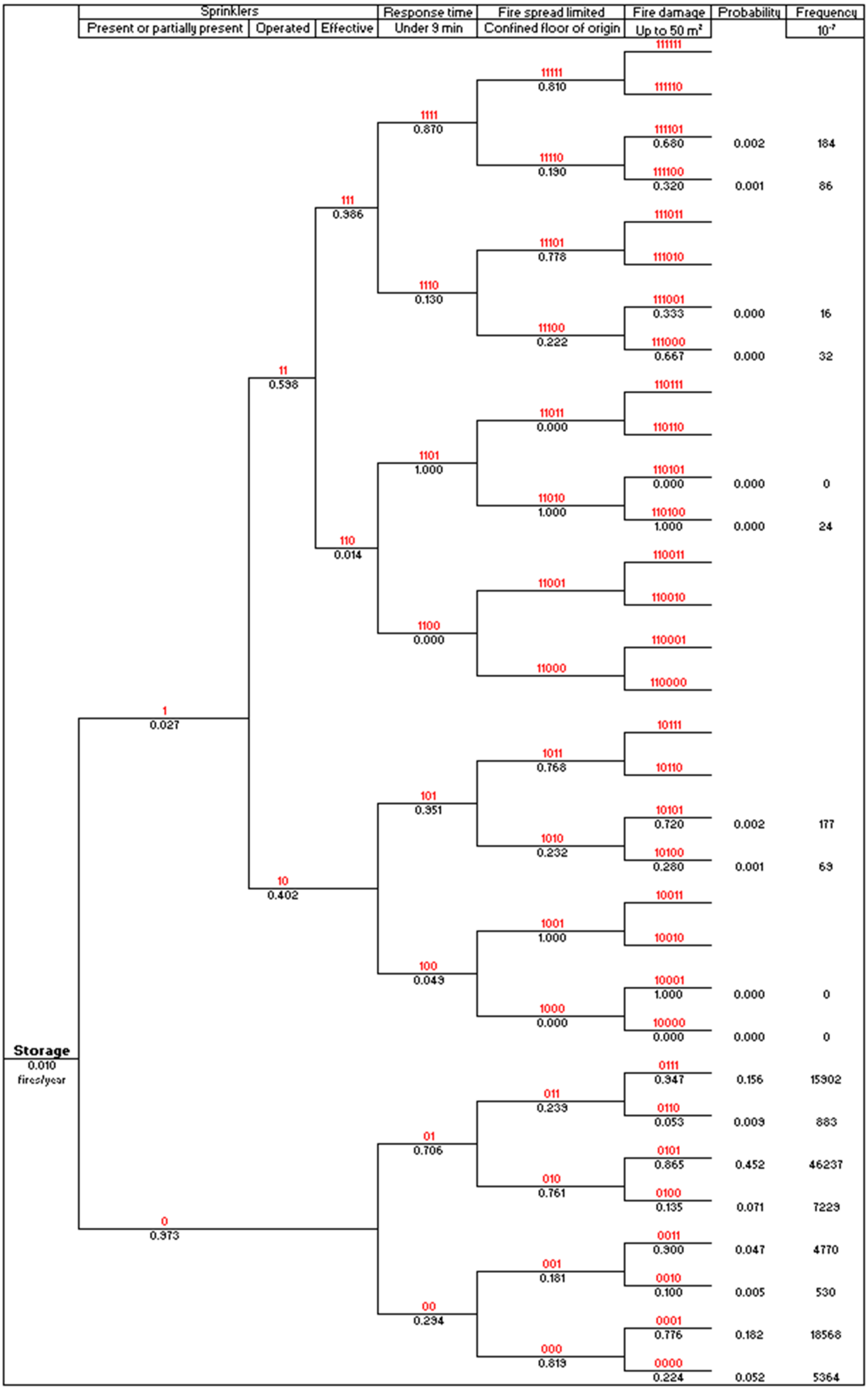


Figure 137: Event tree analysis fire damage of Storage in USA statistics

In *Assembly* and *Educational*, more than 0.5 fire incidents are recorded for the absence of safety systems. When sprinklers are present, they mainly did not operate for more than 0.5 cases while when they operated, they were effective for more than 0.8 fire incidents recorded. Response time is mainly within 9 minutes and fire appears to be confined to the floor of origin and limited to 50 m^2 (Figure 135 and Figure 169 in Annex).

In *Mercantile, business* and *Industrial, manufacturing* (Figure 136 and Figure 170 in Annex), the majority of fire incidents are recorded in buildings without safety systems (more than 0.50) where response time is under 9 minutes and fire generally confined to floor of origin. However, in absence of safety systems, when response time is greater than 9 minutes fire spread appears to be not confined to floor of origin for more than 0.55 while fire damage remains limited to 50 m^2 in both *Mercantile, business* and *Industrial, manufacturing*. When the presence of sprinklers is investigated, while in *Mercantile, business* sprinklers did not operate for 0.56, in *Industrial, manufacturing* they operated for more than 0.60. The presence of sprinklers usually confines the fire spread to the room of origin and the fire damage to 50 m^2.

As described in Figure 137 for *Storage* and in Figure 171 in Annex for *Outside and special property*, more than 0.96 fire incidents are recorded for the absence of safety systems. Therefore, considerations for the presence of sprinklers are avoided due to the related limited number of data recorded. For fires in buildings not equipped with sprinklers, response time is usually within 9 minutes while in these two property types, the fire appears not confined to the floor of origin for more than 0.7 in *Storage* and more than 0.6 in *Outside and special property.* However, fire damage appears limited to 50 m^2.

As already developed in section 6.2.1 for English statistics, the overall probability and frequencies related to the examined fire scenarios will be investigated renaming the fire scenarios in sequential order to increase clarity for readers. Within the 32 scenarios (24 for the presence of sprinklers and 8 for their absence), 7 scenarios appear to be the most relevant where 2 are associated with the presence of sprinklers and 5 with the absence of sprinklers as shown in Table 47. In the two scenarios considered for the presence of safety systems (17s and 19s), sprinklers failed to operate while response time is within 9 minutes. Fire spread is limited to the floor of origin in 17s while is not limited in 19s. However, in both scenarios fire damage appears limited to 50 m^2. The relevant scenarios investigated for the absence of sprinklers are characterized by fire spread not limited to the room of origin except for 25ns while response time is less than 9 minutes in 25ns, 27ns and 28ns and greater than 9 minutes in 31ns and 32ns. Fire damage exceeds in 28ns and 32ns while in the other scenarios is limited to 50 m^2 as described by Table 47.

Table 47: Relevant fire scenarios for the event tree of fire damage in USA statistics

Sprinklers			**Response time** [9 min]	**Fire spread** Floor of origin	**Fire damage** [50 m^2]	**Scenario**
Presence	**Operation**	**Effectiveness**				
Present	Failed	/	<	Limited	<	17s
Present	Failed	/	<	Not limited	<	19s
Absent	/	/	<	Limited	<	25ns
Absent	/	/	<	Not limited	<	27ns
Absent	/	/	<	Not limited	>	28ns
Absent	/	/	>	Not limited	<	31ns
Absent	/	/	>	Not limited	>	32ns

Sprinklers = s; No sprinklers = ns

In Figure 138 (a), in the scenario 17s the highest peaks are represented by *Health care, detention and correction* with 0.42 and *Educational* with 0.25 where *Mercantile, Business* and *Industrial, manufacturing* assume approximately 0.12. In the relevant scenarios for absence of sprinklers, in 25ns when the fire is limited to the floor of origin and fire damage up to 50 m^2, the highest value is reached by *Educational* with 0.45 followed by *Mercantile, Business*, *Assembly* and *Health care, detention and correction* with 0.40, 0.33 and 0.28, respectively. In 27ns, fire spread is not limited to the floor of origin and probabilities present a range between 0.06 in *Health care, detection and correction* and 0.45 in *Storage* as described in Figure 138 (a). In 31ns, an approximate 0.20 is reached by *Storage* and *Outside or special property*.

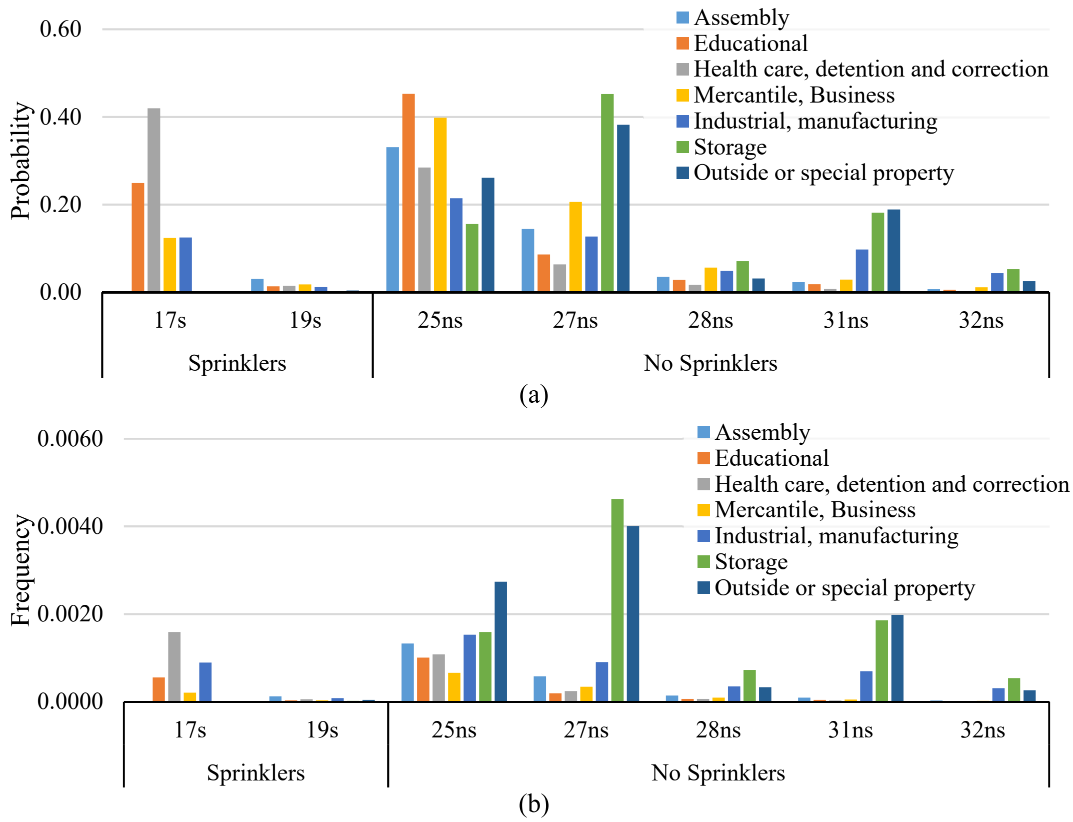


Figure 138: (a) Probability and (b) frequency in the most relevant damage scenarios in USA statistics

The overall frequency is obtained multiplying the overall probability by the frequency of the initiating event which in this case is the fire incident. Figure 138 (b) describes the frequencies in the relevant scenarios where values are generally less than 0.0020. The property types in the scenario 25ns seem to assume a value which could be approximated to 0.0014 with the only exception of *Outside or special property* which presents 0.0027. In 27ns and 31ns, the highest values are in *Storage* with 0.0046-0.0019 and *Outside or special property* with 0.0040-0.0020 followed by *Industrial, manufacturing* with 0.0009-0.0006, respectively.

The event tree analysis developed for fire damage in the USA statistics presents fire incidents mainly in buildings not equipped with sprinklers and when they are present, they usually did not operate. However, in the case of successful operation, they appear effective. Response time of fire brigade is generally within 9 minutes, the fire spread confined to floor of origin and fire damage up to 50 m^2.

6.3 Chapter Summary

According to the analysis developed in this Chapter, in both English and USA statistics, detectors appear to be effective in terms of operation and alert of occupants. When the spread and damage induced by fire are examined based on the presence and absence of safety systems, usually fires are mainly recorded in buildings not equipped with sprinklers. Again fire spread and damage appear to be limited to the floor of origin and up to 50 m^2. The response of fire brigades to arrive at the fire scene is within 9 minutes based on the considerations expressed for the event tree analysis related to fire response and damage.

The event tree analyses developed in this Chapter are considered as a risk assessment able to evaluate the components of fire risk represented by likelihood and consequences determining magnitudes and probabilities. Moreover, they provide assessments on the success and failure of a set of mitigation measures producing the hazards for occupants and consequences for properties. The event tree analyses created could provide information to support risk identification, analysis, evaluation and treatment necessary in the risk assessments and management process and they can support risk-informed decisions. For example, if *Educational* buildings are considered in English statistics, 0.987 fire incidents are characterized by the absence of sprinklers. In this case, when fire spread at arrival is confined to room, usually, the fire spread remains confined to the floor origin while when fire spread at arrival exceeds the room of origin, the likelihood of having a fire spread not confined to the floor of origin is usually greater than 0.50 for a response time within 9 minutes.

Therefore, these event trees can be easily adopted to decide on mitigation measures to prevent damage and reduce the loss in functionality based on the assessments of the implication of the extension of fire spread and the beneficial effects of safety measures. The event trees could be included in the technical dimension of the evaluation of internal resilience. Finally, they could contribute to the various missions of the fire resilience function (prevent, respond, absorb/mitigate, recovery, adapt and learn) to:

- increase the awareness of hazards and fire consequences;
- investigate the fire response of alarms, occupants and fire brigades;
- understand how the presence of automatic extinguishing systems could absorb and mitigate fire consequences;
- limit the fire impact and support a quick recovery;
- evaluate the fire consequences and adapt the system or buildings to an increased level of performance; and
- learn from previous fire incidents.

Once the data have been described, compared to current fire safety predictions in the PD 7974-7 and applied to probabilistic risk analyses to evaluate several fire scenarios, the following Chapter of this thesis will now be focused on the main and specific conclusions obtained for each Chapter to discuss the results and summarize the main findings.

Chapter 7. Conclusions

"Consider your origins: you were not made to live as brutes,
but to follow virtue and knowledge."

- Dante Alighieri

7.1 Resilience and fire statistics

Chapter 2 presents the fundamental literature review at the base of all the concepts and analyses introduced and developed in the thesis. Table 48 shows the connections between the various chapters. In particular, the definitions and characteristics of resilience were introduced in Chapter 2 and applied to fire incidents in Chapter 3. Once resilience has been adopted in the fire safety field, its quantification and evaluation are usually based on data that can be obtained by the investigation of fire incidents in various property types. Therefore, fire safety data and current fire statistics datasets of England and USA were deeply investigated in Chapter 4 considering all the available fields, analogies and differences. The datasets described in Chapter 4 are also extended and considered as inputs for the analysis developed in Chapter 5 and Chapter 6. While Chapter 5 has presented the comparisons between PD 7974-7:2003 (2003), English and USA fire safety data and evaluated the impact of response time on life safety and fire damage, Chapter 6 has applied fire statistics to probabilistic risk assessments considering event trees for fire response and damage.

Table 48: Connections between the chapters of the thesis

<table>
<tr><td colspan="3">Chapter 1 - Introduction</td></tr>
<tr><td rowspan="3">Chapter 2 – Literature review</td><td colspan="2">Chapter 3 – Fire resilience</td></tr>
<tr><td colspan="2">Chapter 4 – Fire statistics</td></tr>
<tr><td>Chapter 5 – Evaluation on BS PD 7974-7:2003 based on English and USA statistics</td><td>Chapter 6 – Probabilistic fire risk assessments</td></tr>
<tr><td colspan="3">Chapter 7 - Conclusions</td></tr>
</table>

According to the literature review of Chapter 2, resilience is strictly linked to the evaluation of hazards, disruption, emergency and therefore risk which, in this case, is represented by the fire event. This is supported by the definitions of the United Nation (2009), U.S. Department of Homeland Security (2011), Linkov et al. (2014) and Bruneau et al. (2003).

Fire statistics cover all the four dimensions such as the social dimension with the evaluation of fatalities and casualties, the technical dimension with the investigation of fire causes and quantification of fire consequences, the economic dimension with the evaluation of the direct cost of fire incidents and the organizational dimension with the analysis of the effects of response time on life and property. All the above could be used as inputs in supporting the development of the resilience characteristics such as robustness, redundancy, resourcefulness and rapidity, and the resilience absorptive, adaptive and transformative capacities. Moreover, fire incidents generally affect occupants, property, business, indirectly community, if the fire is in a functional building or business company, and environment. Therefore, the internal fire resilience could be evaluated by the loss in functionality of the building and the external resilience by the one of the community or business after the fire incident. Furthermore, the main objectives of resilience are similar to those of fire safety which are assumed by life safety, property protection and continuity. The three resilience objectives of life safety, property protection and continuity can be evaluated through fire statistics for what concerns the number of fatalities and casualties, fire and total damage and the beneficial effects of safety systems in alerting the occupants and in the reduction of losses. Finally, the mission to prevent, absorb, respond, recover, adapt and learn apply to every hazard, especially, to fire.

According to the resilience function by Kurth et al. (2019), the loss in functionality is determined by the loss of performances and this can be evaluated by the damage after the fire in terms of fire spread, fire and total damage as evaluated in Chapter 4 and Chapter 5. The majority of the resilience framework described in Chapter 2, foresees the assessment and analysis of risk, and the implementation of risk management and activities to increase effectiveness during a hazard (US department of homeland security, 2013). In particular, Farsangi (2019) applies a holistic approach under fire conditions moving from goal problem of protecting life to scale problem shifting the approach from individual components to the system. Moreover, Farsangi addresses the need to identify uncertainties, evaluate probabilistic risk assessments to reduce risks and investigate multiple hazards scenarios. Finally, he determines a framework composed of the following steps:

- data collection;
- characterization of design fire scenarios,
- analysis of structure response,
- assessment of damage, and
- evaluation of performances and consequences.

This is also expressed by the frameworks available in Standards and codes as discussed in section 2.2, in which a recurrent approach could be structured as:

- creation of a plan or strategy;
- identification of hazards, people and activities potentially affected;
- implementation of training and system operation;
- continuous monitor and review of performances to strengthen the system; and
- performance improvements based on validation and critical review process.

Therefore, fire statistics as presented within this thesis provide a collection of data considered at the base of every resilience assessment. Fire safety data are also able to characterise potential fire scenarios, describe the response of various buildings and quantify the damage they incur. From these data, it is possible to identify hazards, people and activities potentially affected and create an appropriate plan and strategy to mitigate against the fire hazard, whether it is internal (for instance by adding sprinklers or fire alarms), or external (for instance by increasing fire service provision to reduce response times). Moreover, the evolution of fire statistics in time can be used as a tool to determine a continuous monitor and review of the performance of buildings subjected to fires based on a critical review. Whilst these are all concerning the reduction of damage (reducing loss of functionality), designing easily replaceable components for a building would reduce the time to recovery.

In Chapter 3, resilience is applied to the fire safety problem and in Table 14, the fire resilience questions are answered according to the resilience categories. In properties, the hazards are described by the likelihood of fire incidents and the consequences of fire damage. Only understanding these two components, it is possible to achieve resilience in terms of fire prevention, mitigation, business preparedness and economic evaluation. For business, the effect of fire on activities is fundamental for the evaluation of disruption based on impact and continuity analyses. Fire prevention will protect occupants and other two important categories to be included in the fire strategy are community and the environment. All these aspects can be developed only with a critical and deep evaluation of the performances of current building stock when subjected to fire. Therefore, fire statistics can be considered as an assessment and review based on yearly updated data able to allow a continuous assessment of potential improvements. The fire resilience measures expressed in Table 15 are strongly connected to the measure of likelihood and damage of fire, evaluation of fatalities and casualties, and economic impact caused by the fire incident which are all fields covered in the fire statistics analysed in Chapter 4 and Chapter 5. The assessment of fire risk has been deeply determined in Chapter 6 with the quantification of the likelihood and consequences of various fire scenarios.

Finally, in every fire design, it is necessary to consider inputs representative of the performance of the building considered, actors involved and hazards present. Therefore, fire statistics provide specific data for each property type and quantify causes and consequences.

The research developed in this thesis provides valuable fields of investigations that should be further extended in future. It will be important to understand how governments could adopt the information and data introduced and generated in this thesis for decisions about resource optimizations and allocations. Relevant future research should also be focused on the evaluation of how fire safety approaches change considering different authorities and locations, particularly assessing the difference in the economic development of countries.

The discussion about fire resilience clearly demonstrates the need for cooperation between various experts and fields to be able to address all the aspects necessary for a comprehensive assessment of life safety, property protection and business continuity. The fire resilience framework introduced in Chapter 3 could be increased in the level of complexity where collaborations with social science would be fundamental to improve social aspects while those with engineers and managers could support the enhancement of the technical and organizational dimensions.

The evaluation of resilience developed in this thesis could be further improved. For example, the damage is binary in the statistics and provides us with a proxy for the loss of functionality of the building while for the rebuild, it is necessary to know the damage, cost and time to repair. Light damage over a large area might be easier to repair than severe damage very localised. Moreover, fire risk has been identified according to the likelihood and consequences of fire incidents in various property types. However, for a complete resilience assessment, the risk mitigation and the evaluation of people involved assume relevant aspects and need to be based on the specific characteristics and organization of the building considered.

A unified and universal fire safety terminology and methodology of data collection about buildings subjected to fires could define uniform fire safety fields available and support a direct comparison of the trends provided by the fire statistics of various countries. Furthermore, the evaluation of similarities and differences between English and USA fire statistics determines a discussion about potential changes in current fire recording systems to define improvements in the fire safety fields recorded and missing to provide a complete dataset able to represent the fire scenarios and support the inputs data in the resilience assessment.

The creation of evolution in time of the fire safety data could be developed to examine the beneficial effects of the applications of various fire safety measures and how specific fire safety approaches impact the safety of buildings over a specific time range. The evaluation of the effects of safety measure in the reduction of the fire consequences will also be beneficial in the evaluation of the loss in functionality and resilience improvements. The fire safety data introduced in Chapter 4 and analysed in Chapter 5 could be investigated evaluating how they inform the design and practice of engineers and how they influence the code guidelines and development.

The evaluation of indirect financial losses could provide a comprehensive description of the economic costs due to fire incidents affecting occupants, business and property in short and long-terms covering the economic dimension of resilience. Finally, probabilistic risk assessments should be integrated with sensitivity and cost-benefits analysis to understand the effects of fire safety components in terms of fire likelihood and consequences according to various fire safety measures and support risk identification, evaluation and mitigation necessary for the application and improvement of resilience.

7.2 Conclusions

Conclusions derived from the research developed in this thesis could be summarized according to general and specific discussions for each Chapter.

Chapter 2 – Literature review

The literature review described in this Chapter specifies the level of complexity found in the application of a holistic view based on resilience approaches. The resilience definitions, missions, characteristics and capacities have been studied based on their evaluations in other disciplines such as critical infrastructures and earthquake engineering, and in English Standards and Codes based on their resilience guidelines. However, from the considerations deduced by previous research, it is clear the limited applications that these concepts have in fire safety. Moreover, the fire resilience approaches imply a continuous flow of evaluation, assessment and improvement that could be determined only from critical analysis of the data available. Therefore, fire statistics represents a collection of fire incident data gathered by the fire brigades in the aftermath of a fire event able to describe the performance of buildings affected by fires. Studies about the evaluation of direct and indirect fire financial losses have been examined considering the previous methodologies. Finally, the importance of probabilistic risk assessments has been described in terms of the quantification of likelihoods and consequences of fire events.

Specific conclusions from the literature review include:

- resilience aspects related to life safety, property protection and business continuity are limited in fire safety and need to be improved to address not only technical considerations but also organizational, economic and environmental aspects;
- when the guidelines provided by standards and codes about the application of resilience are plotted with respect to resilience function, they appear mainly confined

to the prevention, absorption and mitigation missions and they are scarce in the response, adaption and learning missions;

- the paucity of safety data can be filled by a critical analysis of fire statistics of England and USA. The reporting systems appear similar for the two statistics; however, the fields collected present some differences in the description of the safety fields, damage and financial losses recorded;
- fire financial losses could be considered as direct and indirect ones where several classifications could be found as well as methodologies to estimate them;
- British Standard PD 7974-7:2003 (2003) presents fire safety data from 1966 to 1987 and updates and comparisons with more recent data are required. Furthermore, a literature review about the studies that converge in the document has been developed to understand the origin of the data and potential methodologies adopted to obtain them; and
- Probabilistic risk assessments are developed to quantify risk defined as likelihood multiplied by consequences of an event (fire in this case) according to various methodologies such as qualitative, semi-qualitative and quantitative. Amongst the logic tree of quantitative methodology, event tree analysis has been discussed to evaluate the impact that several fires safety measures can have in limiting fire consequences.

Chapter 3 – Fire resilience

The fire resilience concepts specified in Chapter 1 have been applied in the fire safety field considering buildings affected by fires investigating not only the resilience categories, dimensions, characteristics and capacities but also the approaches and the resilience measures. A comprehensive fire resilience approach for an educational building and a fire resilience design has been created. Other specific conclusions from the Chapter are:

- the resilience in fire safety needs to be addressed considering the fire resilience questions related to actors (users, community, property, business and environment), dimensions (technical, organizational, economic and social), characteristics (robustness, rapidity, redundancy, resourcefulness) and missions (to prevent, response, absorb/mitigate, recovery, adapt and learn). It is important to define the objectives of resilience, how this should be achieved and planned in time;
- various resilience measures could determine the progress of the resilience approach such as system, negative resilience, process, output and recovery indicators defined in specific time over the process applied;

- the resilience approach should consider internal and external resilience defining objectives and actions to follow. Furthermore, internal resilience should include safe facility, risk reduction and disaster management; and
- A fire resilience design has been created based on the definition of inputs, requirements and objectives, structural design and fire design following a continuous flow of assumptions and validation based on deterministic and probabilistic variables and acceptable performances.

Chapter 4 – Fire statistics

English and USA fire statistics have been investigated to understand the fire safety fields recorded by each of them in terms of fire incidents in various property types, fire causes, consequences in terms of fire spread, damage and financial losses, and safety measures such as alarms and automatic extinguishing systems.

- The recording system for the two fire statistics is given by fire brigades collecting information in the aftermath of an event and filling in an online form. Data are partially annually released in English Statistics or specifically provided by the Home Office and US Fire Administration.
- The fields related to fire incidents, causes, item first ignited and material affecting the fire appear similar in the two fire statistics;
- Fires in *Residential* assume 66.8% and 79.2% while in *Non-residential* 33.2% and 20.8% in England and the USA, respectively.
- Fire causes are attributable to faulty of fuel supplies, faulty of appliances and leads and misuse of equipment or appliances in England and to heating, electrical malfunction and cooking in the USA.
- The source of ignition is represented by cooking appliances and electrical distribution in England and operating equipment and other heat source in the USA.
- Item first ignited is usually characterized by food; textiles, upholstery and fittings and paper and cardboard in England and by organic material and the material ignited by wood or paper in the USA. In England, the material mainly responsible for fire assumes the same classes as the item first ignited.
- The fire spread appears generally limited to the room of origin in English and USA and statistics. Damage is recorded such as *fire* and *total damage* in m^2 in England and fire damage according to four classes (Minor, Significant, Heavy and Extreme) in the USA. In England, the average damage is 18.5 m^2 in *Dwellings* and 76.7 m^2 in *Other buildings* and Minor damage presents the highest value of 49.6% in the USA.

- Direct fire financial losses are evaluated in USA statistics applying the BVD formula (International Code Council, 2017). In England, no direct fire economic losses are available. In USA a total fire losses of US $6,900,300,000 in *Residential* and $2,628,000,000 in *Non-residential* are recorded.
- Fire alarms are generally present and operating in English and USA statistics. In the USA, they are generally represented by smoke detectors and detector failures are attributable to battery missing or disconnected and battery discharged or dead. The majority of fire false alarms are due to fire alarms not operating properly represented by 66.6% and this describes a relevant datum which leads to significant resource waste in England.
- Information about sprinklers is not available in English statistics in the data published in 2014/15. In the USA, the main type is a wet pipe sprinkler system and reason for the automatic extinguishing system failure in the USA is represented by 33.9% for the presence of fire in an area not protected by the system.
- The average response time is 7.7 minutes in *Dwellings* and 8.5 minutes in *Other buildings* in England and 8.5 minutes in the USA.
- The IRS in England could be improved adding questions about building dimensions and construction types, presence of fires with multiple seats or travelling fires, description of means of escapes and compartmentation. Damage should be reported in terms of horizontal and vertical spread subdividing the fire consequences in terms of fire, flame, smoke and water. Finally, a methodology for the evaluation of direct fire financial losses should be provided.

Chapter 5 – Evaluation of BS PD 7974-7:2003 based on USA and English statistics

The analyses developed in this Chapter investigate the British Standard PD 7974-7 (named PD 7974-7) (BSI PD 7974-7, 2003) comparing the fire safety data from 1966 to 1987 present in its Annex with current English and USA fire statistics for what concerns fire frequency and damage according to presence and absence of automatic extinguishing systems and fatality rate based on the discovery times. The analysis present in PD 7974-7 has been extended considering the full English and USA datasets and applied to various property types. Finally, the evaluation of response time in England to understand potential optimization of fire stations and resources allocation appears to influence the fatality/casualty rate up to 4 minutes and the property loss up to 7 minutes.

- Fire overall probability has been obtained considering the number of fires divided by building stock for specific property types where PD 7974-7 usually overestimates fire frequency if compared to contemporary English and USA statistics.
- When fire frequency is plotted against the total floor area of a building, PD 7974-7 suggests a power law with a positive exponent to represent the trends. However, this function overestimates the distribution available for England and USA that are better represented by a power law with a positive or negative exponent or by a polynomial function.
- In PD 7974-7, the area damage increases while the fire frequency decreases with the extension of the fire spread. Automatic extinguishing systems appear to limit the damage in English and USA statistics while their absence determines a greater area of damage obtained. Data for the presence of sprinklers need to be treated carefully due to the limited dataset.
- The prediction of the frequency distribution of area damage of PD 7974-7 overestimates the one of USA statistics and it is located between the *fire damage* and *total damage* trends in English statistics.
- The financial losses of PD 7974-7 are greater than those obtained in USA statistics. Moreover, in England, the economic losses due to fires have been calculated applying the BVD formula suggested in the USA statistics and results obtained show that the values for presence of sprinklers are less than those found for their absence only in *fire damage* while this difference is generally not as relevant for *total damage*.
- The fatality rate in PD 7974-7 has been compared to the fatality/casualty rate in England due to the unique field recorded in the related fire statistics. However, the data of PD 7974-7 are obtained by a study of Ramachandran (Ramachandran, 1993) that contains also the casualty rate. Therefore, fatality/casualty rates of Ramachandran appear similar to those described by English statistics.
- Response time of fire brigades in English statistics appears similar and confined from 4-5 to 7-8 minutes when *Dwellings* and *Other buildings* are examined. However, in *Other buildings*, the class of response time between 9 and 10 minutes is not negligible and greater than 7%.
- The response time appears relevant in the first 4 minutes of attendance when it is considered in relation to the fatality/casualty rate in English statistics.
- Prompt response time within 7-8 minutes corresponds to a peak in fires where usually a large number of small fires confined to the room of origin is recorded. More severe damage classes have been obtained analysing *total damage*.

Chapter 6 – Probabilistic fire risk assessment

The probabilistic risk assessments developed considering event tree analysis in various property types in English and USA statistics have been created evaluating the fire response of occupants and fire brigades and fire damage in terms of spread and area damaged for presence and absence of detectors and automatic safety systems, respectively. Differences in the fire safety fields available in England and the USA have generated differences in the event tree analyses created for the two fire statistics. However, the event tree analyses developed to consider the same areas of investigation provide a comparison as similar as possible. Despite the differences in procedures and practice, in English and USA statistics, fire brigade response time is usually within 9 minutes. Moreover, in both countries, detectors appear effective with the successful operation and alerting of occupants. In the presence and absence of safety systems, fires are usually in buildings not equipped with sprinklers where fire spread is limited to the floor of origin and *fire* and *total damage* confined to 50 m^2.

- In English statistics, the event tree analysis for fire response shows that fires recorded for presence and absence of detectors provide similar values and the response of occupants and fire brigades is generally efficient in the first minutes after the ignition.
- In the event tree analysis for fire response of USA statistics, when detectors are present they are usually effective and alert occupants. Fire incidents in buildings without detectors are characterized by a response time within 9 minutes.
- Fires are generally in buildings not equipped with sprinklers as described by the event tree analyses for fire damage in English statistics where response time is limited to 9 minutes, fire size on arrival limited to the room of origin and fires with no rapid growth. If fire size on arrival is not confined to the room of origin, it is more likely to have a fire spread beyond the floor of origin. *Fire* and *total damage* are usually up to 50 m^2.
- In the USA statistics, the event tree analysis for fire damage presents fire incidents mainly in buildings without sprinklers where the fire spread and damage are usually limited to the floor of origin and up to 50 m^2. Response time of fire brigades is generally within 9 minutes. Therefore, in the design and optimization of fire safety strategies, this value should be considered accordingly.

Annex

Table 49: Assembly: area damage and fire spread according to damage class; fire frequency with respect to fire spread in presence and absence of automatic extinguishing systems, with weighted area damage, and frequency for fires and unclassified damage fires in the USA fire statistics.

	Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* [m²]	F		F+U	
		F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	169	65	97.01%	29.41%	29.86	29.86	2	2.99%	11.11%	6.84	2.22	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	29.18	26.59%	26.59%	34.85%	34.85%
2	245	106	94.64%	47.96%	25.38	25.38	4	3.57%	22.22%	12.11	3.93	1	0.89%	10.00%	134.29	25.99	1	0.89%	33.33%	1.88	0.26	25.67	44.44%	71.03%	50.52%	85.36%
3	16	10	90.91%	4.52%	1.69	1.69	0	0.00%	0.00%	0.00	0.00	1	9.09%	10.00%	3.29	0.64	0	0.00%	0.00%	0.00	0.00	1.83	4.37%	75.40%	3.30%	88.66%
4	50	39	67.24%	17.65%	5.57	5.57	10	17.24%	55.56%	45.99	14.92	7	12.07%	70.00%	138.65	26.84	2	3.45%	66.67%	19.06	2.60	29.07	23.02%	98.41%	10.31%	98.97%
5	5	1	25.00%	0.45%	0.13	0.13	2	50.00%	11.11%	2.09	0.68	1	25.00%	10.00%	1.15	0.22	0	0.00%	0.00%	0.00	0.00	1.36	1.59%	100.00%	1.03%	100.00%
Total weighted area damage																						25.96				
	No Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* m²	F		F+U	
		F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± m²	F	% F		Av. [m²]	± [m²]					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	111	75	83.33%	28.30%	12.53	12.53	9	10.00%	14.75%	10.73	3.48	1	1.11%	2.13%	0.66	0.13	5	5.56%	5.56%	1.27	0.17	11.59	19.44%	19.44%	25.52%	25.52%
2	185	106	77.37%	40.00%	12.31	12.31	20	14.60%	32.79%	39.73	12.89	9	6.57%	19.15%	45.63	8.83	2	1.46%	2.22%	0.08	0.01	18.32	29.59%	49.03%	42.53%	68.05%
3	22	17	51.52%	6.42%	1.18	1.18	6	18.18%	9.84%	8.32	2.70	6	18.18%	12.77%	17.30	3.35	4	12.12%	4.44%	4.97	0.68	5.87	7.13%	56.16%	5.06%	73.10%
4	109	58	34.52%	21.89%	5.79	5.79	24	14.29%	39.34%	42.36	13.74	29	17.26%	61.70%	76.31	14.77	57	33.93%	63.33%	278.47	37.97	115.71	36.29%	92.44%	25.06%	98.16%
5	8	9	25.71%	3.40%	0.37	0.37	2	5.71%	3.28%	21.63	7.01	2	5.71%	4.26%	12.92	2.50	22	62.86%	24.44%	194.94	26.58	124.60	7.56%	100.00%	1.84%	100.00%
Total weighted area damage																						59.50				

1. Spread confined to object of origin; **2**. Spread confined to room of origin; **3**. Spread confined to floor of origin; **4**. Spread confined to building of origin; **5**. Spread beyond building of origin; **U**. Unclassified fires; **F**. Fires; **S**. spread; **D**. Damage; **Av**. Average area damage; ±. Standard deviation

Table 50: Educational: area damage and fire spread according to damage class; and fire frequency with respect to fire spread in presence and absence of automatic extinguishing systems, with weighted area damage, and frequency for fires and unclassified damage fires in the USA fire statistics.

	Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* m²	F		F+U	
		F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	40	19	100.00%	31.15%	31.10	31.10	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	31.10	29.23%	29.23%	32.00%	32.00%
2	73	35	97.22%	57.38%	133.90	133.90	1	2.78%	50.00%	6.92	2.24	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	130.38	55.38%	84.62%	58.40%	90.40%
3	4	4	100.00%	6.56%	13.53	13.53	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	13.53	6.15%	90.77%	3.20%	93.60%
4	8	3	50.00%	4.92%	6.45	6.45	1	16.67%	50.00%	0.65	0.21	0	0.00%	0.00%	0.00	0.00	2	33.33%	100.00%	148.43	20.24	52.81	9.23%	100.00%	6.40%	100.00%
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total weighted area damage																						87.01				
	No Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* [m²]	F		F+U	
		F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	47	32	88.89%	31.07%	105.44	105.44	1	2.78%	6.25%	0.98	0.32	0	0.00%	0.00%	0.00	0.00	3	8.33%	18.75%	600.90	81.94	143.82	25.53%	25.53%	31.13%	31.13%
2	73	52	88.14%	50.49%	347.17	347.17	5	8.47%	31.25%	112.37	36.44	2	3.39%	33.33%	528.00	102.19	0	0.00%	0.00%	0.00	0.00	333.40	41.84%	67.38%	48.34%	79.47%
3	4	4	50.00%	3.88%	8.94	8.94	3	37.50%	18.75%	79.81	25.88	1	12.50%	16.67%	192.00	37.16	0	0.00%	0.00%	0.00	0.00	58.40	5.67%	73.05%	2.65%	82.12%
4	23	15	45.45%	14.56%	50.65	50.65	7	21.21%	43.75%	62.68	20.33	3	9.09%	50.00%	2140.80	414.35	8	24.24%	50.00%	2660.32	362.77	875.87	23.40%	96.45%	15.23%	97.35%
5	4	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	5	100.00%	31.25%	150.59	20.54	150.59	3.55%	100.00%	2.65%	100.00%
Total weighted area damage																						389.87				

1. Spread confined to object of origin; **2**. Spread confined to room of origin; **3**. Spread confined to floor of origin; **4**. Spread confined to building of origin; **5**. Spread beyond building of origin; **U**. Unclassified fires; **F**. Fires; **S**. spread; **D**. Damage; **Av**. Average area damage; ±. Standard deviation

Table 51: Health care, detection and correction: area damage and fire spread according to damage class; and fire frequency with respect to fire spread in presence and absence of automatic extinguishing systems, with weighted area damage, and frequency for fires and unclassified damage fires in the USA fire statistics.

	Sprinklers - Area damage																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* m^2	F		F+U	
		F	% F		Av. [m^2]	± [m^2]	F	% F		Av. [m^2]	± [m^2]	F	% F		Av. [m^2]	± [m^2]	F	% F		Av. [m^2]	± [m^2]					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	87	34	100.00%	37.36%	45.75	45.75	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	45.75	36.56%	36.56%	39.55%	39.55%
2	124	45	97.83%	49.45%	103.85	103.85	1	2.17%	50.00%	29.79	9.66	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	102.24	49.46%	86.02%	56.36%	95.91%
3	2	2	100.00%	2.20%	1.65	1.65	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	1.65	2.15%	88.17%	0.91%	96.82%
4	7	10	90.91%	10.99%	21.43	21.43	1	9.09%	50.00%	98.31	31.88	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	28.42	11.83%	100.00%	3.18%	100.00%
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total weighted area damage																						70.70				
	No Sprinklers - Area damage																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* [m^2]	F		F+U	
		F	% F		Av. [m^2]	± [m^2]	F	% F		Av. [m^2]	± [m^2]	F	% F		Av. [m^2]	± [m^2]	F	% F		Av. [m^2]	± [m^2]					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	27	15	100.00%	25.00%	53.17	53.17	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	53.17	17.65%	17.65%	31.03%	31.03%
2	41	30	85.71%	50.00%	47.97	47.97	4	11.43%	36.36%	17.60	5.71	0	0.00%	0.00%	0.00	0.00	1	2.86%	11.11%	10.22	1.39	43.42	41.18%	58.82%	47.13%	78.16%
3	5	3	75.00%	5.00%	0.26	0.26	1	25.00%	9.09%	6.87	2.23	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	1.92	4.71%	63.53%	5.75%	83.91%
4	13	12	40.00%	20.00%	17.53	17.53	6	20.00%	54.55%	51.17	16.60	5	16.67%	100.00%	166.12	32.15	7	23.33%	77.78%	613.23	83.62	188.02	35.29%	98.82%	14.94%	98.85%
5	1	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	1	100.00%	11.11%	68.13	9.29	68.13	1.18%	100.00%	1.15%	100.00%
Total weighted area damage																						94.51				

1. Spread confined to object of origin; **2**. Spread confined to room of origin; **3**. Spread confined to floor of origin; **4**. Spread confined to building of origin; **5**. Spread beyond building of origin; **U**. Unclassified fires; **F**. Fires; **S**. spread; **D**. Damage; **Av**. Average area damage; ±. Standard deviation

Table 52: Residential: area damage and fire spread according to damage class; and fire frequency with respect to fire spread in presence and absence of automatic extinguishing systems, with weighted area damage, and frequency for fires and unclassified damage fires in the USA fire statistics.

	Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* m²	F		F+U	
		F	% F S	% F D	Av. m²	± m²	F	% F S	% F D	Av. m²	± m²	F	% F S	% F D	Av. m²	± m²	F	% F S	% F D	Av. m²	± m²		%	Cum	%	Cum
1	404	163	98.79%	21.68%	3.35	3.35	1	0.61%	0.95%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	1	0.61%	2.17%	0.02	0.00	3.30	17.03%	17.03%	23.96%	23.96%
2	1061	466	89.44%	61.97%	6.19	6.19	47	9.02%	44.76%	1.52	0.49	6	1.15%	9.09%	2.26	0.44	2	0.38%	4.35%	0.16	0.02	5.70	53.77%	70.79%	62.93%	86.89%
3	82	30	76.92%	3.99%	0.21	0.21	6	15.38%	5.71%	0.53	0.17	2	5.13%	3.03%	0.03	0.01	1	2.56%	2.17%	0.02	0.00	0.25	4.02%	74.82%	4.86%	91.76%
4	118	91	40.27%	12.10%	2.16	2.16	47	20.80%	44.76%	1.81	0.59	53	23.45%	80.30%	14.13	2.73	35	15.49%	76.09%	5.88	0.80	5.47	23.32%	98.14%	7.00%	98.75%
5	21	2	11.11%	0.27%	0.00	0.00	4	22.22%	3.81%	0.10	0.03	5	27.78%	7.58%	0.14	0.03	7	38.89%	15.22%	0.32	0.04	0.19	1.86%	100.00%	1.25%	100.00%
Total weighted area damage																						4.92				
	No Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* m²	F		F+U	
		F	% F S	% F D	Av. m²	± m²	F	% F S	% F D	Av. m²	± m²	F	% F S	% F D	Av. m²	± m²	F	% F S	% F D	Av. m²	± m²		%	Cum	%	Cum
1	3902	2652	82.08%	18.74%	4.44	4.44	217	6.72%	4.35%	2.34	0.76	108	3.34%	2.98%	2.17	0.42	254	7.86%	4.73%	3.36	0.46	4.14	11.48%	11.48%	17.97%	17.97%
2	9574	7303	78.84%	51.60%	12.79	12.79	1535	16.57%	30.77%	17.65	5.72	344	3.71%	9.50%	9.45	1.83	81	0.87%	1.51%	1.87	0.25	13.38	32.92%	44.41%	44.10%	62.08%
3	1784	1056	39.62%	7.46%	1.75	1.75	842	31.59%	16.88%	10.54	3.42	556	20.86%	15.35%	166.01	32.13	211	7.92%	3.93%	4.92	0.67	39.05	9.47%	53.88%	8.22%	70.30%
4	5538	2883	25.76%	20.37%	6.19	6.19	2228	19.91%	44.66%	34.22	11.10	2341	20.91%	64.65%	74.02	14.33	3741	33.42%	69.66%	123.36	16.82	65.12	39.78%	93.67%	25.51%	95.81%
5	910	260	14.59%	1.84%	0.31	0.31	167	9.37%	3.35%	2.48	0.80	272	15.26%	7.51%	8.29	1.60	1083	60.77%	20.17%	28.74	3.92	19.01	6.33%	100.00%	4.19%	100.00%
Total weighted area damage																						35.69				

1. Spread confined to object of origin; **2**. Spread confined to room of origin; **3**. Spread confined to floor of origin; **4**. Spread confined to building of origin; **5**. Spread beyond building of origin; **U**. Unclassified fires; **F**. Fires; **S**. spread; **D**. Damage; **Av**. Average area damage; ±. Standard deviation

Table 53: Mercantile, business: area damage and fire spread according to damage class; and fire frequency with respect to fire spread in presence and absence of automatic extinguishing systems in USA fire statistics, with weighted area damage, and frequency for fires and unclassified damage fires in the USA fire statistics.

	Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* m²	F		F+U	
		F	% F		Av. m²	± m²	F	% F		Av. m²	± m²	F	% F		Av. m²	± m²	F	% F		Av. m²	± m²					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	165	68	95.77%	29.06%	29.47	29.47	2	2.82%	13.33%	4.47	1.45	1	1.41%	16.67%	2.86	0.55	0	0.00%	0.00%	0.00	0.00	28.39	27.31%	27.31%	35.18%	35.18%
2	228	115	93.50%	49.15%	64.07	64.07	5	4.07%	33.33%	19.16	6.22	2	1.63%	33.33%	58.94	11.41	1	0.81%	20.00%	0.81	0.11	61.64	47.31%	74.62%	48.61%	83.80%
3	19	13	86.67%	5.56%	8.63	8.63	2	13.33%	13.33%	4.97	1.61	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	8.14	5.77%	80.38%	4.05%	87.85%
4	51	36	75.00%	15.38%	56.89	56.89	5	10.42%	33.33%	138.18	44.82	3	6.25%	50.00%	38.83	7.51	4	8.33%	80.00%	13.72	1.87	60.63	18.46%	98.85%	10.87%	98.72%
5	6	2	66.67%	0.85%	0.33	0.33	1	33.33%	6.67%	0.30	0.10	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	0.32	1.15%	100.00%	1.28%	100.00%
Total weighted area damage																						48.58				
	No Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* m²	F		F+U	
		F	% F		Av. m²	± m²	F	% F		Av. m²	± m²	F	% F		Av. m²	± m²	F	% F		Av. m²	± m²					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	221	151	87.79%	27.66%	16.79	16.79	10	5.81%	7.25%	11.90	3.86	0	0.00%	0.00%	0.00	0.00	11	6.40%	5.70%	9.07	1.24	16.01	17.53%	17.53%	24.07%	24.07%
2	337	230	81.56%	42.12%	35.34	35.34	36	12.77%	26.09%	29.24	9.48	12	4.26%	11.54%	19.37	3.75	4	1.42%	2.07%	3.73	0.51	33.43	28.75%	46.28%	36.71%	60.78%
3	62	34	51.52%	6.23%	49.68	49.68	21	31.82%	15.22%	17.83	5.78	6	9.09%	5.77%	10.45	2.02	5	7.58%	2.59%	7.42	1.01	32.77	6.73%	53.01%	6.75%	67.54%
4	254	124	29.81%	22.71%	10.52	10.52	67	16.11%	48.55%	74.57	24.19	85	20.43%	81.73%	300.41	58.14	140	33.65%	72.54%	341.46	46.56	191.44	42.41%	95.41%	27.67%	95.21%
5	44	7	15.56%	1.28%	0.36	0.36	4	8.89%	2.90%	8.30	2.69	1	2.22%	0.96%	2.00	0.39	33	73.33%	17.10%	44.57	6.08	33.52	4.59%	100.00%	4.79%	100.00%
Total weighted area damage																						97.34				

1. Spread confined to object of origin; **2**. Spread confined to room of origin; **3**. Spread confined to floor of origin; **4**. Spread confined to building of origin; **5**. Spread beyond building of origin; **U**. Unclassified fires; **F**. Fires; **S**. spread; **D**. Damage; **Av**. Average area damage; ±. Standard deviation

Table 54: Industrial, utility, defence, agricultural, mining: area damage and fire spread according to damage class; and fire frequency with respect to fire spread in presence and absence of automatic extinguishing systems, with weighted area damage, and frequency for fires and unclassified damage fires in the USA fire statistics.

	Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* [m²]	F		F+U	
		F	% F S	% F D	Av. [m²]	± [m²]	F	% F S	% F D	Av. [m²]	± [m²]	F	% F S	% F D	Av. [m²]	± [m²]	F	% F S	% F D	Av. [m²]	± [m²]		%	Cum	%	Cum
1	11	8	88.89%	32.00%	90.34	90.34	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	1	11.11%	100.00%	0.39	0.05	80.34	29.03%	29.03%	31.43%	31.43%
2	20	11	84.62%	44.00%	58.34	58.34	1	7.69%	25.00%	14.06	4.56	1	7.69%	100.00%	123.43	23.89	0	0.00%	0.00%	0.00	0.00	59.94	41.94%	70.97%	57.14%	88.57%
3	1	2	66.67%	8.00%	133.30	133.30	1	33.33%	25.00%	188.63	61.18	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	151.74	9.68%	80.65%	2.86%	91.43%
4	3	1	50.00%	4.00%	36.35	36.35	1	50.00%	25.00%	46.87	15.20	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	41.61	6.45%	87.10%	8.57%	100.00%
5	0	3	75.00%	12.00%	22.88	22.88	1	25.00%	25.00%	15.62	5.07	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	21.07	12.90%	100.00%	0.00%	100.00%
Total weighted area damage																						68.55				
	No Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* m²	F		F+U	
		F	% F S	% F D	Av. [m²]	± [m²]	F	% F S	% F D	Av. [m²]	± [m²]	F	% F S	% F D	Av. [m²]	± [m²]	F	% F S	% F D	Av. [m²]	± [m²]		%	Cum	%	Cum
1	34	10	71.43%	16.39%	2.97	2.97	2	14.29%	12.50%	23.50	7.62	0	0.00%	0.00%	0.00	0.00	2	14.29%	1.90%	1.55	0.21	5.70	6.97%	6.97%	24.82%	24.82%
2	28	20	83.33%	32.79%	31.38	31.38	3	12.50%	18.75%	87.50	28.38	1	4.17%	5.26%	4.11	0.80	0	0.00%	0.00%	0.00	0.00	37.26	11.94%	18.91%	20.44%	45.26%
3	8	8	53.33%	13.11%	6.46	6.46	2	13.33%	12.50%	25.00	8.11	2	13.33%	10.53%	12.62	2.44	3	20.00%	2.86%	75.62	10.31	23.58	7.46%	26.37%	5.84%	51.09%
4	54	21	19.09%	34.43%	32.46	32.46	9	8.18%	56.25%	279.68	90.71	13	11.82%	68.42%	180.64	34.96	67	60.91%	63.81%	1122.31	153.04	734.02	54.73%	81.09%	39.42%	90.51%
5	13	2	5.26%	3.28%	0.32	0.32	0	0.00%	0.00%	0.00	0.00	3	7.89%	15.79%	34.81	6.74	33	86.84%	31.43%	220.97	30.13	194.66	18.91%	100.00%	9.49%	100.00%
Total weighted area damage																						445.11				

1. Spread confined to object of origin; **2**. Spread confined to room of origin; **3**. Spread confined to floor of origin; **4**. Spread confined to building of origin; **5**. Spread beyond building of origin; **U**. Unclassified fires; **F**. Fires; **S**. spread; **D**. Damage; **Av**. Average area damage; ±. Standard deviation

Table 55: Manufacturing area: area damage and fire spread according to damage class; and fire frequency with respect to fire spread in presence and absence of automatic extinguishing systems, with weighted area damage, and frequency for fires and unclassified damage fires in the USA fire statistics.

	Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* [m²]	F		F+U	
		F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	146	54	93.10%	29.51%	203.12	203.12	3	5.17%	20.00%	120.31	39.02	1	1.72%	25.00%	248.68	48.13	0	0.00%	0.00%	0.00	0.00	199.62	28.02%	28.02%	44.11%	44.11%
2	138	81	95.29%	44.26%	420.41	420.41	3	3.53%	20.00%	86.25	27.97	1	1.18%	25.00%	60.10	11.63	0	0.00%	0.00%	0.00	0.00	404.38	41.06%	69.08%	41.69%	85.80%
3	15	21	95.45%	11.48%	100.03	100.03	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	1	4.55%	20.00%	2.23	0.30	95.58	10.63%	79.71%	4.53%	90.33%
4	28	25	65.79%	13.66%	204.15	204.15	9	23.68%	60.00%	2856.61	926.47	1	2.63%	25.00%	4.86	0.94	3	7.89%	60.00%	410.57	55.99	843.41	18.36%	98.07%	8.46%	98.79%
5	4	2	50.00%	1.09%	41.62	41.62	0	0.00%	0.00%	0.00	0.00	1	25.00%	25.00%	200.35	38.78	1	25.00%	20.00%	98.11	13.38	95.42	1.93%	100.00%	1.21%	100.00%
Total weighted area damage																						388.81				
	No Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* [m²]	F		F+U	
		F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	29	18	78.26%	21.69%	10.93	10.93	1	4.35%	4.00%	4.69	1.52	0	0.00%	0.00%	0.00	0.00	4	17.39%	9.52%	288.07	39.28	58.86	13.69%	13.69%	19.59%	19.59%
2	69	32	80.00%	38.55%	52.92	52.92	6	15.00%	24.00%	39.61	12.85	2	5.00%	11.11%	3.01	0.58	0	0.00%	0.00%	0.00	0.00	48.42	23.81%	37.50%	46.62%	66.22%
3	8	9	56.25%	10.84%	13.57	13.57	2	12.50%	8.00%	11.72	3.80	4	25.00%	22.22%	116.75	22.60	1	6.25%	2.38%	129.14	17.61	46.36	9.52%	47.02%	5.41%	71.62%
4	36	24	30.77%	28.92%	19.65	19.65	16	20.51%	64.00%	459.44	149.01	10	12.82%	55.56%	144.50	27.97	28	35.90%	66.67%	2007.78	273.79	839.56	46.43%	93.45%	24.32%	95.95%
5	6	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	2	18.18%	11.11%	29.43	5.70	9	81.82%	21.43%	240.45	32.79	202.08	6.55%	100.00%	4.05%	100.00%
Total weighted area damage																						427.03				

1. Spread confined to object of origin; **2**. Spread confined to room of origin; **3**. Spread confined to floor of origin; **4**. Spread confined to building of origin; **5**. Spread beyond building of origin; **U**. Unclassified fires; **F**. Fires; **S**. spread; **D**. Damage; **Av**. Average area damage; ±. Standard deviation

Table 56: Storage: area damage and fire spread according to damage class; and fire frequency with respect to fire spread in presence and absence of automatic extinguishing systems in USA fire statistics, with weighted area damage, and frequency for fires and unclassified damage fires in the USA fire statistics.

	Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* [m²]	F		F+U	
		F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	24	13	100.00%	32.50%	8.01	8.01	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	8.01	27.08%	27.08%	28.57%	28.57%
2	45	18	90.00%	45.00%	37.65	37.65	2	10.00%	40.00%	30.37	9.85	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	36.92	41.67%	68.75%	53.57%	82.14%
3	3	2	50.00%	5.00%	0.54	0.54	2	50.00%	40.00%	59.86	19.41	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	30.20	8.33%	77.08%	3.57%	85.71%
4	11	6	60.00%	15.00%	18.15	18.15	1	10.00%	20.00%	1.82	0.59	0	0.00%	0.00%	0.00	0.00	3	30.00%	100.00%	3.23	0.44	12.04	20.83%	97.92%	13.10%	98.81%
5	1	1	100.00%	2.50%	0.50	0.50	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	0	0.00%	0.00%	0.00	0.00	0.50	2.08%	100.00%	1.19%	100.00%
Total weighted area damage																						22.59				
	No Sprinklers - Area damage [m²]																									
	U	*Minor*					*Significantly*					*Heavy*					*Extreme*					*Weighted area damage* [m²]	F		F+U	
		F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]	F	% F		Av. [m²]	± [m²]					
			S	D				S	D				S	D				S	D				%	Cum	%	Cum
1	171	106	46.49%	15.06%	7.69	7.69	14	6.14%	5.26%	1.39	0.45	14	6.14%	5.91%	3.60	0.70	94	41.23%	6.59%	5.64	0.77	6.21	8.66%	8.66%	9.53%	9.53%
2	234	196	73.13%	27.84%	6.61	6.61	39	14.55%	14.66%	10.98	3.56	8	2.99%	3.38%	3.14	0.61	25	9.33%	1.75%	0.77	0.11	6.60	10.18%	18.84%	13.04%	22.58%
3	50	38	59.38%	5.40%	0.92	0.92	13	20.31%	4.89%	2.48	0.80	8	12.50%	3.38%	1.86	0.36	5	7.81%	0.35%	0.54	0.07	1.33	2.43%	21.27%	2.79%	25.36%
4	986	293	20.71%	41.62%	8.98	8.98	168	11.87%	63.16%	49.58	16.08	166	11.73%	70.04%	72.97	14.12	788	55.69%	55.26%	69.72	9.51	55.14	53.74%	75.01%	54.96%	80.32%
5	353	71	10.79%	10.09%	4.35	4.35	32	4.86%	12.03%	2.13	0.69	41	6.23%	17.30%	46.07	8.92	514	78.12%	36.04%	49.03	6.69	41.75	24.99%	100.00%	19.68%	100.00%
Total weighted area damage																						41.30				

1. Spread confined to object of origin; **2**. Spread confined to room of origin; **3**. Spread confined to floor of origin; **4**. Spread confined to building of origin; **5**. Spread beyond building of origin; **U**. Unclassified fires; **F**. Fires; **S**. spread; **D**. Damage; **Av**. Average area damage; ±. Standard deviation

Table 57: Table A.6 Frequency distribution of area damage in terms of number of fires in Office building, PD 7974-7 vs USA fire statistics

	Office rooms							
	Sprinklers				No sprinklers			
Area damage [m^2]	PD 7974-7		USA		PD 7974-7		USA	
	fires	%	fires	%	fires	%	fires	%
1 and under	13	27.8%	15	34.78%	908	51.2%	19	54.76%
2-4	3	11.1%	0	34.78%	379	30.8%	0	54.76%
5-9	0	11.1%	0	34.78%	144	23.1%	2	50.00%
10-19	2	0.0%	0	34.78%	116	16.8%	0	50.00%
20-49	0	0.0%	1	30.43%	154	8.5%	2	45.24%
50-99	0	0.0%	0	30.43%	69	4.8%	7	28.57%
100-199	0	0.0%	1	26.09%	35	3.0%	4	19.05%
200-499	0	0.0%	4	8.70%	33	1.2%	6	4.76%
500-999	0	0.0%	0	8.70%	13	0.5%	1	2.38%
1000 and above	0	0.0%	2	0.00%	9	0.0%	1	0.00%
Total fires	18		23		1860		42	
	Other areas							
	Sprinklers				No sprinklers			
Area damage [m^2]	PD 7974-7		USA		PD 7974-7		USA	
	fires	%	fires	%	fires	%	fires	%
1 and under	95	25.2%	66	37.74%	2588	40.8%	126	48.36%
2-4	17	11.8%	0	37.74%	902	20.1%	1	47.95%
5-9	9	4.7%	2	35.85%	303	13.2%	5	45.90%
10-19	2	3.1%	2	33.96%	199	8.6%	6	43.44%
20-49	3	0.8%	1	33.02%	180	4.5%	18	36.07%
50-99	1	0.0%	3	30.19%	75	2.8%	29	24.18%
100-199	0	0.0%	6	24.53%	53	1.6%	25	13.93%
200-499	0	0.0%	10	15.09%	40	0.7%	19	6.15%
500-999	0	0.0%	3	12.26%	18	0.3%	11	1.64%
1000 and above	0	0.0%	13	0.00%	11	0.00%	4	0.00%
Total fires	127		106		4369		244	

Fires = number of fires; % = % of fires exceeding upper limit

Table 58: Table A.6 Frequency distribution of area damage in terms of number of fires in Office building, PD 7974-7 vs English fire statistics

		Office rooms											
		Sprinklers						No Sprinklers					
Area damage [m²]		PD 7974-7		Eng F		Eng T		PD 7974-7		Eng F		Eng T	
PD 7974-7	Eng	fires	%	fires	%	fires	%	fires	%	fires	%	fires	%
	0			7	53.33%	2	86.67%			351	73.85%	219	83.68%
1 and under		13	27.8%					908	51.2%				
	Up to 5			7	6.67%	9	26.67%			715	20.57%	667	33.98%
2-4		3	11.1%					379	30.8%				
5-9	6 to 10	0	11.1%	1	0.00%	2	13.33%	144	23.1%	64	15.80%	68	28.91%
10-19	11 to 20	2	0.00%	0	0.00%	0	13.33%	116	16.8%	54	11.77%	73	23.47%
20-49	21 to 50	0	0.00%	0	0.00%	0	13.33%	154	8.5%	62	7.15%	94	16.47%
50-99	51 to 100	0	0.00%	0	0.00%	0	13.33%	69	4.8%	35	4.55%	86	10.06%
100-199	101 to 200	0	0.00%	0	0.00%	0	13.33%	35	3.0%	29	2.38%	53	6.11%
200-499	201 to 500	0	0.00%	0	0.00%	2	0.00%	33	1.2%	19	0.97%	43	2.91%
500-999	501 to 1000	0	0.00%	0	0.00%	0	0.00%	13	0.5%	8	0.37%	26	0.97%
1000 and above	Over 1000	0	0.00%	0	0.00%	0	0.00%	9	0.0%	5	0.00%	13	0.00%
Total fires		18		15		15		1860		1342		1342	
		Other rooms											
		Sprinklers						No Sprinklers					
Area damage [m²]		PD 7974-7		Eng F		Eng T		PD 7974-7		Eng F		Eng T	
PD 7974-7	Eng	fires	%	fires	%	fires	%	fires	%	fires	%	fires	%
	0			20	68.75%	11	82.81%			917	69.94%	529	82.66%
1 and under		95	25.2%					2588	40.8%				
	Up to 5			42	3.13%	38	23.44%			1748	12.65%	1672	27.86%
2-4		17	11.8%					902	20.1%				
5-9	6 to 10	9	4.7%	1	1.56%	2	20.31%	303	13.2%	177	6.85%	267	19.11%
10-19	11 to 20	2	3.1%	1	0.00%	5	12.50%	199	8.6%	83	4.13%	194	12.75%
20-49	21 to 50	3	0.8%	0	0.00%	3	7.81%	180	4.5%	49	2.52%	131	8.46%
50-99	51 to 100	1	0.0%	0	0.00%	4	1.56%	75	2.8%	31	1.51%	112	4.79%
100-199	101 to 200	0	0.0%	0	0.00%	0	1.56%	53	1.6%	25	0.69%	69	2.52%
200-499	201 to 500	0	0.0%	0	0.00%	0	1.56%	40	0.7%	9	0.39%	41	1.18%
500-999	501 to 1000	0	0.0%	0	0.00%	0	1.56%	18	0.3%	4	0.26%	17	0.62%
1000 and above	Over 1000	0	0.0%	0	0.00%	1	0.00%	11	0.0%	8	0.00%	19	0.00%
Total fires		127		64		64		4369		3051		3051	

F = fire damage; T= total damage; Fires = number of fires; % = % of fires exceeding upper limit

Table 59: Table A.7 Frequency distribution of area damage in terms of number of fires in Retail premises, PD 7974-7 vs USA fire statistics part 1

	Assembly or Sales Areas (Group of people)							
	Sprinklers				No sprinklers			
Area damage [m^2]	PD 7974-7		USA		PD 7974-7		USA	
	fires	%	fires	%	fires	%	fires	%
1 and under	154	30.9%	37	40.32%	4197	48.9%	38	58.24%
2-4	37	14.3%	0	40.32%	1987	24.6%	0	58.24%
5-9	9	10.3%	0	40.32%	619	17.1%	2	56.04%
10-19	13	4.5%	0	40.32%	463	11.5%	2	53.85%
20-49	6	1.8%	2	37.10%	430	6.2%	12	40.66%
50-99	4	0.0%	4	30.65%	221	3.5%	11	28.57%
100-199	0	0.0%	3	25.81%	127	2.0%	6	21.98%
200-499	0	0.0%	6	16.13%	100	0.8%	14	6.59%
500-999	0	0.0%	0	16.13%	29	0.4%	2	4.40%
1000 and above	0	0.0%	10	0.00%	34	0.0%	4	0.00%
Total fires	223		62		8207		91	

	Storage Areas							
	Sprinklers				No sprinklers			
Area damage [m^2]	PD 7974-7		USA		PD 7974-7		USA	
	fires	%	fires	%	fires	%	fires	%
1 and under	261	26.3%	65	30.11%	1679	67.4%	93	58.85%
2-4	51	11.9%	1	29.03%	1306	42.0%	2	57.96%
5-9	22	5.6%	0	29.03%	722	27.9%	5	55.75%
10-19	11	2.5%	0	29.03%	543	17.4%	9	51.77%
20-49	6	0.8%	3	25.81%	476	8.1%	21	42.48%
50-99	1	0.6%	2	23.66%	177	4.7%	24	31.86%
100-199	0	0.6%	6	17.20%	116	2.4%	23	21.68%
200-499	2	0.0%	4	12.90%	74	1.0%	28	9.29%
500-999	0	0.0%	4	8.60%	24	0.5%	12	3.98%
1000 and above	0	0.0%	8	0.00%	27	0.0%	9	0.00%
Total fires	354		93		5144		226	

Fires = number of fires; % = % of fires exceeding upper limit; **Red**: Corrected values

Table 60: Table A.7 Frequency distribution of area damage in terms of number of fires in Retail premises, PD 7974-7 vs USA fire statistics part 2

	Other Areas							
	Sprinklers				No sprinklers			
Area damage [m^2]	PD 7974-7		USA		PD 7974-7		USA	
	fires	%	fires	%	fires	%	fires	%
1 and under	135	26.2%	376	34.38%	4066	43.5%	807	47.67%
2-4	22	14.2%	3	33.86%	1638	20.7%	9	47.08%
5-9	8	9.8%	8	32.46%	490	13.9%	18	45.91%
10-19	9	4.9%	4	31.76%	404	8.3%	44	43.06%
20-49	5	2.2%	26	27.23%	323	3.8%	144	33.72%
50-99	2	1.1%	22	23.39%	128	2.0%	146	24.25%
100-199	2	0.0%	16	20.59%	68	1.1%	133	15.63%
200-499	0	0.0%	49	12.04%	57	0.3%	133	7.00%
500-999	0	0.0%	20	8.55%	15	0.1%	65	2.79%
1000 and above	0	0.0%	49	0.00%	5	0.0%	43	0.00%
Total fires	183		573		7194		1542	

Fires = number of fires; % = % of fires exceeding upper limit

Table 61: Table A.7 Frequency distribution of area damage in terms of number of fires in Retail premises, PD 7974-7 vs English fire statistics part 1

		Assembly areas											
		Sprinklers						No Sprinklers					
Area damage [m^2]		PD 7974-7		Eng F		Eng T		PD 7974-7		Eng F		Eng T	
PD 7974-7	Eng	fires	%	fires	%	fires	%	fires	%	fires	%	fires	%
	0			9	75.68%	3	91.89%			252	70.39%	131	84.61%
1 and under		154	30.9%					4197	48.9%				
	Up to 5			27	2.70%	22	32.43%			455	16.92%	463	30.20%
2-4		37	14.3%					1987	24.6%				
5-9	6 to 10	9	10.3%	0	2.70%	1	29.73%	619	17.1%	47	11.40%	55	23.74%
10-19	11 to 20	13	4.5%	1	0.00%	3	21.62%	463	11.5%	36	7.17%	42	18.80%
20-49	21 to 50	6	1.8%	0	0.00%	2	16.22%	430	6.2%	27	4.00%	54	12.46%
50-99	51 to 100	4	0.0%	0	0.00%	2	10.81%	221	3.5%	20	1.65%	57	5.76%
100-199	101 to 200	0	0.0%	0	0.00%	1	8.11%	127	2.0%	12	0.24%	30	2.23%
200-499	201 to 500	0	0.0%	0	0.00%	2	2.70%	100	0.8%	0	0.24%	11	0.94%
500-999	501 to 1000	0	0.0%	0	0.00%	0	2.70%	29	0.4%	2	0.00%	6	0.24%
1000 and above	Over 1000	0	0.0%	0	0.00%	1	0.00%	34	0.0%	0	0.00%	2	0.00%
Total fires		223		37		37		8207		851		851	
		Storage areas											
		Sprinklers						No Sprinklers					
Area damage [m^2]		PD 7974-7		Eng F		Eng T		PD 7974-7		Eng F		Eng T	
PD 7974-7	Eng	fires	%	fires	%	fires	%	fires	%	fires	%	fires	%
	0			15	72.73%	7	87.27%			370	77.87%	224	86.60%
1 and under		261	26.3%					1679	67.4%				
	Up to 5			31	16.36%	27	38.18%			893	24.46%	762	41.03%
2-4		51	11.9%					1306	42.0%				
5-9	6 to 10	22	5.6%	5	7.27%	3	32.73%	722	27.9%	146	15.73%	162	31.34%
10-19	11 to 20	11	2.5%	2	3.64%	1	30.91%	543	17.4%	101	9.69%	130	23.56%
20-49	21 to 50	6	0.8%	1	1.82%	2	27.27%	476	8.1%	64	5.86%	146	14.83%
50-99	51 to 100	1	0.6%	0	1.82%	7	14.55%	177	4.7%	46	3.11%	113	8.07%
100-199	101 to 200	0	0.6%	1	0.00%	3	9.09%	116	2.4%	19	1.97%	54	4.84%
200-499	201 to 500	2	0.0%	0	0.00%	1	7.27%	74	1.0%	20	0.78%	54	1.61%
500-999	501 to 1000	0	0.0%	0	0.00%	2	3.64%	24	0.5%	6	0.42%	14	0.78%
1000 and above	Over 1000	0	0.0%	0	0.00%	2	0.00%	27	0.0%	7	0.00%	13	0.00%
Total fires		354		55		55		5144		1672		1672	
F = fire damage; T= total damage; Fires = number of fires; % = % of fires exceeding upper limit; **Red**: Corrected values													

Table 62: Table A.7 Frequency distribution of area damage in terms of number of fires in Retail premises, PD 7974-7 vs English fire statistics part 2

		Other areas											
		Sprinklers						No Sprinklers					
Area damage [m2]		PD 7974-7		Eng F		Eng T		PD 7974-7		Eng F		Eng T	
PD 7974-7	Eng	fires	%	fires	%	fires	%	fires	%	fires	%	fires	%
	0			82	74.53%	37	88.51%			2016	78.50%	1175	87.47%
1 and under		135	26.2%					4066	43.5%				
	Up to 5			211	9.01%	193	28.57%			5648	18.28%	4919	35.02%
2-4		22	14.2%					1638	20.7%				
5-9	6 to 10	8	9.8%	12	5.28%	21	22.05%	490	13.9%	663	11.21%	772	26.79%
10-19	11 to 20	9	4.9%	6	3.42%	12	18.32%	404	8.3%	357	7.40%	640	19.96%
20-49	21 to 50	5	2.2%	6	1.55%	15	13.66%	323	3.8%	305	4.15%	678	12.73%
50-99	51 to 100	2	1.1%	1	1.24%	13	9.63%	128	2.0%	154	2.51%	526	7.12%
100-199	101 to 200	2	0.0%	2	0.62%	12	5.90%	68	1.1%	88	1.57%	308	3.84%
200-499	201 to 500	0	0.0%	1	0.31%	8	3.42%	57	0.3%	68	0.84%	181	1.91%
500-999	501 to 1000	0	0.0%	0	0.31%	7	1.24%	15	0.1%	35	0.47%	99	0.85%
1000 and above	Over 1000	0	0.0%	1	0.00%	4	0.00%	5	0.0%	44	0.00%	80	0.00%
Total fires		183		322		322		7194		9378		9378	

F = fire damage; T= total damage; Fires = number of fires; % = % of fires exceeding upper limit

Table 63: Table A.8 Frequency distribution of area damage in terms of number of fires in Hotels, PD 7974-7 vs USA fire statistics part 1

	Assembly or Sales Areas (Group of people)							
	Sprinklers				No sprinklers			
Area damage [m²]	PD 7974-7		USA		PD 7974-7		USA	
	fires	%	fires	%	fires	%	fires	%
1 and under	/	/	5	37.50%	321	38.0%	4	66.67%
2-4	/	/	1	25.00%	76	23.4%	0	66.67%
5-9	/	/	0	25.00%	31	17.4%	0	66.67%
10-19	/	/	1	12.50%	17	14.1%	1	58.33%
20-49	/	/	0	12.50%	30	8.3%	0	58.33%
50-99	/	/	0	12.50%	10	6.4%	1	50.00%
100-199	/	/	0	12.50%	13	3.9%	1	41.67%
200-499	/	/	1	0.00%	13	1.4%	4	8.33%
500-999	/	/	0	0.00%	6	0.2%	0	8.33%
1000 and above	/	/	0	0.00%	1	0.0%	1	0.00%
Total fires			8		518		12	
	Bedrooms							
	Sprinklers				No sprinklers			
Area damage [m²]	PD 7974-7		USA		PD 7974-7		USA	
	fires	%	fires	%	fires	%	fires	%
1 and under	/	/	29	34.09%	634	47.0%	39	53.57%
2-4	/	/	1	31.82%	324	19.9%	0	53.57%
5-9	/	/	1	29.55%	94	12.0%	3	50.00%
10-19	/	/	2	25.00%	59	7.1%	4	45.24%
20-49	/	/	0	25.00%	54	2.6%	11	32.14%
50-99	/	/	1	22.73%	18	1.1%	6	25.00%
100-199	/	/	1	20.45%	4	0.8%	4	20.24%
200-499	/	/	3	13.64%	2	0.6%	11	7.14%
500-999	/	/	4	4.55%	7	0.0%	3	3.57%
1000 and above	/	/	2	0.00%	0	0.0%	3	0.00%
Total fires			44		1196		84	

Fires = number of fires; % = % of fires exceeding upper limit; **Red**: Corrected values

Table 64: Table A.8 Frequency distribution of area damage in terms of number of fires in Hotels, PD 7974-7 vs USA fire statistics part 2

Area damage [m^2]	Storage Areas and other areas							
	Sprinklers				No sprinklers			
	PD 7974-7		USA		PD 7974-7		USA	
	fires	%	fires	%	fires	%	fires	%
1 and under	31	11.4%	174	31.76%	2789	27.0%	133	43.88%
2-4	2	5.7%	4	30.20%	459	15.0%	2	43.04%
5-9	1	2.9%	7	27.45%	162	10.8%	11	38.40%
10-19	1	0.0%	3	26.27%	136	7.2%	10	34.18%
20-49	0	0.0%	2	25.49%	124	4.0%	15	27.85%
50-99	0	0.0%	4	23.92%	67	2.2%	9	24.05%
100-199	0	0.0%	4	22.35%	31	1.4%	14	18.14%
200-499	0	0.0%	18	15.29%	31	0.6%	26	7.17%
500-999	0	0.0%	18	8.24%	8	0.4%	9	3.38%
1000 and above	0	0.0%	21	0.00%	14	0.0%	8	0.00%
Total fires	35		255		3821		237	

Fires = number of fires; % = % of fires exceeding upper limit

Table 65: Table A.8 Frequency distribution of area damage in terms of number of fires in Hotels, PD 7974-7 vs English fire statistics part 1

		Assembly											
		Sprinklers						No Sprinklers					
Area damage [m²]		PD 7974-7		Eng F		Eng T		PD 7974-7		Eng F		Eng T	
PD 7974-7	Eng	fires	%	fires	%	fires	%	fires	%	fires	%	fires	%
	0			1	75.00%	1	75.00%			56	66.47%	29	82.63%
1 and under		/	/					321	38.03%				
	Up to 5			3	0.00%	1	50.00%			91	11.98%	99	23.35%
2-4		/	/					76	23.36%				
5-9	6 to 10	/	/	0	0.00%	1	25.00%	31	17.37%	4	9.58%	10	17.37%
10-19	11 to 20	/	/	0	0.00%	1	0.00%	17	14.09%	7	5.39%	5	14.37%
20-49	21 to 50	/	/	0	0.00%	0	0.00%	30	8.30%	5	2.40%	9	8.98%
50-99	51 to 100	/	/	0	0.00%	0	0.00%	10	6.37%	1	1.80%	7	4.79%
100-199	101 to 200	/	/	0	0.00%	0	0.00%	13	3.86%	1	1.20%	4	2.40%
200-499	201 to 500	/	/	0	0.00%	0	0.00%	13	1.35%	1	0.60%	3	0.60%
500-999	501 to 1000	/	/	0	0.00%	0	0.00%	6	0.19%	0	0.60%	0	0.60%
1000 and above	Over 1000	/	/	0	0.00%	0	0.00%	1	0.00%	1	0.00%	1	0.00%
Total fires		/		4		4		518		167		167	
		Bedrooms											
		Sprinklers						No Sprinklers					
Area damage [m²]		PD 7974-7		Eng F		Eng T		PD 7974-7		Eng F		Eng T	
PD 7974-7	Eng	fires	%	fires	%	fires	%	fires	%	fires	%	fires	%
	0			1	50.00%	1	50.00%			74	79.78%	42	88.52%
1 and under		/	/					634	47.0%				
	Up to 5			1	0.00%	0	50.00%			200	25.14%	152	46.99%
2-4		/	/					324	19.9%				
5-9	6 to 10	/	/	0	0.00%	0	50.00%	94	12.0%	28	17.49%	40	36.07%
10-19	11 to 20	/	/	0	0.00%	0	50.00%	59	7.1%	21	11.75%	42	24.59%
20-49	21 to 50	/	/	0	0.00%	1	0.00%	54	2.6%	20	6.28%	32	15.85%
50-99	51 to 100	/	/	0	0.00%	0	0.00%	18	1.1%	8	4.10%	16	11.48%
100-199	101 to 200	/	/	0	0.00%	0	0.00%	4	0.8%	4	3.01%	20	6.01%
200-499	201 to 500	/	/	0	0.00%	0	0.00%	2	0.6%	6	1.37%	9	3.55%
500-999	501 to 1000	/	/	0	0.00%	0	0.00%	7	0.0%	3	0.55%	10	0.82%
1000 and above	Over 1000	/	/	0	0.00%	0	0.00%	0	0.0%	2	0.00%	3	0.00%
Total fires		/		2		2		1196		366		366	
F = fire damage; T= total damage; Fires = number of fires; % = % of fires exceeding upper limit; **Red**: Corrected values													

Table 66: Table A.8 Frequency distribution of area damage in terms of number of fires in Hotels, PD 7974-7 vs English fire statistics part 2

		Storage areas											
		Sprinklers						No Sprinklers					
Area damage [m^2]		PD 7974-7		Eng F		Eng T		PD 7974-7		Eng F		Eng T	
PD 7974-7	Eng	fires	%	fires	%	fires	%	fires	%	fires	%	fires	%
	0			1	90.00%	0	100.00%			57	81.25%	29	90.46%
1 and under		31	11.4%					2789	27.0%				
	Up to 5			7	20.00%	3	70.00%			190	18.75%	145	42.76%
2-4		2	5.7%					459	15.0%				
5-9	6 to 10	1	2.9%	2	0.00%	3	40.00%	162	10.8%	26	10.20%	36	30.92%
10-19	11 to 20	1	0.0%	0	0.00%	0	40.00%	136	7.2%	13	5.92%	27	22.04%
20-49	21 to 50	0	0.0%	0	0.00%	2	20.00%	124	4.0%	9	2.96%	28	12.83%
50-99	51 to 100	0	0.0%	0	0.00%	1	10.00%	67	2.2%	1	2.63%	16	7.57%
100-199	101 to 200	0	0.0%	0	0.00%	1	0.00%	31	1.4%	4	1.32%	8	4.93%
200-499	201 to 500	0	0.0%	0	0.00%	0	0.00%	31	0.6%	3	0.33%	9	1.97%
500-999	501 to 1000	0	0.0%	0	0.00%	0	0.00%	8	0.4%	0	0.33%	2	1.32%
1000 and above	Over 1000	0	0.0%	0	0.00%	0	0.00%	14	0.0%	1	0.00%	4	0.00%
Total fires		35		10		10		3821		304		304	

F = fire damage; T= total damage; Fires = number of fires; % = % of fires exceeding upper limit; **Red**: Corrected values

Table 67: Frequency distribution of area damage in terms of number of fires in Assembly in USA statistics

	USA - Assembly			
	Sprinklers		No sprinklers	
Area damage [m²]	fires	%	fires	%
1 and under	482	33.97%	449	49.38%
2-4	3	33.56%	11	48.14%
5-9	2	33.29%	19	46.00%
10-19	7	32.33%	20	43.74%
20-49	47	25.89%	99	32.58%
50-99	69	16.44%	80	23.56%
100-199	50	9.59%	76	14.99%
200-499	43	3.70%	75	6.54%
500-999	10	2.33%	31	3.04%
1000 and above	17	0.00%	27	0.00%
Total fires	730		887	
Fires = number of fires; % = % of fires exceeding upper limit				

Table 68: Frequency distribution of area damage in terms of number of fires in Educational in USA statistics

	USA – Educational			
	Sprinklers		No sprinklers	
Area damage [m²]	fires	%	fires	%
1 and under	127	33.16%	155	46.55%
2-4	1	32.63%	5	44.83%
5-9	2	31.58%	7	42.41%
10-19	1	31.05%	12	38.28%
20-49	2	30.00%	15	33.10%
50-99	4	27.89%	10	29.66%
100-199	4	25.79%	15	24.48%
200-499	17	16.84%	30	14.14%
500-999	11	11.05%	15	8.97%
1000 and above	21	0.00%	26	0.00%
Total fires	190		290	
Fires = number of fires; % = % of fires exceeding upper limit				

Table 69: Frequency distribution of area damage in terms of number of fires in Health Care, Detention and Correction in USA statistics

	USA – Health Care, Detention and Correction			
	Sprinklers		No sprinklers	
Area damage [m²]	fires	%	fires	%
1 and under	222	28.62%	90	45.78%
2-4	1	28.30%	2	44.58%
5-9	3	27.33%	3	42.77%
10-19	2	26.69%	3	40.96%
20-49	8	24.12%	13	33.13%
50-99	5	22.51%	14	24.70%
100-199	12	18.65%	12	17.47%
200-499	22	11.58%	10	11.45%
500-999	18	5.79%	9	6.02%
1000 and above	18	0.00%	10	0.00%
Total fires	311		166	
Fires = number of fires; % = % of fires exceeding upper limit				

Table 70: Frequency distribution of area damage in terms of number of fires in Residential in USA statistics

	USA - Residential			
	Sprinklers		No sprinklers	
Area damage [m²]	fires	%	fires	%
1 and under	1722	33.92%	22129	54.31%
2-4	27	32.89%	268	53.76%
5-9	28	31.81%	478	52.77%
10-19	89	28.40%	1854	48.94%
20-49	202	20.64%	9705	28.90%
50-99	119	16.08%	6676	15.12%
100-199	100	12.24%	4462	5.91%
200-499	140	6.87%	2120	1.53%
500-999	74	4.03%	485	0.53%
1000 and above	105	0.00%	255	0.00%
Total fires	2606		48432	
Fires = number of fires; % = % of fires exceeding upper limit				

Table 71: Frequency distribution of area damage in terms of number of fires in Mercantile, Business in USA statistics

	USA- Mercantile, Business			
	Sprinklers		No sprinklers	
Area damage [m^2]	fires	%	fires	%
1 and under	478	34.34%	938	49.54%
2-4	4	33.79%	11	48.95%
5-9	8	32.69%	25	47.61%
10-19	4	32.14%	55	44.65%
20-49	31	27.88%	177	35.13%
50-99	28	24.04%	181	25.39%
100-199	25	20.60%	162	16.68%
200-499	59	12.50%	175	7.26%
500-999	24	9.20%	79	3.01%
1000 and above	67	0.00%	56	0.00%
Total fires	728		1859	
Fires = number of fires; % = % of fires exceeding upper limit				

Table 72: Frequency distribution of area damage in terms of number of fires in Industrial, Utility, Defence, Agricultural and Mining in USA statistics

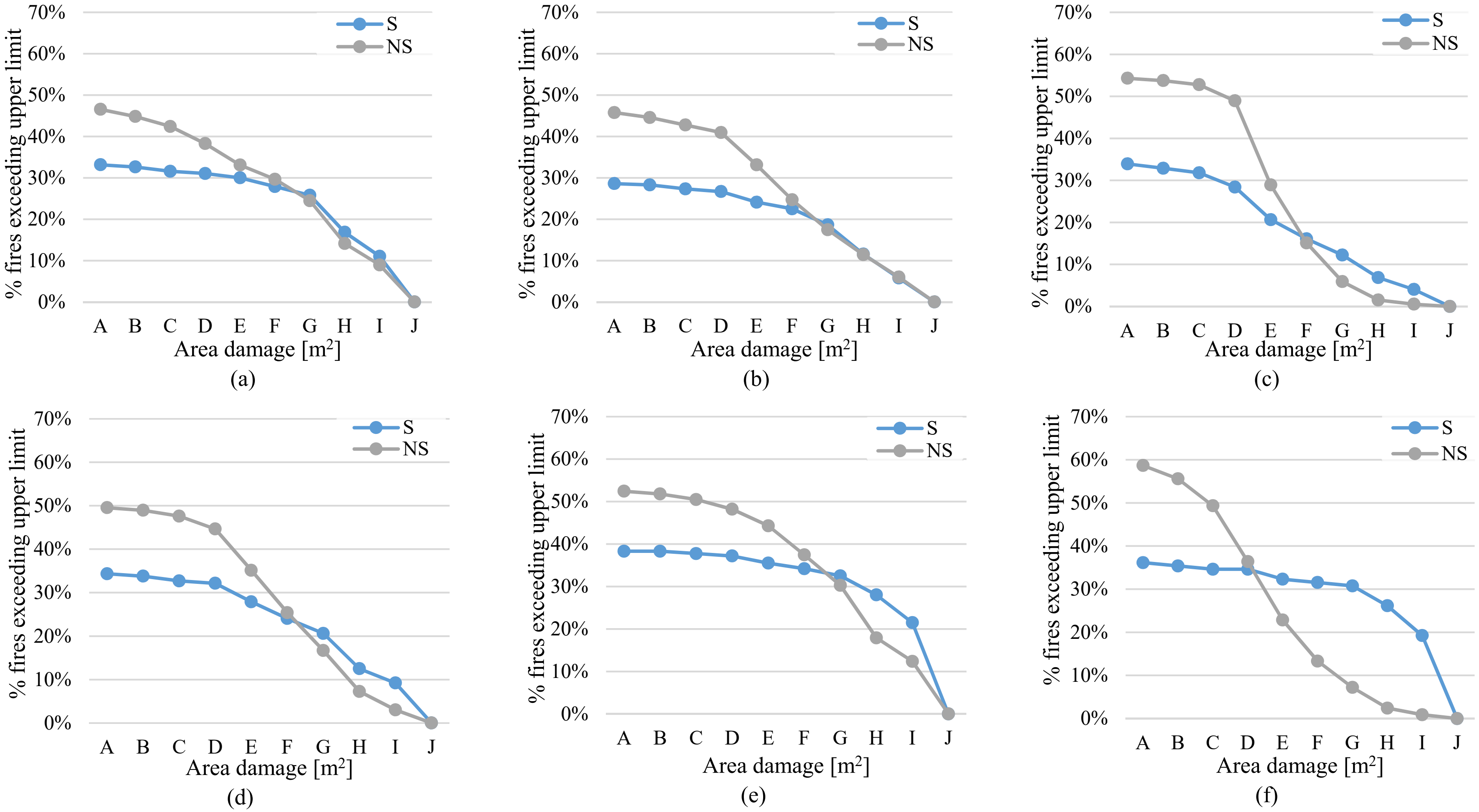
	USA- Industrial, Utility, Defence, Agricultural and Mining			
	Sprinklers		No sprinklers	
Area damage [m^2]	fires	%	fires	%
1 and under	34	46.03%	136	59.16%
2-4	0	46.03%	7	57.06%
5-9	1	44.44%	7	54.95%
10-19	0	44.44%	21	48.65%
20-49	3	39.68%	21	42.34%
50-99	1	38.10%	22	35.74%
100-199	1	36.51%	38	24.32%
200-499	6	26.98%	41	12.01%
500-999	4	20.63%	17	6.91%
1000 and above	13	0.00%	23	0.00%
Total fires	63		333	
Fires = number of fires; % = % of fires exceeding upper limit				

Table 73: Frequency distribution of area damage in terms of number of fires in Manufacturing, Processing in USA statistics

	USA – Manufacturing, Processing			
	Sprinklers		No sprinklers	
Area damage [m²]	fires	%	fires	%
1 and under	330	38.32%	146	52.44%
2-4	0	38.32%	2	51.79%
5-9	3	37.76%	4	50.49%
10-19	3	37.20%	7	48.21%
20-49	9	35.51%	12	44.30%
50-99	7	34.21%	21	37.46%
100-199	9	32.52%	22	30.29%
200-499	24	28.04%	38	17.92%
500-999	35	21.50%	17	12.38%
1000 and above	115	0.00%	38	0.00%
Total fires	535		307	
Fires = number of fires; % = % of fires exceeding upper limit				

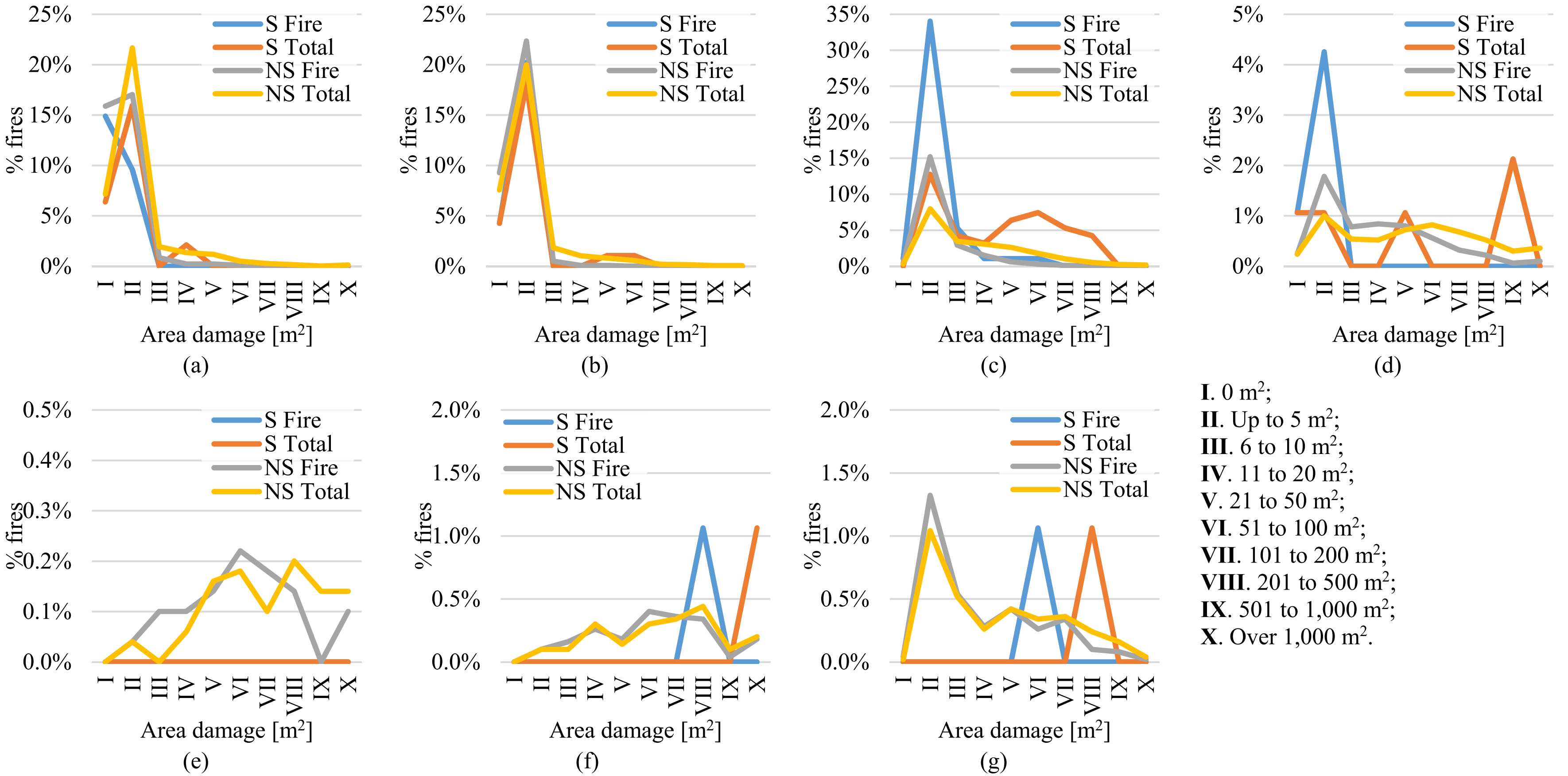
Table 74: Frequency distribution of area damage in terms of number of fires in Storage in USA statistics

	USA - Storage			
	Sprinklers		No sprinklers	
Area damage [m²]	fires	%	fires	%
1 and under	83	36.15%	1815	58.67%
2-4	1	35.38%	136	55.58%
5-9	1	34.62%	274	49.34%
10-19	0	34.62%	569	36.38%
20-49	3	32.31%	595	22.84%
50-99	1	31.54%	418	13.32%
100-199	1	30.77%	268	7.22%
200-499	6	26.15%	211	2.41%
500-999	9	19.23%	67	0.89%
1000 and above	25	0.00%	39	0.00%
Total fires	130		4392	
Fires = number of fires; % = % of fires exceeding upper limit				



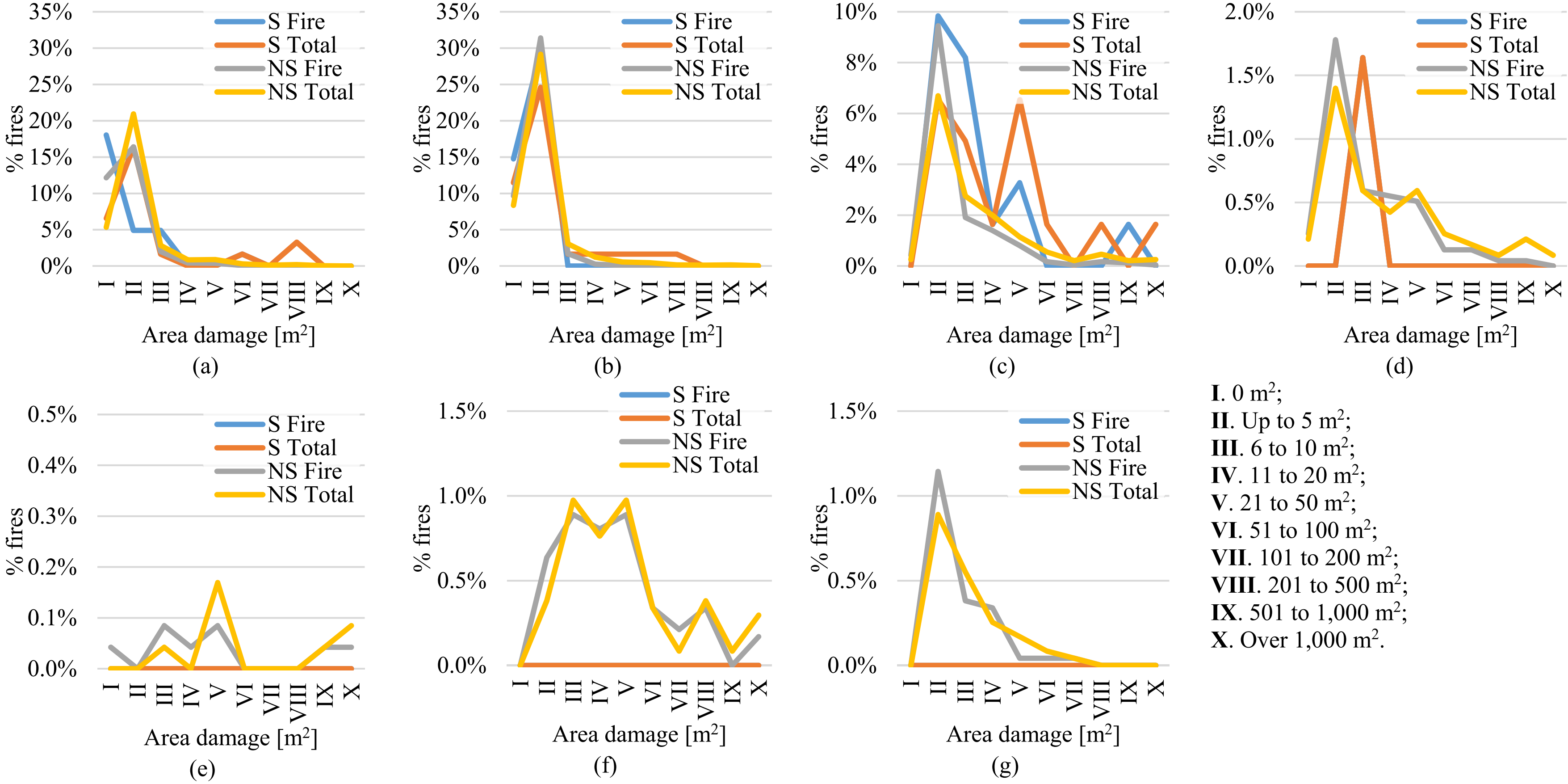
A. 1 m^2 and under; **B**. 2 to 4 m^2; **C**. 5 to 9 m^2; **D**. 10 to 19 m^2; **E**. 20 to 49 m^2; **F**. 50 to 99 m^2; **G**. 100 to 199 m^2; **H**. 200 to 499 m^2; **I**. 500 to 999 m^2; **J**. 1000 m^2 and above

Figure 139: Frequency distribution of area damage in (a) Educational; (b) Health Care, Detention and Correction, (c) Residential; (d) Mercantile, Business; (e)Manufacturing, Processing and (f) Storage [S=Sprinklers; NS=No sprinklers] in USA statistics



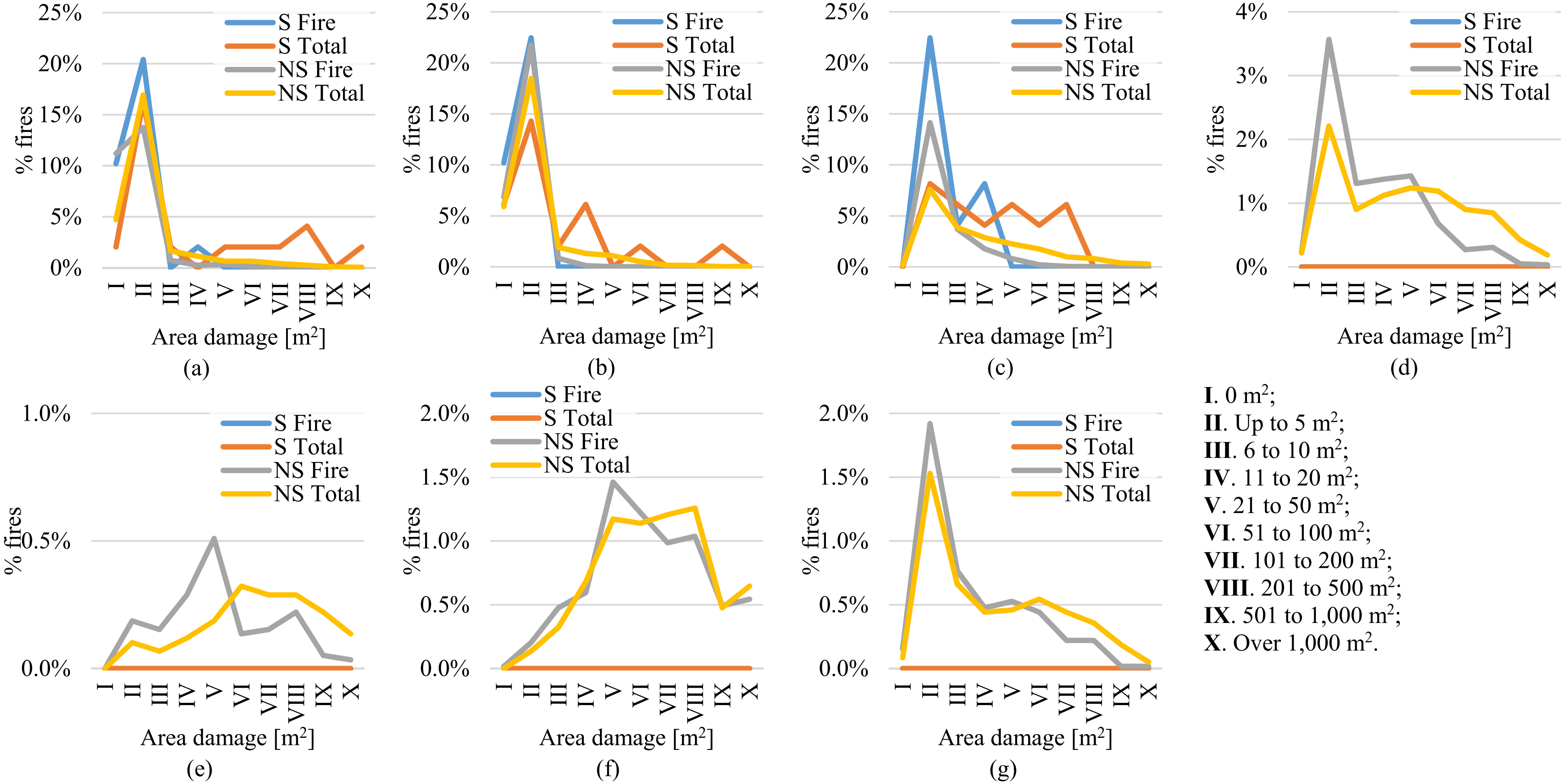
a. No fire damage; **b**. Limited to item ignited; **c**. Limited to room of origin; **d**. Limited to floor of origin; **e**. Limited to two floors; **f**. Whole building/ more than two floors; **g**. Roofs/Roof spaces; **S**. Sprinklers; **NS**. No Sprinklers; **Fire**. Fire damage; **Total**. Total damage

Figure 140: Frequency distribution of area damage in Educational [S=Sprinklers; NS=No sprinklers] in English statistics



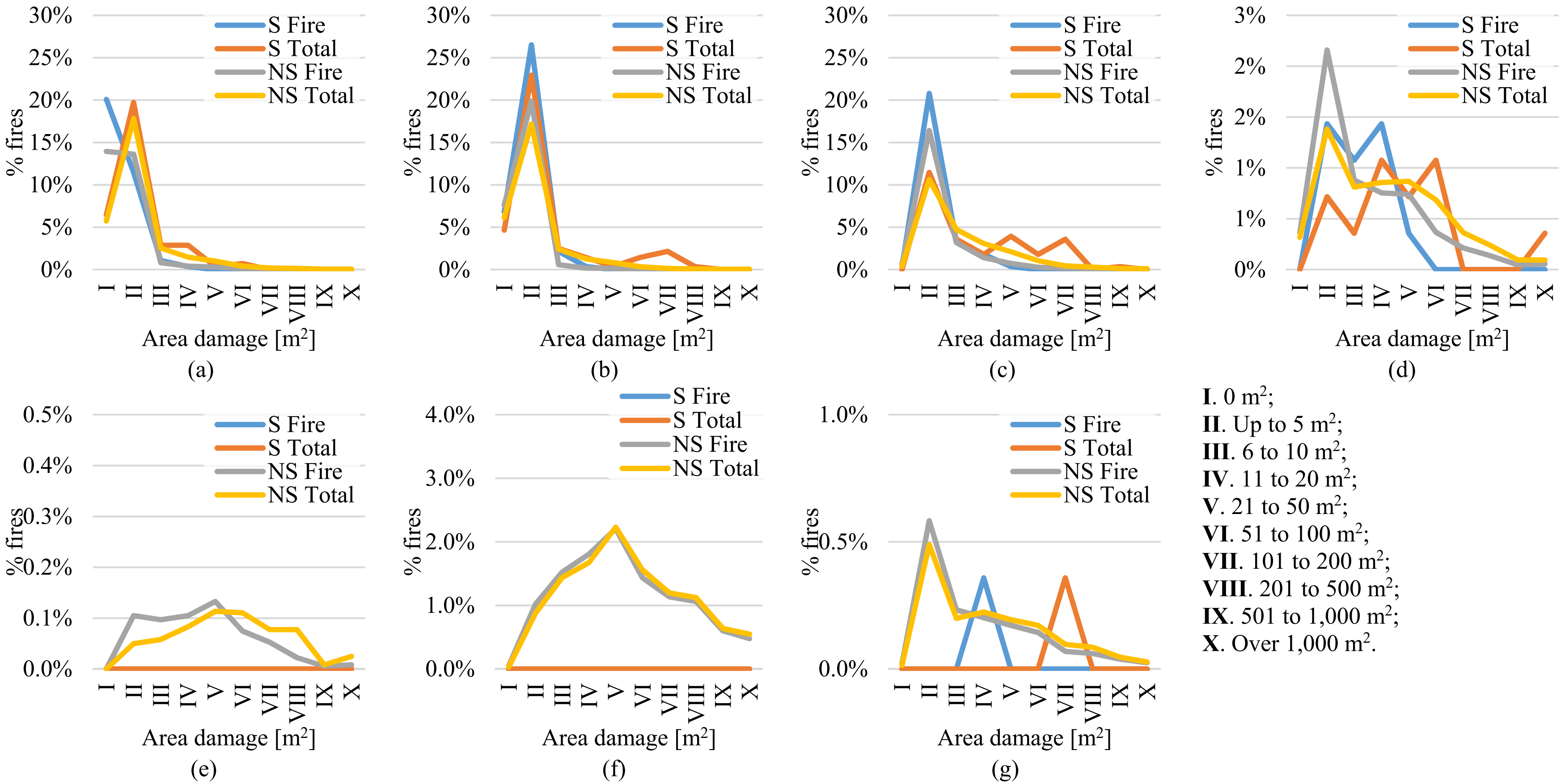
a. No fire damage; **b**. Limited to item ignited; **c**. Limited to room of origin; **d**. Limited to floor of origin; **e**. Limited to two floors; **f**. Whole building/ more than two floors; **g**. Roofs/Roof spaces; **S**. Sprinklers; **NS**. No Sprinklers; **Fire**. Fire damage; **Total**. Total damage

Figure 141: Frequency distribution of area damage in Utilities [S=Sprinklers; NS=No sprinklers] in English statistics



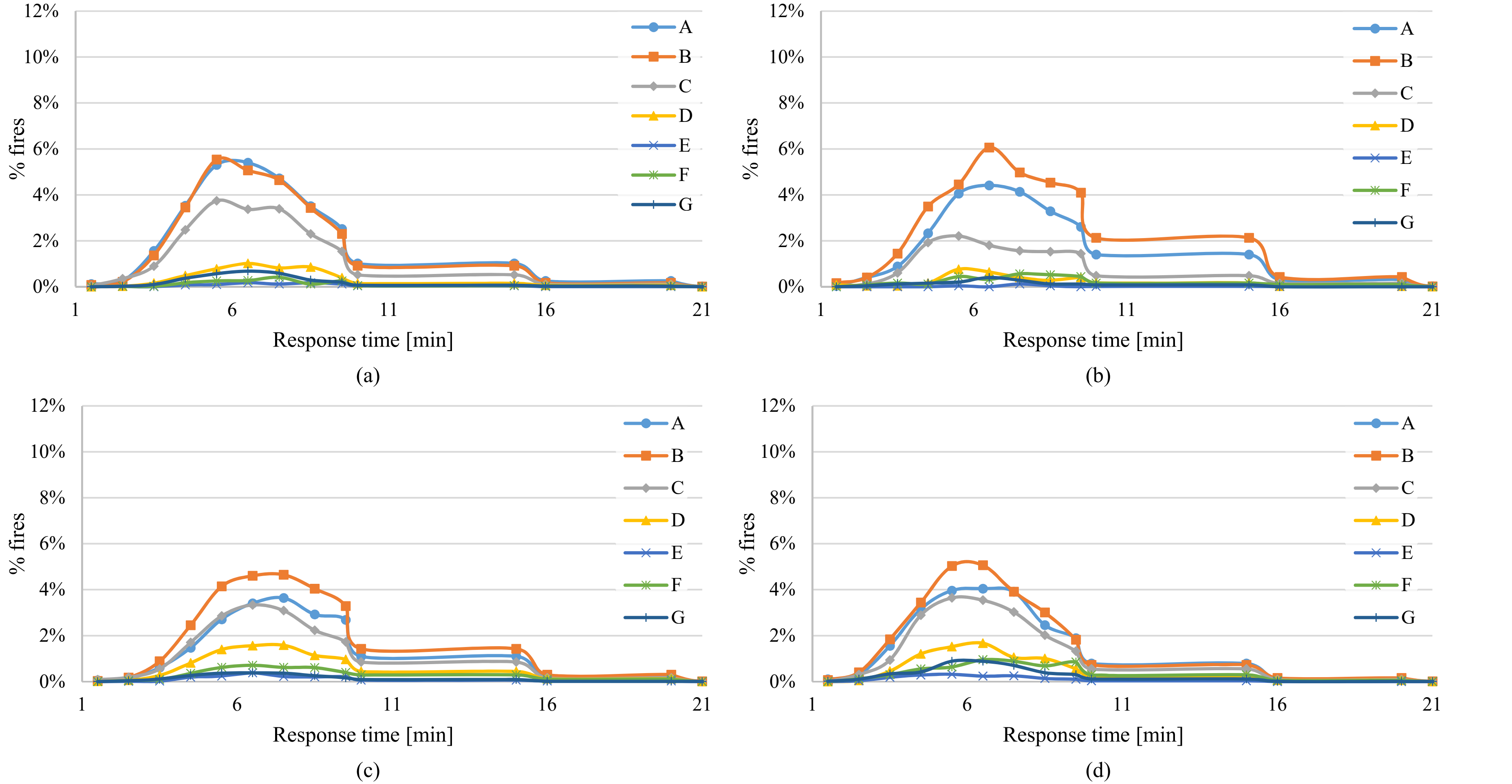
a. No fire damage; **b**. Limited to item ignited; **c**. Limited to room of origin; **d**. Limited to floor of origin; **e**. Limited to two floors; **f**. Whole building/ more than two floors; **g**. Roofs/Roof spaces; **S**. Sprinklers; **NS**. No Sprinklers; **Fire**. Fire damage; **Total**. Total damage

Figure 142: Frequency distribution of area damage in Leisure [S=Sprinklers; NS=No sprinklers] in English statistics



a. No fire damage; **b**. Limited to item ignited; **c**. Limited to room of origin; **d**. Limited to floor of origin; **e**. Limited to two floors; **f**. Whole building/ more than two floors; **g**. Roofs/Roof spaces; **S**. Sprinklers; **NS**. No Sprinklers; **Fire**. Fire damage; **Total**. Total damage

Figure 143: Frequency distribution of area damage in Miscellaneous [S=Sprinklers; NS=No sprinklers] in English statistics



A. No fire damage; **B**. Limited to 1st ignited; **C**. Limited to room of origin; **D**. Limited to floor of origin (not whole building); **E**. Limited to 2 floors; **F**. Whole building/Affecting more than 2 floors; **G**. Roofs/Roof spaces

Figure 144: Response time and fire spread of (a) Educational, (b) Utilities, (c) Industrial and (d) Leisure in English statistic

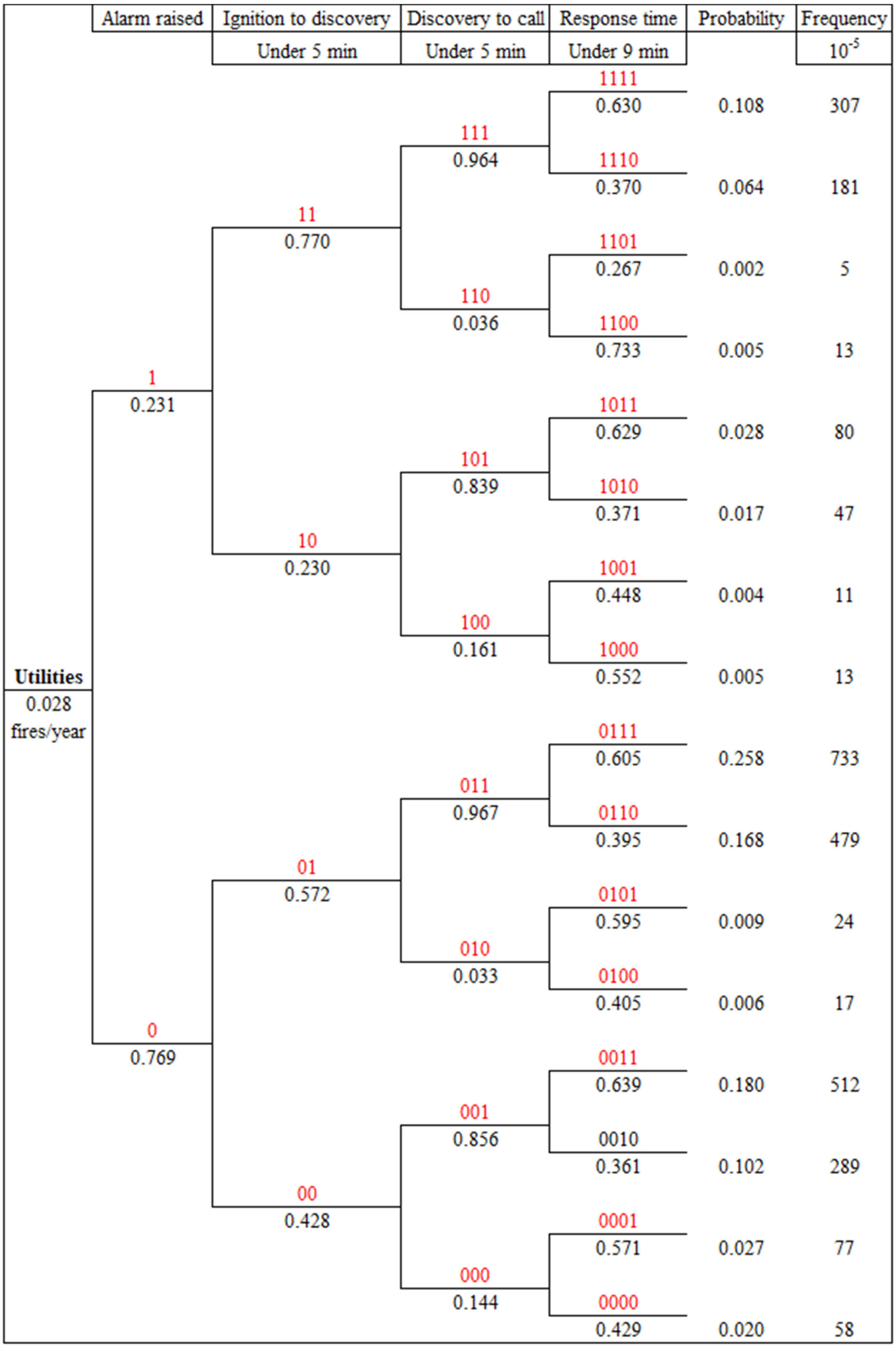


Figure 145: Event tree analysis fire response of Utilities in English statistics

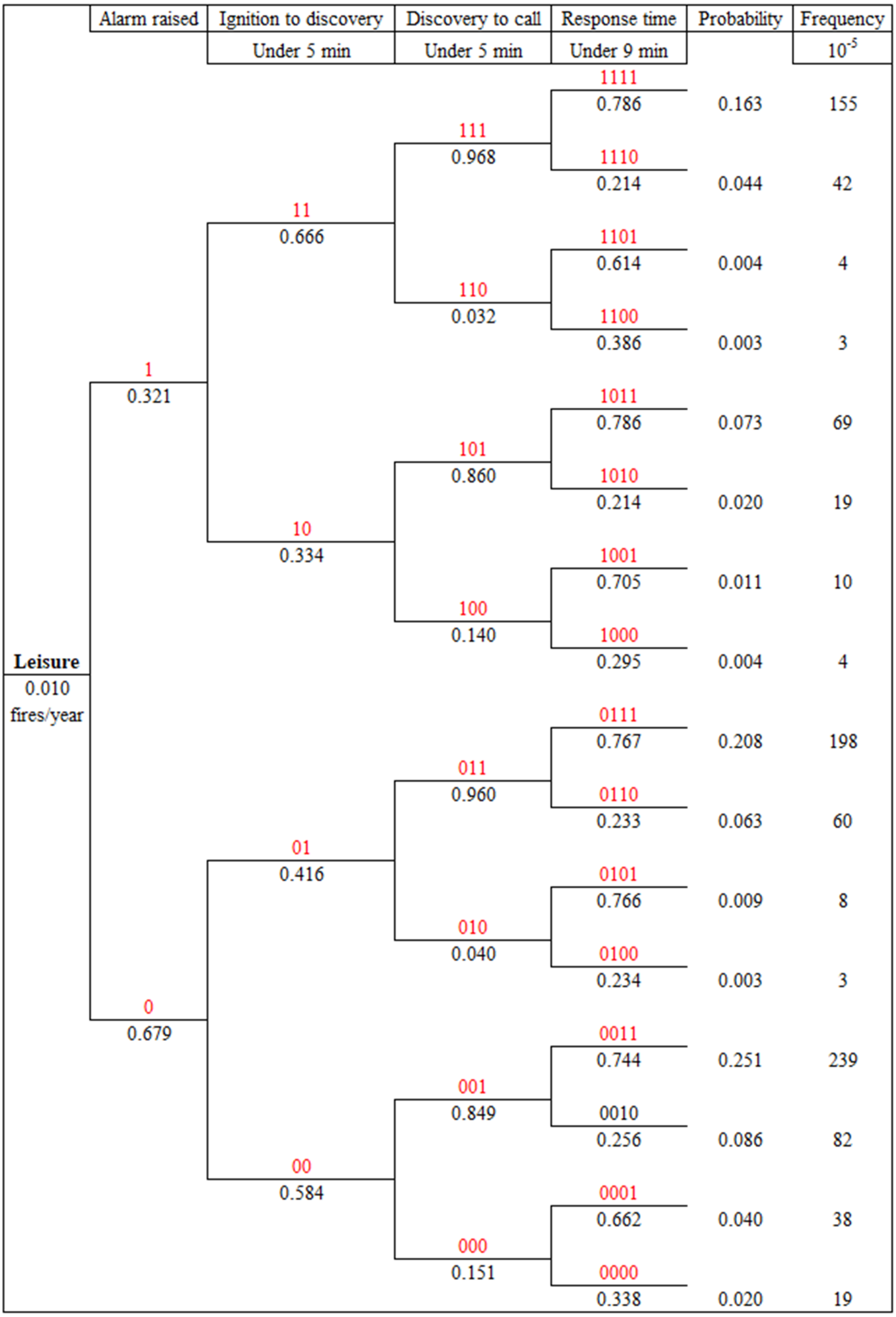


Figure 146: Event tree analysis fire response of Leisure in English statistics

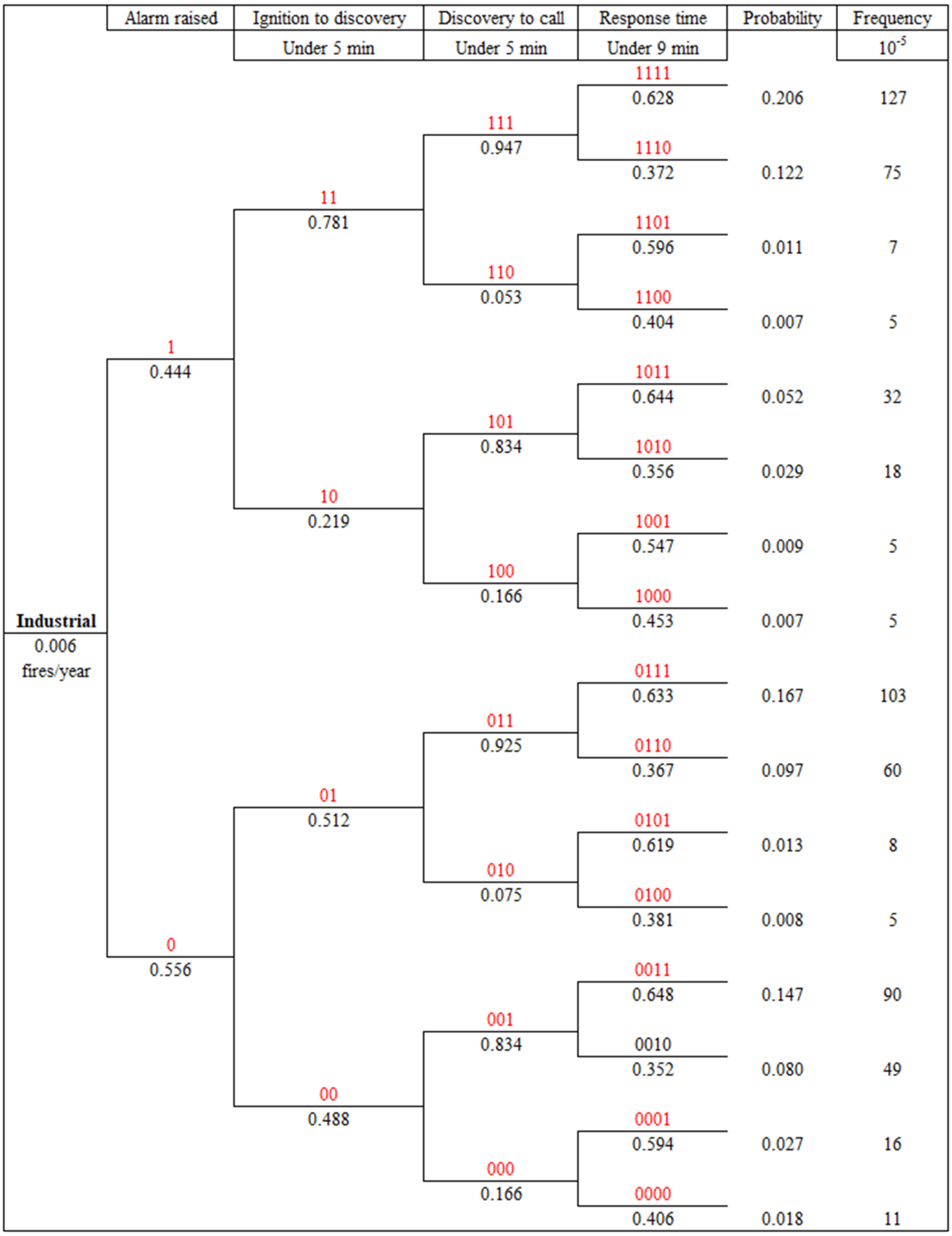


Figure 147: Event tree analysis fire response of Industrial in English statistics

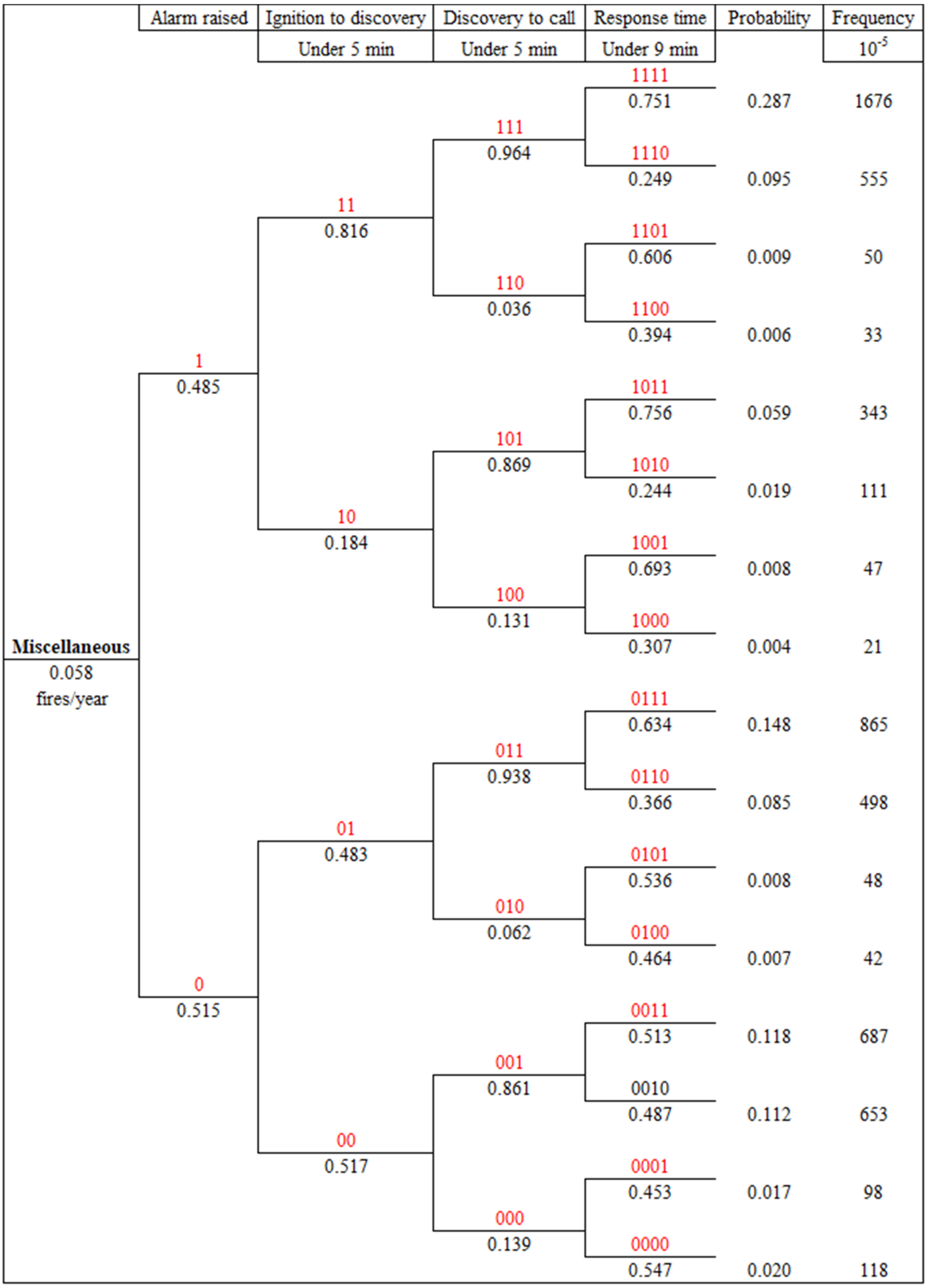


Figure 148: Event tree analysis fire response of Miscellaneous in English statistics

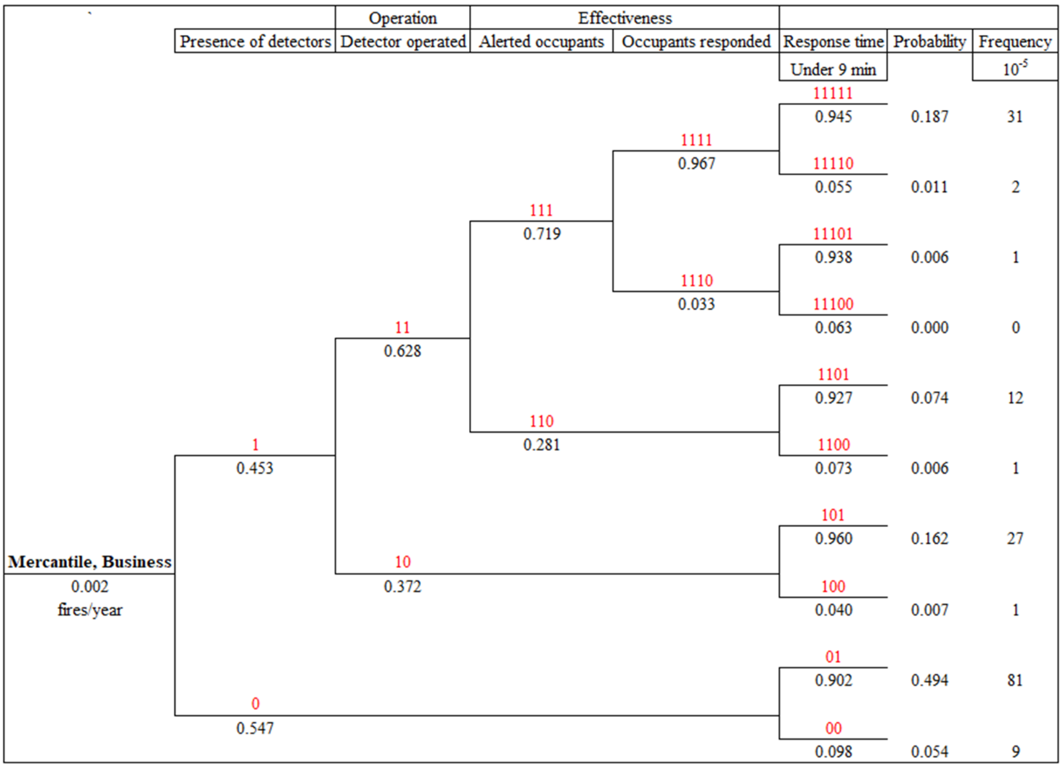


Figure 149: Event tree analysis fire response of Mercantile, Business in USA statistics

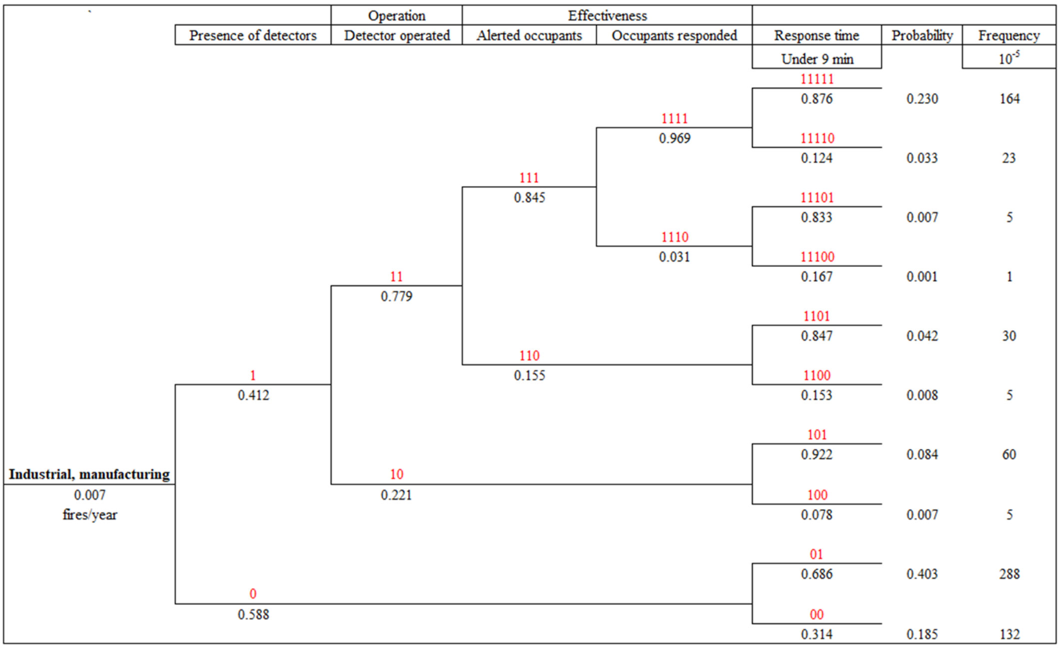


Figure 150: Event tree analysis fire response of Industrial, manufacturing in USA statistics

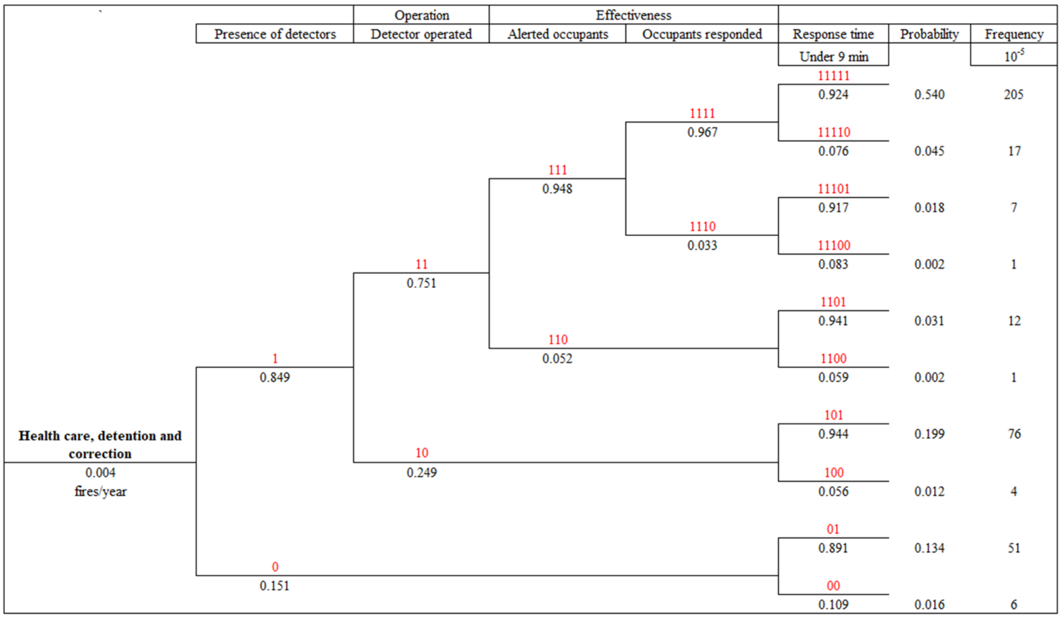


Figure 151: Event tree analysis fire response of Health care, detention and correction in USA statistics

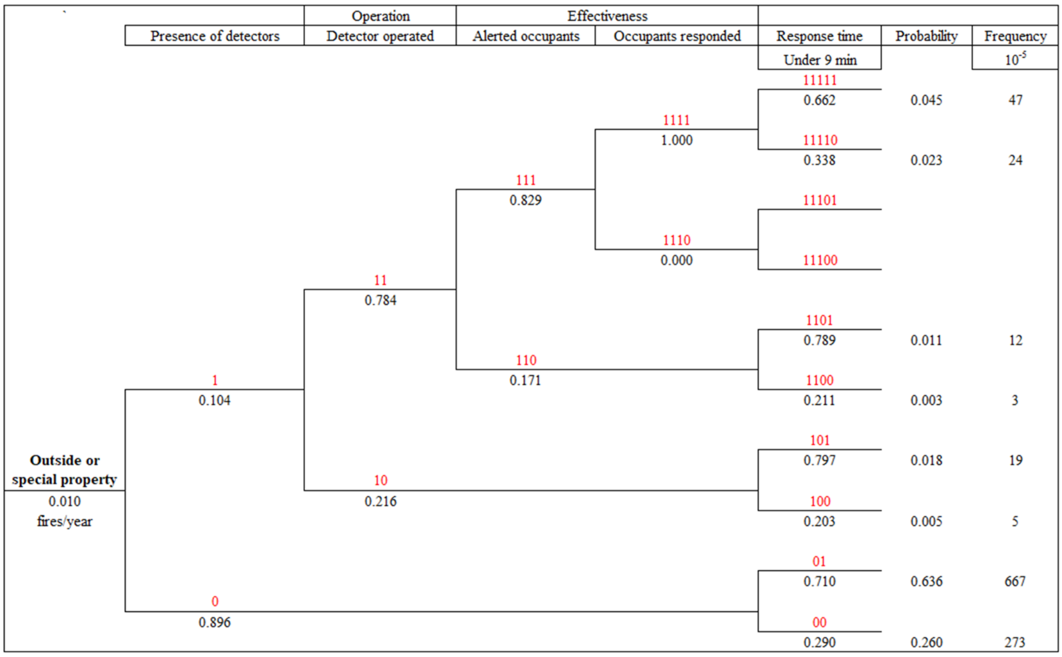


Figure 152: Event tree analysis fire response of Outside or special property in USA statistics

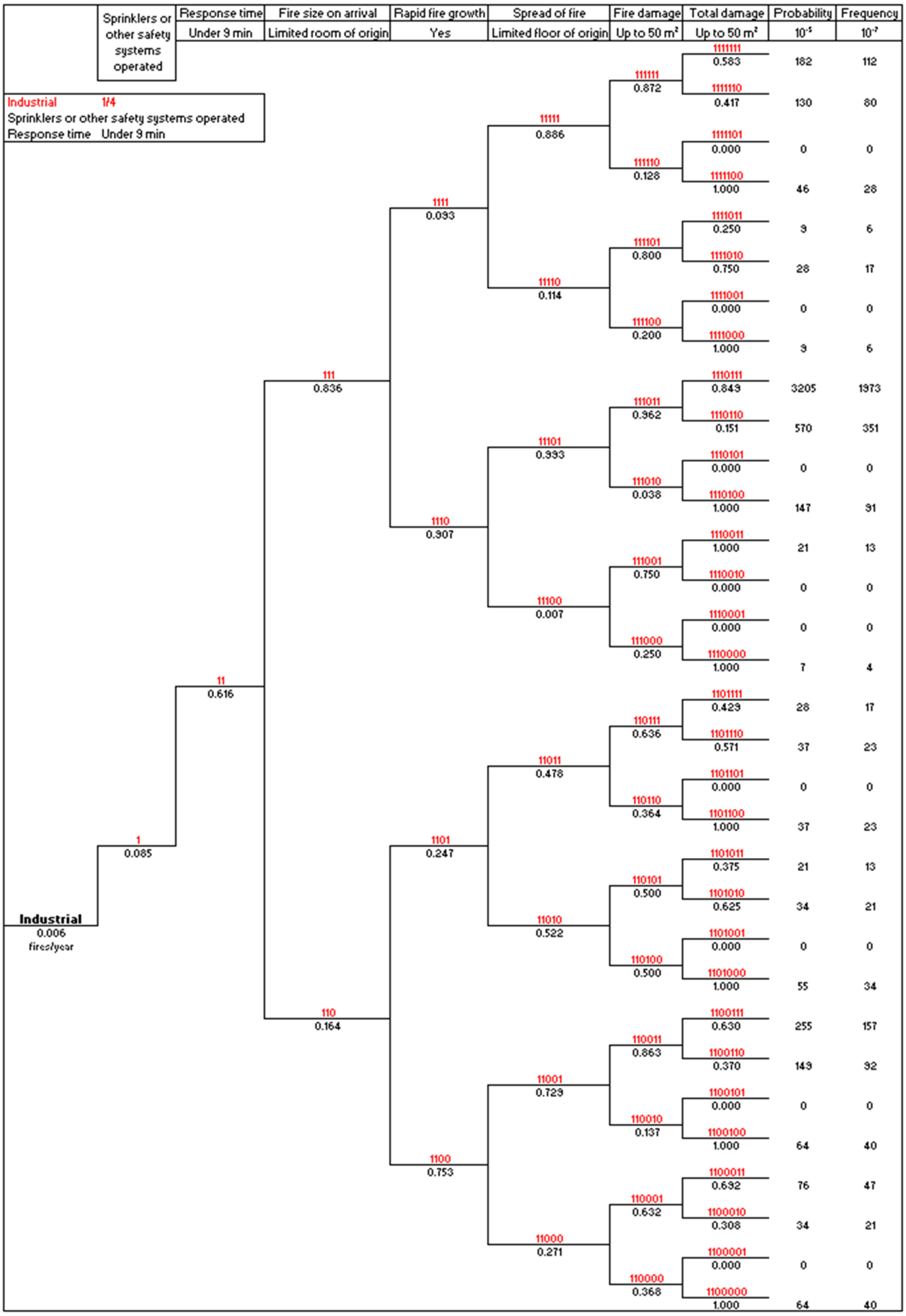


Figure 153: Event tree analysis fire damage of Industrial part 1/4 in English statistics

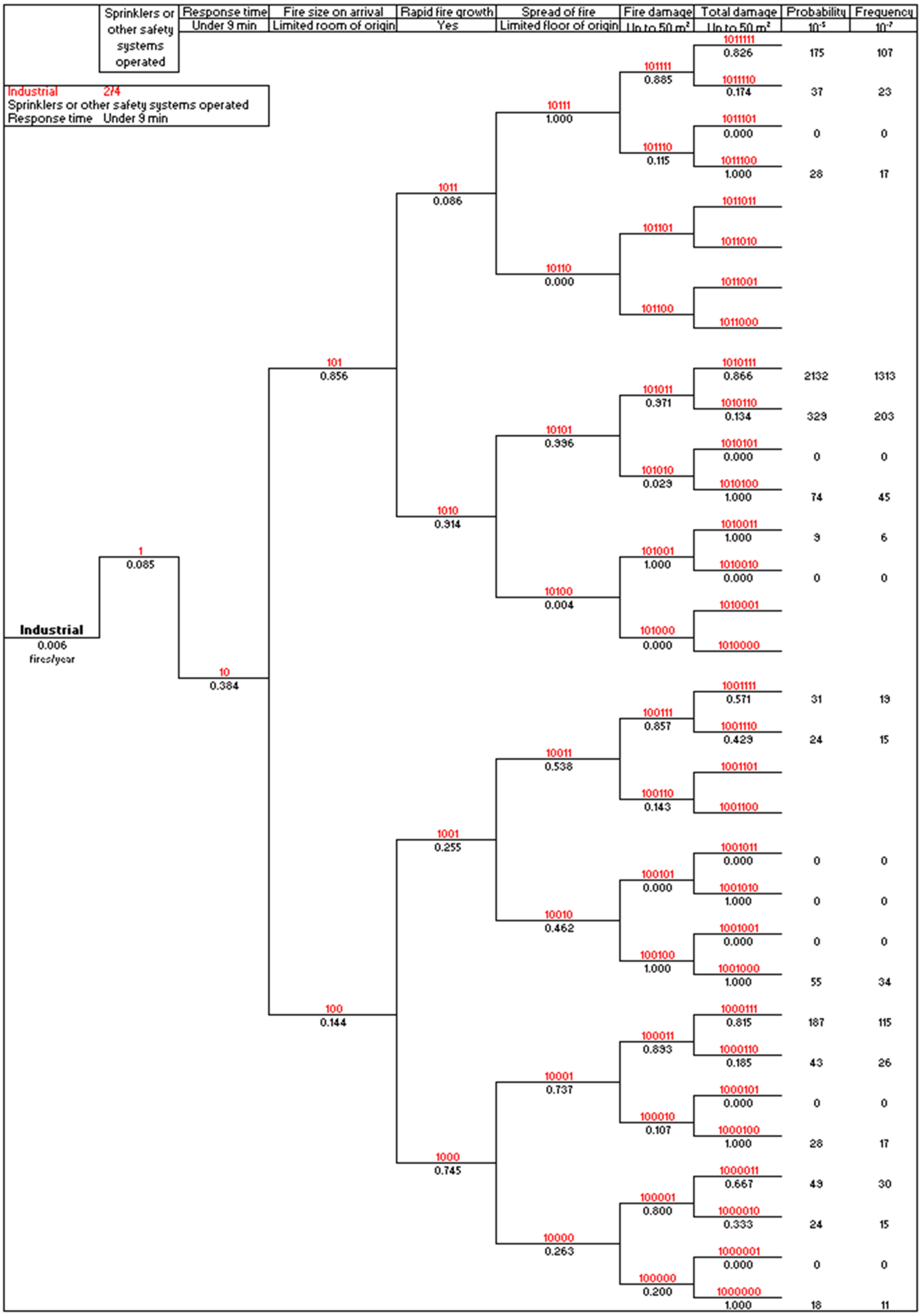


Figure 154: Event tree analysis fire damage of Industrial part 2/4 in English statistics

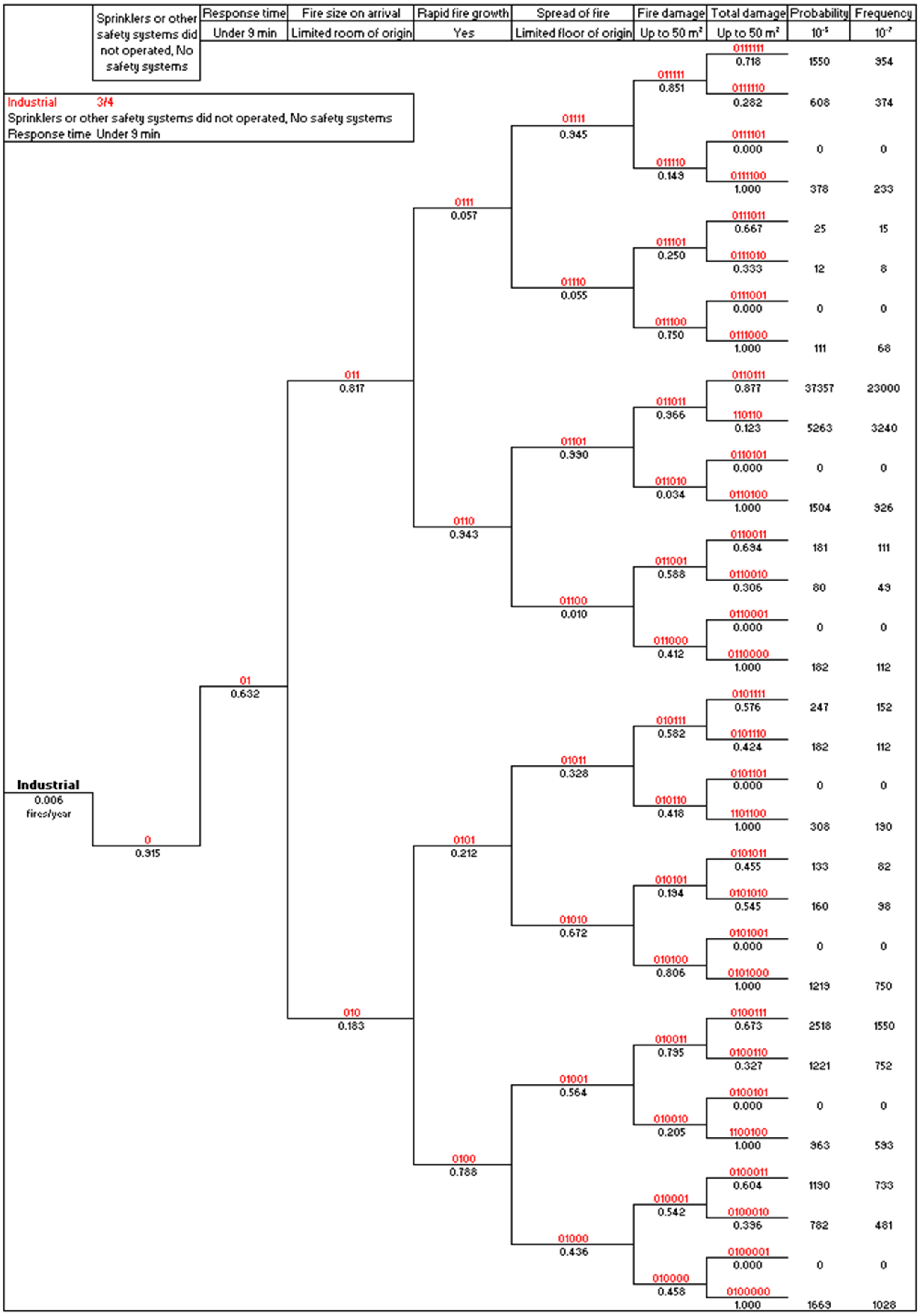


Figure 155: Event tree analysis fire damage of Industrial part 3/4 in English statistics

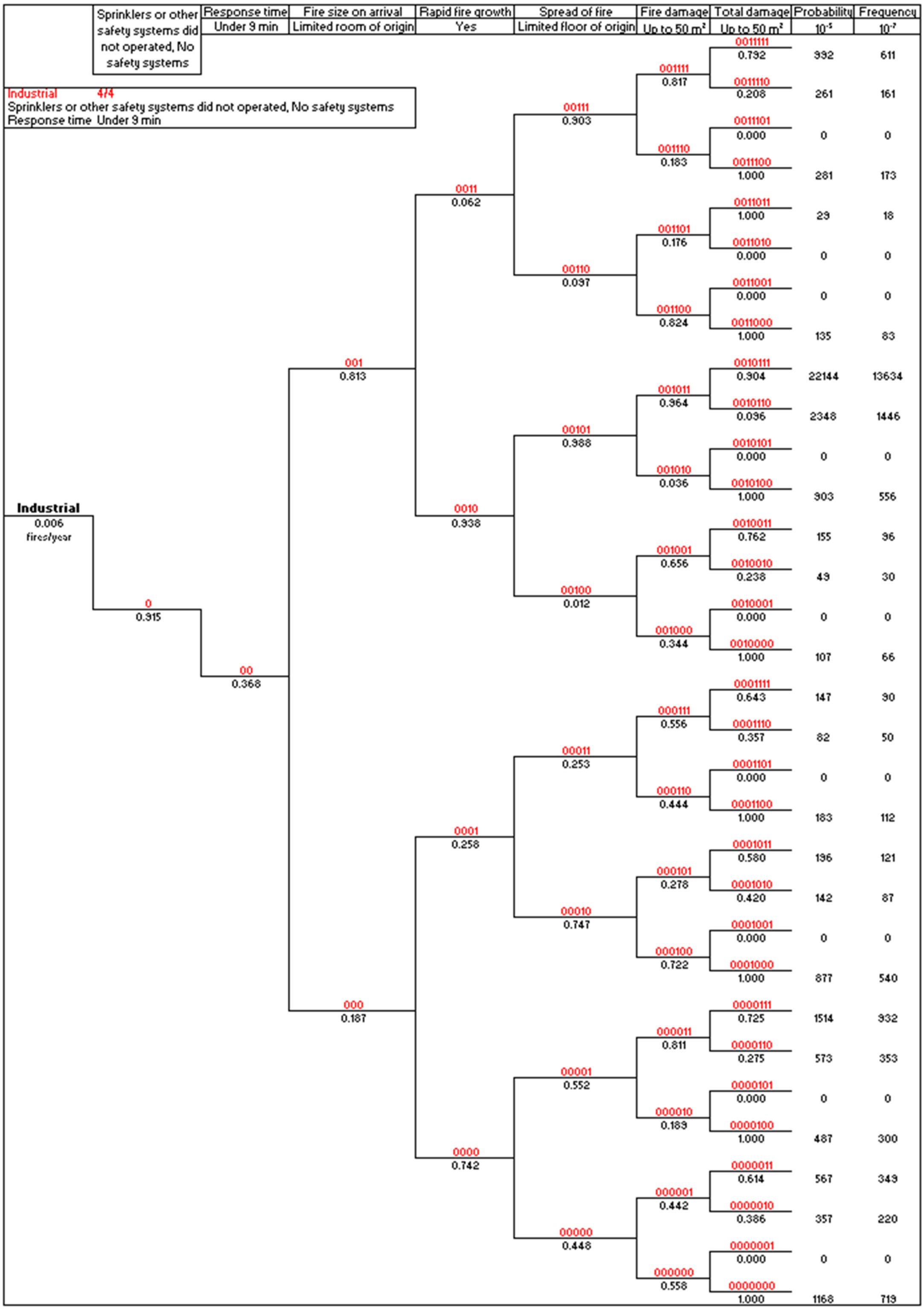


Figure 156: Event tree analysis fire damage of Industrial part 4/4 in English statistics

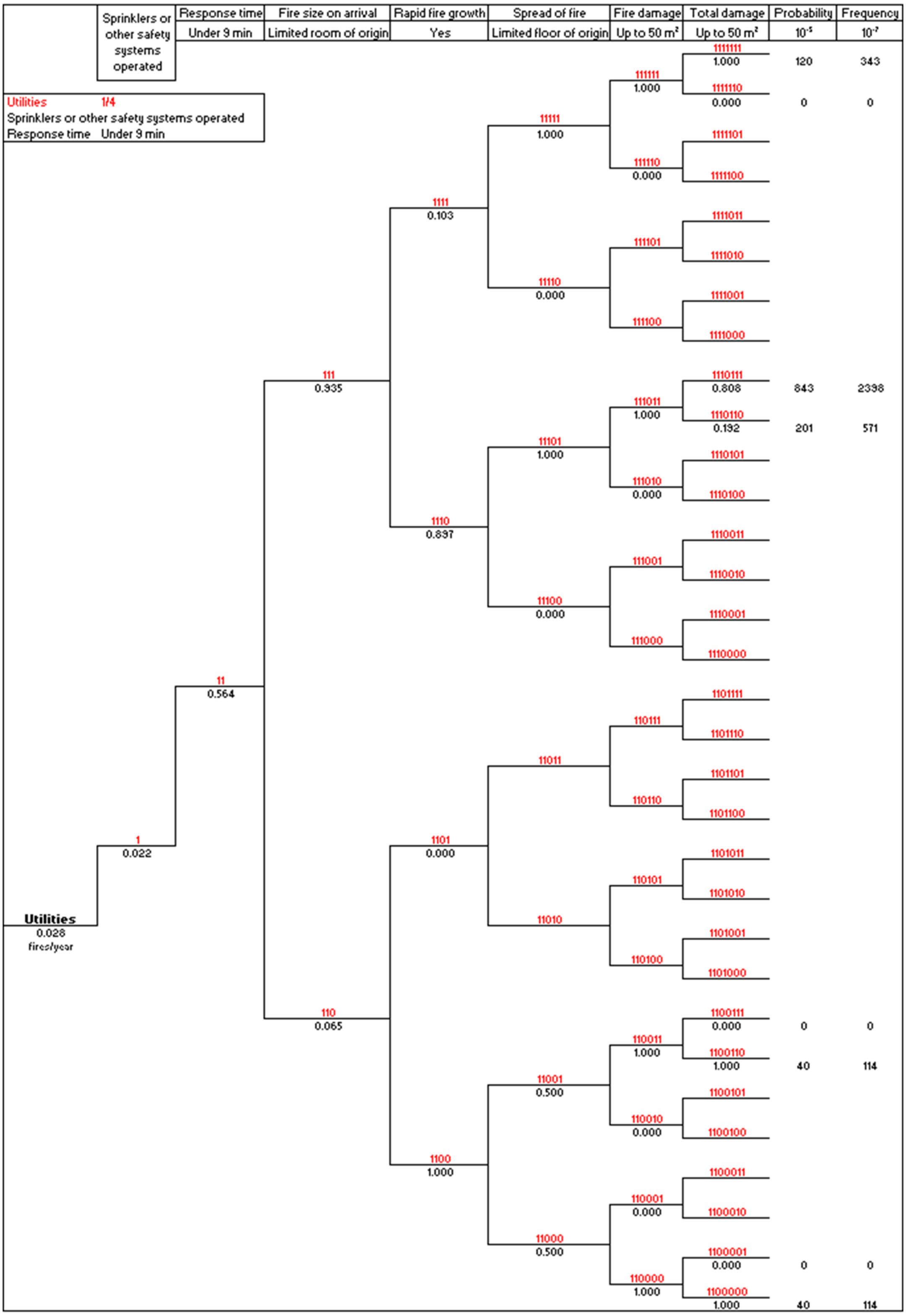


Figure 157: Event tree analysis fire damage of Utilities part 1/4 in English statistics

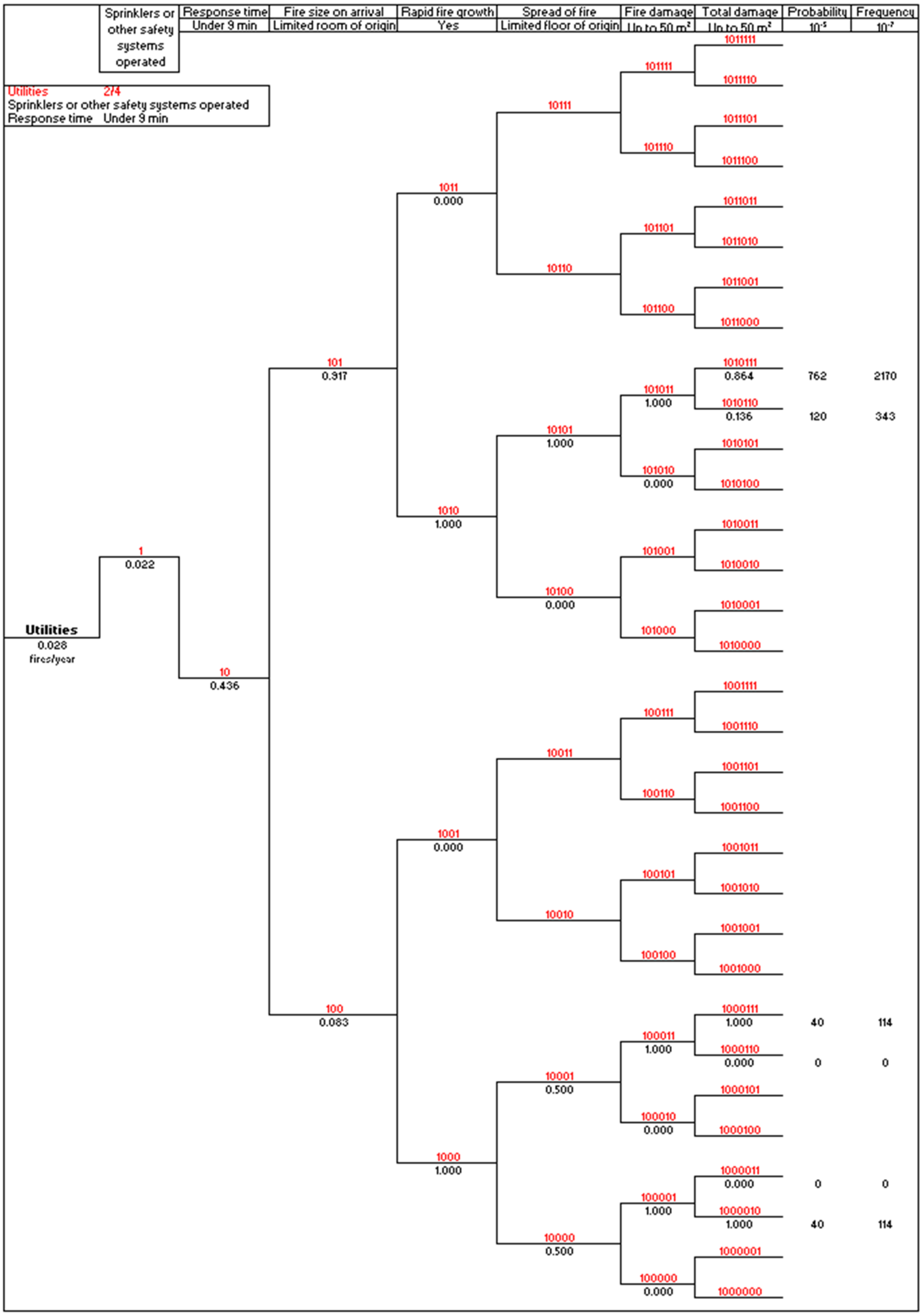


Figure 158: Event tree analysis fire damage of Utilities part 2/4 in English statistics

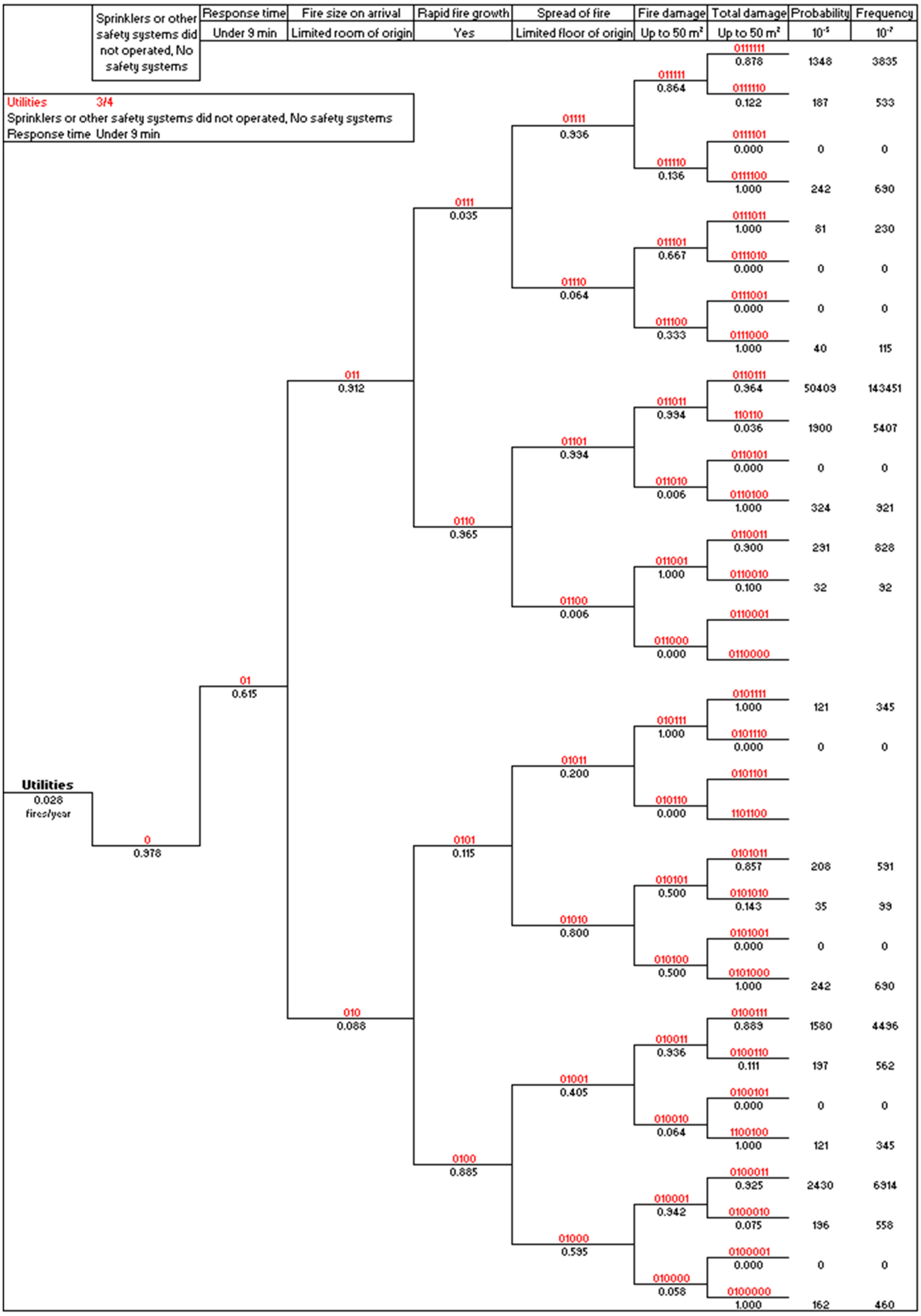


Figure 159: Event tree analysis fire damage of Utilities part 3/4 in English statistics

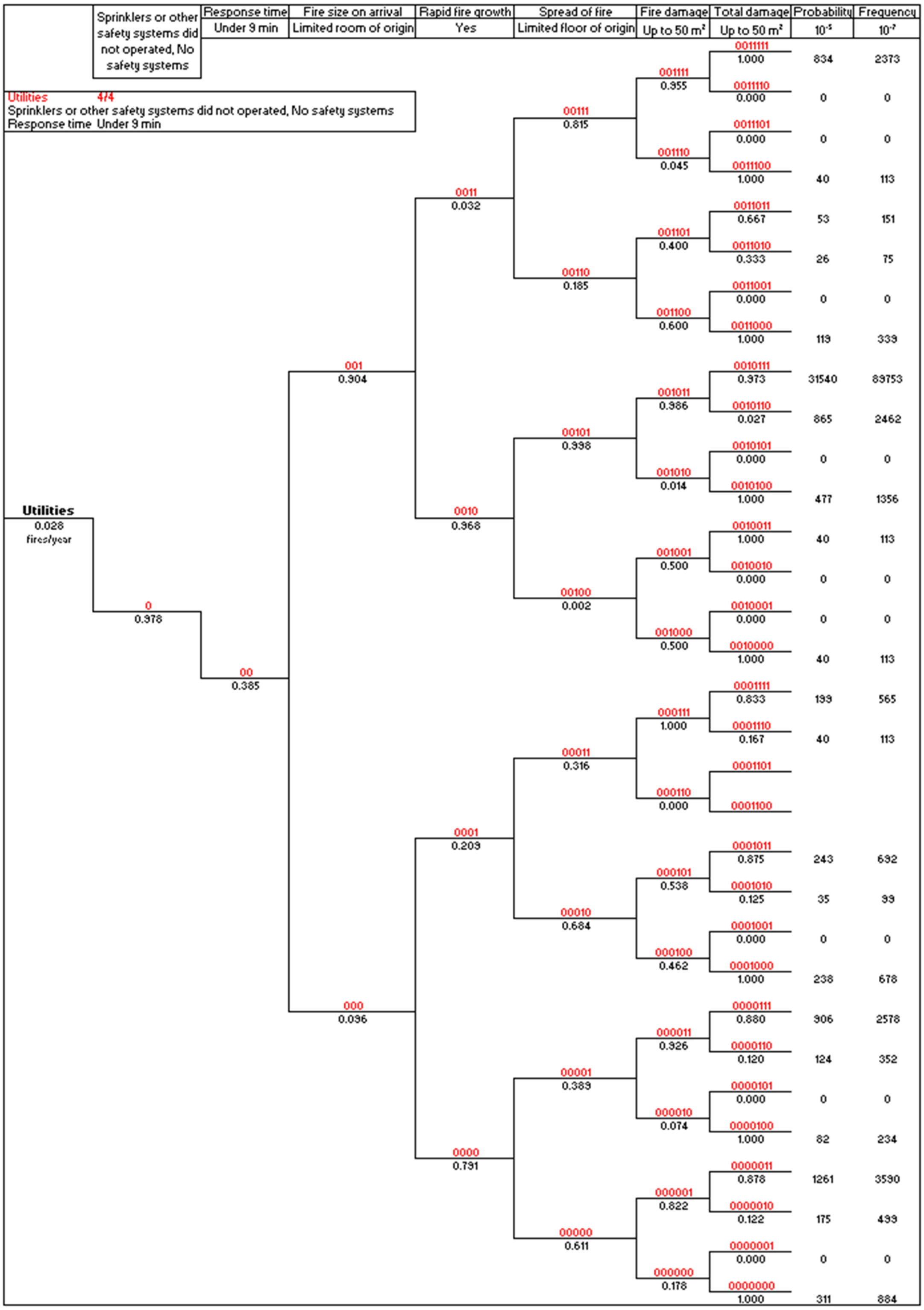


Figure 160: Event tree analysis fire damage of Utilities part 4/4 in English statistics

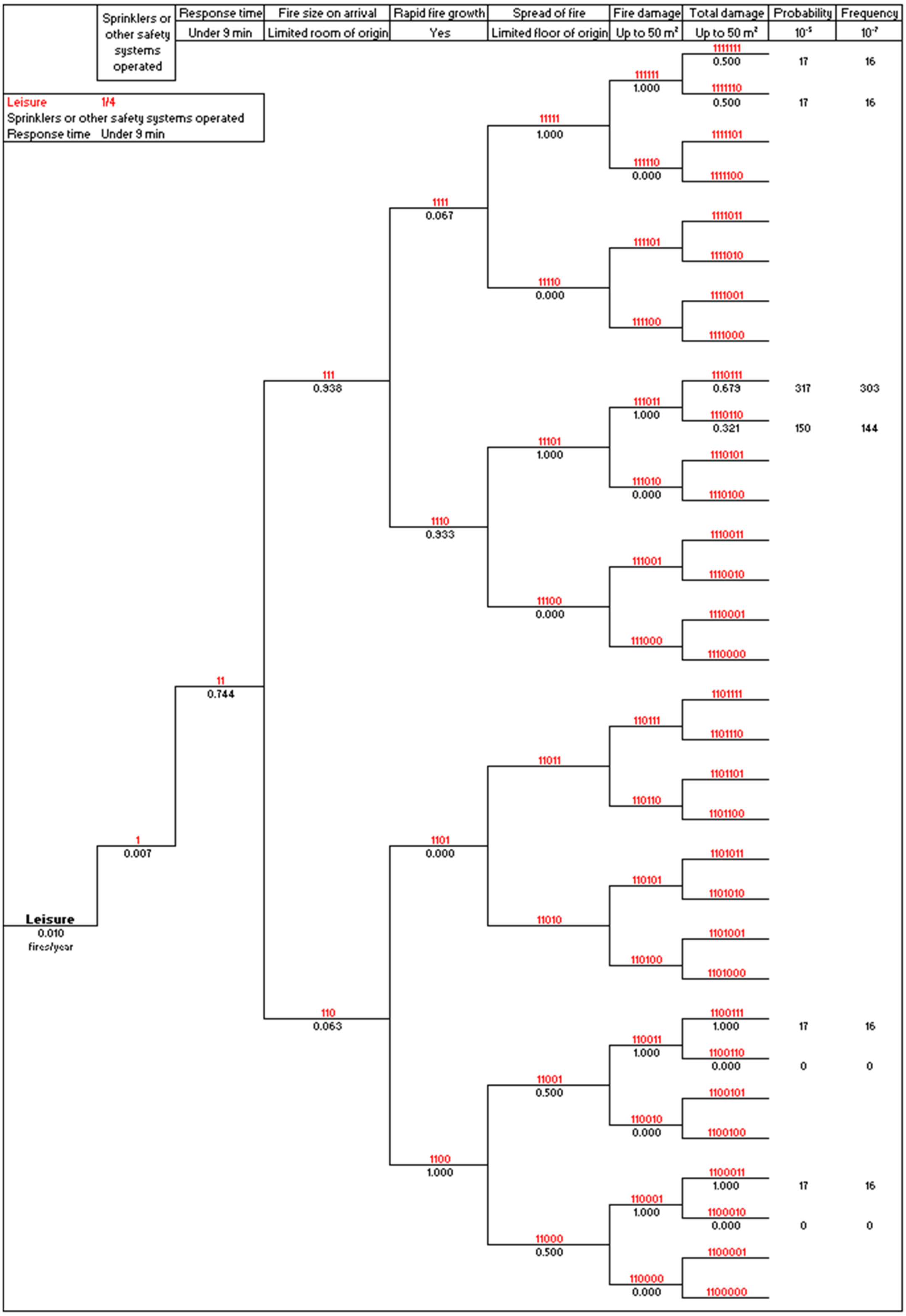


Figure 161: Event tree analysis fire damage of Leisure part 1/4 in English statistics

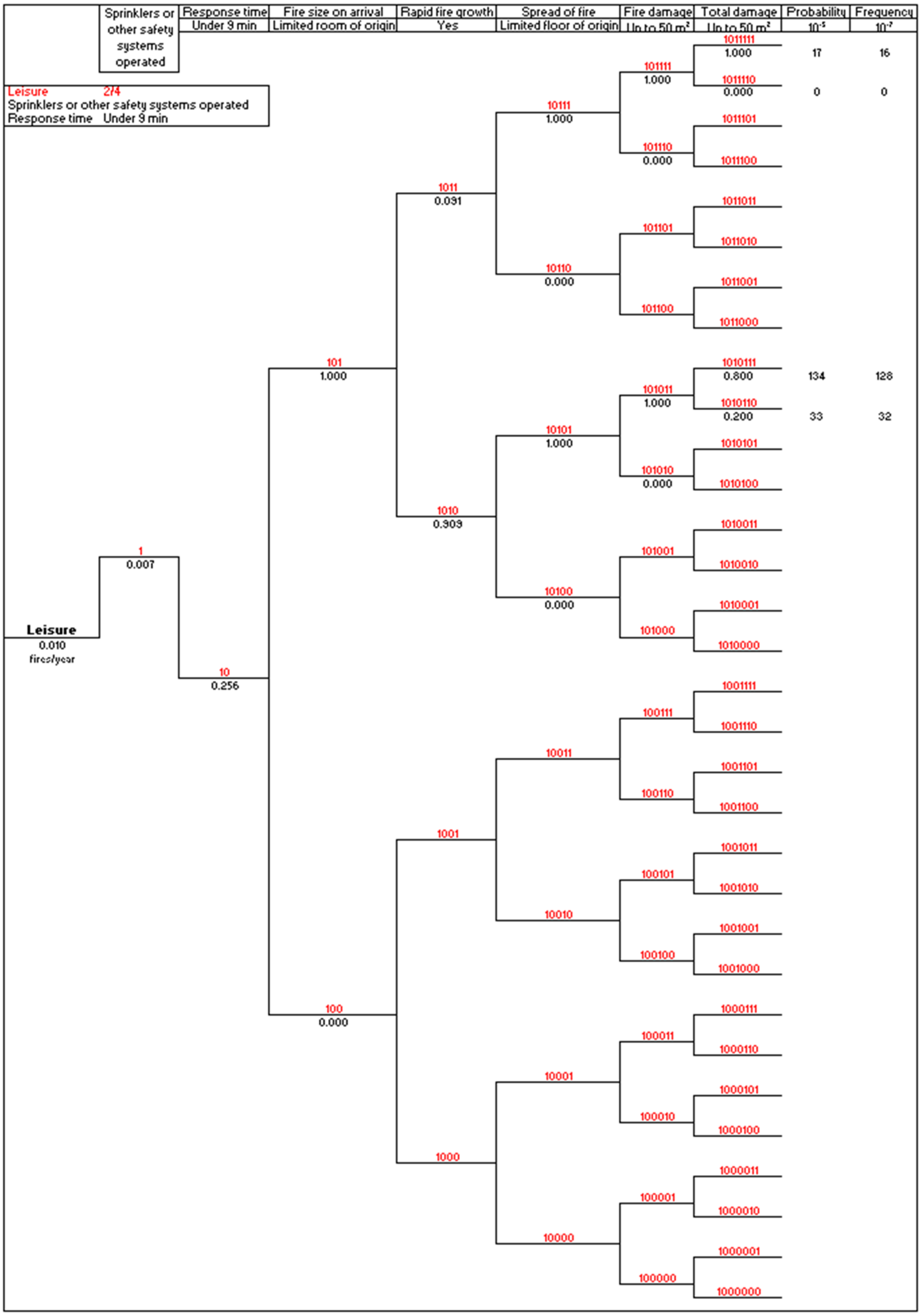


Figure 162: Event tree analysis fire damage of Leisure part 2/4 in English statistics

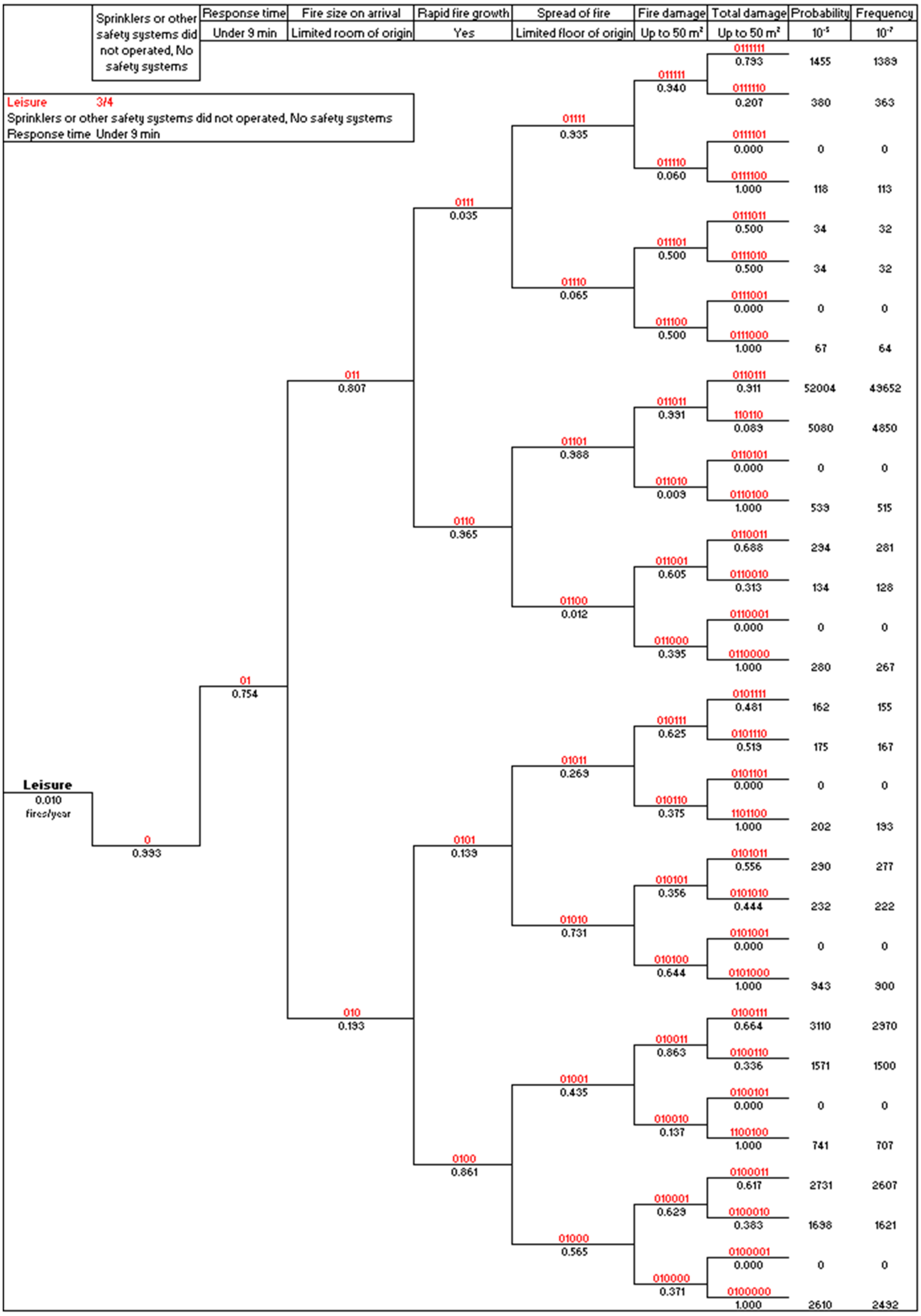


Figure 163: Event tree analysis fire damage of Leisure part 3/4 in English statistics

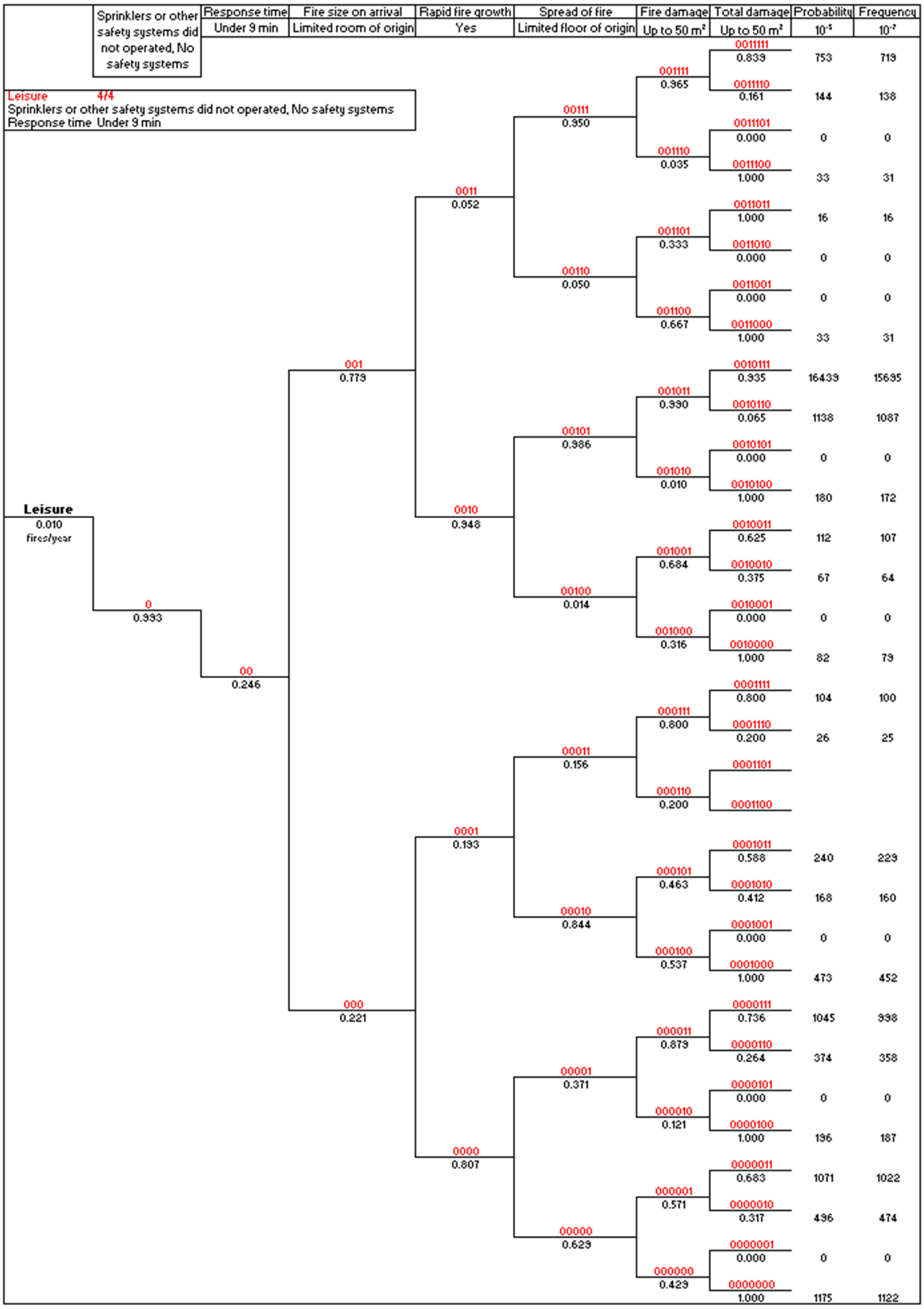


Figure 164: Event tree analysis fire damage of Leisure part 4/4 in English statistics

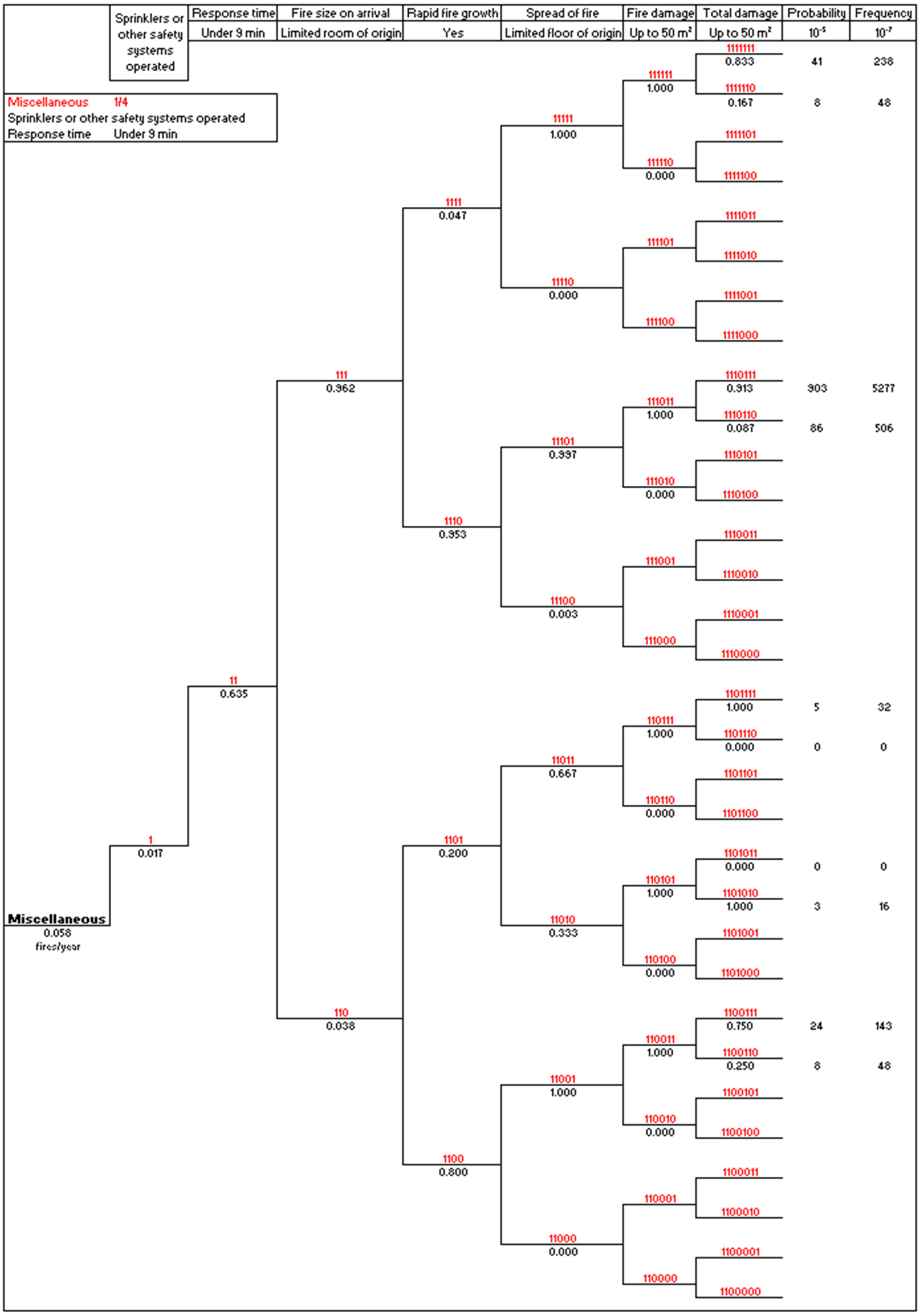


Figure 165: Event tree analysis fire damage of Miscellaneous part 1/4 in English statistics

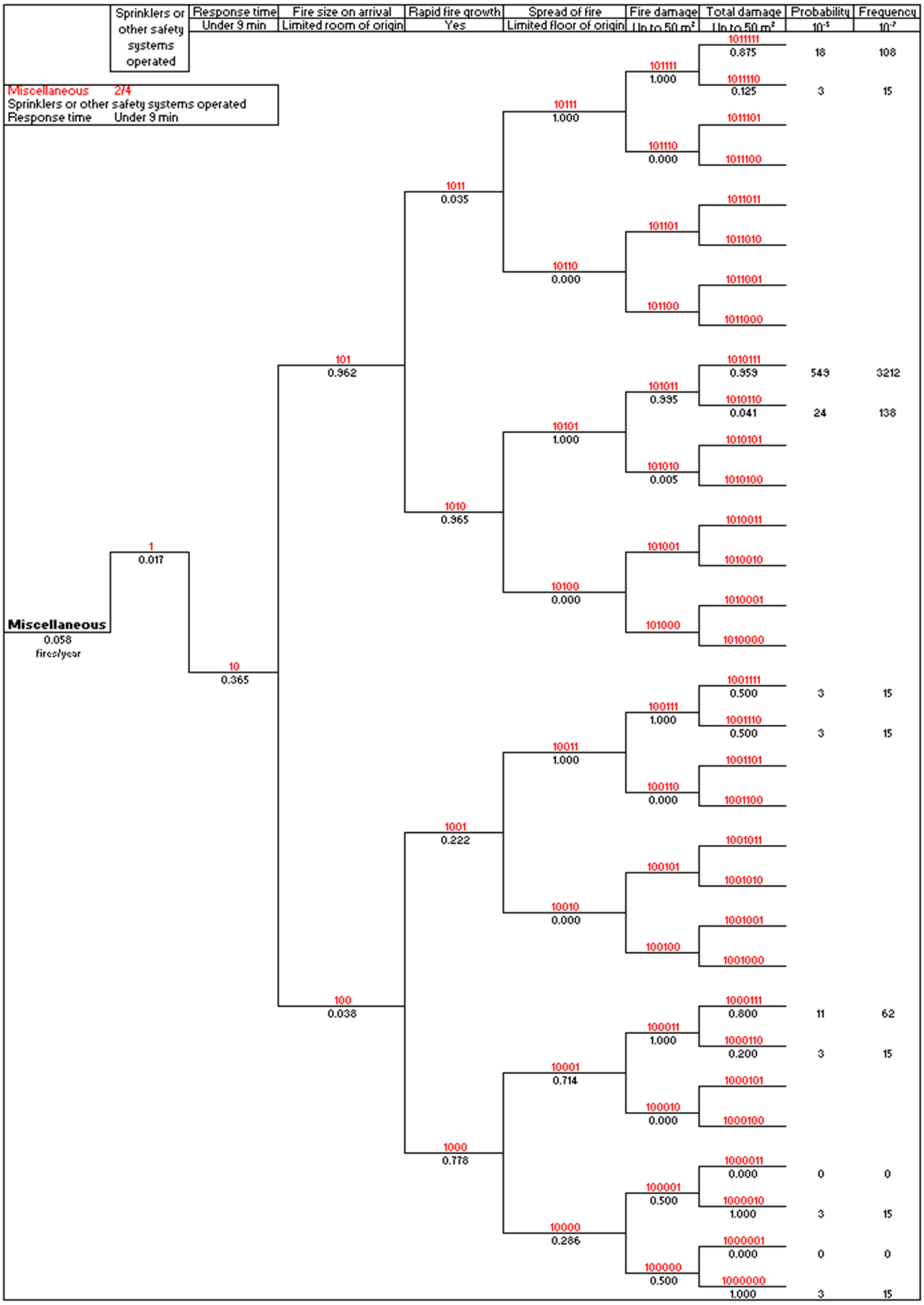


Figure 166: Event tree analysis fire damage of Miscellaneous part 2/4 in English statistics

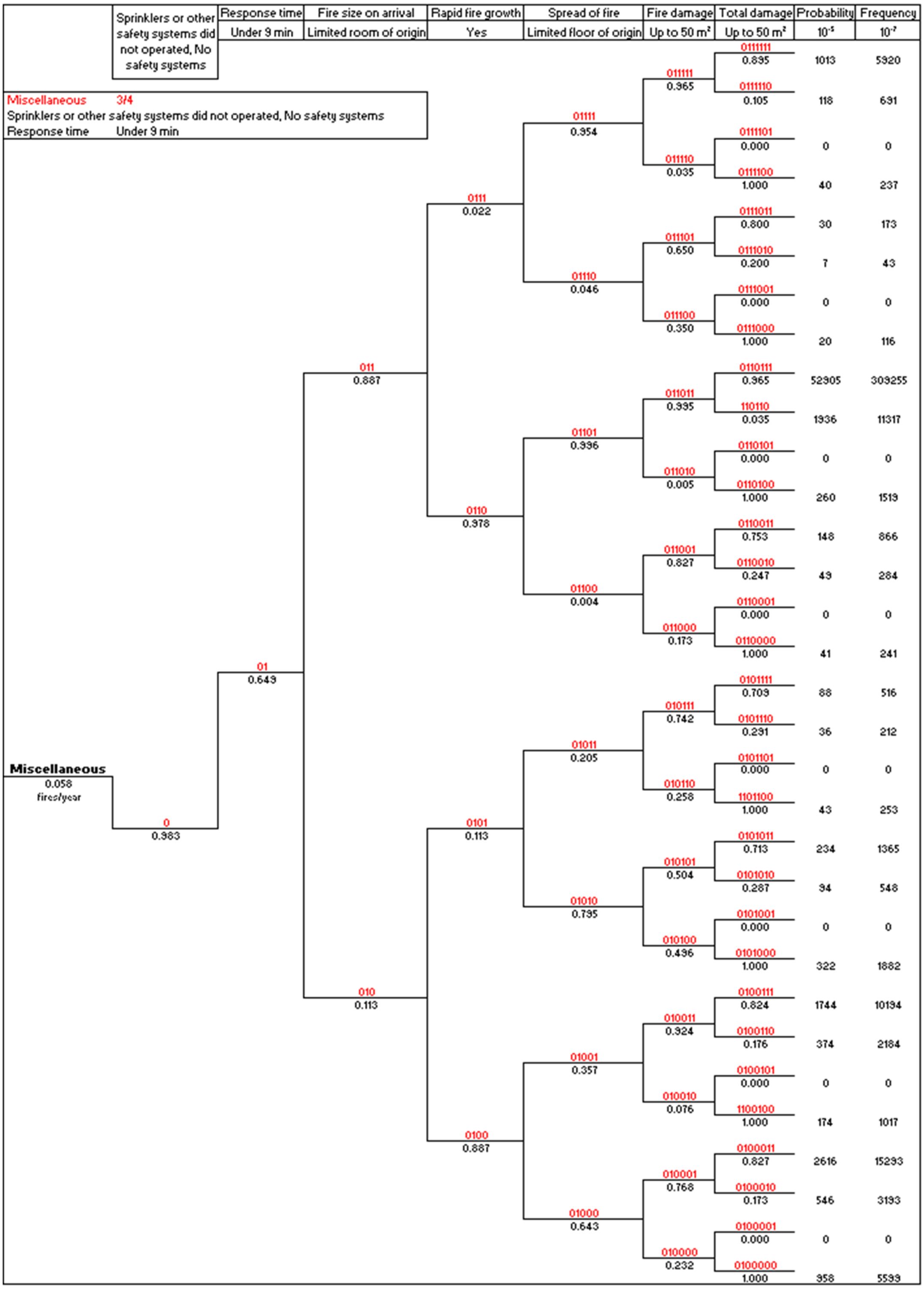


Figure 167: Event tree analysis fire damage of Miscellaneous part 3/4 in English statistics

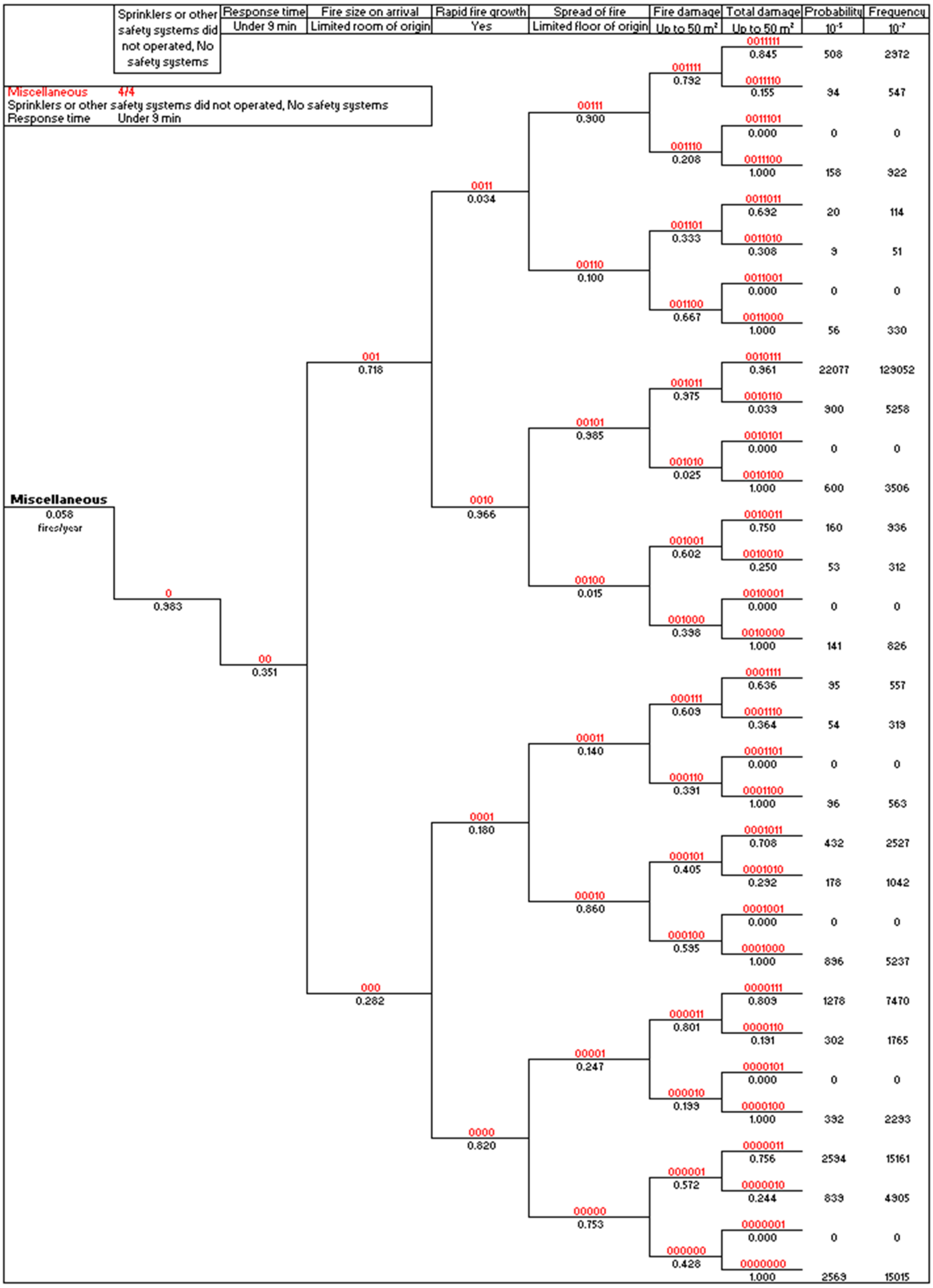


Figure 168: Event tree analysis fire damage of Miscellaneous part 4/4 in English statistics

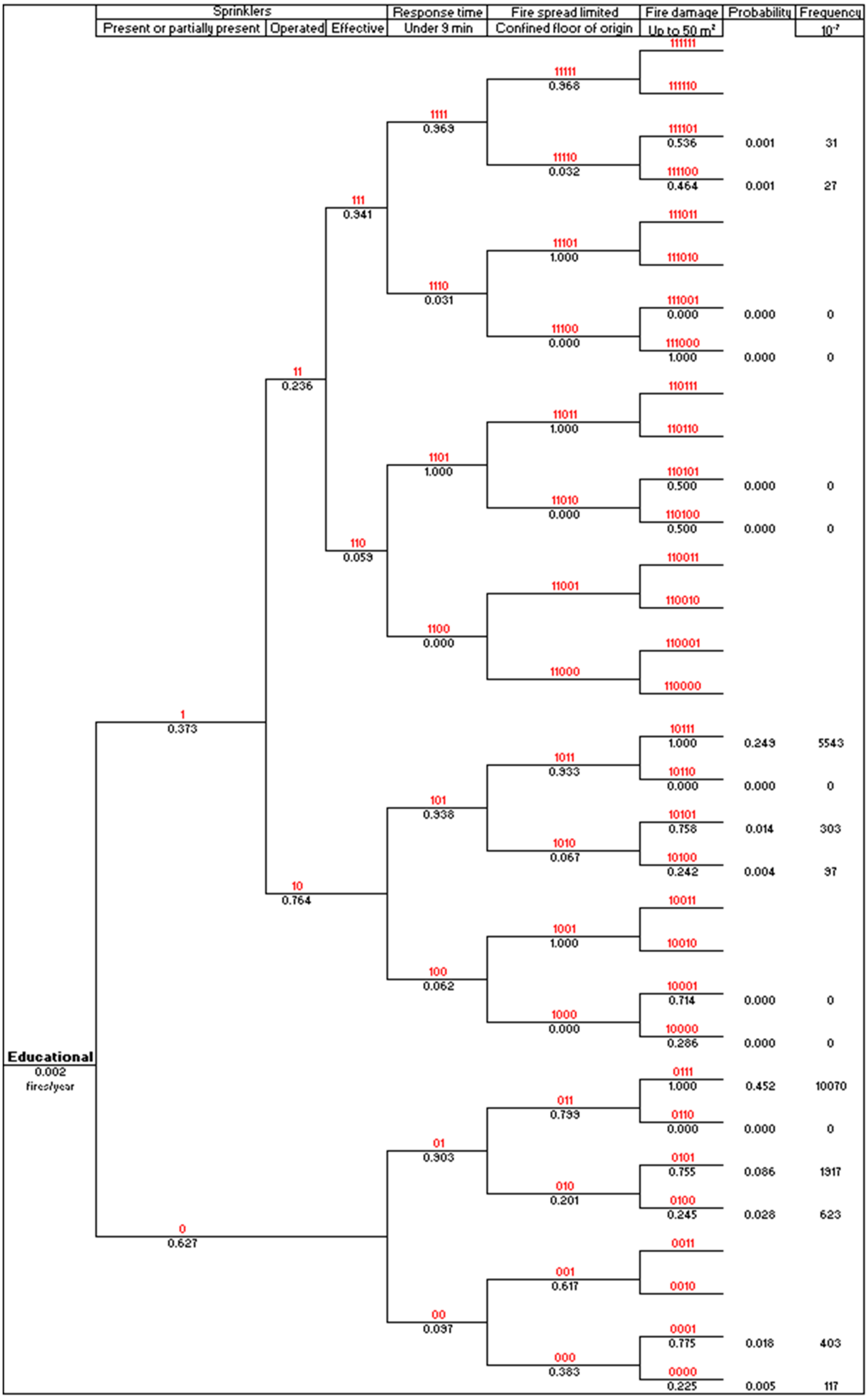


Figure 169: Event tree analysis fire damage of Educational in USA statistics

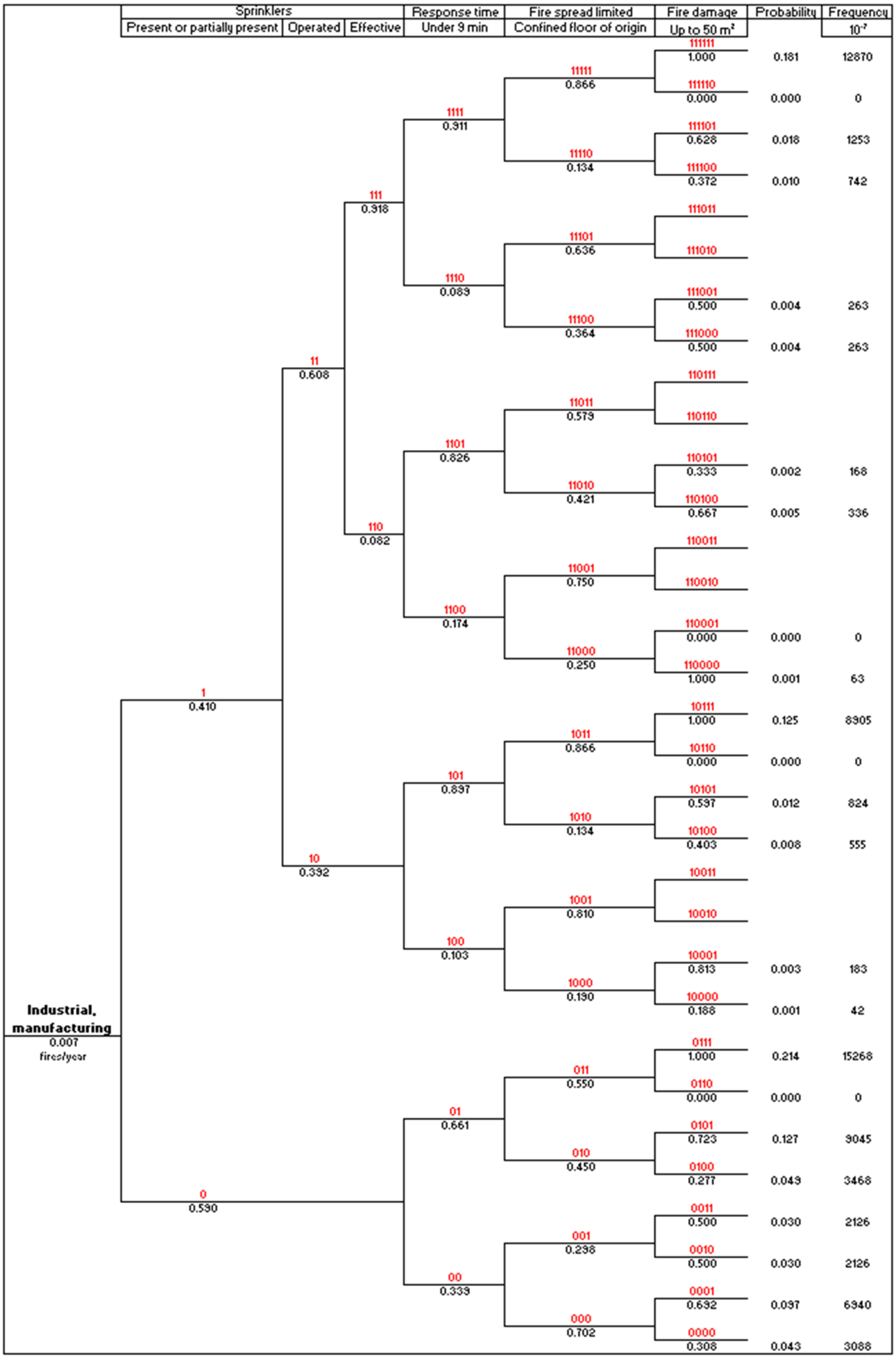


Figure 170: Event tree analysis fire damage of Industry, manufacturing in USA statistics

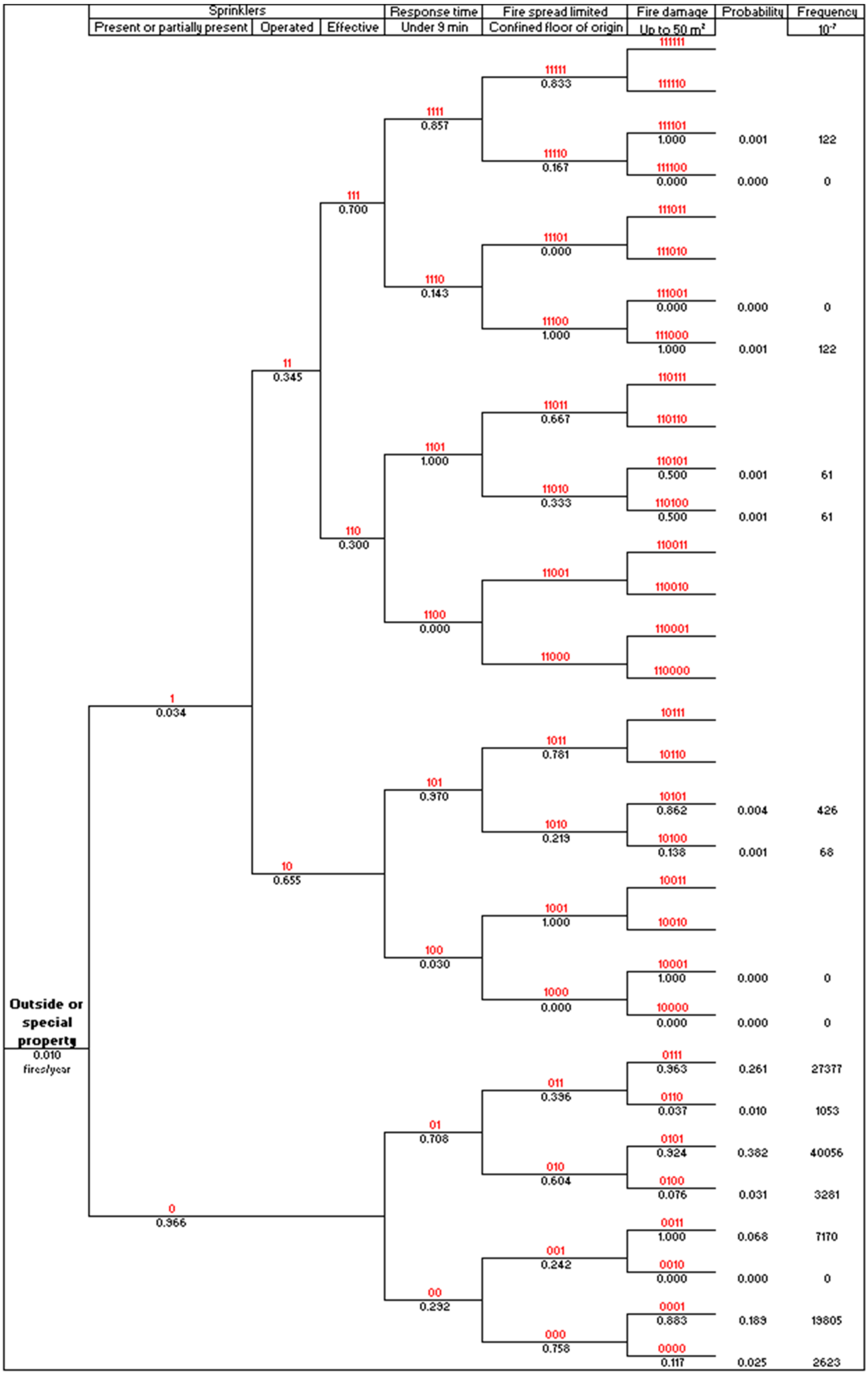


Figure 171: Event tree analysis fire damage of Outside or special property in USA statistics

Appendix: New Zealand fire statistics

The New Zealand statistics present several fields not included in the other two sources of fire statistics of England and USA. In particular, the construction type, age of the building and building owners are recorded. Furthermore, various fields related to the evaluation of fire consequences are available such as fire arrival conditions, expected heat transfer, the classification of fire, flame, smoke and water damage, and the evaluation of property saved. The reason for the exclusion of the New Zealand statistics in the analyses is due to several fields with data not recorded for more than 50% of cases. However, a description of the New Zealand statistics in this Appendix is fundamental to highlight differences in the fields covered and possible implementations.

New Zealand Fire Service Incident Database

The New Zealand Fire Service Incident database contains information filled in the aftermath of an event by the New Zealand Fire Service. Currently, in the New Zealand Fire and Emergency web page, it is possible to access an extract from the system maintained by the Fire and Emergency New Zealand with only the incidents report data from the last seven days. An annual report is not published or available (New Zealand Fire and Emergency, 2019). At the time of the research developed in Chapter 4, the New Zealand Fire and Emergency kindly provided the database with incidents from 2001 to 2016. In order to create a direct comparison with the statistics of England and USA, only the data of 2014/2015 are considered. A total of 5,466 incidents with 80 columns of fields recorded for each fire incident are investigated including structure fires with and without damage, derelict building fires and chimney fires.

Table 75: New Zealand modules

New Zealand modules			
Incident	Equipment	Vegetation	Hazard
General	Fire	Fire Weather	Chemical
Response	Structure	Casualty	Mobile

The modules reported in the New Zealand dataset are expressed in Table 75. The fields related to the Incident, General, Equipment and Response are always filled by the fire brigades.

The spread of fire in New Zealand is classified according to fire, flame, smoke and water damage and the damage is quantified according to the percentage of property saved instead of the one damaged as in England and USA. Since the total area of the structures is available in the dataset, it is possible to obtain the m^2 of property damage based on the class of property saved. The response time of fire brigades includes Start-Stop and En route-Arrival time and fire causes, heat source, object ignited first and material most flamed are other fields recorded in the database. Again, fires in various property types are investigated and the occupancy types have been reclassified to be able to create a direct comparison with the categories present in England and USA. Moreover, listed as fire detectors, both alarms and sprinklers are collected in a unique field while in England and USA statistics, detectors and sprinklers are separately investigated. Finally, the financial losses are evaluated in term of an approximate value of damage to the structure expressed in New Zealand dollars. However, this estimate is not clearly explained and a methodology is not provided.

Fire Statistics in New Zealand

The dataset provided by the New Zealand Fire Service contains a total of 94,621 rows from 2011 to 2016. The research has selected those between April 2014 and March 2015 which are 5,466 incidents to recreate the comparison with England and USA statistics. As already explained for the fire statistics of the other two countries, the analysis is divided into fire incidents, causes, growth and consequences, safety measures and response time.

Fire incidents

The total of 5,466 incidents are classified according to five classes presenting the following percentages: 49.7% structures fire with damage, 40.7% structure fire with no damage, 8.2% Chimney fires, 1.2% Derelict building fires and 0.2% structure fire called new where this class is not further specified (Figure 172).

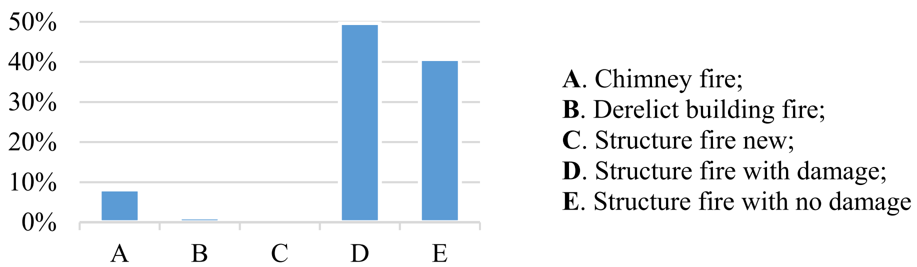
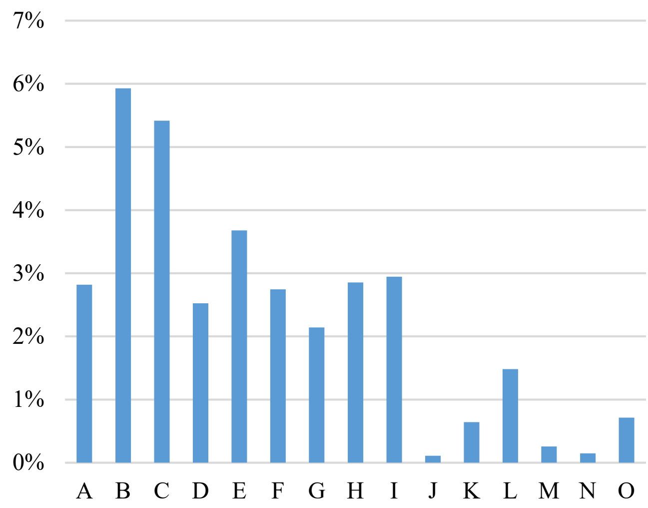


Figure 172: Incident types, New Zealand

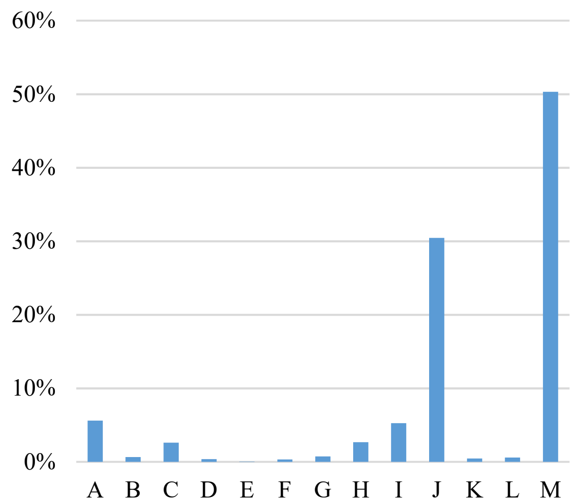
Investigating now the general property uses, the classification has been created according to the one present in the England statistics where 65.6% of fires affect *Dwellings* and for the *Other buildings* percentages are always less than 6% considering the total fires. In particular, 5.9% is found in Retail premises, 5.4% in Industrial premises and 3.7% in Educational premises. Moreover, approximately 3% is reached in Offices and call centres, Hospital and medical care, Entertainment, culture and sports and Hotels, boarding houses, hostels as described in Figure 173.



A. Offices and call center;
B. Retail premises;
C. Industrial premises;
D. Agricultural premises;
E. Educational premises;
F. Hospital and medical care;
G. Food and drink premises;
H. Entertainment, culture and sport;
I. Hotels, Boarding houses, Hostels etc.;
J. Communal living;
K. Private non-residential building;
L. Other public buildings and services;
M. Road Vehicles;
N. Other Outdoors;
O. Others

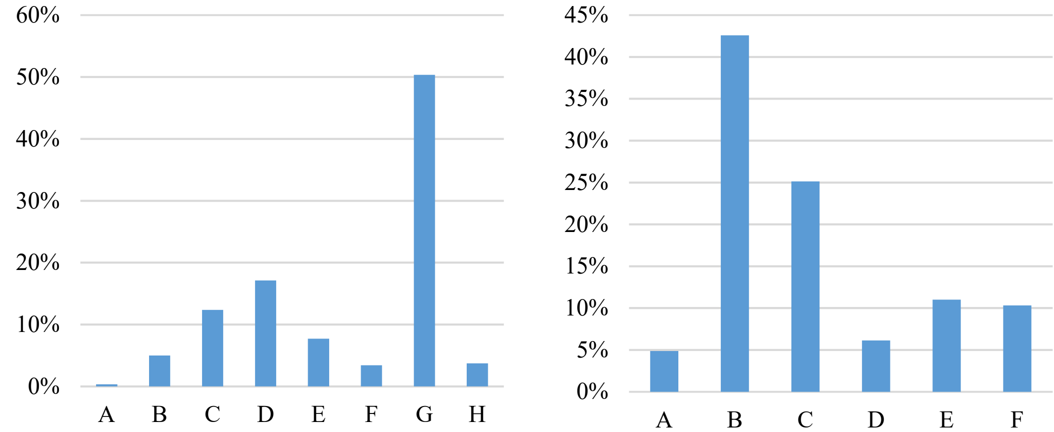
Figure 173: General property use not showing 65% fires in Dwellings, New Zealand

According to Figure 174, if the construction types are examined, 30.4% of fires involved timber frame unprotected in normal housing and 5.3% in Timber frame protected. There is also a 5.6% in bricks and blocks and a very important distinction is available between reinforced concrete construction with and without combustible claddings which show 0.7% and 2.7%. In light of current incidents affecting the international communities, these data assume a relevant role in understanding the behaviours of claddings. The construction type classification presents a more detailed classification than the one for USA statistics. However, a higher number of fires are available in the USA.



A. Brick, Blocks etc.;
B. Metal frame protected;
C. Metal frame unprotected;
D. Plastic Construction: composite formed;
E. Polystyrene Blocks;
F. Reinforced concrete tilt slab;
G. Reinforced concrete with combustible cladding;
H. Reinforced concrete with non-combustible cladding;
I. Timber frame protected;
J. Timber frame unprotected (normal housing);
K. Unable to classify;
L. Unknown;
M. Not Recorded

Figure 174: Construction types, New Zealand



(a) (b)

A. Pre 1900; **B**. 1900 – 1945; **C**. 1946 – 1969; **D**. 1970 – 1991; **E**. 1992 – 2005; **F**. 2006 onwards; **G**. Not Recorded; **H**. Unknown

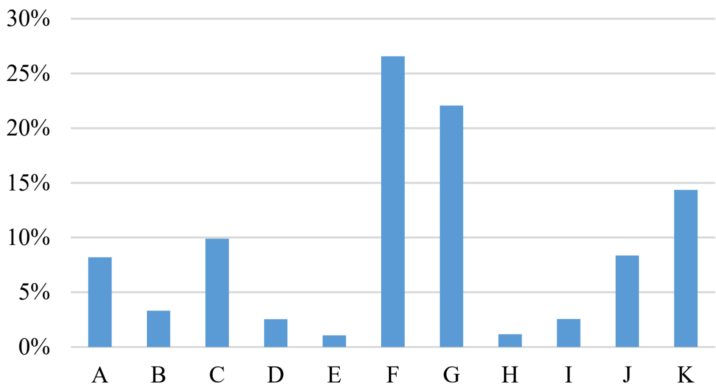
A. Housing NZ (social houses); **B**. Owner occupied; **C**. Rented property; **D**. State owned; **E**. Unknown; **F**. Not Recorded

Figure 175: (a) Building age and (b) building owners, New Zealand

Fire incidents in structures usually seem to affect buildings built between 1946 to 1969 for 12.3%, 1970 to 1991 for 17.1% and 1992 to 2005 for 7.7% of cases as shown in Figure 175 (a). Furthermore, there is 50.3% of data in which the building age was not recorded and 3.7% unknown. In Figure 175 (b), the building at the time of the fire incident was occupied by owners for 42.6%, rented for 25.1% or fire affected social houses or state buildings for 4.9% and 6.1%, respectively. The value of unknown or not recorded data again presents percentages over 10%. Therefore, data need to be treated carefully and uncertainties considered.

Fire causes

The classes of fire cause, item first ignited and material generating most flame present very detailed classes and these have been reorganized by this research in major categories to have a summary of the data present. However, other classifications could be created based on the fields recorded in the New Zealand fire statistics.

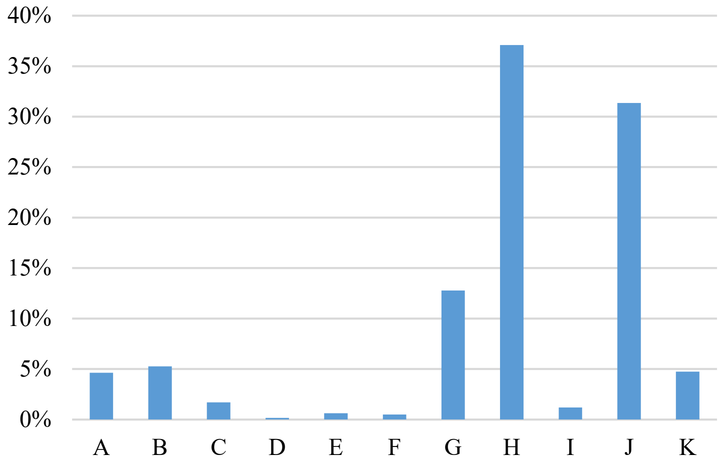


A. Careless;
B. Design, construction and maintenance;
C. Misuse of equipment;
D. Flammable material;
E. Improper actions;
F. Fire or heat source;
G. Failures;
H. Reckless;
I. People;
J. Others;
K. Unknown

Figure 176: Fire cause, New Zealand

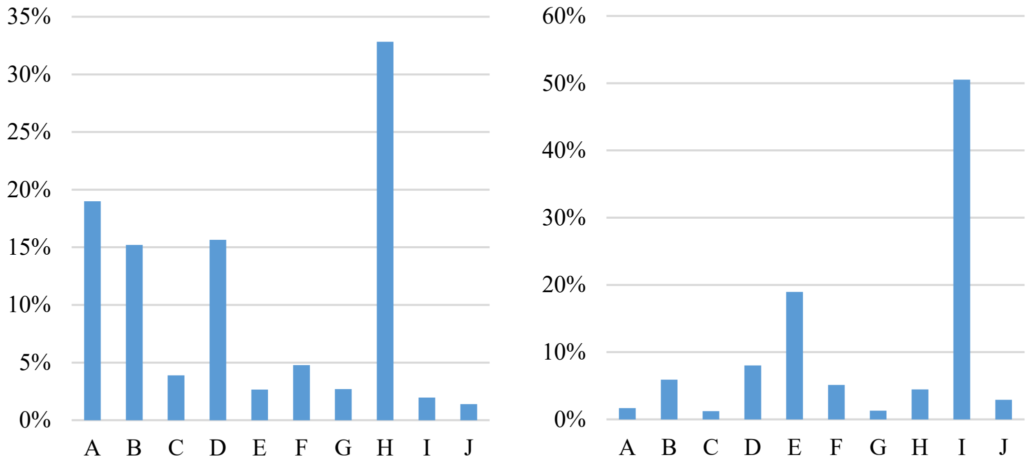
The fire causes appear to be given mainly for 26.6% by fire or heat source and 22.1% by electrical, mechanical, automatic or manual failures. Other relevant classes of fire causes are the one of misuse of equipment with 9.9%, careless with 8.2% and other causes with 8.4%. Even in this field, unknown causes assume 14.3% and further investigations should be developed to understand the reasons at the base of this value (Figure 176).

The heat sources described in Figure 177 present peaks for electric distribution for 12.8%, other electrical appliances for 37.1%, smokers' materials and cigarette lighters for an average of 5% and others for 31.3%. The remaining classes are lower than 2% except for the one in which the heat source was unable to be classified presenting 4.7%.



A. Smokers' materials;
B. Cigarette lighters;
C. Matches;
D. Cooking appliances;
E. Central and water heating appliances;
F. Blowlamps, welding & cutting equipment, working tools;
G. Electrical distribution;
H. Other electrical appliances;
I. Candles;
J. Others;
K. Unable to classify

Figure 177: Heat sources, New Zealand



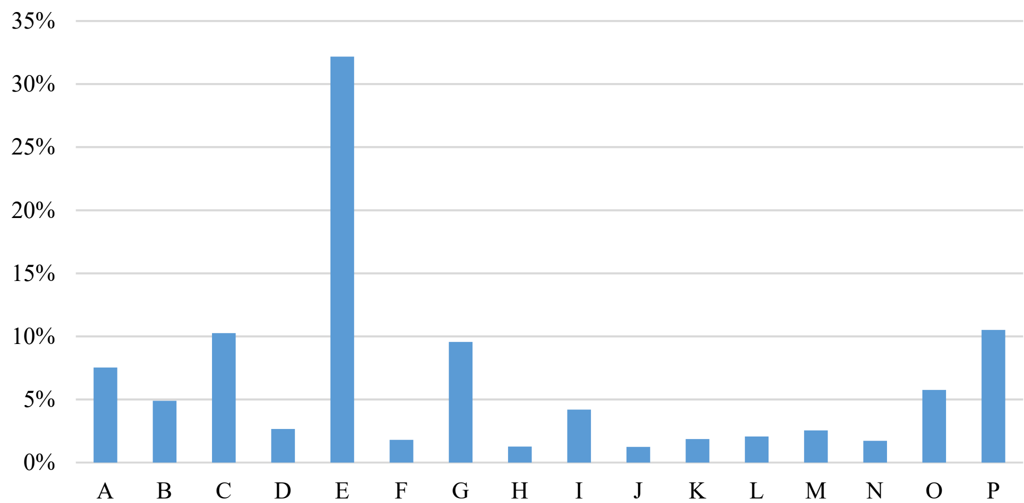
(a) (b)

A. Food; **B**. Textiles, upholstery and furnishings; **C**. Paper, cardboard; **D**. Structure and fittings; **E**. Agricultural and forestry product; **F**. Explosive Gases & Chemical; **G**. Rubbish/Waste/Recycling; **H**. Other items/materials; **I**. Not known; **J**. Unspecified

Figure 178: (a) Object first ignited and (b) material generating most flame, New Zealand

The object first ignited and the material generating most flame have been reclassified according to the same classes as explained in Figure 178. While the main items first ignited appear to be food with 19%, textiles, upholstery and furnishing with 15.2%, structure and fittings with 15.6% and other items with 32.8% (Figure 178 (a)), in the analysis of material first ignited the classes with the highest values are not the same. In particular, the highest peak is represented by agricultural and forestry products for 19%, followed by structure and fittings for 8% and textiles, upholstery and furnishing for 5.9%. A not negligible 50.5% is presented by the class of material not known as explained in Figure 178 (b). Moreover, in the New Zealand fire statistics, the fields of second objected ignited and material generating most smoke are available but they are not described in the research of this thesis.

There are 63 classes of fire origins available in the New Zealand fire statistics and only in this case, they are reclassified according to 16 of them that are those presenting a number of fires greater than 50 for a total of 5,004 fires. Based on Figure 179, the fire origin location appears to be for 32.2% in kitchen or cooking areas, for approximately 10% Garage, Carport, Vehicle storage, Storage Shed, Lounge, common room and fire origin not recorded and finally there is a 7.5% in which the fire ignited in bedrooms or sleeping areas with less than 5 people. The ignition was in the exterior wall surface for 5.8% of cases.



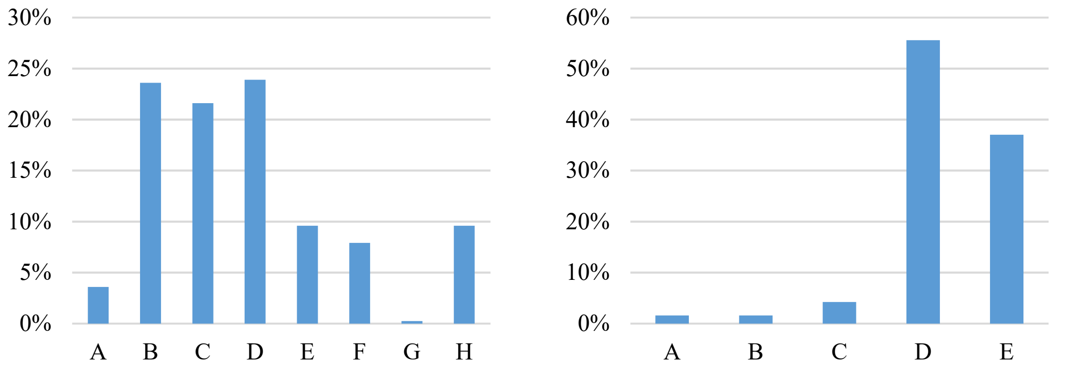
A. Bedroom, Sleeping area, Cell: under 5 persons; **B**. Ceiling and roof assembly; **C**. Garage, Carport, Vehicle storage, Storage Shed; **D**. Hallway, Passageway, Corridor, Walkway in mall; **E**. Kitchen, Cooking area; **F**. Laundry area, Wash house; **G**. Lounge, Common room, TV room, Sitting room, Music room; **H**. Machinery room/area, Engine room, Refrigeration room, Pump room, Lift motor room; **I**. Manufacturing, Process, Work room; **J**. Patio, Court, Terrace, Gazebo; **K**. Product storage, Tank, Bin, Agricultural storage, Hay barn, Hay stack; **L**. Supply room/area, Tool room, Maintenance supply room; **M**. Toilet, Locker room, Washroom, Rest room, Bathroom, Sauna, Out house, Portable toilet; **N**. Wall assembly: Concealed wall space; **O**. Wall surface (exterior); **P**. Not Recorded

Figure 179: Fire origin location, New Zealand

Fire growth and consequences

The fire growth and consequences in New Zealand are recorded with more details than those provided by the fire statistics of England and USA. For example, two fields related to the fire condition at the arrival of fire brigades and the expected heat transfer are recorded while they are not available in England and USA.

Starting with the fire condition at the arrival of the firefighters, the three highest peaks are reached for fire out at arrival with 23.6%, smoke only with 21.6% and small fire with 23.9%. According to these data, there is a large number of small fires which appear extinguished or causing small damage. At the same time, there are 9.6% and 7.9% of cases in which large fires are present or totally involved fires, respectively. The percentage of not recorded fires is equal to 9.6% and it appears less than the usual not recorded data fields available in New Zealand (Figure 180 (a)). The expected heat transfer is evaluated in Figure 180 (b) based on only 189 fire incidents where the predominant one seems to be assumed for 55.6% by the heat from direct flame and for 37% by radiated heat. Therefore, this field present uncertainties due to a high number of empty cells in the statistics.

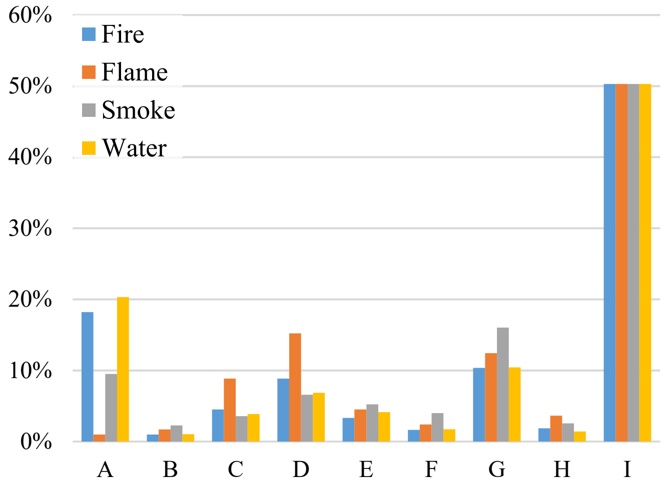


A. No fire or smoke; **B**. Out on arrival; **C**. Smoke only; **D**. Small fire; **E**. Large fire; **F**. Totally involved fire; **G**. Unable To classify; **H**. Not Recorded

A. Conducted heat; **B**. Convection current; **C**. Heat from brand, ember or spark; **D**. Heat from direct flame; **E**. Radiated heat

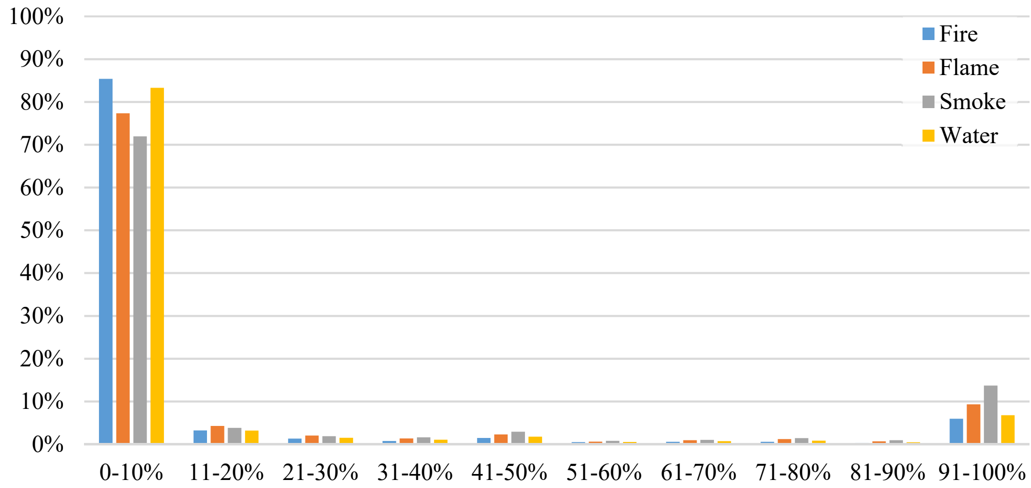
Figure 180: (a) Fire arrival conditions and (b) expected heat transfer, New Zealand

In New Zealand, the damage is composed of fire damage, flame damage including flame and heat damage, smoke damage and water damage. The values found for the extent of each damage are summarized in Figure *181* to create a direct comparison. Despite the 50% of not recorded data, the fire damage is not present for 18.2% of fires damage, flame damage for 1.0%, smoke damage for 9.5% and water damage for 20.3%. Fire damage is confined to structure of origin for 10.4%, smoke damage for 16% and water damage for 10.4% while a peak of 15.2% of flame damage is confined to part of room or area of origin. As found in England and USA, compartmentation seems to confine fires.

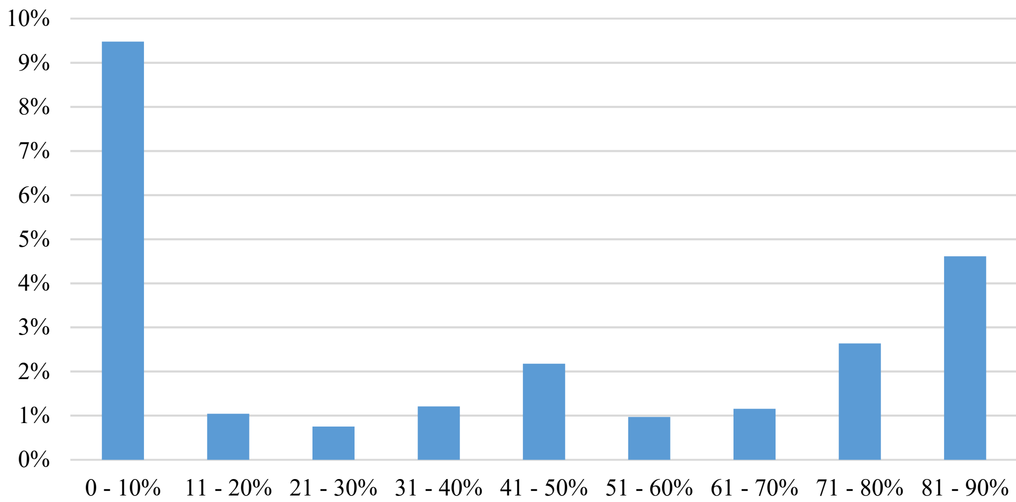


A. No damage of this type;
B. Confined to fire cell of origin;
C. Confined to object of origin;
D. Confined to part of room or area of origin;
E. Confined to room of origin;
F. Confined to floor of origin;
G. Confined to structure of origin;
H. Extended beyond structure of origin;
I. Not Recorded

Figure 181: Extend of fire, flame, smoke and water damage to the structures, New Zealand



(a)



(b)

Figure 182: Percentage (a) of the structure damage by fire, flame, smoke and water and (b) of the property saved not showing the 74.6% of class of 91%-100%, New Zealand

The area of the structure in m^2 damaged by each damage class is recorded. Since a field in which the approximate proportion of property not affected by flame damage (called property saved) is available, the estimates of the four classes are transformed in percentages of damage considering the total floor area of the structures in m^2 provided by the fire statistics. Figure 182 (a) shows the percentages of the structure damage and it is clear how the majority of fires are recorded for the four classes of damage between 0% and 10%. All the other classes assume values in general less than 4% except for the one of property damage between 91% and 100% for which the damage classes vary between 6% (fire damage) and 13.7% (smoke damage). In Figure 182 (b), the property saved is described where the class of property saved between 91% and 100% given by 74.6% is not considered in the figure to better show the other values. Excluding 9.5% in the property saved between 0% and 10%, the other classes of damage present values in general less than 2%. It is, therefore, possible to affirm that a high number of small fires and a low number of large ones are recorded in the New Zealand fire statistics. This is also supported by the evaluation of the approximate financial value of structural damage described in Figure 183.

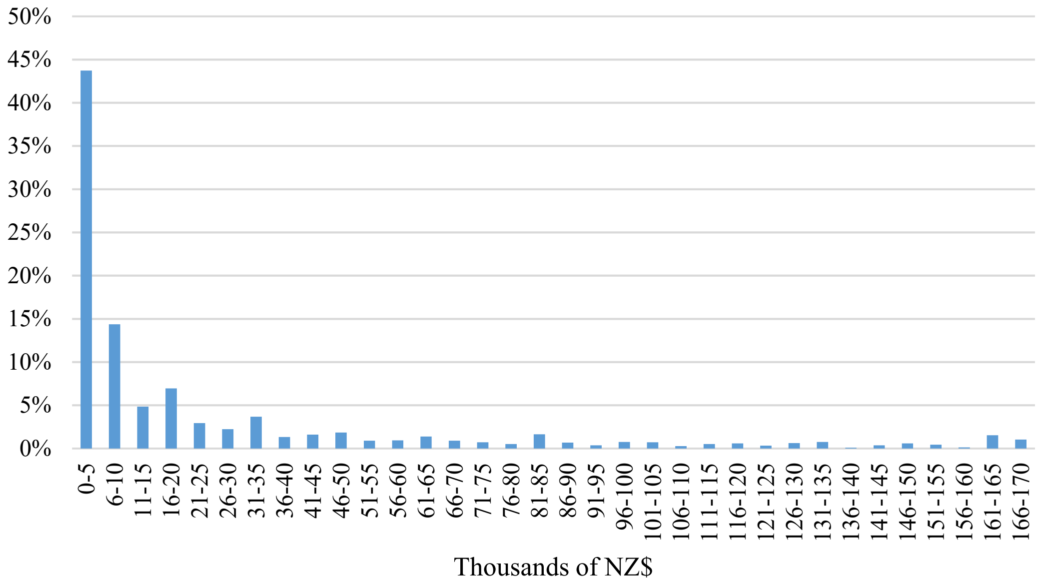
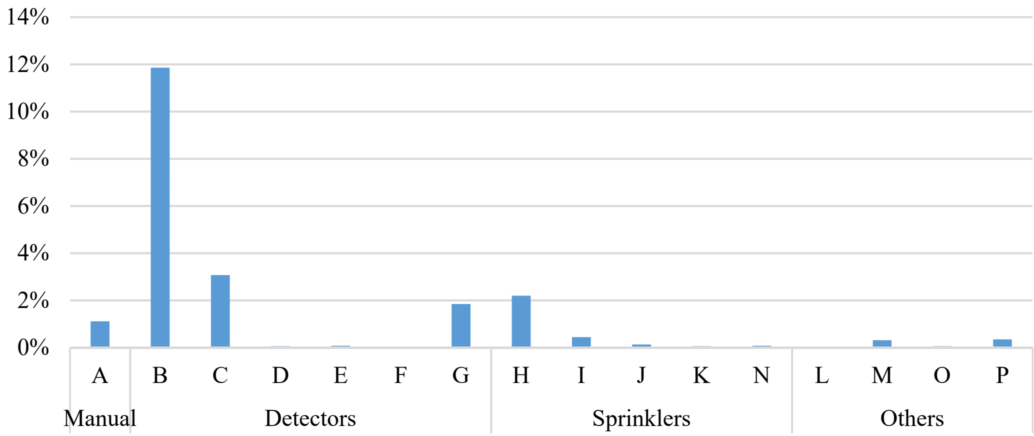


Figure 183: Approximate value of structural damage, New Zealand

The approximate economic value of damage to the structure is calculated using quantity survey tables and specific property use fields expressed in terms of NZ$. In Figure 183, there is a sudden decrement from 0 to 5,000$ to 6,000 to 10,000$ from 43.7% of fire incidents to 14.4%. Moreover, the trend gradually reaches a null percentage for classes greater than 35,000$.

Fire safety measures

For the analysis related to the safety measures, in the New Zealand statistics, the field of fire detectors types includes many classes which are reclassified by this research in four groups: manual fire alarms, detectors, sprinklers and others as described in Figure 184.



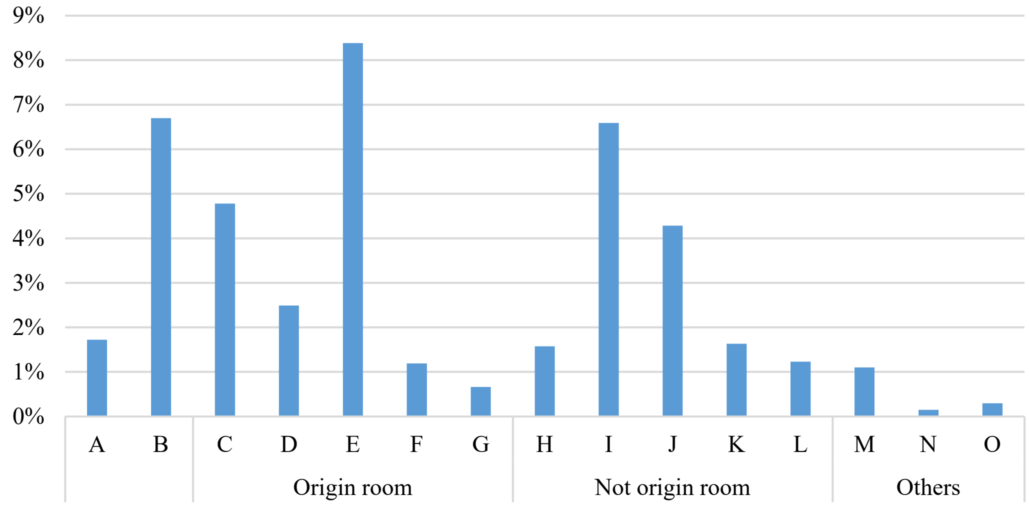
Manual: **A**. Manual Fire Alarm;
Detectors: **B**. Smoke Detector System (Monitored); **C**. Smoke Detector/Security Alarm System; **D**. Smoke sampling system; **E**. Flame detector; **F**. Flammable vapour detector; **G**. Heat detector, Thermal detector;
Sprinklers: **H**. Sprinkler; **I**. Domestic (Home) sprinklers; **J**. Residential sprinkler; **K**. Water spray projection system; **L**. Drencher system; **M**. CO_2; **N**. Deluge system;
Others: **O**. Inert gas (not CO_2); **P**. Unable to classify

Figure 184: Fire detector types not showing 56.7% of not recorded data, New Zealand

While in the other statistics, especially the one in USA, alarms and automatic extinguishing systems are separated, here they are provided in a unique group while it would be better to divide the evaluation according to the specific type. In Figure 184, it is not shown the histogram related to the 56.7% of not recorded data while for the other classes, 11.9% is given by smoke detector systems monitored followed by 3% by smoke detectors-security alarm systems and 1.9% by heat detector-thermal detector. Sprinklers, instead, has only 2.2% of presence and all the other classes are lower than 1.5%.

For the fire detector performance, it is not clear if this field includes only fire detectors or all the detectors types specified in Figure 185. However, the detector performances are classified according to fire too small to activate detector for 1.7%, the system operated and effective for 6.7% (class not specified further), detectors in or outside fire origin room and others for other operation (Figure 185). When the detector is in the origin room, the peaks are reached for 4.8% when operated and was effective, and 8.4% when alerted occupants. Instead, when the detector is outside the room of origin, 1.6%, 6.6% and 4.3% are given for operated and effective, did not operate and alerted occupants, respectively. The class of detectors performance unable to classify or not recorded assume 57.2% but are not shown in Figure 185.

Detector failures are not reported in the analysis because the 88.4% of data are not recorded and the uncertainties appear very significant.

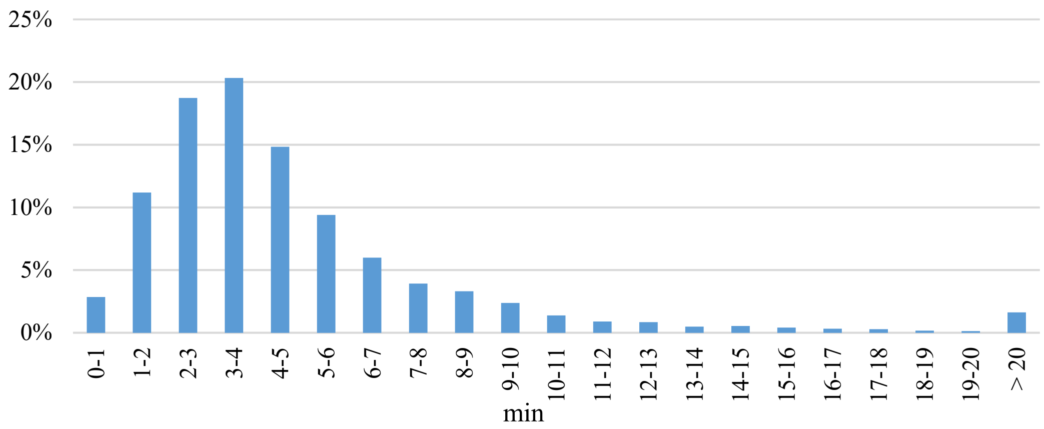


A. Fire too small to activate detector-detector in room of origin; **B**. System operated and effective; **Origin room: C**. Detector in Room operated and was effective; **D**. Did not operate-detector in room of origin; **E**. Alerted occupants-detector in room of origin; **F**. Alerted neighbour/passerby-detector in room of origin; **G**. Detector in room of origin-not classified above;
Not origin room: H. Detector Not in Room operated and effective; **I**. Did not operate-detector not in room of origin; **J**. Alerted occupants-detector not in room of origin; **K**. Alerted neighbour/passerby -detector not in room of origin; **L**. Detector not in room of origin-not classified above;
Others: **M**. Detector operated, but was not a factor in discovery of fire; **N**. Detector operated, but occupants failed to respond; **O**. Detector operated - not classified above

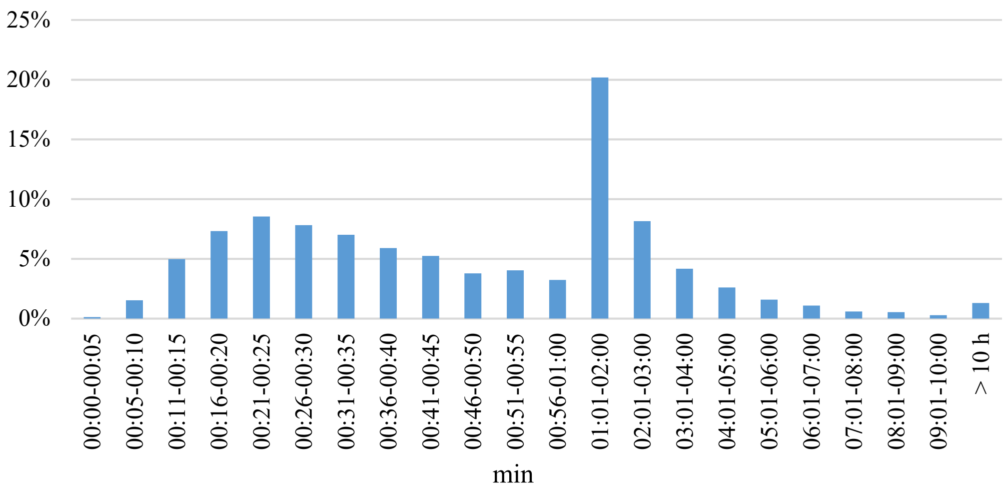
Figure 185: Fire detector performance not showing 57.2% of unable to classify and not recorded data, New Zealand

Fire response

Four different fields are recorded as relevant times during the fire incident in the New Zealand fire statistics according to the following definition provided by the New Zealand Fire Administration: *Start date time* when the incident was notified to the fire service dispatch system, *Stop date time* when the incident was closed in the dispatch system, *En route time* when the unit responded to the incident received from the dispatch system and *Arrival Time* as the time of arrival for the responding unit. Based on these four times, this research evaluates the response time as the difference between the *Arrival and En route times* and the duration of the incident as the one between *Stop and Start times*. The response time reaches a maximum of 20.3% in 3-4 minutes with 18.7% in 2-3 minutes and 14.8% in 4-5 minutes (Figure 186 (a)). It assumes an average of 5 minutes which is faster than the approximate 8 minutes shown by the other two countries. The fire duration time seems to be well confined in approximately one hour with a peak of 8.5% between 21-25 minutes. The highest percentage found between 1-2 hours could be given by the change in time ranges from 5 minutes to 1 hour (Figure 186 (b)).



(a)



(b)

Figure 186: (a) Response time (Arrival and En route times) and (b) Fire duration (Stop and Start times), New Zealand

Since New Zealand fire statistics present several fields in which data are not recorded for more than 50% of fires, it is not considered in the elaborations of this thesis.

Summary of key New Zealand statistics

In New Zealand statistics, 40.7% of fires in structures are with no damage and 49.7% with damage. The main property affected by fire incidents are Dwellings with 65.6% and Industrial premises with 5.9% while all the other properties are below 5.5%. Generally, building age varies between 1946 and 2005.

Fire causes are mainly attributable to fire or heat source (26.6%) and electrical, mechanical and manual failures (22.1%) while the heat source is due to electrical distribution (12.8%) and other electrical appliances (37.1%). The item first ignited is represented by food; textiles, upholstery and furnishing and structure and fittings and the material generating most flame is due to agricultural and forestry products and structure and fittings. The fire origin is usually in the kitchen for 32.2% of fire incidents.

Fire conditions at arrival are mainly characterized by fires out on arrival, fires with smoke only or defined as small fires. Moreover, the principal expected heat transfer is heat from direct flame followed by radiated heat. In New Zealand statistics, a distinction between fire, flame, smoke and water damage is provided. Despite the four damage types are not recorded for 50% of cases, the other values show no fire damage, damage confined to part of room or area of origin and damage confined to structure of origin. If the damage is examined in relation to the whole building, only 10% is recorded for more than 70% for fire, flame, smoke and water damage. This is supported by the financial losses estimated mainly up to NZ $5,000.

Fire detectors and sprinklers are collected in a unique field in New Zeeland and 11.8% are represented by smoke detectors and 2.2% by sprinklers. However, data are not recorded for 56.7% of cases. Safety measure performances are subdivided in and outside the room of origin, where in the room origin 8.4% alerted occupants and outside the room of origin they did not operate for 6.6%. Considerations about failures are avoided due to the 88.4% of data not recorded. The average response time of fire brigades is of 5 minutes which appears less than the approximate 8.5 minutes obtained in England and USA statistics.

References

Almufti, I., Willford, M., Delucchi, M., Davis, C., Hanson, B., Langdon, D., Friedman, D., Johnson, L., Nielsen, G., Riordan, N. O., Roberts, C., Steiner, M., Wilson, A., Wolski, A., & Mote, T. (2013). *REDi ™ Rating System* (Issue October).

America Burning. (1973). *The report of the national commission on fire prevention and control. DC 20402*. US Government Printing Office.

Apostolakis, G. E. (2004). How Useful Is Quantitative Risk Assessment? *Risk Analysis*, *24*(3), 515–520. https://doi.org/10.1111/j.0272-4332.2004.00455.x

Ashe, B., McAneney, J., & Pitman, A. J. (2009). The cost of fire in Australia. *Journal of Risk Research*, *12*(2), 121–136.

Aven, T. (2012). The risk concept-historical and recent development trends. *Reliability Engineering and System Safety*, *99*(0951), 33–44. https://doi.org/10.1016/j.ress.2011.11.006

Ayyub, B. M. (2014). Systems resilience for multihazard environments: Definition, metrics, and valuation for decision making. *Risk Analysis*, *34*(2), 340–355. https://doi.org/10.1111/risa.12093

Bank of England GBP to USD exchange rates. (2019). *https://www.poundsterlinglive.com/bank-of-england-spot/historical-spot-exchange-rates/gbp/GBP-to-USD-2015*.

Bank of England Inflation Calculator. (2018). *http://bankofengland.education/inflationcalculator/*.

Benktander, G. (1972). Claims frequency and risk premium rate as function of the size of the risk. *ASTIN Bulletin: The Journal of the IAA*, *7*(2), 119–136.

Bisby, L., Gales, J., & Maluk, C. (2013). A contemporary review of large-scale non-standard structural fire testing. *Fire Science Reviews*, *2*(1). https://doi.org/10.1186/2193-0414-2-1

Borg, A., Njå, O., & Torero, J. L. (2015). A Framework for Selecting Design Fires in Performance Based Fire Safety Engineering. *Fire Technology*, *51*(4), 995–1017. https://doi.org/10.1007/s10694-014-0454-x

Brand, S., & Price, R. (2000). *The economic and social costs of crime. Home Office Reserach Study 217*.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & Von Winterfeldt, D. (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, *19*(4), 733–752. https://doi.org/10.1193/1.1623497

BSI. (2012). *Pocket Guide to Standards Development*.

BSI BN 25999-1. (2006). *BS 25999-1, Business continuity management – Part 1: Code of practice*.

BSI BS 25999-2. (2007). *BS 25999-2, Business continuity management – Part 2: Specification*.

BSI BS 65000. (2014). *BS 65000 - Guidance on organizational resilience*.

BSI BS 7974. (2019). *BS 7974: Application of Fire Safety Engineering Principles to the Design of Buildings - Code of Practice*.

BSI BS 9991. (2015). *Fire safety in the design, management and use of residential buildings – Code of Practice*.

BSI BS 9999. (2017). *Fire safety in the design, management and use of buildings – Code of Practice*.

BSI BS EN ISO 22301. (2014). *BS EN ISO 22301 Societal security – Business continuity management systems – Requirements*.

BSI BS EN ISO 22313. (2014). *BS EN ISO 22313 Societal security – Business continuity management systems – Guidance*.

BSI PAS 911. (2007). *PAS 911:2007 Fire strategies – Guidance and framework for their formulation*.

BSI PD 7974-7. (2003). *PD 7974-7 Application of fire safety engineering principles to the design of buildings — Part 7: Probabilistic risk assessment*.

BSI PD 7974-7. (2019). *PD 7974-7 Application of Fire Safety Engineering Principles to the Design of Buildings - Part 7: Probabilistic risk assessment*.

BSI PD 7974-8. (2012). *PD 7974-8:2012: Application of fire safety engineering principles to* *the design of buildings; Part 8: Property protection, business and mission continuity, and resilience*.

Building Regulations. (2010). *Approved Document B: Volume 2 – Buildings Other than Dwelling Houses.* (Vol. 2). National Building Specification. https://doi.org/10.1016/B978-0-7506-8580-1.00027-0

Cabinet Office. (2018). *Public Summary of Sector Security and Resilience Plans*.

Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2010). Framework for analytical quantification of disaster resilience. *Engineering Structures*, *32*(11), 3639–3649. https://doi.org/10.1016/j.engstruct.2010.08.008

Cooke, G. M. E., & Latham, D. J. (1987). The inherent fire resistance of a loaded steel framework. In *Steel Construction Today: Vol. 1.2* (pp. 49–58).

D'Addario, R. (1940). *Considerazioni sul tasso di premio delle assicurazioni incendi*.

Del Prete, I., Cefarelli, G., & Nigro, E. (2016). Application of criteria for selecting fire scenarios for structures within fire safety engineering approach. *Journal of Building Engineering*, *8*(October), 208–217. https://doi.org/10.1016/j.jobe.2016.10.010

Department for Communities & Local Government. (2012). *Incident Recording System - Questions and lists Version 1.6*.

Department for Communities and Local Government. (2011a). *The economic cost of fire: estimates for 2006. Fire research report 2/2011*.

Department for Communities and Local Government. (2011b). *The economic cost of fire: estimates for 2008. Fire research report 3/2011*.

Department for Communities and Local Government. (2015). *Fire Incidents Response Times: April 2014 to March 2015, England* (Issue March).

Executive office of the President, & Office of Management and Budget. (2017). *North American Industry Classification System*. 963. https://www.census.gov/eos/www/naics/2017NAICS/2017_NAICS_Manual.pdf

Faber, M. H. (2012). Statistics and probability theory: in pursuit of engineering decision support. In *Springer Science & Business Media* (Vol. 18). https://doi.org/10.1007/978-94-007-4056-3

Farsangi, E. N., Takewaki, I., Yang, T. Y., Astaneh-Asl, A., & Gardoni, P. (2019). *Resilient*

Structures and Infrastructures. Springer.

Federal Emergency Management Agency (FEMA). (2017). *Safer, Stronger, Smarter: A Guide to Improving School Natural Hazard Safety, FEMA P-1000* (Issue June).

Frank, K., Spearpoint, M., & Challands, N. (2014). Uncertainty in Estimating the Fire Control Effectiveness of Sprinklers from New Zealand Fire Incident Reports. *Fire Technology*, *50*(3), 611–632. https://doi.org/10.1007/s10694-012-0297-2

Gaught, P., Gallucci, J., & Smalldridge, G. (2016). *Fire Statistics England, 2014/15*. *June*. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/532364/fire-statistics-england-1415-hosb0816.pdf

Gernay, T., Selamet, S., Tondini, N., & Khorasani, N. E. (2016). Urban Infrastructure Resilience to Fire Disaster: An Overview. *Procedia Engineering*, *161*, 1801–1805. https://doi.org/10.1016/j.proeng.2016.08.782

Goodchild, M., Sanderson, K., Leung-Wai, J., & Nana, G. (2005). The Cost of Managing the Risk of Fire in New Zealand. *Business and Economic Research Limited*.

Hadjisophocleous, G. V., Benichou, N., & Tamim, A. S. (1998). Literature review of performance-based fire codes and design environment. *Journal of Fire Protection Engineering*, *9*(1), 12–40. https://doi.org/10.1177/104239159800900102

Hall, J. R. (2011). *The total cost of fire in the United States* (Issue February). National Fire Protection Association.

Halpern, J., Isherwood, G. D., & Wand, Y. (1979). The relationship between response time and fire property losses. *INFOR: Information Systems and Operational Research*, *17*(4), 373–390.

Hansson, S. O. (2010). Risk: Objective or subjective, facts or values. *Journal of Risk Research*, *13*(2), 231–238. https://doi.org/10.1080/13669870903126226

Hasofer, A., Beck, V., & Bennetts, I. D. (2006). *Risk analysis in building fire safety engineering.* Routledge.

Hasofer, A. M., & Thomas, I. (2006). Analysis of fatalities and injuries in building fire statistics. *Fire Safety Journal*, *41*(1), 2–14. https://doi.org/10.1016/j.firesaf.2005.07.006

Hassanain, M. A. (2006). Towards the design and operation of fire safe school facilities. *Disaster Prevention and Management: An International Journal*, *15*(5), 838–846.

https://doi.org/10.1108/09653560610712775

Hogg, J. M. (1968). The Siting of Fire Stations. *Journal of the Operational Research Society*, *19*(3), 275–287.

Holborn, P. G., Nolan, P. F., & Golt, J. (2004). An analysis of fire sizes, fire growth rates and times between events using data from fire investigations. *Fire Safety Journal*, *39*(6), 481–524. https://doi.org/10.1016/j.firesaf.2004.05.002

Home Office. (2015). *Fire incidents response times: England 2014 to 2015*. https://www.gov.uk/government/statistics/fire-incidents-response-times-england-2014-to-2015

Home Office. (2016). *Fire Statistics definitions for the Incident Recording System*.

Home Office. (2017a). *Publishing Incident Recording System data on the fire and rescue service at an Incident Level: Dwelling Fires Dataset Guidance* (Issue April).

Home Office. (2017b). *Publishing Incident Recording System data on the fire and rescue service at an incident level: 'Other building' fires dataset guidance* (Issue September).

Home Office. (2017c). *Publishing Incident Recording System data on the fire and rescue service at an incident level: Project overview* (Issue April).

Home Office. (2017d). *The UK Fire & Resilience Offer*.

Home Office. (2018). *Response times to fires attended by fire and rescue services: England, April 2016 to March 2017*.

Home Office. (2019). *Fire statistics collection*. https://www.gov.uk/government/collections/fire-statistics

Hopkin, C., Spearpoint, M., Wang, Y., & Hopkin, D. (2019). Design Fire Characteristics for Probabilistic Assessments of Dwellings in England. *Fire Technology*. https://doi.org/https://doi.org/10.1007/s10694-019-00925-6

Hu, J., Shu, X., Xie, S., Tang, S., Wu, J., & Deng, B. (2019). Socioeconomic determinants of urban fire risk: A city-wide analysis of 283 Chinese cities from 2013 to 2016. *Fire Safety Journal*, *110*(December 2018), 102890. https://doi.org/10.1016/j.firesaf.2019.102890

Hynes, W. M., Purcell, S. M., Walsh, S. D., & Ehimen, E. (2016). Formalizing Resilience Concepts for Critical Infrastructure. In *IRGC Resource Guide on Resilience*. https://www.irgc.org/risk- governance/resilience/

Ignall, E., Rider, K., & Urbach, R. (1979). Fire Severity and Response Distance: Initial Findings. *Fire Technology*, *15*(4), 245–261.

IMPROVER. (2016). *Deliverable 2.2: Report of criteria for evaluating resilience*.

International Code Council. (2017). *Building Valuation Data – FEBRUARY 2017* (Issue FEBRUARY).

ISO/FDIS 16732-1:2011(E). (2011). *Fire safety engineering - Fire risk assessment - Part 1: General*.

ISO/IEC 31010. (2009). *Risk management — Risk assessment techniques*.

ISO 31000:2009. (2009). *Risk management - Principles and guidelines*.

Joffe, H., Perez-Fuentes, G., Potts, H. W. W., & Rossetto, T. (2016). How to increase earthquake and home fire preparedness: the fix-it intervention. *Natural Hazards*, *84*(3), 1943–1965. https://doi.org/10.1007/s11069-016-2528-1

Joffe, H., Potts, H. W. W., Rossetto, T., Doğulu, C., Gul, E., & Perez-Fuentes, G. (2019). The Fix-it face-to-face intervention increases multihazard household preparedness cross-culturally. *Nature Human Behaviour*, *3*(5), 453–461. https://doi.org/10.1038/s41562-019-0563-0

Johann, M. A., Albano, L. D., Fitzgerald, R. W., & Meacham, B. J. (2006). Performance-Based Structural Fire Safety. *Journal of Performance of Constructed Facilities*, *20*(1), 45–53. https://doi.org/10.1061/(ASCE)0887-3828(2006)20:1(45)

Johansson, N., & Van Hees, P. (2011). Learning From Real Fire Incidents: a Methodology for case studies. *Fire and Materials Conference*, *1*(Interscience Communications), 171–182.

Khorasani, N. E., Gernay, T., & Garlock, M. (2015). Tools for measuring a city's resilience in a fire following earthquake scenario. *IABSE Conference, Geneva 2015: Structural Engineering: Providing Solutions to Global Challenges - Report*, 886–889.

Kirby, B. R., Lapwood, D. G., & Thompson, G. (1993). *Reinstatement of Fire Damaged Steel and Iron Framed Structures*.

Kurth, M. H., Keenan, J. M., Sasani, M., & Linkov, I. (2019). Defining resilience for the US building industry. *Building Research and Information*, *47*(4), 480–492. https://doi.org/10.1080/09613218.2018.1452489

Labaka, L., Hernantes, J., & Sarriegi, J. M. (2016). A holistic framework for building critical infrastructure resilience. *Technological Forecasting and Social Change*, *103*, 21–33. https://doi.org/10.1016/j.techfore.2015.11.005

Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kröger, W., Lambert, J. H., Levermann, A., Montreuil, B., Nathwani, J., Nyer, R., Renn, O., Scharte, B., Scheffler, A., Schreurs, M., & Thiel-Clemen, T. (2014). Changing the resilience paradigm. *Nature Climate Change*, *4*(6), 407–409. https://doi.org/10.1038/nclimate2227

Linkov, I., & Palma-Oliveira, J. M. (2017). An Introduction to resilience for critical infrastructures. In *NATO Science for Peace and Security Series C: Environmental Security* (Vol. PartF1). https://doi.org/10.1007/978-94-024-1123-2_1

Lovric, M. (2011). International Encyclopedia of Statistical Science. In *Springer*. https://doi.org/10.1007/978-3-642-04898-2_594

Manes, M., & Rush, D. (2018). A Critical Evaluation of BS PD 7974-7 Structural Fire Response Data Based on USA Fire Statistics. *Fire Technology*, *55*(4), 1243–1293. https://doi.org/10.1007/s10694-018-0775-2

Manes, M., & Rush, D. (2020). Assessing fire frequency and structural fire behaviour of England statistics according to BS PD 7974-7. *Fire Safety Journal*. https://doi.org/10.1016/j.firesaf.2020.103030

Meacham, B. J., & Custer, R. L. P. (1995). Performance-based fire safety engineering: An introduction of basic concepts. *Journal of Fire Protection Engineering*, *7*(2).

Meacham, B. J., & Powell, C. (1995). Performance-based fire safety engineering: An introduction of basic concepts. *Journal of Fire Protection Engineering*, *7*(2), 35–54.

Meade, W. P. (1991). A first pass at computing the cost of fire safety in a modern society. *Fire Technology*, *27*(4), 341–345. https://doi.org/10.1007/BF01039885

MSBA Risk Management. (2018). *Fire Safety in Manitoba Educational Facilities. A Guide for Educators.*

National Clearinghouse for Educational Facilities. (2008). *Mitigating Hazards in School Facilities.*

National Fire Protection Association. (2007). *NFPA 550: Guide to the Fire Safety Concepts Tree.* National Fire Protection Association.

National Institute of Standards and Technology. (2016). *NIST Special Publication 1190:*

Community Resilience Planning Guide for Buildings and Infrastructure Systems, Volume II: Vol. I. https://doi.org/10.6028/NIST.SP.1190v1

Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F., & Pfefferbaum, R. L. (2008). Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *American Journal of Community Psychology*, *41*(1–2), 127–150. https://doi.org/10.1007/s10464-007-9156-6

NZIER and Corydon Consultants Ltd. (2002). *School fires in New Zealand Economic and social analysis. Final report to New Zealand Fire Service Commission.*

OFX International Money Transfer and Exchange. (2018). *https://www.ofx.com/en-gb/forex-news/historical-exchange-rates/yearly-average-rates/*.

Organization for Economic Co-operation and Development. (2014). *Guidelines for Resilience Systems Analysis - How to analyse risk and build a roadmap to resilience*. http://www.oecd.org/dac/Resilience Systems Analysis FINAL.pdf

Queensland Fire and Emergency Service. (2019). *QFES Incident data*. https://www.data.qld.gov.au/dataset/qfes-incident-data

Ramachandran, G, Kirsop, P. (1969a). A brief analysis of large fires during 1965 to 1968. *Fire Reserach Note No 792*, *792*.

Ramachandran, G, Kirsop, P. (1969b). Preliminary analysis of large fires during 1968. *Fire Reserach Note No 763*, *October*.

Ramachandran, G. (1970). Fire loss indexes. *Fire Reserach Note No 839*.

Ramachandran, G. (1993). Early detection of fire and life risk. *Fire Engineers Journal*, *53*(171), 33–37.

Ramachandran, G. (2002). *The Economics of Fire Protection* (Routledge (ed.)).

Ramachandran, G., & Charters, D. (2011). *Quantitative risk assessment in fire safety*. Routledge. https://doi.org/10.4324/9780203937693

Rasbash, D., Ramachandran, G., Kandola, B., Watts, J., & Law, M. (2004). *Evaluation of Fire Safety*. John Wiley & Sons.

Readiness and Emergency Management for Schools (REMS) and Technical Assistance (TA) Center. (2017). *Mitigation for Schools and School districts*.

Rebekić, A., Lončarić, Z., Petrović, S., & Marić, S. (2015). Pearson's or Spearman's Correlation Coefficient-Which One To Use? *Poljoprivreda (Osijek)*, *21*(2), 47–54. https://doi.org/10.18047/poljo.21.2.8

Renn, O. (1998). Three decades of risk research: accomplishments and new challenges. *Journal of Risk Research*, *1*(1), 73–76. https://doi.org/10.1080/136698798377330

Rosenberg, T. (1999). Statistics for fire prevention in Sweden. *Fire Safety Journal*, *33*(4), 283–294. https://doi.org/10.1016/S0379-7112(99)00039-9

Rubert, A., & Schaumann, P. (1986). Structural steel and plane frame assemblies under fire action. *Fire Safety Journal*, *10*.

Rutstein, R. (1979a). The estimation of the fire hazard in different occupancies types. *Fire Surveyor*, *8*(2), 21–25.

Rutstein, R. (1979b). The probability of fire in different sectors of industry. *Fire Surveyor*, *8*(1), 20–23.

Rutstein, R., & Cooke, R. A. (1979). The value of fire protection in buildings. *Home Office, Scientific Reserach and Development Branch*.

Salter, C., Ramachandran, G., Emmitt, S., & Bouchlaghem, N. (2013). Economic cost of fire: Exploring UK fire incident data to develop a design tool. *Fire Safety Journal*, *62*, 256–263. https://doi.org/10.1016/j.firesaf.2013.09.018

Schaenman, P., Stern, J., & Bush, R. (1995). *Total Cost of Fire in Canada: an initial estimate*.

Staffordshire Fire and Rescue Service. (2017). *Corporate Safety Plan 2017-2020*.

Statistics Canada. (2015). *Incident-based fire statistics, by type of fire incident and type of structure*. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3510019201

Surrey Fire and Rescue Service Fire. (2019). *Risk assessment for small premises*.

Tehler, H. (2013). A general framework for risk assessment. *Department of Fire Safety Engineering and Systems Safety, Lund University*.

The Building Regulations 2010. (2018). *Approved Document Regulation 7 - Materials and Workmanship*.

The Fire Protection Research Foundation. (2014). *Disaster Resiliency and NFPA Codes and Standards*. www.nfpa.org/freeaccess.

The Geneva Association. (2014). *World Fire Statistics Bullettin* (Vol. 29, Issue April 2014).

Twilt, L., & Vrouwenvelder, A. (1986). CIB-Concept for Probability Based Structural Fire Safety Design. *Fire Safety Science*, *1*, 981–992.

U.S. Department of Homeland Security. (2011). *Presidential Policy Directive 8, PPD-8*.

U.S. Department of Homeland Security. (2013). *NIPP 2013: Partnering for Critical Infrastructure Security and Resilience*.

U.S. Department of Homeland Security. (2018). *Threat and hazard indentification and risk assessment (THIRA) and stakeholder preparedness review (SPR) guide. CPG 201* (Issue May). https://www.fema.gov/media-library-data/1527613746699-fa31d9ade55988da1293192f1b18f4e3/CPG201Final20180525_508c.pdf

U.S. Energy Information Administration. (2019a). *Commercial Buildings Energy Consumption Survey*. https://www.eia.gov/consumption/commercial/

U.S. Energy Information Administration. (2019b). *Independent statistics & analysis*. https://www.eia.gov

U.S. Energy Information Administration. (2019c). *Manufacturing Energy Consumption Survey*. https://www.eia.gov/consumption/manufacturing/

U.S Fire Administration. (1980). *Indirect Costs of Residential Fires*.

U.S Fire Administration. (2019). *NFIRSGram: calculating fire loss*. https://www.usfa.fema.gov/data/nfirs/support/nfirsgrams/nfirsgram_calculating_fireloss.html

UNESCO. (2014). *Towards A Learning Culture of Safety and Resilience. Technical Guidance for Integrating Disaster Risk Reduction in the School Curriculum.*

UNISDR United Nations Office for Disaster Risk Reduction. (2017). *Comprehensive School Safety.* (Issue March).

United Nations. (2009). *UNISDR Terminology on disaster risk reduction*.

USFA. (2014). *National Fire Incident Reporting System*. *2014*(12/31).

Valuation Office Agency. (2016). *Non-domestic rating: Stock of Properties England and Wales, 2010 Rating List*.

Vamvatsikos, D., Kouris, L. A., Panagopoulos, G., Kappos, A. J., Nigro, E., Rossetto, T., Lloyd, T. O., & Stathopoulos, T. (2010). Structural vulnerability assessment under natural hazards: A review. *COST ACTION C26: Urban Habitat Constructions under Catastrophic Events - Proceedings of the Final Conference*, 17–18.

Van Coile, R., Hopkin, D., Lange, D., Jomaas, G., & Bisby, L. (2019). The Need for Hierarchies of Acceptance Criteria for Probabilistic Risk Assessments in Fire Engineering. *Fire Technology*, *55*(4), 1111–1146. https://doi.org/10.1007/s10694-018-0746-7

Wang, Y., Dong, Y. L., Li, B., & Zhou, G. C. (2013). A fire test on continuous reinforced concrete slabs in a full-scale multi-story steel-framed building. *Fire Safety Journal*, *61*, 232–242. https://doi.org/10.1016/j.firesaf.2013.08.005

Weiner, M. (2001). *The Economic Costs of Fire. Home Office Reserach Study 229*.

World Economic Forum. (2014). *Insight Report, Global Risks 2014 Ninth Edition*.

Yung, D. (2008). *Principles of fire risk assessment in buildings*. John Wiley & Sons.