**PROBABILISTIC FIRE RISK ASSESSMENT IN BUILDINGS USING EVENT TREE ANALYSIS BASED ON UK AND USA FIRE STATISTICS.**

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# ABSTRACT

Fire safety engineering is relying more and more on probabilistic risk assessments to understand the individual parameter risks and the combined fault and/or event sequence probabilities to understand the global risk of certain series of events. Contemporary fire statistics of UK and USA are adopted in this research to develop event tree analysis for several property types. It provides a qualitative and quantitative assessment of fire protection in reducing property damage, quantifies the risk associated with particular fire scenarios and predicts the consequences due to the application of different fire safety measures in several property types. The influence of alarms is investigated to evaluate its performances and the impact on occupants as well as the fire brigade notification and attendance. Sprinklers are considered in terms of presence, operation and effectiveness on fire spread and fire and total damage in m2. Buildings stocks of UK and USA is analysed to obtain the total number of buildings at risk and calculate yearly fire frequency defined as fires per building. Response times less than 9 minutes seems to be effective in both UK and USA in reducing damage to properties; ignition to discovery and discovery to call both less than 5 minutes in UK for presence and absence of sprinklers, are also seen to reduce the extent of damage. In UK, fires appear well confined within the floor of origin with no-rapid fire growth and fire damage on average less than 50 m2. In USA, when sprinklers are absent, fires are not limited to the floor of origin with greater fire extents being observed. The analysis is considered as a first attempt to understand the likelihood of fire scenarios in several property types based on real structural fire data.

**Keywords:** fire statistics, probabilistic risk assessment, event tree analysis, fire frequency, fire response, fire consequences

# INTRODUCTION

Fire safety engineering has always faced the uncertainties related to design variables, fire scenarios and reliability of safety measures such as detector systems and sprinklers. The concept of safety itself is uncertain and there is no such thing as absolute safety 1. Furthermore, the real response of buildings subjected to fire is difficult to predict accurately due to various structural configurations that appear across different property types. It is in this light that industry is moving from prescriptive approaches towards more performance-based designs, which provide alternative solutions based on building performances, respecting the fundamental safety and structural rules 2. Indeed, there are different ways to evaluate fire consequences as with computer models or full-scale experiments 3. However, they are often expensive and time-consuming; they usually only consider a single particular fire scenario (predominantly standardised time-temperature fire curves) and use limited number of possible factors (i.e. assessing only single elements).

Risk, therefore, is usually classified as objective and subjective, respectively given by physical facts or social construction 4. Risk assessments provide evidence-based information and analysis to decide and reduce possible risks due to a particular incident. Quantitative risk assessments are useful to consider different fire scenarios and system failure modes, understand the interaction between events/systems and operators, quantify the uncertainties and provide valuable insights about physical phenomena and human behaviour and facilitate risk treatment and management 5. Risk assessments usually includes risk identification, risk analysis and risk evaluation as described in ISO/IEC 31010:2009 6. Moreover, the general framework for a risk assessment presents the definition of values/objectives, context, risk scenarios, likelihood and consequences, risk presentation and risk evaluation 7. The analysis developed in the paper will follow these steps where possible, to provide a complete analysis of fire risks in different property types.

Statistical analyses consider data collected in building fires and convert them into information useful to predict the likelihood of occurrence and consequences 8. Current UK codes such as BSI PD 7974-7:2003 9 provide methods to investigate probabilistic risk assessments for fire incidents based on fire statistics data from 1966 to 1987 9; updates to these 30 or more year old data are needed. The data present in BSI PD 7974-7:2003 have been recently updated according to USA National Fire Incident Reporting System 10 and UK Incident Recording System 11 fire statistics, for what concerns the frequency of fires, direct financial loss and the influence of the presence or absence of automatic extinguish systems on structural damage according to different property types (e.g. assembly, educational, industrial, storage buildings) 12. From the updated data, it is possible to observe that fire frequency in PD 7974-7 usually overestimates the current trends with values up to 10 times bigger, and the flame damage (excluding damage by heath, smoke and water) is underestimated if compared to the USA fire statistics. In this paper the probability of fire and its damage is expressed in probabilistic terms and estimated by examining past fire incidence data 13.

Statistical data and engineering judgements are usually adopted to estimate the severity of the outcomes in event tree analysis. This methodology investigates different fire scenarios with several degrees of complexity, enables the assessment of multiple functioning and failing systems and quantifies the benefits of fire precautions based on related cost-benefit analysis 14. The aims are to ensure life safety and limit property damage, quantify hazards and risks, evaluate analytically the optimum safety measures able to limit the consequences due to fire incidents 15 and guarantee continuity to people or business involved in the fire incident. This approach perfectly fits into the idea of estimating and optimizing building fire resilience, defined as the ability to absorb and quickly recover from disruption to normal functionality.

Event tree analysis is based on the identification of an initiating and undesirable event (fire incident) causing the final outcomes (occupants’ safety and/or structural damage). All the sub-events are placed in branches following a sequential order and ideally need to be independent and mutually exclusive. Event tree analysis is therefore, characterized by a discretization of a finite number of macroscopic events, each of them associated with an intervention aimed to modify the fire development 15. For each branch in the logic tree analysis, a probability is evaluated and probabilities for each sub-event are then combined to obtain the final risk linked to a specific path. Frequency is then obtained multiplying the probability evaluated previously by the frequency associated with that particular event.

In this research, fire incidents are classified according to different property types and the related frequency obtained in terms of fires per buildings per year, where the number of buildings determined by national building stocks. For each property type, an analysis is developed according to different variables and their influence on the final consequences based on UK and USA fire statistics. For safety systems, both alarms and automatic extinguish systems will be investigated regarding their operation and effectiveness respectively on human response and notification and on the reduction of fire spread and associated damage in each property type. Two different event tree analysis have been developed for UK and USA (due to different data available) considering response and damage based on contemporary fire statistics. Moreover, damage is investigated in terms of fire spread and m2 of fire damage and total damage. Response time, defined as the time in minutes of fire brigade from the notification of the incident to the arrival at the scene, has been included to understand its influence in a fire event. Probability given by each scenario is then multiplied by the fire frequency of the analysed property type to evaluate the influence and provide helpful information for possible prevention and mitigation strategies.

The analysis investigates fire statistics data in different property types to understand how different safety protections and response time of occupants and fire brigades affect fire risks and consequences. It provides a qualitative and quantitative assessment of fire protection in reducing property damage, quantifies the risk associated with particular fire scenarios and predicts the consequences due to the application of different fire safety measures in several property types. It will also create a comparison between UK and USA fire statistics and will provides a risk assessment based on data of real buildings subjected to real fires. Further works, will generate cost-benefit and sensitivity analysis to assess the robustness of a decision based on probabilistic risk assessment and will facilitate the creation of continuity and impact plans for specific building type.

**UK AND USA FIRE STATISTICS**

The event trees developed in this paper consider contemporary UK and USA fire statistics according to response and damage. In UK, the Incident Recording System (IRS) collects information on every incident attended by fire and rescue service in the aftermath of an event. The information are gathered by automatic system and people present at the time of the incident for *Other buildings* 16 or *Dwellings* 17. The dataset considered in this analysis is the one for *Other Buildings* which covers primary fires in buildings other than dwellings in England from 2010/2011 to 2016/2017 16 with 121,558 fires. The total number of fires is divided by 7 years to have a yearly evaluation. The property types covered in this database have been group according to the following general classes: *Commercial; Educational; Utilities; Industrial; Leisure and Miscellaneous*.

In USA, the National Fire Incident Reporting System (NFIRS) have similar procedures as the UK statistics in which fire departments fill a form once attended a fire incident. USA statistics is a national collection in which all 50 states, more than 40 metropolitan areas and more than 15,000 fire departments participate every year 10. Property uses are classified in: *Assembly; Educational; Health care, detention and correction; Residential; Mercantile and Business, Industrial, utility, defence, agricultural and mining; Manufacturing, processing; Storage and Outside or Special property*. In this research, the classes of *Industrial, utility, defence, agricultural and mining and Manufacturing, processing* have been considered as a unique class named *Industrial, manufacturing* and the class of *Residential* neglected, being the paper focused on buildings other than dwellings. The USA fire statistics is divided in different parts and the information in the dataset of ‘basic incidents’ has been merged with the one of ‘fire incidents’ to have a full description of fires according to the specific property type. A total of 113,168 fires of the year 2014/2015 have been investigated and UK and USA statistical populations appear similar.

In UK and USA statistics, response time is measured in minutes of attendance after the notification of the fire incidents taken by fire brigades to arrive at the scene. In UK, there are also other two fields related to the respond of occupants described by the time in minutes from ignition to discovery and the time from discovery to call. This research has focused the results considering an ignition to discovery and discovery to call below 5 minutes for UK and response time for both UK and USA less than 9 minutes (Table 1). The value of 9 minutes response time has been based on the evaluations of the average response time in 2016/2017 for *Other Buildings* determined by the Home Office 18 and by previous analysis developed by the authors considering the USA datasets 19.

Table 1: Fire response times in UK and USA fire statistics

|  |  |  |  |
| --- | --- | --- | --- |
| **Fire response times** | | *UK* | *USA* |
| Occupants | Ignition to discovery | Under 5 minutes | / |
| Discovery to call | Under 5 minutes | / |
| Fire brigades | Response time | Under 9 minutes | Under 9 minutes |

For alarms, there are some differences in how they are recorded in the two countries. In UK, there is a unique field in which presence, operation and effectiveness are reported and the answers in which alarms were not present, did not raise the alarm or did not operate have been grouped together to simulate the scenario for no alarms (Table 2). In USA, data for presence, operation and effectiveness are separated and reported in the mentioned order. The three aspects for the alarm presence and performances need to be answered, only if the previous ones are verified as shown in Table 2. For example, if alarms were present and operated, there will be information on alert and occupant response but if alarms failed to operate than there will be no other details about these following specifications. In the case of no alarms, no other values will be provided.

Similar considerations could be applicable to automatic extinguish systems and in UK, the class of no safety systems and sprinklers or other systems which did not did not operate are summed together to simulate the scenario in which there is the absence of safety systems. The presence of sprinklers will be described considering when sprinklers or other safety systems were present, operated and alerted occupants (Table 3). In future works, these aspects will be separated to have similarities with the USA fire statistics datasets. In USA, as already explained for alarms, the classes of automatic extinguish systems present or partially present are considered together and presence, operation and effectiveness reported in the mentioned order. The presence of automatic extinguish systems and operation will provide data on effectiveness but if the fires were too small to activate or sprinklers failed to operate then information on how sprinkler performances were successful is not reported (Table 3).

Table 2: Alarms in UK and USA fire statistics

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Alarms** | | | | |
| *UK* | *USA* | | | |
| Alarm Present and raised the alarm | Present | Operated | Detector alerted | Occupants responded |
| Alarm Absent | Occupants failed to respond |
| Alarm Present but did not raise alarm | Detectors failed to alert or no occupants | |
| Alarm Present but did not operate | Failed to operate or fire too small to activate | | |
|  | None present | | | |

Table 3: Automatic extinguish systems in UK and USA fire statistics

|  |  |  |  |
| --- | --- | --- | --- |
| **Automatic extinguish systems** | | | |
| *UK* | *USA* | | |
| Sprinklers present and raised the alarm | Present or partial present | Operated | Operated and effective |
| Sprinklers operated but did not raise alarm | Operated and not effective |
| Other System present and raised the alarm | Fire too small to activate or Failed to operate, Other | |
| Other System operated but did not raise alarm | None present | | |
| No Safety System |  |  |  |
| Sprinklers present but did not operate |  |  |  |
| Other System present but did not operate |  |  |  |

In UK, for the evaluation of damage, fire size on arrival of fire brigades at the fire scene is considered if limited to room of origin. The room of origin, even if not specified in the fire statistics, will be assumed as a compartment. The fire descriptions in UK also specify if there was a rapid fire growth and fire spread is evaluated if limited to the floor of origin allowing a greater spread of fire after the arrival of fire and rescue services (Table 4). Finally, fire and total damage up to 50 m2 investigated where fire damage is defined as the total horizontal area damaged by flame and/or heat (in m2) and total damage as the total horizontal area damaged by flame, heath, smoke and/or water (in m2), both at the stop of the fire 16. In USA, fire spread is considered as limited to the floor of origin and the number of stories damaged by fire is reported. Fire damage is defined as the area (in ft2) actually burned or charred and does not include areas receiving heath, smoke, water or damage 10. Four different classes of fire damaged are specified: Minor damage (0-24%), Significantly (25-49%), Heavy (50-74%) and Extreme (75-100%). Each percentage of damage has been multiplied by the related number of floors and converted in m2 to obtain the total fire damage. Again, a limit of 50 m2 considered to have similarities with the UK statistics (Table 4).

Table 4: Damage in UK and USA fire statistics

|  |  |  |
| --- | --- | --- |
| **Damage** | *UK* | *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 m2 | Minor (0-24%) |
| Significantly (25-49%) |
| Heavy (50-74%) |
| Extreme (75-100%) |
| Total damage | Up to 50 m2 | / |

Fire statistics parameters have been consequently inserted in the event trees to understand likelihood and consequences of several scenarios based on fire incidents of UK and USA. The results will increase the awareness of the influence of failure systems on response time and structural damage, provide an optimization in evacuations measures and time of attendance of fire brigade as well as investigate performances of different safety measures on fire growth and spread.

# UK AND USA FIRE FREQUENCIES

Once context and objectives of the analysis have been specified, it is important to evaluate the frequency and the likelihood. Frequency is defined as the number of fires divided by the total number of buildings and it is determined for each property type in UK and USA. Numbers of fires according to specific building occupancies have been obtained respectively in the IRS for UK and in the NFIRS for USA. Since in UK data are collected from 2010/2011 to 2016/2017, the total number of fires is divided by seven to have a yearly estimate while in USA data are already referred to a single year 2014/2015.

Two different building stocks have been investigated for UK and USA. In UK, ‘Non-domestic rating stock: Stock of Property England and Wales’ published by the Valuation Office Agency 20, has been considered to obtain the rateable number of properties to associate with the number of fires in the IRS. In USA, building stock is determined by the US Energy Information Administration 21, which includes the Commercial buildings energy consumption survey (CBECS) 22 and the Manufacturing energy consumption survey (MECS) 23. Both are national surveys that determine the number of non-residential buildings in USA according to different building sizes.

Fire frequency in UK appears to have a range of values approximately 5 times bigger considering peaks, than the one in USA according to Figure 1. This could be due to the fact that only the USA fire statistics in which the property types are specified has been used. In UK, the highest values are reached for *Miscellaneous* (0.058%) and *Utilities* (0.028%) while the lowest in *Commercial* (0.006%) as shown in Figure 1(a). The classes of *Educational* and *Industrial* buildings could be found in both countries with values respectively of 0.016-0.002% and 0.006-0.007% correspondently in UK and USA. While *Educational* in UK has a higher percentage than in USA, in *Industrial* the values in the two countries appear comparable. In USA, *Storage* and *Outside or Special Property* assume a similar value of 0.010% which represents also the highest frequency, followed by *Industrial* (0.007%) and *Assembly* (0.004%) (Figure 1(b)). It is important to specify that the frequency for each property type describes how often the related event tree will occur.

|  |  |
| --- | --- |
| (a) | (b) |
| **A**. Commercial; **B**. Educational; **C**. Utilities; **D**. Industrial; **E**. Leisure; **F**. Miscellaneous | **A**. Assembly; **B**. Educational; **C**. Health care, detention and correction; **D**. Mercantile, Business; **E**. Industrial; **F**. Storage; **G**. Outside or Special property |

Figure 1: Frequency in a) UK and b) USA

The frequencies evaluated in this analysis will multiply the probability obtained in each path of the event tree to understand the influence that a fire scenario has in relation to the fire frequency per building per year of different property types.

# EVENT TREE ANALYSIS FOR RESPONSE

Event trees have been developed for each property type in UK and USA to understand the detector performances and the response of occupants and fire brigades to fire incidents. The analysis for each country has been evaluated separately to consider differences in data collection and fire safety fields reported by the two fire statistics. The values adopted for the response, ignition to discovery and discovery to call times in UK and USA are specified in Table 1 and how alarm fields are applied described in Table 2. Probability for each path calculated in the event trees, will be multiplied by the frequency related to the specific property type analysed.

# UK response

The event tree related to the fire response in UK is evaluated considering the present and absent of alarms as specified in Table 2. The paths analysed present three different phases: the first one in which it is verified if the ignition to discovery time is under five minutes, the second one in which the discovery to call is checked if under five minutes and the third phase where a response time less than 9 minutes is considered. There are 8 total scenarios and once these are repeated for the two conditions of presence (called alarms ‘a’) and absence of alarms (named as no alarms ‘na’), 16 total response scenarios are obtained as described in Table 5.

Table 5: Event tree for response in UK

|  |  |  |  |
| --- | --- | --- | --- |
| **Ignition to discovery**  [5 mins] | **Discovery to call**  [5 mins] | **Response time**  [9 mins] | **Scenarios** |
| 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 presence and absence of alarms are compared, scenarios 1 and 2 assume the highest percentages where the ignition to discovery and discovery to call are both under 5 minutes and the response time is less than or more than 9 minutes for Scenario 1 and Scenario 2, respectively. The related percentages when alarms are present, could vary in Scenario 1a between 0.11% in *Commercial* and *Utilities* and approximately 0.30% in *Educational* and *Miscellaneous* while in Scenario 2a the highest value is reached in *Industrial* with 0.12%. When no alarms are present, Scenario 1na assumes values between approximately 0.16% in *Educational*, *Industrial* and *Miscellaneous* and 0.25% in *Commercial* and *Utilities* while in Scenario 2na between 0.06% in *Educational* and 0.17% in *Utilities*. Scenario 5na and 6na present particular relevance in fires with no alarmsand they are described as ignition to discovery greater than 5 minutes, discovery to call less than 5 minutes and the response time is less than or greater than 9 minutes for Scenario 5na and Scenario 6na, respectively. In particular, values vary in Scenario 5na between 0.12% in *Miscellaneous* and 0.28% in *Commercial* and in Scenario 6na between 0.05% in *Educational* and 0.12% in *Commercial*, *Utilities* and *Miscellaneous* (Figure 2).

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Figure 2: Probability in response scenarios in UK

In Figure 3, frequency is calculated multiplying the probabilities by the related frequency expressed in Figure 1. Figure 3 shows that the highest frequencies are reached in *Educational* 0.0047-0.0015% and *Utilities* 0.0031-0.0018% respectively in Scenarios 1a and 2a. When alarms are absent, frequencies assume the greatest influence in scenario 1na, 2na, 5na and 6na. The class of *Utilities* has the highest peaks approximately of 0.0073-0.0048-0.0051% followed by *Educational* 0.0024-0.0009-0.0021% respectively in scenario 1na, 2na and 5na. In Figure 3, *Miscellaneous* property is not reported because it presents the highest values of 0.0168-0.0056-0.0086-0.0050% respectively in 1a, 2a, 1na and 2na.

|  |
| --- |
| No Miscellaneous property |

Figure 3: Frequency in response scenarios in UK

As evaluated in Figure 2 and Figure 3, probabilities in different occupancy types assume values 10 times bigger than the related frequencies where the immediate response of occupants and fire brigade is very efficient in the first minutes after the ignition of the fire. Response time is well confined within 9 minutes and general considerations could be deduced for both presence and absence of alarms with small differences in values except for scenario 5 and 6.

# USA response

The event tree for response in USA, present non-symmetric paths for presence (called detectors ‘d’) and absence of detectors (named as no detectors ‘nd’). This is due to how the data are collected in the NFIRS and, when detectors are present, there are other fields related to operation, effectiveness and occupant response. These mentioned aspects are empty when detectors are absent. The total number of scenarios is less than the one in UK and equals to 10 with 8 scenarios for detectors and 2 for absence of detectors as shown in Table 6.

Table 6: Event tree for response in USA

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Detectors** | **Operation** | **Effectiveness** | | **Response time**  [9 mins] | **Scenarios** |
| 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** | | | | | |

In Figure 4, it is clear that when detectors are present the most likely scenarios are the 1d, 7d and 5d in this order. In Scenario 1d, detectors operated, alerted occupants, occupants responded and the response time is less than 9 minutes; in 7d, detectors failed to operate but response time is less than 9 minutes and in 5d, detectors operated, failed to alert occupants and response time is less than 9 minutes. In Scenario 1d, probabilities vary from 0.18% in *Mercantile, Business* to 0.54% in *Health care, detention and correction*. In Scenario 7d, values assume percentages between 0.08% in *Industrial, manufacturing* and approximately 0.20% in *Assembly* and *Health care, detention and correction*. In both scenarios, values for *Storage* and *Outside or Special property* are neglected having approximately null values. Even if detectors are not present, response time seems to be less than 9 minutes for the majority of cases as shown by Scenario 9nd with values from 0.13% in *Health care, detention and correction* to 0.68% in *Storage*. Finally, in Scenario 10nd the highest values are reached in *Industrial, manufacturing*, *Storage* and *Outside or special property* (0.18-0.28-0.26%) while the other properties have less than 0.06%. In 4d, probabilities are less than 0,02% for the occupancy types analysed.

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Figure 4: Probability in response scenarios in USA

When frequencies are evaluated by multiplying the probabilities in Figure 4 by the building frequencies in Figure 1, the most relevant scenarios are the same found for the probability in Figure 4. The difference is given by values that for frequencies are approximately 10 times smaller than the ones for probabilities. In the case when detectors are present, values are always less than 0.0020%. In Scenario 9nd and 10nd, the highest values are given in *Industrial, manufacturing* (0.0028-0.0013%) and in *Storage* and *Outside or special property* (approximately 0.0070-0.0030%). In Scenario 9nd, *Assembly* assumes 0.0016% and the other properties are less than 0.0010% while in Scenario 10nd the other occupancies are approximately null (Figure 5).

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Figure 5: Frequency in response scenarios in USA

In USA, the event trees evaluated for the response show that fire scenarios more likely to happen, are the ones in which detector were present, operated, alerted occupants and occupants responded with attendance of the fire brigade less than 9 minutes. Even when detectors are not present, response time of fire brigade appear to be less than 9 minutes for the majority of cases

# EVENT TREE ANALYSIS FOR DAMAGE

Event trees for damage in UK and USA have been developed according to the presence or absence of sprinklers as described in Table 3 and the parameters for damage specified in Table 4. Unfortunately, due to the elevated number of scenarios considered, only the most relevant paths will be presented in this paper. The event tree scenarios related to the presence of sprinklers will be called ‘s’ while the ones related to the absence of sprinklers named as ‘ns’ in both UK and USA.

# UK damage

In UK fire statistics, several damage paths have been considered to evaluated fire size on arrival, rapid fire growth and fire and total damage in m2 according to the parameters in Table 4. A total of 64 scenarios have been obtained but due to data missing and values approximately equal to zero, 8 paths (4 for sprinklers and 4 for no sprinklers) have been found as the most significant and described in Table 7. The four damage scenarios considered in Figure 6 present different values for probabilities but they all represent cases in which spread of fire is well confined, fire damage up to 50 m2 while response time could be less (Scenario 9 and 10) or greater (41-42) than 9 minutes and total damage greater than 50 m2 in Scenario 10 and 42.

Table 7: Event tree for damage in UK

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Response time**  [9 mins] | **Fire size on arrival**  [Limited to room of origin] | **Rapid fire growth** | **Spread of fire**  [Limited to floor of origin] | **Fire damage**  [50 m2] | **Total damage**  [50 m2] | **Scenarios** |
| Response time < | Limited | No | Limited | Fire damage < | Total damage < | 9 |
| Response time < | Limited | No | Limited | Fire damage < | Total damage > | 10 |
| Response time > | Limited | No | Limited | Fire damage < | Total damage < | 41 |
| Response time > | Limited | No | Limited | Fire damage < | Total damage > | 42 |
|  | **Sprinklers = s; No sprinklers = ns** | | | | | |

When sprinklers are present, the property types which assumes the greatest values is *Industrial* with 0.03-0.01-0.02% respectively in 9s, 10s and 41s (Figure 6(a)). In 9s and 41s, the second and third highest values are reached by *Utilities* and *Miscellaneous* with a value of approximately 0.01%. In 42s, *Commercial*, *Leisure* and *Miscellaneous* present approximately null values. While when sprinklers are present there is greater variation in values for the different property types, when sprinklers are absent values appear similar with a percentage of approximately 0.50% in 9ns and 0.20% in 41ns as showed in Figure 6(b) where *Educational* present 0.59% in 9ns and *Utilities* 0.32% in 41ns.

|  |
| --- |
| (a) |
| (b) |

Figure 6: Probability in the most relevant damage scenarios (a) with and (b) without sprinklers in UK

Frequencies for scenarios with and without sprinklers (Figure 7) assume similar trends but with percentages approximately 10 times greater when sprinklers are absent. The peaks are reached in *Miscellaneous* (0.0005-0.0309%) followed by *Utilities* (0.0002%-0.0143%) respectively in 9s and 9ns. In Scenario 41, while the third highest value is represented by *Industrial* when sprinklers are present (0.0001%) when sprinklers are absent the third property is given by *Educational* (0.0032%).

In UK, the most likely scenarios representing the damage conditions in different property types are described by fire well confined in the room of origin at arrival of fire brigade and to the floor of origin at the end of the incident with no-rapid fire growth. Even when response time is greater than 9 mins, fire damage appear well confined within 50 m2 of fire damage. According to the results obtained, compartmentation is efficient in the property types analyzed and fires do not grow rapidly.

|  |
| --- |
| (a) |
| (b) |

Figure 7: Frequency in the most relevant damage scenarios (a) with and (b) without sprinklers in UK

# USA damage

The event tree to evaluate damage in USA considers 32 scenarios with 24 scenarios for presence of sprinklers and 8 for absence. Parameters considered for response time, automatic extinguish systems and damage are described respectively in Table 1, Table 3 and Table 4. The paths, which appear to be the most relevant, are reported in Table 8. Within the 7 scenarios considered, 2 are associated with presence of sprinklers and 5 with absence of sprinklers. In 17s and 19s, sprinklers failed to operate, response time is less than 9 mins, and fire damage confined to 50 m2 but while fire spread is limited to the floor of origin in 17s, it is not limited in 19s. The scenarios related to absence of sprinklers in Table 8 describe fire situations in which fire spread is not limited in the majority of paths (27ns, 28ns, 31ns and 32ns) while response time is limited to 9 minutes in 25ns, 27ns and 28ns. Fire is limited to floor of origin and fire damage less than 50 m2 only in 25ns.

Table 8: Event tree for damage in USA

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Sprinklers** | | | **Response time**  [9 mins] | **Fire spread**  Limited floor of origin | **Fire damage**  [50 m2] | **Scenarios** |
| **Presence** | **Operation** | **Effectiveness** |
| Present | Failed to operate | / | Response time < | Limited | Fire damage < | 17s |
| Present | Failed to operate | / | Response time < | Not limited | Fire damage < | 19s |
| Absent | / | / | Response time < | Limited | Fire damage < | 25ns |
| Absent | / | / | Response time < | Not limited | Fire damage < | 27ns |
| Absent | / | / | Response time < | Not limited | Fire damage > | 28ns |
| Absent | / | / | Response time > | Not limited | Fire damage < | 31ns |
| Absent | / | / | Response time > | Not limited | Fire damage > | 32ns |

When probability is analysed in 17s, *Health care, detention and correction* presents 0.42%, *Educational* 0.25%, and *Mercantile, Business* and *Industrial, manufacturing* 0.12%. In building fires without sprinklers, scenarios 25ns and 27ns assume the highest percentages with response time less than 9 mins. In 25ns, when fire is limited to floor of origin and fire damage up to 50 m2, the highest peaks are reached by *Educational* (0.45%), *Mercantile, Business* (0.40%), *Assembly* (0.33%) and *Health care, detention and correction* (0.28%). In 27ns, fire spread is not limited to floor of origin and percentages vary between 0.06% in *Health care, detection and correction* and 0.45% in *Storage* as showed by Figure 8.

Again, frequencies are obtained multiplying percentages in Figure 8 by the frequencies in Figure 1. In Figure 9, similar considerations as in Figure 8 can be deduced with the difference that in 17s values are less than 0.0020%. In 25ns, the average frequency is approximately 0.0014% with a peak of 0.0027% in *Outside or special property*. In 27ns, the highest values are in *Storage* (0.0046%) and *Outside or special property* (0.0040%) followed by *Industrial, manufacturing* (0.0009%) and *Assembly* (0.0006%).

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Figure 8: Probability in the most relevant scenarios in USA

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Figure 9: Frequency in the most relevant scenarios in USA

The damage scenarios analyzed in USA reveal that the typical fire incidents according to the parameters considered in the analysis, are in buildings not equipped with sprinklers, with response time within 9 minutes and fire that could be not limited to the floor of origin. Further works, will investigate if the limited data in sprinklered buildings are given by the nature of the datasets or by the fire safety fields involved.

# CONCLUSIONS

In this paper, current UK and USA fire statistics have been analysed to investigate fire scenarios in different building types related to the response and damage of fire incidents according to presence and performances of alarms and sprinklers. Building stock of UK and USA have been analysed to obtain the total number of buildings at risk and calculate fire frequencies defined as total number of fires per building per year. Frequencies are then multiplied by the probability obtained in each path of the event trees to understand the implication of particular scenarios in real world.

In the event trees for response, alarms presence, operation and effectiveness as well as occupants and fire brigade response have been considered to evaluate the time between ignition and first mitigation measures. In UK, for presence or absence of alarms, ignition to discovery and discovery to call appear less than 5 minutes and response time confined to 9 minutes. In USA, values are greater when detectors are absent but, even in this case, response time seems well confined within 9 minutes. The most relevant damage scenarios in UK present fire size on arrival limited to room of origin, not-rapid fire growth, spread of fire within room of origin and fire damage up to 50 m2 where total damage is in general less than 50 m2 for both presence or absence of sprinklers. In USA, the most significant scenarios appear especially when sprinklers are absent with greater consequences being the fire not limited to the floor of origin.

Further works, will analyse how changing the limits in the parameters analysed has an influence on the consequences in terms of increase in response and structural damage. The results could be applied to cost-benefits analysis to assess the decisions in fire risk assessments. Fire statistics of future years will be adopted to implement the datasets considered and increase the number of fires for the different property types.

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