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# Fire safety design of open plan apartments in England

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# Abstract

A review has been undertaken which focusses on the fire safety document ‘Open plan flat layouts’ (NF 19), where the review identifies that NF 19 comes with limitations in its representation of sprinkler performance and its adopted values for door closing behaviours, location of fires, heat release rate and number of occupants when compared to more recent literature. To assess the impact of assumptions for door closing behaviours and fire location specifically, an event tree analysis of exemplar apartments has been undertaken, comparing NF 19 assumptions to data from literature. This analysis indicates that the previous assumptions for these parameters would not be expected to alter the conclusions of NF 19. As a result of the review and analysis, recommendations are made for the design of open plan apartments. The paper ultimately lays the groundwork for future studies, where additional assessments are needed to consider other NF 19 assumptions, including sprinkler performance, as well as to reassess existing guidance limitations derived from NF 19.

# Keywords

Residential; Apartments; Flats; Open plan; Fire safety.

# Introduction

There appears to be an increasing desire by apartment residents in England to have more open plan living arrangements than in the past. As a result, a greater number of construction projects include open plan apartment layouts (otherwise referred to as open plan flats). In the context of fire safety, open plan apartments refer to situations where there are ‘inner rooms’ connected to an ‘access room’ which forms the only escape route. For open plan design, the access room is typically adopted as the living area and includes the apartment exit, and inner rooms can include bedrooms and kitchens. The access room will include combustible items which, in the event of a fire, could present a hazard the escape of occupants located within the inner rooms. Open plan apartments therefore present several fire design challenges, mainly because of the lack of fire separation that is present, combined with there being the potential for sleeping occupants (located in inner rooms) at the time of an incident.

In the UK, the first set of nationwide building standards were introduced as part of the Building Regulations 1965, although other local standards, such as the London Building Acts and the Building Standards (Scotland) Regulations 1963 pre-dated its introduction. In 1985, the Building Act 1984 was introduced, with the provision of ‘approved documents’ (discussed below) outlining non-prescriptive recommendations on how to meet the Building Regulations. The devolvement of the UK into its constituent countries has resulted in separate building regulations for each country, such as the Scottish Building Standards and the Building Regulations (Northern Ireland). For this reason, the guidance of England is specifically referred to and discussed in this paper, although much of the discussion still has relevance to the wider UK.

In England, the Secretary of State provides a series of documents that give practical guidance on how to meet the functional requirements of the Building Regulations, referred to as approved documents. These documents provide guidance for common building situations. Approved Document B (ADB) (HM Government, 2019a, 2019b) focusses on guidance for fire safety, providing design recommendations relating to means of escape and warning, internal fire spread, external fire spread and access and facilities for the fire service. ADB is distributed in two volumes, where Vol. 1 (HM Government, 2019a) is for dwellings and Vol. 2 (HM Government, 2019b) is for buildings other than dwellings. Prior to the release of the 2019 edition, ADB Vol. 2 (HM Government, 2013) previously included recommendations for the design of residential buildings excluding 'dwellinghouses', a unit of accommodation occupied by not more than six residents living together as a single household.

Applying the guidance of ADB is one means of demonstrating that a common building complies with the Building Regulations, but ADB notes that there are other ways to comply with the requirements beyond the means described in an approved document. One method referred to in ADB is to use 'fire safety engineering', the application of scientific and engineering principles to the protection of people, property and the environment from fire (BSI, 2019a). Other guidance documents may also be adopted instead, such as British Standards in the form of BS 9999 (BSI, 2017) for general building design and BS 9991 (BSI, 2015) for residential buildings.

# Methodology

### *Guidance and literature review*

This paper presents a review of the fire safety design of open plan apartments in England, where the intent of the review is to identify important considerations for future computational studies of safety levels associated with open plan apartments. The review begins by discussing the progression of (design) guidance documents in England from the 1970s to present day, noting the challenges faced by fire safety engineers in the limited flexibility of open plan apartment design.

The document ‘Open plan flat layouts – Assessing life safety in the event of fire’ (Fraser-Mitchell & Williams, 2009a, 2009b) (referred to hereafter as NF 19), which has had a strong influence on practices and guidance in England (and the wider UK) from 2009 onwards, is then reviewed from a technical viewpoint.

For brevity, the review of NF 19 is structured to focus on key assumptions most likely to impact the outcome of the study. These are:

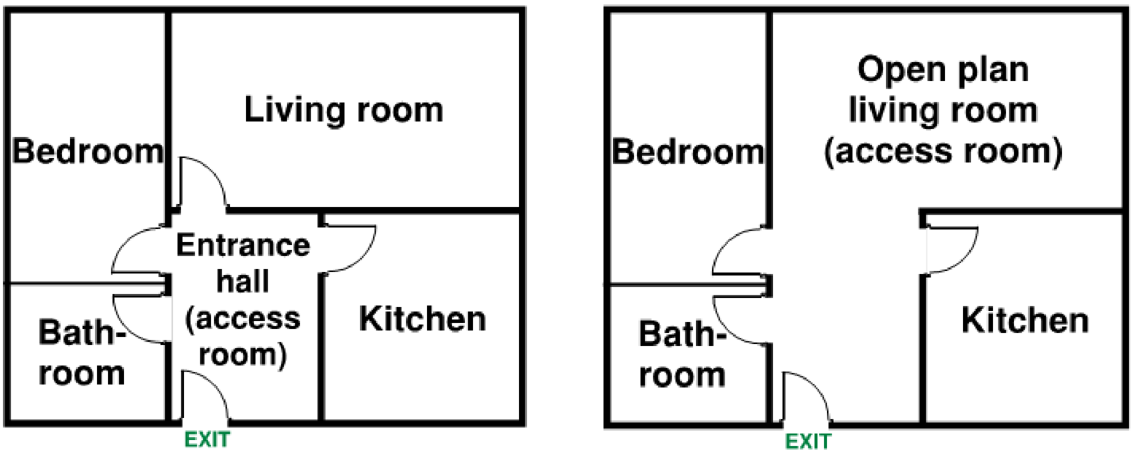
- **Door closing behaviours** – internal door closing behaviours play a significant role in smoke spread between rooms during the development of a fire;
- **Location of fires** – when twinned with door closing behaviour assumptions, the fire location is also important in considering the possibility of smoke spread between rooms;
- **Heat release rate (HRR)** – the HRR directly affects the gas temperature and the production of soot and toxic gases, influencing the tenability of an environment;
- **Sprinkler reliability and performance** – sprinkler performance impacts the HRR and temperatures of a sprinkler protected enclosure affected by fire; and
- **Number of occupants** – the number of occupants is an indicator of the potential consequence of a fire and the resulting risk, where risk is a function of hazard, likelihood and consequence (Watts & Hall, 2016).

The conclusions of NF 19 have been assessed with additional discussion on the implications this has for approaches to future design, particularly in circumstances where fire safety engineers wish to consider designs outside the scope of NF 19 and the associated recommendations of BS 9991.

### *Event tree analysis*

Following the review, an event tree analysis has been undertaken to determine differences in the assumptions of NF 19 compared to information available in more recent literature, focussing on probabilities associated with internal door closing habits and the likelihood of fires occurring in certain room types. Hurley & Rosenbaum (2016) suggest that event trees are often used in fire safety engineering to analyse complex situations where many outcomes are possible, and event trees are therefore considered a valuable tool when identifying possible fire scenarios (Hadjisophocleous & Mehaffey, 2016). Frantzich (1998) provides an example application of event trees to determine solutions which achieve an adequate level of safety compared to commonly accepted designs.

The event tree analysis focusses on two exemplar apartment scenarios. Scenario I, an exemplar single bedroom apartment with protected entrance hall, designed to the recommendations of ADB, is shown in Figure 1a. Scenario II is a single bedroom open plan apartment with an enclosed kitchen (with a floor area greater than 8 m by 4 m) and is shown in Figure 1b. The fire safety relevance of these arrangements is discussed later as part of the guidance and literature review.



a) Scenario I, protected entrance hall apartment

(Meet the recommendations of ADB)

b) Scenario II, open plan apartment

(Meets the recommendations of BS 9991)

*Figure 1: Exemplar apartments arrangements considered in the event tree analysis.*

For these arrangements, occupants may experience greater consequences from a fire should it occur while they are sleeping, due a reduced susceptibility to auditory and visual cues and the possibility of prolonged pre-evacuation times (Gwynne & Boyce, 2016). This observation was demonstrated in NF 19 (Fraser-Mitchell & Williams, 2009a), where greater sensitivity in results was associated with waking time of sleeping agents. Given this, an event tree analysis of an apartment fire has been considered while an occupant is sleeping in the bedroom. This fire is assumed to be of a great enough severity to cause smoke spread between rooms if doors are left open.

The analysis considers a fire in three main room types: kitchens, living rooms and bedrooms. The possibility of a fire in other rooms, such as bathrooms and utility rooms has been excluded from the event tree analysis due to their lower likelihood of occurrence and also to simplify the analysis. It has also been assumed that a fire will not occur in the protected entrance hall, for reasons discussed in the next section.

The analysis therefore serves solely as a comparison between the NF 19 assumptions for door closing behaviours and fire location and is not intended to provide a comparison of performance between apartments with protected entrance halls and open plan apartments.

Figure 2 provides an example event tree for a protected entrance hall arrangement, where the outcome focusses on the likelihood that bedroom or access room becomes contaminated with smoke. The final probabilities are generated by multiplying probabilities along the branches of the tree. For example, the uppermost branch of Figure 2 is determined by multiplying the probability that a fire occurs in a kitchen by the probability that a kitchen door is open and then by the probability that the bedroom door is open.

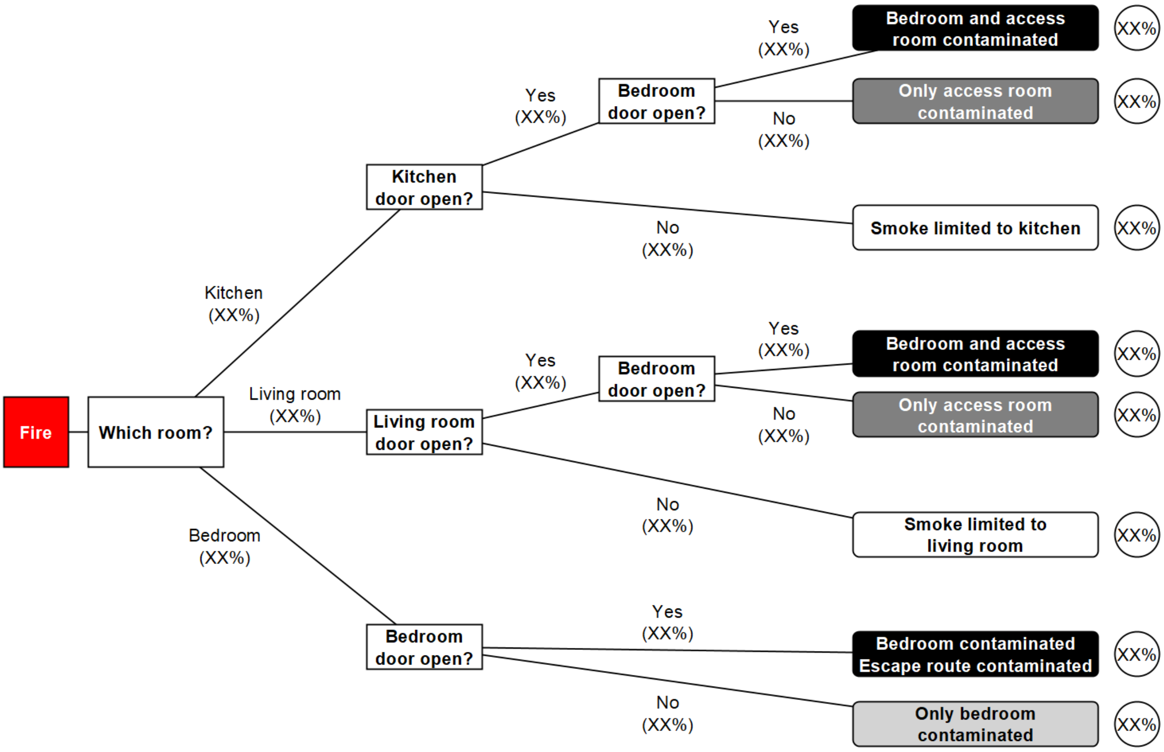


*Figure 2: Example event tree for a protected entrance hall arrangement (XX% indicates probability).*

# Review of fire design guidance in England

### *Progression of guidance*

In the British Standard ‘Code of Practice CP 3 Chapter IV – precautions against fire’ (CP 3) (BSI, 1971) first issued in 1971, it recommends that any apartment provided with a single exit should include a protected escape route within it (an ‘entrance hall’), and that there is ‘no appreciable fire risk’ located in the entrance hall or circulation space. It goes on to state that if it were not the case then it would otherwise be necessary for every apartment to have an alternative exit from every room. As described in CP 3, the reason for the need for a protected escape route is that fires occurring in kitchens or living rooms (particularly when these rooms are unoccupied) are considered a major threat to occupant safety as they may develop to ‘serious proportions’ whilst occupants are asleep in their bedrooms. The purpose of such an arrangement is therefore to help limit fire and smoke spread from the room of fire origin into the entrance hall, and to maintain a tenable escape route for evacuating occupants for an appropriate period.

With the introduction of means of escape recommendations from CP 3 into ADB in 1992 (Department of the Environment and the Welsh Office, 1992), the recommendations regarding entrance halls were adopted. These recommendations have broadly been maintained with the 2019 edition of ADB Vol. 1 (HM Government, 2019a) recommending that any apartment which incorporates ‘inner’ rooms (except for certain exclusions discussed later), or where travel distances to the apartment exit exceed 9 m, are provided with a protected entrance hall. This is shown indicatively in Figure 3, for an apartment where the final exit is assumed to open into a common corridor with the door fitted with a self-closing device. In these circumstances, internal fire doors are required to separate the fire-resisting protected entrance hall from connected rooms, but a self-closing device is not recommended – this was amended in the 2006 edition of ADB as it was found that internal doors with self-closing devices were commonly tampered with or propped open (Hopkin et al., 2019a). The maximum travel distance from the door of any habitable room to the apartment final exit door (shown in green in Figure 3) should also be 9 m or less.

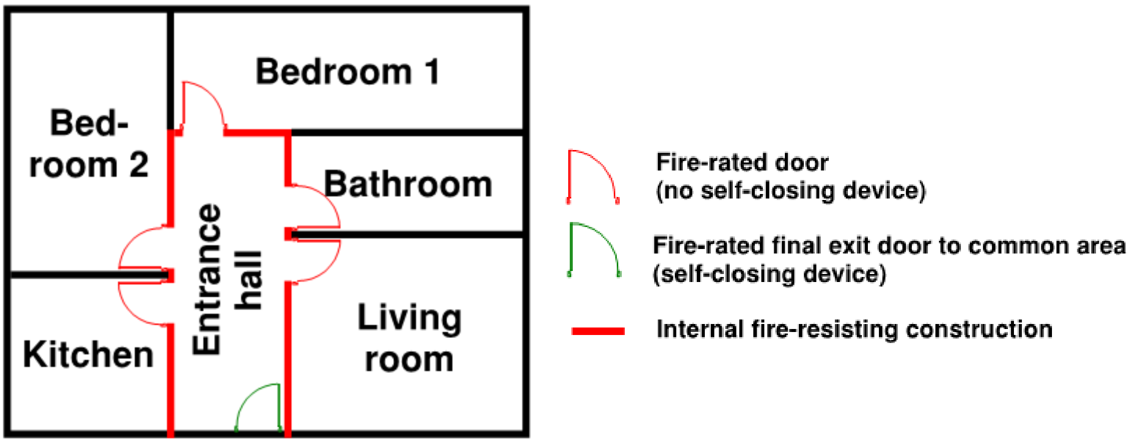


*Figure 3: Indicative protected entrance hall arrangement designed to ADB (reproduced from Hopkin et al. [2019a]).*

In circumstances where a protected entrance hall is not provided, the 2019 edition of ADB Vol. 1 (HM Government, 2019a) (and prior editions of ADB Vol. 2 [HM Government, 2013]) sets out permissible arrangements for inner rooms. It notes that an inner room is acceptable when: it is a kitchen; a laundry or utility room; a dressing room; a bathroom; a toilet or shower room; or any other room on a floor not more than 4.5 m above ground level (subject to inclusion of escape windows). Where inner rooms are incorporated, the access room should not be a kitchen. Such arrangements, where the sleeping accommodation, living area and / or kitchen are all part of the same room, are considered permissible when travel distances in a single direction (i.e. to the apartment final exit) are limited to 9 m, shown indicatively in Figure 4. These are described in ADB as ‘flats with restricted travel distances’ but for the purposes of conciseness and common understanding are referred to hereafter as studio apartments.

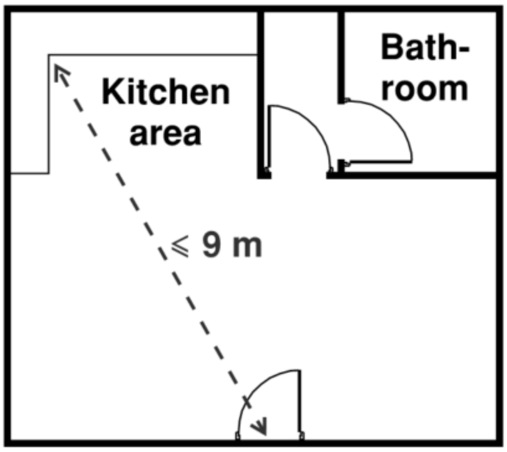


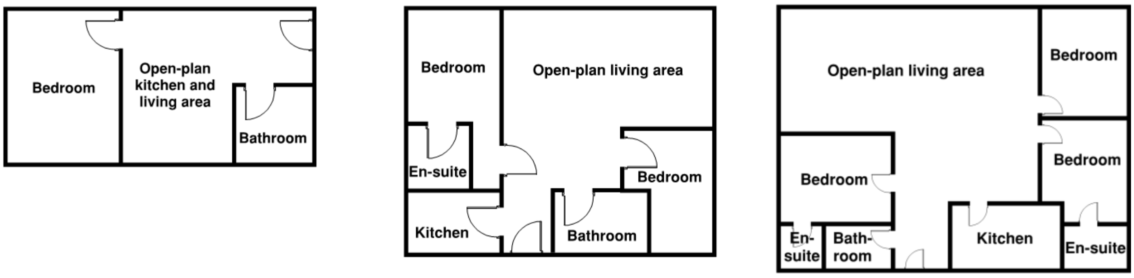
*Figure 4: 'Flats with restricted travel distance', reproduced from ADB (HM Government, 2019a).*

For the above described arrangements, i.e. both those with protected entrance halls and restricted travel, ADB recommends that a Grade D2 LD3 automatic detection and alarm system is provided in accordance with BS 5839-6 (BSI, 2019b). This type of system typically incorporates interlinked domestic smoke alarms in all circulation spaces that form part of the escape routes from the apartment (e.g. within the protected entrance hall or within the main room of a studio apartment).

For apartment design, the recommendations of ADB pose a significant limitation on the conditions for adopting bedrooms as inner rooms. In recognition of this, the National House Building Council (NHBC) commissioned the Building Research Establishment (BRE) to undertake a study (NF 19) into the risk from fires associated with open plan apartment arrangements. This study formed the basis for recommendations in both BS 9991:2011 (BSI, 2011) and its revision in 2015 (BSI, 2015).

NF 19 included computational modelling and Monte Carlo simulations of several apartment arrangements and fire and evacuation scenarios, where the relative level of safety achieved in ADB-based (protected entrance hall) layouts and open plan apartment layouts were assessed via comparative analyses. The analyses considered three 'typical' apartment layouts, shown in

Figure 5, with one-bedroom, two-bedroom and three-bedroom apartments. From NF 19 it was determined that open plan apartment arrangements could achieve an equivalent or improved level of safety relative to guidance recommendations. This was reliant on the additional measures of residential sprinkler protection and the inclusion of an enhanced automatic detection and alarm system. With respect to detection and alarm, NF 19 recommended that smoke detectors / alarms be included in all habitable rooms (excluding bathrooms) and heat detectors / alarms provided in kitchens. This aligns with a Grade D LD1 system designed to BS 5839-6 (BSI, 2019b). An LD1 system incorporates interlinked detectors / alarms in all circulation areas that form part of the escape route. Detectors / alarms are also in all rooms and areas, other than those with 'negligible sources of ignition', which includes toilets, bathrooms and shower rooms.



a) Case 1c

(8 m by 4 m)

b) Case 2c

(10 m by 8 m)

c) Case 3c

(16 m by 12 m)

*Figure 5: Open plan apartment layouts considered in NF 19 (reproduced from Hopkin et al. [2019c] and NF 19 [Fraser-Mitchell & Williams, 2009a]).*

Following these analyses, BS 9991:2011 (BSI, 2011) adopted recommendations in which it was considered acceptable for open plan apartments (with enhanced detection and sprinkler protection) smaller than 10 m by 8 m to have an unenclosed kitchen (i.e. a kitchen directly open to the living room). However, as shown in Figure 5, this did not align with the original recommendations of NF 19, where only one of the apartment arrangements assessed had the kitchen unenclosed – an 8 m by 4 m single bedroom apartment. In the 2015 revision of BS 9991 (BSI, 2015), the room size restriction was reduced to an area of 8 m by 4 m to align with NF 19.

The current situation is that should a fire safety engineer want to consider a building design in England which includes open plan arrangements, it is necessary that they consider one of the following: a) adopt BS 9991 for the fire safety design of the building in its entirety; b) adopt ADB but reference BS 9991 or NF 19 specifically in the context of the open plan apartments design; or c) provide an alternative fire engineering assessment to demonstrate that the design meets the Building Regulations.

### ***Unenclosed kitchens and kitchen location***

In 2014, BRE were commissioned to undertake additional research into whether unenclosed kitchens posed an elevated risk to occupants in open plan apartments. The research also considered the use of concealed sprinkler heads compared to NF 19 which adopted quick response heads. The outcomes of this research are discussed by Davis et al. (2016), where a single three-bedroom apartment layout was assessed again but for an unenclosed kitchen (an adaptation of Figure 5c shown previously). The procedure, inputs, personnel, modelling tools, etc., were identical to that originally reported in NF 19.

The results of the updated 2014 BRE study were compared against the original NF 19 study and it was found that the risk to occupants in the cases where the kitchen was not enclosed was lower than in the case for an enclosed kitchen (even when subject to quick response sprinkler heads). According to Davis et al., this was attributed to providing earlier smoke detection, and therefore a quicker time to evacuation for occupants. In addition, an open plan apartment with an unenclosed kitchen was also demonstrated to provide a better level of safety to occupants than an apartment with a protected entrance hall not afforded sprinklers (per ADB), inclusive of cases where concealed heads were adopted. This assessment indicated that adopting unenclosed kitchens in open plan apartment design can be considered acceptable for apartments up to a floor area of 16 m by 12 m, noting that 'although it cannot be categorically confirmed without further simulations, it is likely that the conclusions of this study would [also] extend to a two-bedroom case'.

By including unenclosed kitchens in an apartment design, additional considerations are needed in terms of what is considered an acceptable location of the kitchen, such as where it is located relative to the occupant escape route and where it is located relative to the final exit of the apartment. For the internal planning of single level apartments, ADB (HM Government, 2019a) recommends that cooking facilities are positioned remote from the main entrance exit door and that they should not impede the escape route from 'anywhere' in the apartment. Similarly, BS 9991 (BSI, 2015) specifies that cooking facilities in open plan apartments should be located in such a way that they 'do not prevent escape if they are involved in a fire' and that cooking facilities should be sited away from the apartment exit door and the internal escape route. However, neither document details nor defines what can be considered 'remote', such as in terms of distance of the cooking facilities from the escape route / apartment exit. Fire safety engineers are therefore required to undertake a quantitative assessment, or make a qualitative judgement in the context of other guidance recommendations, to determine an adequate separation distance between cooking facilities and the escape route.

# Review of NF 19

### *Overview*

As can be seen from the previous discussion, residential design for apartments in England has been significantly influenced by NF 19 and its adoption in guidance documents such as BS 9991.

NF 19 adopted comparative analyses to determine whether open plan apartment arrangements could achieve an equivalent level of safety to guidance-based designs, i.e. the safety levels were not explicitly quantified. To achieve this, the Computation of Risk Indices by Simulation Procedures (CRISP) evacuation and fire spread computer model (Fraser-Mitchell, 1999) was used to model fire and smoke as well as human behaviour, applying the Monte Carlo method to generate a series of simulation results and a distribution of tenability outputs, where the results were reliant on repeated sampling of inputs from defined distributions or discrete probabilities.

CRISP includes a two-layer zone model coupled with a model of human behaviour and movement. For the human behaviour, agents can adopt a number of behavioural roles, such as whether to escape, investigate, warn others, fight the fire or await rescue. These roles are influenced by the status of an agent and whether they are considered dependent (such as children), a follower or a leader. The geometry can be populated with multiple agents whose type, such as whether they are elderly or disabled, dictates their dependent / follower / leader status. Tenability of these agents is measured using fractional effective dose (FED), a measure of incapacitation from asphyxiant gases (Purser & McAllister, 2016).

In NF 19, both agents who were awake (day time) and sleeping (night time) were considered, although it is indicated that the time taken by an agent who was already awake to react to an alarm made limited difference to the results and greater sensitivity was associated with the time taken by sleeping agents to awaken (Fraser-Mitchell & Williams, 2009a). Sensitivity results were therefore presented in the form of FED against a ‘waking-up time’.

Fire scenarios within the CRISP zone model are generated randomly based on ‘UK fire statistics’. The permutations of fire scenarios are dependent upon season, time of day, room type and type of burning item. The burning item then determines the fire growth rate, burning duration and associated yields. Various types of detectors may be located within the model, including smoke detectors, heat detectors and sprinklers. Alarm resulting from smoke and heat detection can in turn influence the response of occupants and sprinklers influence the fire and smoke modelling by extinguishing the fire.

Using the above modelling capabilities, NF 19 considered a total of nine modelling scenarios for different apartments with protected entrance halls or open plan living areas, for arrangements (and variations) shown previously in Figure 5. These scenarios considered the impact of enhanced automatic detection and alarm with and without the inclusion of a sprinkler system.

However, in undertaking the assessment, several assumptions had to be made during the modelling, which are detailed and discussed herein.

### *Door closing behaviours*

Keeping doors closed within an apartment provides a means of protection during the development of a fire by limiting smoke and fire spread. Therefore, a key parameter in terms of occupant tenability is whether doors between rooms are simulated as open or closed during the development of a fire.

NF 19 refers to the likelihood of doors being opened or closed in its assessment. These probabilities were determined from a separate unpublished document on observations of domestic properties surveyed in 1995 (Leathley & Gibson, 1995). Two separate time periods of day and night were considered, where day is defined in NF 19 as any time between 9:00 AM and 9:30 PM and night as any time outside of this period. The surveys were undertaken in two locations in England, with 12 in Ipswich and 12 in London but no further information is available on the methodology or types of survey.

Given the lack of recent data on the topic of internal door closing habits in domestic premises, Hopkin et al. (2019a) undertook a study, collating 304 responses for a simple online survey. Hopkin et al. analysed the data to determine the probability of internal doors being closed while respondents were either awake or sleeping, further considering different habits based on whether respondents lived in houses or apartments. The results of the survey for respondents living in apartments has been reproduced in Table 1 and compared to the assumptions in NF 19.

*Table 1: Probability of doors being closed while occupants are awake or sleeping for apartments.*

| **Door** | **Probability closed (NF 19)** | | **Probability closed (Hopkin et al.)** | | **Percentage point difference** | |
|---|---|---|---|---|---|---|
| | **Awake (‘Day’)** | **Sleeping (‘Night’)** | **Awake** | **Sleeping** | **Awake** | **Sleeping** |
| Kitchen | 20% | 40% | 34% | 38% | +14% | -2% |
| Living room | 20% | 40% | 23% | 25% | +3% | -15% |
| Bedroom | 30% | 50% | 38% | 73% | +8% | +23% |
| Bathroom | 90% | 90% | Not considered | Not considered | N/A | N/A |
| Note: Hopkin et al. did not consider door closing habits in bathrooms due to the lower likelihood of bathrooms being occupied and the lower likelihood of fires occurring in bathrooms. | | | | | | |

The comparison indicates a noticeable difference in habits between the assumptions of NF 19 and the surveys of Hopkin et al. The biggest differences observed are for living rooms and bedrooms when occupants are sleeping, with Hopkin et al. indicating a 15% lower probability that a living room door is closed and a 23% higher probability that the bedroom door is closed.

### *Location of fires*

In the NF 19 assessment, fires were simulated to ignite in four primary room types: kitchens, lounges (referred to herein as living rooms), bedrooms and bathrooms. Assessing data presented in the NF 19 CD-ROM (Fraser-Mitchell & Williams, 2009b), 40-42% of fires were simulated to occur in kitchens, 28-30% in living rooms, 26-28% in bedrooms and 1-3% in bathrooms.  A recent study by Spearpoint & Hopkin (2019) of the West Midlands Fire Service (WMFS) datasets for fire incidents recorded between 2009 and 2017 indicates that, for fires in apartments, 76% of recorded fire incidents occurred in kitchens, 12% in living rooms, 10% in bedrooms and 2% in bathrooms. Spearpoint & Hopkin also note that the WMFS correlated well with the Dwelling Fires Dataset in England, and therefore the WMFS data appears to be a reasonable representation of England as a whole. In comparison to the WMFS dataset, NF 19 under-represents kitchen fires by up to -36% and over-represents living room and bedroom fires by up to +18%.

NF 19 used two time periods (day / night) when assigning door closing probabilities, but it is not clear whether day and night are also used to consider the likelihood of ignition in given rooms of fire origin. In the work of Spearpoint & Hopkin, it is proposed that fire scenarios could accommodate temporal factors, such as the time of day a fire occurs. In the case of apartments, it was found that approximately 81% of fires occur while occupants were awake, with the remaining 19% while sleeping. Figure 6 provides a comparison between NF 19 and the WMFS dataset by room of fire origin, as well as a comparison between incidents in sleeping and waking hours.

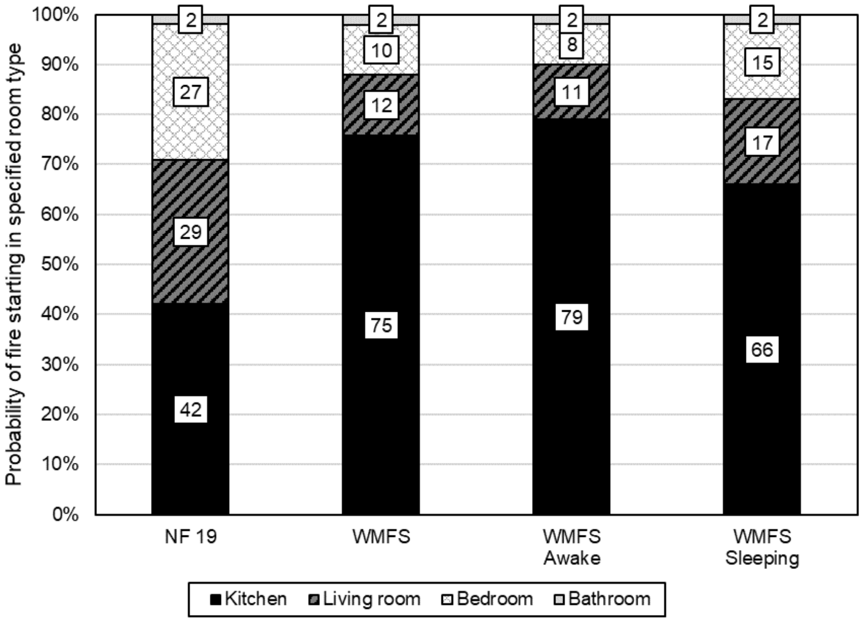


*Figure 6: Comparison between NF 19 and WMFS for percentage of fires starting by room type, adapted from Spearpoint & Hopkin (2019).*

### *Heat release rate*

The HRR is the fire energy output per unit of time (BSI, 2019c) and therefore is one of the most important parameters in influencing the tenability of an environment, as it directly affects the temperature and the production of soot and toxic gases. The HRR of a fire is linked to the fire growth rate, which is the rate in which the HRR increases over time, often presented in the characteristic $\alpha t^2$ exponential form. For dwellings, PD 7974-1:2003 (BSI, 2003) and CIBSE Guide E (Harrison et al., 2019) recommends a medium growth rate ($\alpha$ = 0.0117 kW/s$^2$).

In NF 19, the HRR is influenced by the interaction of the sprinklers. NF 19 assumes that, in all instances, sprinklers extinguish the fire upon operation. There is further discussion on sprinkler reliability and performance later in this paper. However, NF 19 also considered cases which did not incorporate sprinkler protection, i.e. the same cases as shown in Figure 5 but with the inclusion of protected entrance hall, referred to in NF 19 as Case 1a to 3a.

NF 19 does not specify the fire growth rate simulated for its burning items, but the maximum HRR is provided. Using the outputs provided in the NF 19 CD-ROM (Fraser-Mitchell & Williams, 2009b), the maximum HRR distributions for the non-sprinklered cases have been reproduced in Figure 7. The maximum available window area for the entirety of each apartment arrangement is 4.8 m$^2$, 9.8 m$^2$ and 16.8 m$^2$, respectively. In all instances the mode for maximum HRR (not impacted by sprinklers) is 250 kW. The mean HRR is 560 kW, 590 kW and 600 kW for Case 1a, 2a and 3a, respectively. Given the size of the fires relative to the available window area, it is unlikely that most fires simulated are ventilation-controlled (i.e. limited by the availability of oxygen), with a 4.8 m$^2$ window breakage area having the potential to support a fire in the region of 7 MW. Instead assumptions have likely been made in relation to the maximum HRR achieved by any burning items and associated fire spread. This will be heavily influenced by the arrangement of simulated items within the space, with NF 19 study detailing that each room is provided with a representative list of contents. In comparison, Baker et al.

(2013) used Monte Carlo simulations using the B-RISK tool (Wade et al., 2016) to determine a maximum residential HRR. The HRR was estimated to be normally distributed, with a mean of 4.6 MW and a standard deviation of 0.07 MW. In their assessment of design fire characteristics for probabilistic assessments of dwellings, calculated from incident data for fires in England, Hopkin et al. (2019b) determined an overall lognormal distribution for the maximum HRR of apartments, with a mean of 1 MW and a standard deviation of 2.3 MW. This distribution is also represented in Figure 7, alongside the NF 19 data, where comparatively NF 19 appears to have underestimated the maximum HRR.

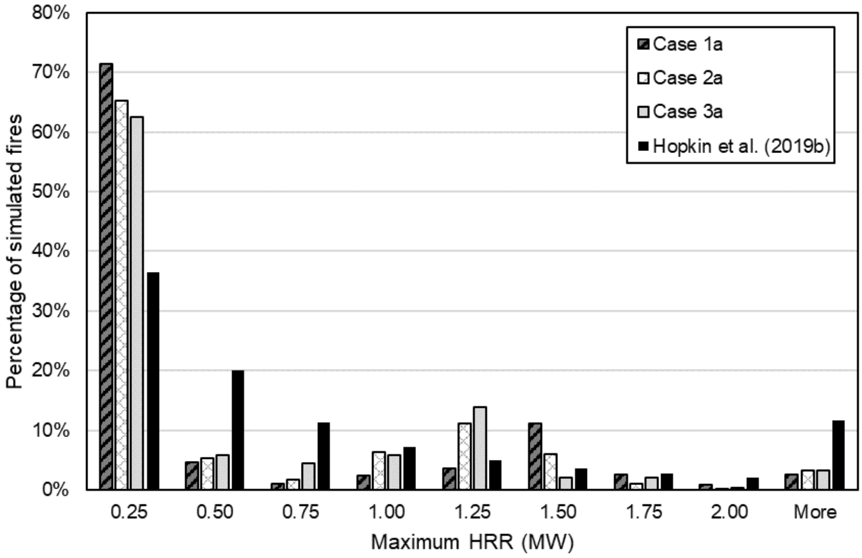


*Figure 7: Maximum HRR simulated for non-sprinklered cases in NF 19 (adapted from Fraser-Mitchell & Williams [2009b] and Hopkin et al. [2019b]).*

In the case of design, the quantity and type of combustibles in a residential space is broadly unknown, with variations that are influenced by complex factors, such as demographics and culture. To accommodate the uncertainty associated with the potential fuel load in an apartment, a simplified alternative to the method adopted in NF 19 is to use distributions for fire growth rate and maximum HRR, and consider the interaction of the fire with the environment in terms of whether it becomes fuel-bed or ventilation controlled. Baker et al.

(2013), Holborn et al. (2004), Nilsson et al. (2014) Deguchi et al. (2011) and Hopkin et al. (2019b) have all provided examples of probabilistic distributions for design fire growth rates, mostly derived from the analysis of fire incident and fire investigation data. They each estimated that the growth rate could be represented by a lognormal distribution, with mean growth rates ranging from 0.006 $kW/s^2$ to 0.052 $kW/s^2$ depending on the study.

### ***Sprinkler reliability and performance***

A literature review by Koffel (2005) on sprinkler reliability concluded that ‘when combining the operational effectiveness and performance effectiveness data as published in the August 2005 NFPA report, the overall reliability of automatic sprinkler systems is 91%’. PD 7974-7 (BSI, 2019d) provides indicative probabilities of sprinkler reliability based on US data, indicating a 93% ‘reliability where the equipment operated’, 96% ‘effective of those that operated’ and 89% ‘where operated effectively’. In contrast NF 19 assumed that sprinklers will always operate successfully once the actuation temperature is reached and that they will always extinguish the fire upon operation. NF 19 goes on to state that ‘while this is optimistic, it is likely not to be too unrealistic’, stating that correctly maintained sprinkler systems have ‘very high’ reliability.

Estimates of operation reliability by Bukowski et al. (1999) suggest that there is limited information on the reliability of modern-day residential sprinkler systems. Bukowski et al. also note that residential systems are generally less likely to be maintained properly and a decrease in operational reliability may be expected. PD 7974-7 (BSI, 2019d) provides a range of values for sprinkler ‘effectiveness’ (a combination of availability, reliability and efficacy) from New Zealand data, with the effectiveness of residential systems ranging from a lower bound of 46% to an upper bound of 99%.

One of the key parameters in sprinkler modelling is the response time index (RTI), where the RTI represents the rate at which the sprinkler element heats up when exposed to hot smoke (Harrison et al., 2019). NF 19 originally adopted a 50 $m^{½}s^{½}$ response time index (RTI) for unconcealed, quick response sprinkler heads. However, in the subsequent work summarised by Davis et al. (2016) it was identified in many modern residential designs sprinkler heads can be concealed, increasing the effective RTI of the head and increasing the sprinkler actuation time. Therefore, the work of NF 19 was revisited for concealed sprinkler heads, adopting an effective RTI of 115 $m^{½}s^{½}$.

The work by Williams & Annable (2006a, 2006b) and elsewhere by Yu (2007) has shown that the effective RTI of concealed sprinkler heads can vary between 104 and 766 $m^{½}s^{½}$ depending on a number of factors, including the mechanism and orientation of the sprinkler head. The 115 $m^{½}s^{½}$ RTI valued adopted in the Davis et al. works appear favourable compared to these studies.

Another important parameter in sprinkler performance is its conduction factor (C-factor), which characterises the heat loss to the sprinkler housing due to conduction (McGrattan & Forney, 1999). NF 19 assumes a C-factor of 0 $(m/s)^{½}$, i.e. that there are no heat losses due to conduction. This will result in a faster estimated sprinkler actuation time than if a C-factor was incorporated. In comparison, Tsui & Spearpoint (2010) measured the C-factor for residential sprinkler heads, measuring values in the range of 0.33 to 0.45 $(m/s)^{1/2}$ and an estimated uncertainty of up to 20%.

The interaction of smoke with the sprinkler head is dictated by the ceiling jet, which is the flow of hot gases under a ceiling, driven by the buoyancy of the combustion produces from a fire plume (Alpert, 2016). The CRISP software used in the NF 19 study does not calculate ceiling jet parameters and instead adopts a default value of 2 m/s for ceiling jet velocity (Fraser-

Mitchell & Williams, 2009a). This is a simplification of the interaction of the flow of smoke with the sprinkler head, with more complex ceiling algorithms, such as Alpert's ceiling jet (Alpert, 2016) and NIST/JET ceiling jet (Davis, 1999), commonly adopted in other zone modelling tools, such as B-RISK (Wade et al., 2016).

### *Number of occupants*

In an assessment of risk from a fire event, consideration needs to be given to the consequence of a fire. In this instance, the consequence is associated with the number of occupants within an apartment who may be impacted by a fire.

NF 19 considered distributions for the number of agents simulated within apartments, said to be derived from census surveys from 1991. The NF 19 CD-ROM (Fraser-Mitchell & Williams, 2009b) provides outputs for the simulated number of 'people at risk', ranging from zero to 'more than 6'. Table 2 provides the mean occupant densities and agents per bedroom, as calculated by Hopkin et al. (2019c) using the NF 19 data. Also shown in Table 2 is the mean occupant density and mean agents per bedroom if the distributions for apartments determined by Hopkin et al. were applied. To determine these occupant density distributions, Hopkin et al. analysed data from 15,715 surveys provided by the English Housing Survey (EHS), finding apartments produced a mean occupant density of 38.7 $m^2$/person and a standard deviation of 20.9 $m^2$/person. Considering occupancy with respect to the number of bedrooms produced a mean of 0.97 occupants per bedroom with a standard deviation of 0.49.

Hopkin et al. analysed the sensitivity on occupant load of applying distributions based on occupants per bedroom in contrast to occupant density using floor area, considering the arrangements used in NF 19 (Figure 5). It was found that NF 19 provided a marginally larger mean number of occupants to the EHS distribution for Case 1c, but when it came to the larger apartments (2c and 3c), the calculated mean number of occupants is lower in NF 19.

*Table 2: Mean occupant densities and agents per bedroom modelled in NF 19 (Fraser-Mitchell & Williams, 2009a) compared to Hopkin et al. (2019c) distributions.*

| **Apartment type** | **NF 19** | | | | | **Hopkin et al.** | |
|---|---|---|---|---|---|---|---|
| | **Floor area (m$^2$)** | **Mean number of agents** | **Standard deviation** | **Mean occupant density (m$^2$/person)** | **Mean agents per bedroom** | **Mean occupant density (m$^2$/person)** | **Mean occupants per bedroom** |
| One bedroom (1c) | 32 | 1.370 | 0.90 | 23.4 | 1.37 | 38.7 | 0.97 |
| Two bedroom (2c) | 80 | 1.630 | 1.12 | 49.1 | 0.82 | | |
| Three bedroom (3c) | 192 | 2.389 | 1.53 | 80.4 | 0.80 | | |

### *NF 19 conclusions*

The NF 19 results showed that, in all cases except one, the provision of enhanced detection and alarm alone resulted in an improved level of relative safety. The only case where this was not shown was Case 1b, a single bedroom inner room arrangement which was compared to an ADB-based studio apartment, i.e. a situation where the occupant(s) would be required to sleep in the same room as the living and kitchen areas. The exact reason for the disparity observed for this single case is unclear. As a result, NF 19 stated that it was ‘not possible to state with sufficient confidence that the enhanced detection alone could satisfy the requirements of the Building Regulations’.

NF 19 ultimately concluded that open plan apartments can achieve an adequate level of safety with the inclusion of both a sprinkler system and enhanced detection and alarm. It was caveated that these recommendations should not be applied for open plan apartments which: are larger than 16 m by 12 m; multi-level; incorporate smoke control or water mist; have open plan with kitchens ‘close to the front door’; or are in buildings taller than 30 m. The final point is a because of the comparative nature of the analysis. Since the 2006 edition of ADB (HM Government, 2013), a building taller than 30 m would be expected to include sprinkler protection within apartments even when protected entrance halls are provided, and therefore the inclusion of sprinkler protection would not be an enhancement upon guidance expectations. Any guidance informed comparison for buildings taller than 30 m would be based upon sprinkler protected apartments with protected entrance halls. However, BS 9991 (BSI, 2015) did not consider this caveat and allows for open plan apartments irrespective of building height.

### *Implications on design approach*

There has been further desire in industry to adjust and optimise residential and open plan living, posing questions not originally covered by the analyses in NF 19, such as whether open plan apartment sizes greater than 16 m by 12 m achieve a comparable level of safety to guidance-based designs and whether the conclusions drawn in NF 19 are transferrable to multi-level open plan apartments, e.g. duplexes and triplexes. However, the CRISP tool used in NF 19 is not available for public use and is not provided with public documentation, such as verification and validation guides. The nature and availability of modelling tool means there is currently limited opportunity for others to revisit or reproduce the work in the same manner as NF 19.

As identified in this review, the number of stochastic variables involved in this type of assessment, such as door opening probabilities, sprinkler reliability, fire location, etc., means that open plan apartment design is difficult to analyse deterministically.

Salter (2016) notes that the ‘common approach’ to assessing open plan apartment designs which are outside the scope of guidance is to use computational fluid dynamics (CFD) modelling. However, this approach typically considers a limited number of (deterministic) scenarios. It would therefore not be able to adequately capture the wide variation of possible outcomes and does not allow for the computation of the achieved level of safety (Van Coile et al., 2019). Furthermore, adopting absolute acceptance criteria with respect to tenability, such as layer height and visibility, can result in complications. For example, applying the framework of BS 7974 (BSI, 2019a) can result in an observed ‘failure’ of the design, even for apartment arrangements which meet the recommendations of guidance, because of the protracted pre-evacuation times in contrast to the fire development. These limitations of traditional absolute and deterministic methods, which are discussed by Hopkin et al. (2017), are contributing reasons as to why NF 19 considered a comparative and probabilistic assessment.

## Event tree analysis results

In contrast to deterministic methods, event tree analysis can help to demonstrate the range of situations which may occur in the event of a fire and highlight the impact that specific variables may have on fire safety.

The event tree analysis focusses on two exemplar apartment scenarios, shown in Figure 1 previously. Scenario I is a single bedroom apartment with protected entrance hall and Scenario II is a single bedroom open plan apartment with an enclosed kitchen.

Figure 8 provides simplified event trees for a fire for Scenario I and Figure 9 for Scenario II. Incorporated into the event tree are the probabilities of a fire within a given room (living room, kitchen or bedroom) from Spearpoint & Hopkin (2019) and the probabilities of a door being closed from the values of Hopkin et al. (2019a), both for sleeping occupancies. Certain percentages shown within the event trees do not collectively add up to 100% due to rounding.

Figure 10 provides a comparison of the event tree scenarios and their impact on access room and bedroom contamination. An additional scenario (Scenario III) is also shown in this figure, which equates to a single bedroom apartment  with a floor area of less than 8 m by 4 m, with an unenclosed kitchen (shown previously in Figure 5a). The event tree has not been presented for this scenario because of its relative simplicity, i.e. there are only two potential rooms of fire origin and the connecting door.

Using NF 19 assumptions for Scenario I (ADB protected entrance hall) indicates that the probability that a fire would result in the smoke contamination of the protected entrance hall (referred to the ‘access room’) is 58% and the probability that the bedroom where the occupant sleeping becomes contamination is shown to be 50%. In contrast, adopting the literature presented in this review results in a 57% and 29% probability that the entrance hall and bedroom become contaminated, respectively.

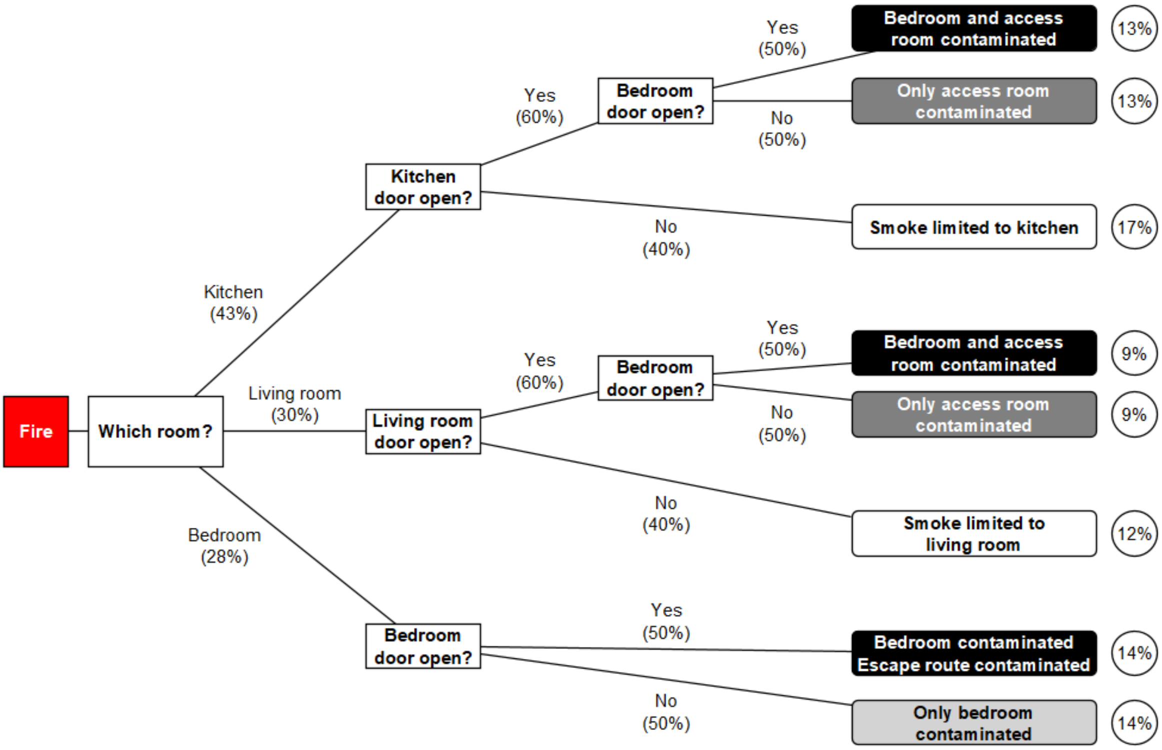
For Scenario II (BS 9991 open plan apartment with enclosed kitchen), NF 19 indicates a 70% probability that the access room (i.e. the open plan living area) becomes contaminated and a 56% probability the bedroom is contaminated. Using the literature presented in this review, the figures reduce to 62% and 27%, respectively.

Scenario III (BS 9991 open plan apartment with unenclosed kitchen) shows an equivalent probability that the access room becomes contaminated (88%) for both NF 19 and data from the recent literature. However, the probability that the bedroom becomes contaminated is 65% for NF 19 and 38% for the recent literature.

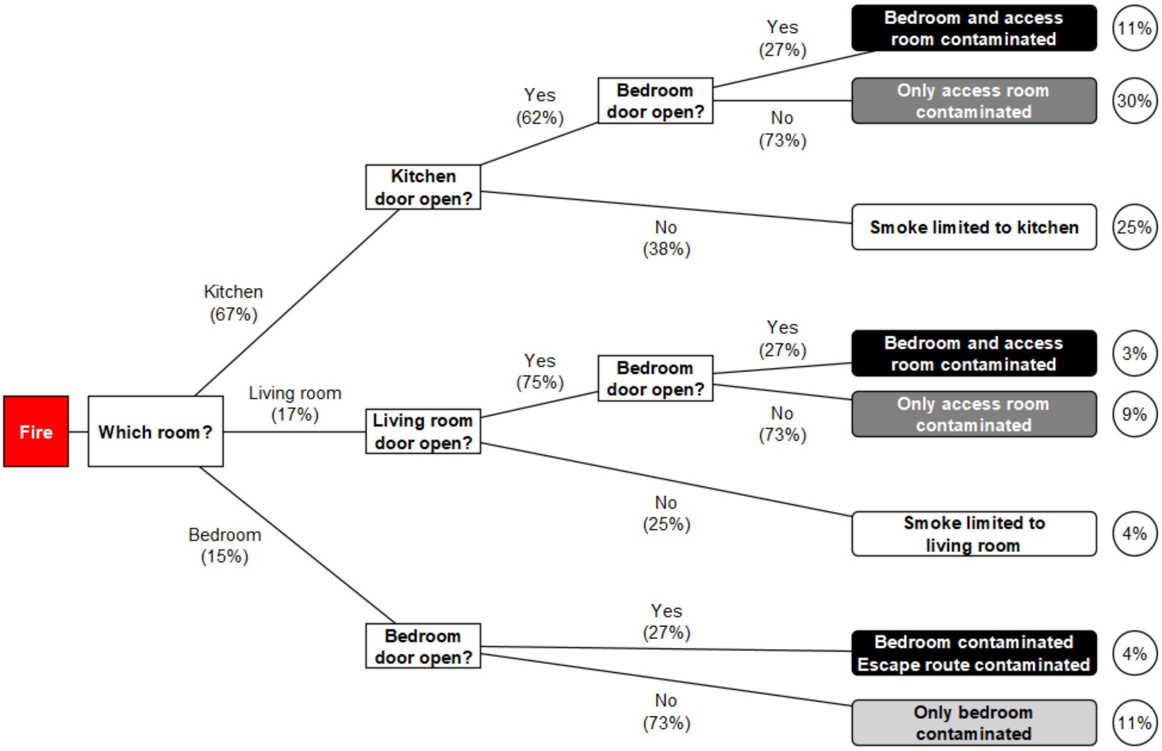
As would be expected, both Scenario II and Scenario III results in a greater likelihood that the access room and bedroom become contaminated when compared to Scenario I, supporting the need for extra fire safety provisions in open plan apartment design. However, this difference is less pronounced when adopting the data from this review, with a percentage point difference for Scenario II of only 5% and 2% for contamination of the access room and bedroom, respectively.

The event tree analysis suggests that the NF 19 assumptions for internal door closing behaviours and the room of fire origin result in a reduction of smoke spread into the protected entrance hall and bedrooms compared to data from recent literature. For the open plan arrangement (Scenario II), NF 19 appears to over-estimate the likelihood that both the open plan living area (access room) and the bedroom will become smoke contaminated.

Comparing the results of the event tree analysis, changes in door closing behaviours and the room of fire origin observed from recent literature would not be expected to alter the existing conclusions of NF 19 (when observed in isolation), and therefore the recommendations of NF 19 for open plan apartment design can still be considered appropriate in the context of more recent data from Hopkin et al. (2019a) and Spearpoint & Hopkin (2019). Applying the new data may also support changes to the open plan apartment limitations within guidance which are derived from NF 19, such as the apartment size, subject to further computational analyses.

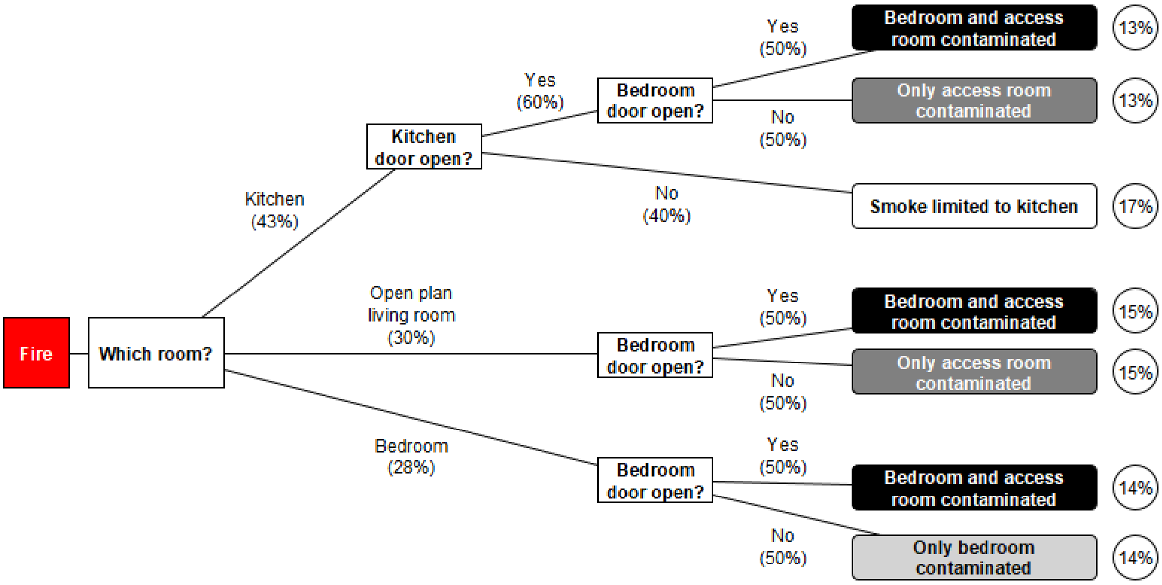


a) Using values adopted in NF 19

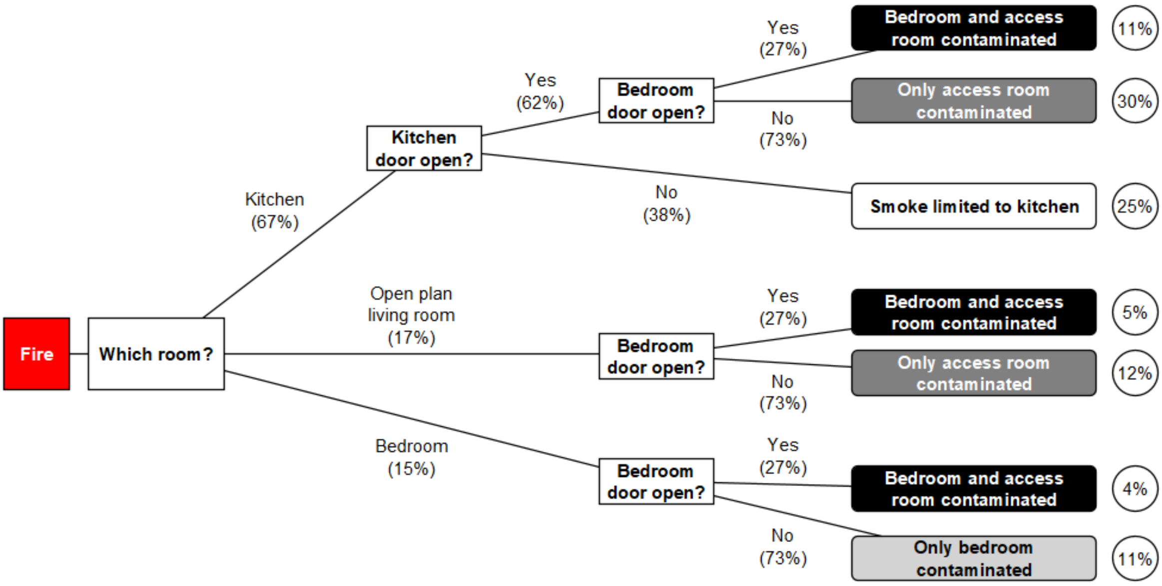


b) Using values from literature identified in this review

*Figure 8: Event tree for a severe fire in a single bedroom apartment incorporating protected entrance hall (Scenario I).*



a) Using values adopted in NF 19



b) Using values from literature identified in this review

*Figure 9: Event tree for a severe fire in a single bedroom open plan apartment with enclosed kitchen (Scenario II).*

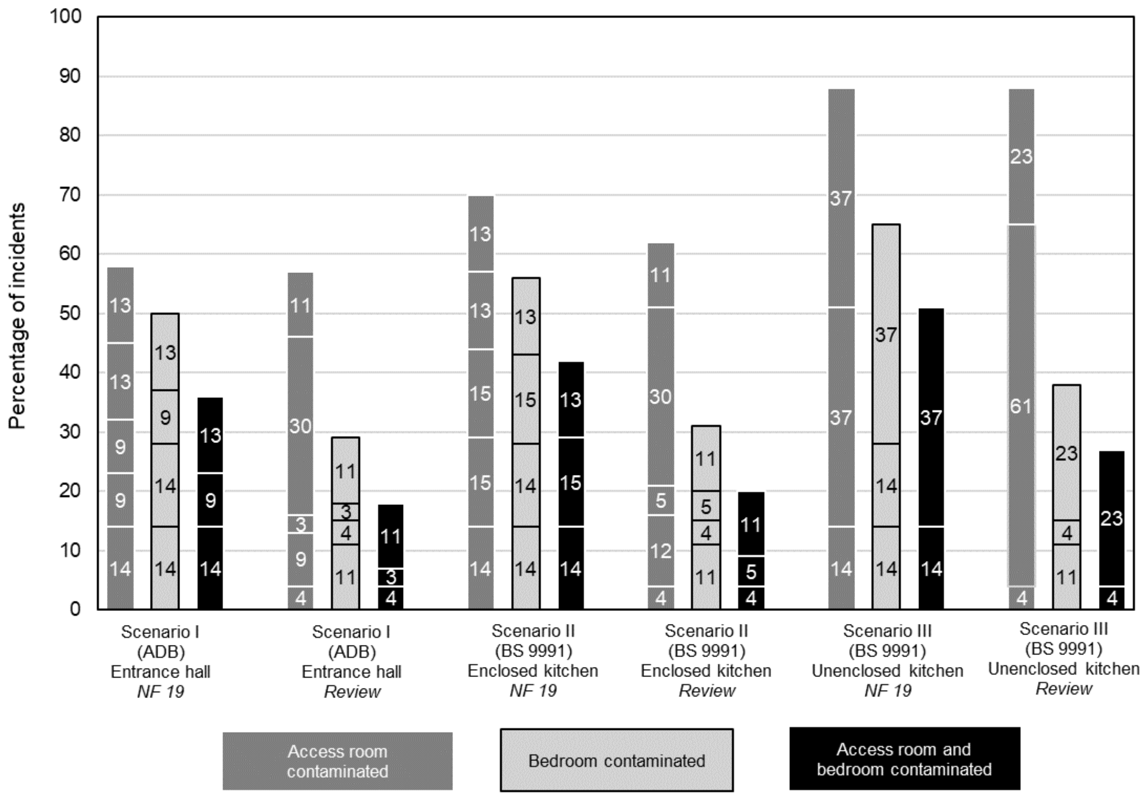


*Figure 10: Comparison of event tree scenarios and their impact on access room and bedroom smoke contamination.*

# Limitations

It is important to note that the event tree analysis is heavily simplified, focussing on only two variables, and thus does not consider several other variable factors which will influence possible fire scenarios. These include:

- Sprinkler reliability and performance, where it is difficult to quantify the benefits of these provisions on occupant tenability using an event tree method;
- Similarly, the reliability and impact of smoke detection provisions upon evacuation;
- The impact that smoke and heat may have on the tenability of evacuating occupants;
- The variation and complexity in human evacuation behaviours, such as their interaction with the fire and their reaction to auditory and visual cues; and

- The number of occupants who may be impacted by a fire.

Given these limitations, work is underway by the authors to produce a method of analysing open plan apartment design using the B-RISK (Wade et al., 2016) zone modelling tool for fire and smoke modelling, alongside evacuation modelling using Evacuationz (Spearpoint, 2017), in a semi-probabilistic framework. In contrast to the CRISP software used in NF 19, both B-RISK and Evacuationz are publicly available tools, and both are provided with user guides, technical manuals and benchmarking examples. The intent is that future work will help to provide a foundation to be adopted, scrutinised and iteratively improved for future use in academic research and commercial environments.

## Conclusions

The review detailed in this paper has been able to identify recommendations for single-level open plan apartment design, where some of these recommendations are not fully captured in existing guidance documents ADB Vol. 1 (HM Government, 2019a) and BS 9991 (BSI, 2015). These recommendations are:

- As identified in NF 19 (Fraser-Mitchell & Williams, 2009), open plan apartments can be considered acceptable, subject to certain limitations, when provided with a sprinkler system designed in accordance with BS 9251 (BSI, 2014) and a Grade D LD1 enhanced early warning detection and alarm system in accordance with BS 5839-6 (BSI, 2019b);
- In a follow up study to NF 19 by Davis et al. (2016), unenclosed kitchens are acceptable in open plan apartments, irrespective of the apartment floor area (up to a given limit), but the cooking facilities should be located remote from both the final exit and occupant escape routes. The responsibility of demonstrating that cooking facilities are sufficiently remote will require engineering judgement and assessment, where it is

noted that there is no clear nor fixed means of demonstrating an adequate separation distance; and

- The maximum dimensions of an open plan apartment should not exceed 16 m by 12 m, or 192 $m^2$ in floor area, as this is the maximum apartment size which has been studied to date.

However, it has been identified that the studies which inform these recommendations come with limitations in their representation of sprinkler performance and adopted values for door closing behaviours, location of fires, heat release rate and number of occupants when compared to more recent literature. Event tree analysis detailed in this paper indicate that the previous modelling assumptions for door closing behaviours and location of fires are conservative in the context of open plan design, helping to support the above recommendations. However, further computational modelling is needed to substantiate that the recommendations remain adequate for the other assumptions, most noticeably the favourable representation of sprinkler reliability and performance.

Applying the new data from Hopkin et al. (2019a) and Spearpoint & Hopkin (2019) may be also able to support changes to NF 19 recommendations and existing guidance limitations, with additional analyses which consider apartment arrangements with areas greater than 16 m by 12 m, open plan duplexes, triplexes, etc. This paper ultimately lays the groundwork for these future studies by identifying the limitations of NF 19 and establishing the key parameters that differ between NF 19 and more recent analyses.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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