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Estimating Door Open Time Distributions for Occupants Escaping from Apartments

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Abstract

The door open time, resulting from occupants evacuating from apartments, is an important parameter when assessing the performance of smoke ventilation systems in high-rise apartment buildings. However, the values recommended in UK design guidance appear to have limited substantiation. Monte Carlo simulations have been carried out considering variabilities in door swing time, flow rate and number of occupants. It has been found that the door open time can be represented by a lognormal distribution with a mean of 6.6, 8.7 and 11.1 s and a standard deviation of 1.7, 3.2 and 4.7 s for one, two and three-bedroom apartments, respectively. For deterministic analyses, it is proposed that the 95th percentile values may be adopted in line with recommended practice for other fire safety design parameters such as fuel load density and soot yield, giving door open times of 10 s to 19 s, depending on the number of bedrooms.

Keywords: Residential fire safety, egress, doors, smoke ventilation, common corridor.

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1. Introduction

Apartment fires represent approximately 32% of all dwelling fire occurrences recorded in England between 2009 and 2017 (Spearpoint and Hopkin, 2019) and there are an increasing number of high-rise apartment buildings being planned and built around the world (Al-Kodmany, 2012; Generalova and Generalov, 2015). The potential for smoke spread when escaping occupants open their fire-affected apartment exit door and enter a common corridor, i.e. the corridor connecting apartments to stairs, can have a substantial impact on how residential fire safety strategy development is approached. As a consequence, the common corridor in most high-rise apartment buildings in the UK is afforded a smoke ventilation system to mitigate this hazard. An important parameter in considering this interaction is the time it takes occupants to negotiate the door, travel through it and for the door to subsequently close behind them, with guidance recommending that a self-closing mechanism be provided to the door (Hopkin et al., 2020). This process represents the time that a door remains open and is referred to in this paper collectively as the 'door open time'. As will be demonstrated in the next section, this time will have a direct impact on the quantity of smoke which could enter the common corridor, potentially resulting in the corridor becoming untenable for escape within a very short timeframe. The door open time is therefore an important consideration in this context and can be an area of debate and contention between practitioners.

The most regularly adopted UK document on this topic is the Smoke Control Association (SCA) guidance on smoke control to common escape routes in apartment buildings (flats and maisonettes) (SCA, 2020), referred to hereafter as the SCA Guide, although fire safety engineers are free to adopt alternative guidance or utilise tailored performance-based methods, such as by citing published research and / or undertaking unique calculations specific to the project's circumstances. The most recent version of the SCA Guide (SCA, 2020) recommends in its timeline that an apartment door open time of 20 s be adopted. In the previous edition, it was recommended that the door should close "between 10 s and 20 s after the door opens" (SCA, 2015). While these times do not appear unreasonable from an anecdotal perspective, neither the latest nor previous editions of the SCA Guide provide substantiation or context as to how these values were derived.

This paper details a simple calculation method, using probabilistic input functions derived from data recorded by Frank (2013), to estimate an output distribution of potential door open times for apartments. Frank collated door opening data for trial evacuations of university buildings using a combination of door position data loggers and video recordings, monitoring usage and flow through doors for a range of locations, widths and leaf configurations. This data has been used to support the analysis detailed in this paper and, as a result, recommended input values for deterministic design are provided based on reasonable worst-case percentiles.

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2. Common Corridor Smoke Ventilation System Design and Principles

UK fire safety guidance documents, such as Approved Document B (ADB) vol. 1 (HM Government, 2020), BS 9991:2015 (BSI, 2015) and the Building Standards Technical Handbook: Domestic (Scottish Government, 2019), recommend that the common corridor of multi-apartment buildings be afforded a means of smoke ventilation. In instances where travel distances meet the recommendations of guidance, a natural means of ventilation is usually provided, either in the form of a 1.5 m^2 geometric free area automatically openable vent (AOV) connecting the protected space directly to outside, or a natural smoke shaft (achieving a 1.5 m^2 cross-sectional free area) which can protrude through the height of the building and exhaust smoke at high level (2.5 m above the ceiling of the highest storey served by the shaft). For most high-rise apartment buildings, these ventilation systems initiate upon activation of an automatic smoke detector within the common corridor.

As discussed by D. Hopkin et al. (2019), the natural ventilation systems recommended in guidance are shown to provide limited benefit to corridor smoke clearance, often resulting in prolonged periods for the corridor to clear after it has become contaminated with smoke. Hence, they are usually only deemed sufficient when the corridor travel distances for a single direction of travel are constrained, for example to 7.5 m in ADB or 15 m in BS 9991:2015 when sprinkler protection is provided to the apartments. By extension, the adoption of these natural ventilation systems is only considered to be adequate in circumstances where the building design is representative of a ‘common building’ situation (Van Coile et al., 2019). In such situations, no further performance-based assessment of the ventilation system is expected.

Mechanical ventilation systems are often adopted as an alternative when the guidance recommended natural provisions are not considered feasible from a design perspective, owing to architectural constraints. Examples of this include where it may not be possible to incorporate a 1.5 m^2 AOV directly to outside due to the ‘landlocked’ nature of a corridor, or where a 1.5 m^2 natural shaft occupies too much floor area and the design team wish to reduce this by exploring mechanical options. Mechanical ventilation systems are also adopted when the corridor travel distances are greater than the maximum bounds recommended in guidance (referred to as ‘extended travel distances’). Under these circumstances, guidance in BS 9991:2015 (BSI, 2015) notes that the primary objective of the system is to “return the extended corridor and the associated stair enclosure to tenable conditions for means of escape and rescue purposes”, with the SCA Guide (SCA, 2020) recommending a clearance time of two minutes. This expectation usually results in a corridor smoke ventilation system which incorporates both a means of exhaust and a means of inlet. An example corridor smoke ventilation arrangement is given in Figure 1.

To determine whether a proposed corridor smoke ventilation system can adequately support a design which includes extended travel distances, a performance-based, fire and smoke modelling assessment is typically undertaken using computational fluid dynamics (CFD) tools. The SCA Guide (SCA, 2020) recommends that the assessment considers both the means of escape phase and the firefighting phase. The latter is not discussed any further in this paper due to its limited relevance to the door open time. In the means of escape phase, a typical modelling timeline considers: the development of a fire within an apartment; the occupants escaping from the fire-affected apartment, where the apartment door opens, smoke flows into the corridor and the door then closes behind them (i.e. the collective door open time); and following this, the corridor tenability is assessed and the smoke clearance time is determined.

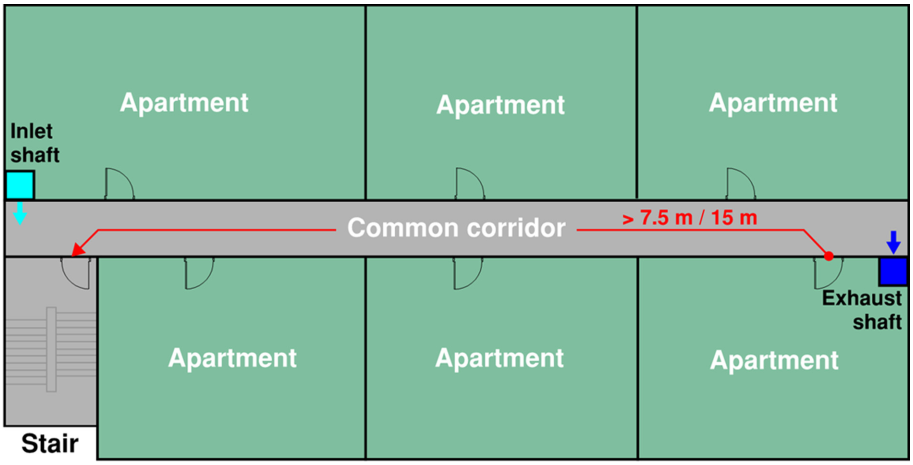


Figure 1. An example common corridor arrangement incorporating extended travel distances and a mechanical smoke ventilation system.

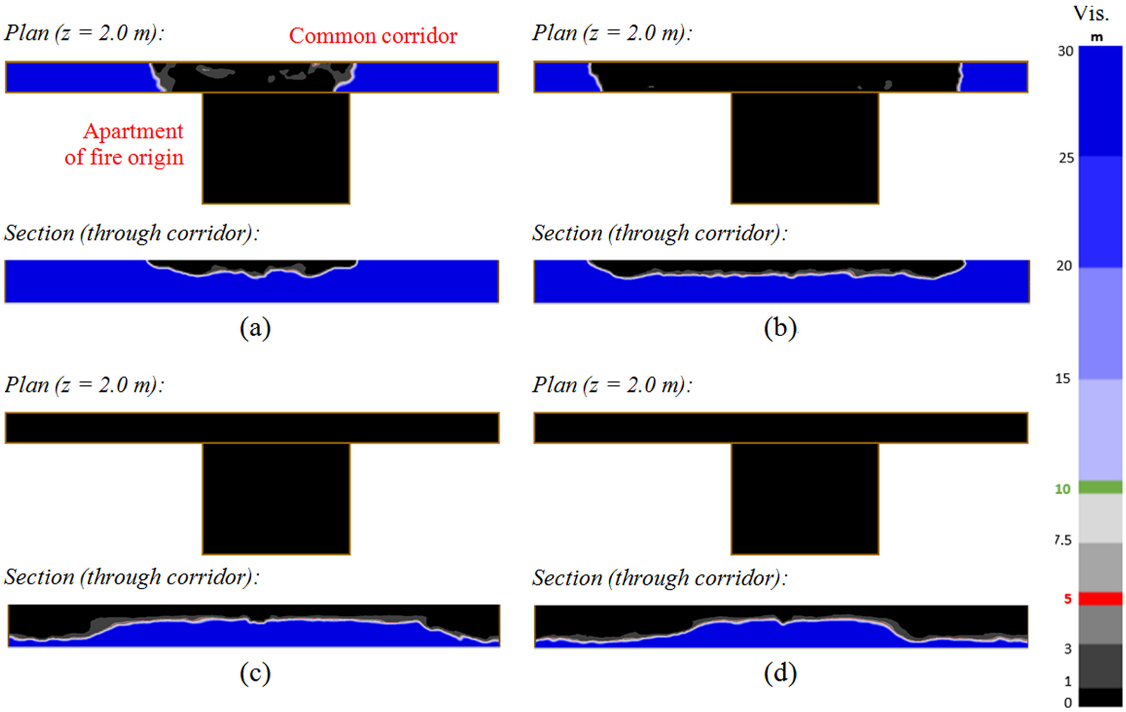


Figure 2. Estimated visibility conditions (assuming light-reflecting signage, C = 3) for an exemplar common corridor CFD simulation. Visualisations presented at four different door open times: (a) 5 s; (b) 10 s; (c) 15 s; (d) 20 s.

For its timeline, the SCA Guide notes that a 1 MW heat release rate (HRR) “might be considered appropriate at the time of the occupants make their escape” (SCA, 2020). This recommendation is made assuming that a fire burns following an αt^2 (BSI, 2019a) relationship with a medium growth rate ($\alpha = 0.0117$ kW/s^2), reaching 1 MW at approximately 300 s. This typical timeline highlights how the adopted door open time is a key parameter to be considered by practitioners when assessing smoke ventilation performance, for example where an HRR of 1 MW will generate a substantial mass flow rate of smoke through the door in the relatively brief period that it is open.

The importance of the door open time is demonstrated indicatively in Figure 2, which presents example simulation outputs for modelling undertaken using the Fire Dynamics Simulator (FDS) CFD tool, version 6.7.4 (McGrattan et al., 2019). Estimated visibility conditions within an exemplar common corridor arrangement (based on Figure 1) are presented at four different door open time intervals, with the modelling applying the recommended methodology of the SCA Guide, including its suggested timeline (discussed above) and modelling input parameters. The burner has been simulated with a heat release rate per unit area of 500 kW/m^2 (C. Hopkin et al., 2019a) for an area of 2 m^2 and the apartment of fire origin incorporates a 1.6 m^2 vent at low-level to allow for enough oxygen to reach the fuel bed to sustain the HRR (SCA, 2020). The combustion reaction uses a soot yield of 0.1 kg/kg (BRE, 2005), an effective heat of combustion of 20 MJ/kg and a radiative fraction of 0.35 (Ministry of Business, Innovation and Employment, 2017). Representative surface properties have been adopted for 15 mm thick plasterboard (Hopkin et al., 2012) and 100 mm thick concrete (BSI, 2005), with the former applied to walls and ceilings and the latter to the floor slab. A uniform mesh cell size of 0.1 m has been used throughout, determined as adequate in a previous common corridor modelling study (D. Hopkin et al., 2019). In the visibility scale presented in Figure 2, 10 m and 5 m are marked in green and red, respectively, for the standard tenability limits specified in PD 7974-6:2019 (BSI, 2019b). From this it can be observed that after a door open time of 15 s, the corridor (which is 28.0 m long by 1.6 m wide by 2.4 m high) becomes smoke logged and untenable at a height of 2 m from floor level. The smoke is shown to have a high soot density and the resulting visibility is less than 1 m for the smoke affected regions of the corridor, and thus the 10 m and 5 m visibility regions are not evident in the plot.

3. Methodology

The methodology discussed in this paper begins with a summary of the calculation methods and relevant equations considered applicable for the estimation of the door open time. The summary also introduces a series of cumulative distribution functions (CDFs), cited from previous literature, which are used as part of the calculation process. The constituent elements of the calculation method and their associated distributions are then discussed in subsequent sections. Lastly, a flow chart is used to collate and present the final Monte Carlo procedure.

3.1. Summary of Calculation Methods

It is postulated that the door open time comprises three constituent parts:

1. The time for the occupant(s) to initially operate the door, noting that this paper does not consider this time to include aspects such as unlocking the door, turning the handle etc., instead focussing on the period of time where the door is in swing and therefore 'open'.
2. The time for the occupant(s) to travel through the door.
3. The time for the door to shut behind them, e.g. by the self-closing mechanism.

Based on the available data, parts 1 and 3 of the above have been combined into one time (represented by a single evacuating occupant), referred to hereafter as the 'door swing time' (t_s, s). The time to travel through the door is referred to as the 'flow time' (t_f, s). The door open time (t_d, s) can therefore be simply expressed as the sum of these two parts:

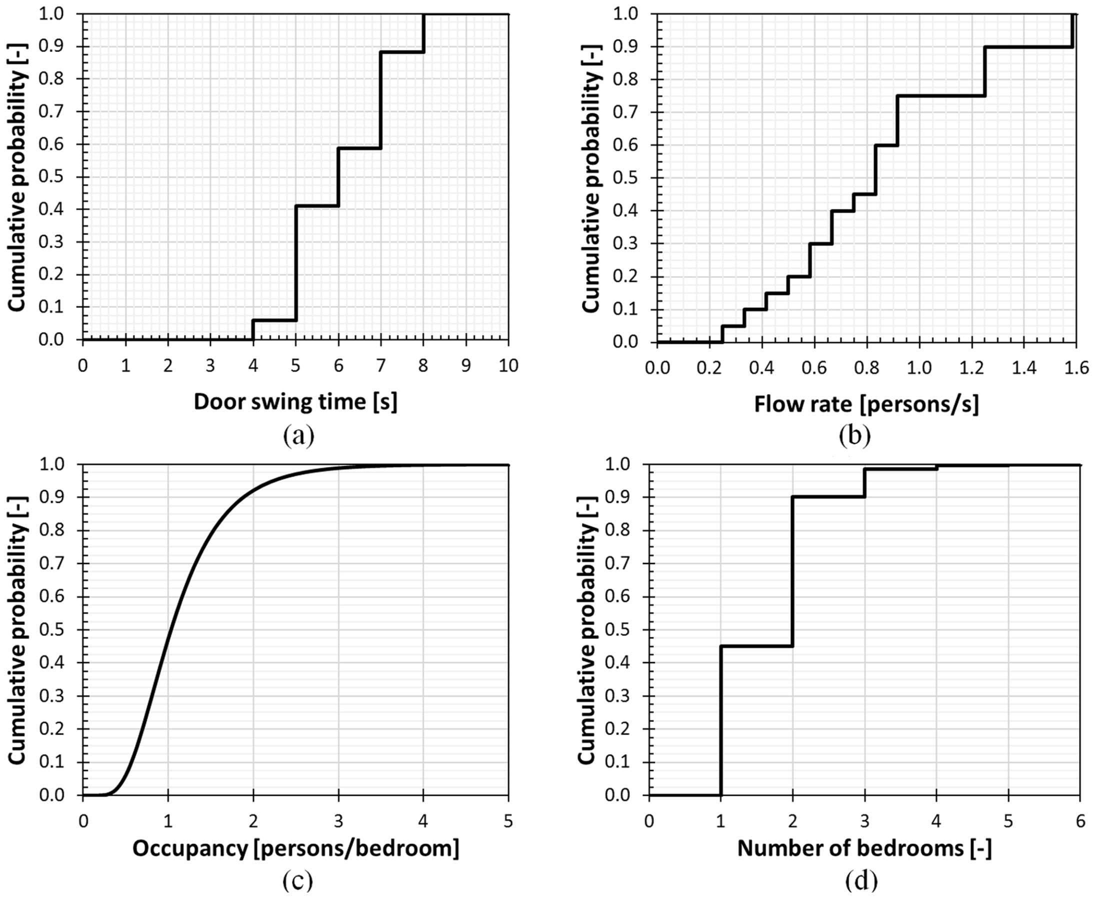
$$t_d = t_s + t_f \tag{1}$$

The flow time is a function of the number of occupants who form a continuous stream at the door. Therefore, particularly if it is assumed all occupants evacuate simultaneously, this time is dependent on the number of occupants present in the apartment. In the context of assessing the performance of a corridor smoke ventilation system, all occupants evacuating simultaneously later in a fire's development is more likely to be the worst-case, as it will result in a greater quantity of hot smoke entering the corridor in a single instance, prior to corridor smoke detection and the activation of the ventilation system. In contrast, if occupants were to evacuate at different intervals and the door was opened for multiple shorter periods of time, then the ventilation system would likely be activated following the first instance and thus would demonstrate improved clearance performance for the following instances.

C. Hopkin et al. (2019b) previously identified that the number of expected occupants in an apartment can be assessed in the context of the number of bedrooms. Eq. (1) can therefore be expressed as:

$$t_d = t_s + \frac{1}{f}[(n \times B) - 1] = t_s + \frac{1}{f}[N - 1] \tag{2}$$

where *f* is the flow rate through the open door (persons/



(a) (b) (c) (d)

Figure 3. CDFs adopted for the door open time calculation: (a) the door swing time (adapted from Frank [2013]); (b) the door flow rate (adapted from Frank); (c) the occupancy by persons per bedroom (adapted from the lognormal distribution of C. Hopkin et al. [2019b]); (d) the number of bedrooms in an apartment (adapted from C. Hopkin et al.).

s), n is the number of occupants per bedroom and B is the number of bedrooms. $N = n \times B$ represents the total number of occupants present in the apartment, where a single occupant is deducted from this value (i.e. $N - 1$) as the initial occupant's flow time through the door is inherently captured in the door swing time (t_s), discussed later.

In this paper, Eq. (2) has been assessed probabilistically by application of the Monte Carlo method (Notarianni & Parry, 2016), using distributions for the door swing time, the flow rate, the number of occupants per bedroom and the number of bedrooms in an apartment. These distributions are shown in Figure 3 in the form of CDFs and each are discussed later. For the Monte Carlo method, which involves repeated sampling of inputs from the distributions, 50,000 iterations have been generated using a simple random sampling method (Lovreglio et al., 2019a). Applying the calculation method outlined in PD 7974-7:2019 (BSI, 2019c), considering the interrogation of the 95th percentile (referred to later in the results), the resultant coefficient of variation (V) is 0.02, with PD 7974-7:2019 stating that "typically, the final coefficient of variation should be below 0.05". Applying a V of 0.05 would suggest that the 99th percentile could be reasonably interrogated using 50,000 iterations. When considering the convergence of consecutive means (Ronchi et al., 2014) for the door open time, after ~2000 iterations the change in the mean value, between iterations, is shown to be effectively nil. The selected number of iterations is therefore considered adequate for the outcome to be independent of the sample size.

The calculation assumes that the four variable input functions indicated in Figure 3 are independent of each other, i.e. the alteration of one variable does not impact another, and thus that they can be sampled independently. However, it may be hypothesised that the 'opening' portion of the door swing time and the flow rate are dependent variables, for example where an apartment containing elderly occupants or occupants of reduced mobility may produce a longer 'opening' swing time and also a flow rate which is slower. Likewise, an apartment of able-bodied occupants may comparatively produce a shorter 'opening' swing time and a faster flow rate. In addition to this, the force of the self-closing mechanism will affect the effort required to open a door as well as the rate at which it closes. The ability of the occupants to overcome the door closing force will have an impact on the 'opening' swing time, but the closing rate will likely be independent of the occupants' characteristics, and the door closing force and closing rate may vary between different self-closing mechanisms and doors. In the absence of any further data that is known to the authors, the existence of a relationship between the variables cannot be verified. Analysing a very limited quantity of data presented by Frank (2013) in which the measured door position is shown with respect to time, the 'opening' portion of the door swing time is demonstrated to constitute in the region of 30% of the total door swing time for a single occupant. This could indicate that the time for the door to close behind occupants, by the self-closing mechanism, likely comprises a more significant proportion (e.g. around 70%) of the combined door swing time. In this limited context, it does not appear unreasonable to consider the door swing time and flow rate to be sufficiently independent of the occupant characteristics for the purposes of this paper, although the relationship would be worth exploring in more detail in the future.

3.2. Door Swing Time

During trial evacuations of university buildings, Frank (2013) undertook an evaluation of the door swing times. The doors included a range of widths, leaf configurations and locations, although it was noted that there was only a small number of instances where double door leaves were used and hence the door types were sufficiently representative of those used in apartments. The operation of the doors was observed using a combination of video recording and logging devices that measured the door angle as a function of time. As part of the process, Frank assessed what he referred to as the 'door negotiation time', described as "the time between the door states of being completely closed", i.e. the time from the occupant initially opening the door to it closing behind them after they had passed through. Within this paper, this has instead been referred to as the door swing time. The door swing times ranged from 4 to 8 s for the 17 instances where a single occupant passed through the door. This resulted in the data presented in Figure 3a, having been converted from a frequency plot into a 'step' CDF. In comparison, the New Zealand Verification Method C/VM2 (Ministry of Business, Innovation and Employment, 2017) advocates a time of 3 s per occupant when "occupant load is low" and recommends to directly apply the queuing time when occupant load is high.

Without the authors of this paper being aware of any better data in the literature, in adopting the data from Frank, it has been assumed that the occupancy type (i.e. university building instead of apartment) does not significantly affect the door operation by occupants, nor that it results in different performance of the door-closer mechanisms. It is also assumed that occupants evacuating in a fire-affected environment will not negotiate the door differently than in a trial evacuation, although it is possible that the urgency of escaping a fire will result in occupants evacuating more quickly, or alternatively that the impediment from smoke and heat could increase their time at the door.

3.3. Flow Rate and Flow Time

For the evacuation trials of the university buildings discussed previously, Frank (2013) identified 15 instances where more than two occupants evacuated in a continuous stream, with a maximum of up to 37 occupants in one single stream. From this, the average door swing time per occupant (s/person) was determined by Frank, and this has been adapted herein (to persons/s), as presented in Figure 3b. It is important to note that while it is referred to as the flow rate in this paper, in Frank's original study this does not exclusively represent the flow time, as it includes the action of the initial door opening and the door closing behind the stream of occupants. Therefore, by adopting this distribution for the flow time, there may be a certain degree of 'double counting', resulting in a more conservative estimation of the total door open time in this work.

Frank compared data presented in Figure 3b to traditional flow calculation methods, such as those outlined in C/VM2 (Ministry of Business, Innovation and Employment, 2017):

$$F_c = (1 - aD)kDW_e \quad (3)$$

where F_c is the calculated flow (persons/s), D is the occupant density near the door (C/VM2 recommends using 1.9 persons/m^2), W_e is the effective width of the door and k and a are factors which vary depending on whether travel is horizontal or vertical (by accounting for stair riser / tread dimensions), with values of $k = 1.4$ and $a = 0.266$ recommended in C/VM2 for horizontal travel. This calculation method and the associated parameters are also consistent with the recommendations of PD 7974-6:2019 (BSI, 2019b). For a typical apartment door, with an effective width of circa 0.85 m (HM Government, 2016), this would result in a fixed flow rate of 1.1 persons/s.

Frank identified that the C/VM2 calculation resulted in a relative under-estimation of the time taken for occupants to travel through the door compared to the evacuation trial data, although this will have been influenced by the inclusion of the door swing time in his measurements. Similarly, previous experimental flow rates discussed in PD 7974-6:2019, ranging from 1.2 to 1.8 persons/s per metre effective width (1.0 to 1.5 persons/s for a typical 0.85 m wide apartment door), broadly appear more favourable (i.e. faster) than Frank's measurements with a median value of 0.8 persons/s.

For the calculation undertaken herein, the distribution has been adopted as per Figure 3b, as well as considering a fixed flow rate of 1.1 persons/s from Eq. (3), with the former expected to provide a more conservative estimation of the occupant flow time. In estimating the flow time, the initial occupant's contribution to the flow has been deducted in Eq. (2) (i.e. N – 1), as their flow time through the door is inherently captured in the door swing time discussed in the previous section.

3.4. Number of Occupants per Bedroom and Number of Bedrooms

C. Hopkin et al. (2019b) evaluated the English Housing Survey (EHS) to estimate distributions for occupant density in dwellings, using data from approximately 70,000 surveys. As part of this, distributions were identified for occupant density as a function of floor area (m^2/person), and occupant density as a function of the number of bedrooms (persons/bedroom). It was recommended that the latter be adopted to determine the occupancy of a dwelling, due to the observed variation in the relationship

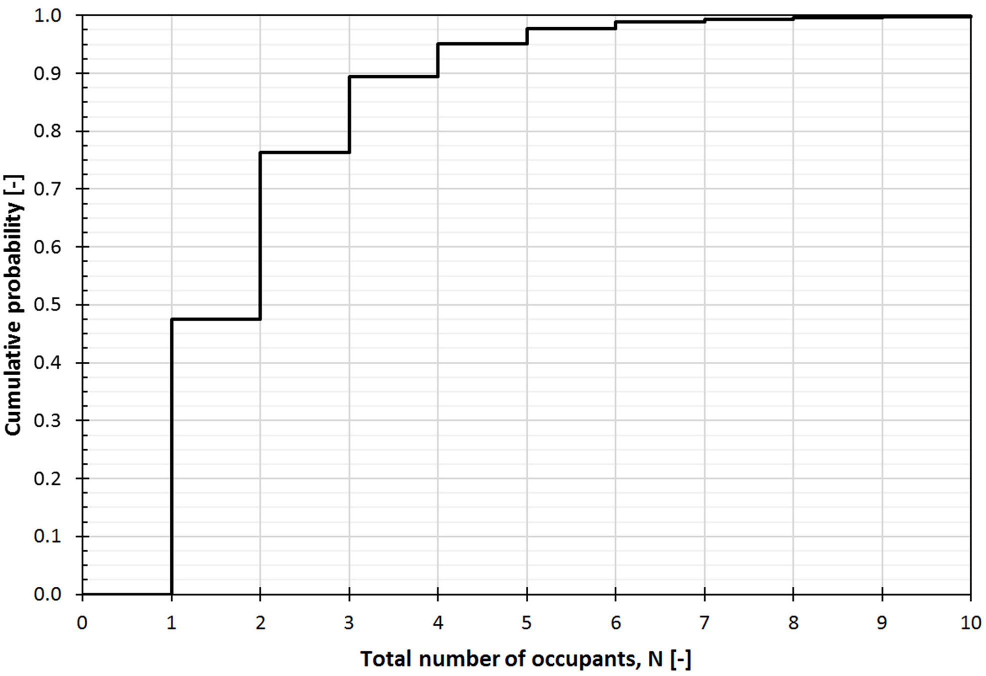


Figure 4. Example CDF for total number of occupants (considering all apartments).

between floor area and number of bedrooms, and as the number of bedrooms “provides a stronger indication of the number of occupants who may be sleeping in a dwelling”. Data was separated into different dwelling types, including apartments (high-rise and low-rise) and houses. For the number of occupants per bedroom in all apartment types, a lognormal distribution with a mean of 1.15 persons and a standard deviation of 0.57 persons was proposed. This distribution has been reproduced in Figure 3c.

Hopkin et al. also collated data for the number of bedrooms in apartments, finding that very few of the surveyed apartments include more than three bedrooms, and most were either one-bedroom or two-bedroom apartments. The data for this has been adapted into a step function and is presented in Figure 3d.

As observed in Figure 3c, it is possible that the lognormal distribution may return an apartment occupancy of less than 1 person (e.g. where anything less than 0.5 persons is rounded to the nearest integer). To remove the possibility of this occurring for the calculation, all instances where the occupancy has been estimated to be less than 1 person have been rounded up, i.e. $N = n \times B$ is always considered to be ≥ 1. In other instances, N has been rounded to the nearest integer. The resulting CDF using this method is presented in Figure 4, providing the total estimated number of occupants (N) from the combination of the distributions shown in Figure 3c and Figure 3d.

When undertaking a fire safety engineering assessment, the number of bedrooms may already be known. Therefore, the probabilistic calculation has been undertaken to focus separately on one to three-bedroom apartments (where B is fixed), as well as adopting the distribution in Figure 3d to produce a more general output. A full representation of the Monte Carlo calculation process is given in Figure 5.

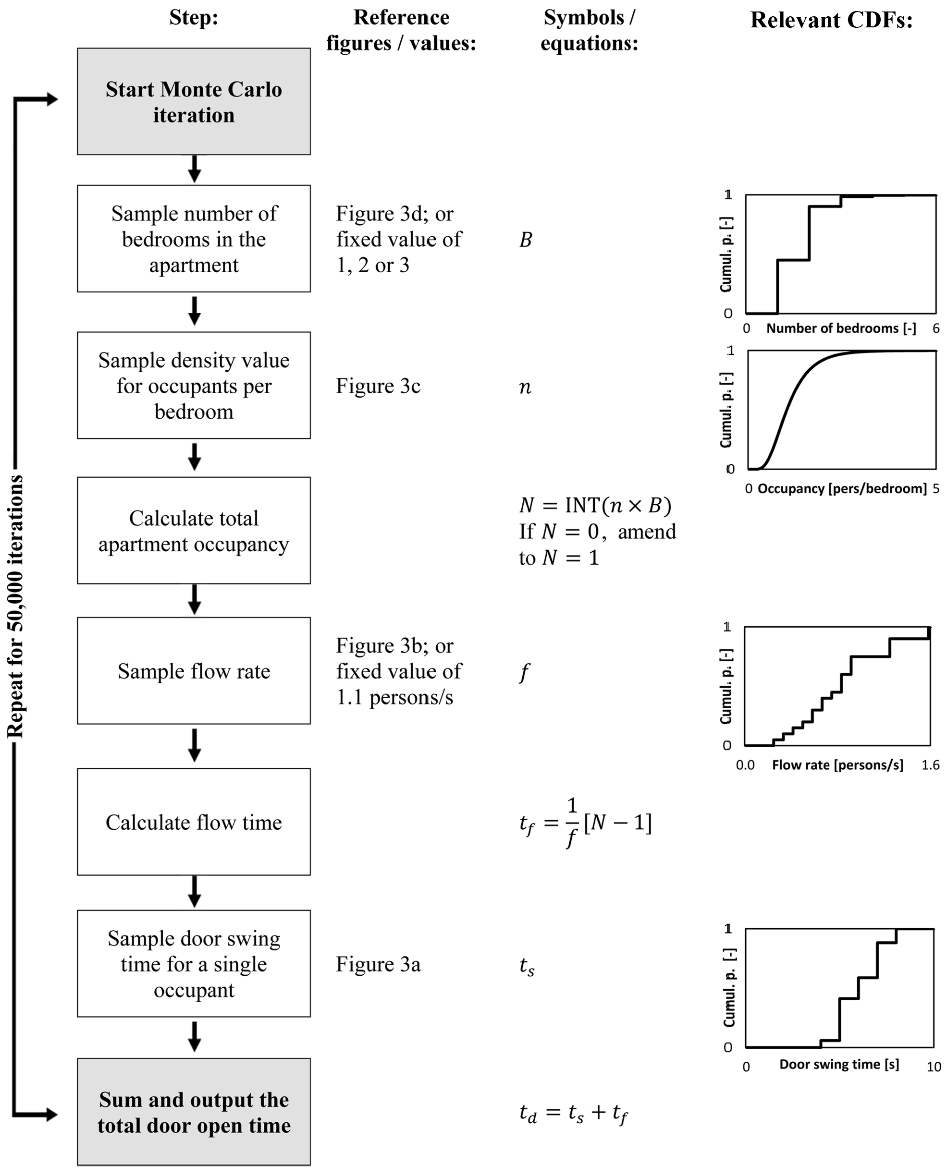
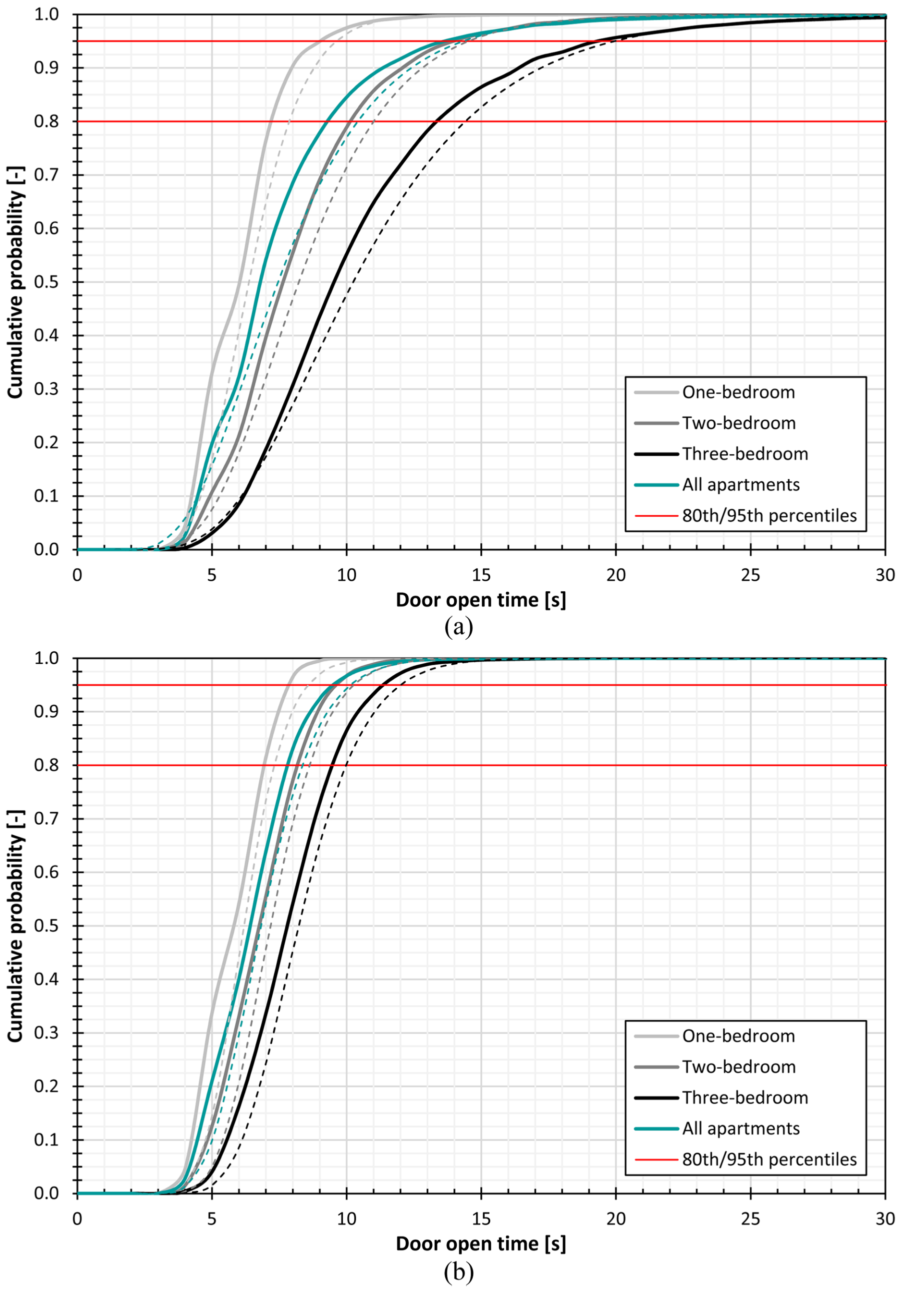


Figure 5. Flow chart to demonstrate Monte Carlo calculation process.

4. Results and Discussion

Figure 6 presents the CDF for the calculated door open time, for one to three-bedroom apartments and for all apartments more generally. Two sets of results are presented: one using the flow rate distribution adapted from Frank (2013) and given previously in Figure 3b (referred to as Method 1); and the other using a fixed flow rate of 1.1 persons/s estimated from Eq. (3), for a typical 0.85 m wide apartment door (referred to as Method 2). Also shown in the figure are the 80th and 95th percentiles, as well as equivalent lognormal distributions (using dashed lines). C. Hopkin et al. (2019c) previously identified the 80th to 95th percentile range as likely reasonable worst-case values for design fire characteristics, referring to the discussion on fire scenarios and fuel load density detailed in the SFPE Handbook of Fire Protection Engineering (Hadjisophocleous and Mehaffey, 2016). Following this, Hopkin et al. ultimately proposed that a 95th percentile be adopted for fire growth rate and maximum HRR. Similarly, C/VM2 (Ministry of Business, Innovation and Employment, 2017) recommends a 95th percentile design value be adopted for



(a)

(b)

Figure 6. CDF for calculated door open time: (a) using the flow rate adapted from Frank (2013) (Method 1); (b) using a fixed flow rate of 1.1 persons/s (Method 2). Dashed lines indicate equivalent lognormal distributions.

Table 1. Distribution parameters for one to three-bedroom apartments and all apartments combined, for the flow distribution adapted from Frank (2013) [Method 1]. 80th and 95th percentile values are rounded to the nearest integer

# of bedrooms	Mean [s]	Standard dev. [s]	80th %ile [s]	95th %ile [s]
One-bedroom	6.6	1.7	8	10
Two-bedroom	8.7	3.2	11	14
Three-bedroom	11.1	4.7	14	19
All apartments	8.1	3.3	11	14

Table 2. Distribution parameters for one to three-bedroom apartments and all apartments combined, for a fixed 1.1 persons/s flow rate [Method 2]. 80th and 95th percentile values are rounded to the nearest integer

# of bedrooms	Mean [s]	Standard dev. [s]	80th %ile [s]	95th %ile [s]
One-bedroom	6.3	1.3	8	9
Two-bedroom	7.4	1.6	9	11
Three-bedroom	8.5	2.0	11	13
All apartments	7.0	1.8	9	11

soot yield.

Table 1 and Table 2 present the distribution parameters for the apartment types, for the two different flow rate methods. For Method 1, the mean door open time ranges from 6.6 to 11.1 s, with a standard deviation ranging from 1.7 to 4.7 s. For Method 2, the mean ranges from 6.3 to 8.5 s and the standard deviation ranges from 1.3 to 2.0 s. Method 2 therefore provides a lower mean and less spread in the door open time output, consistent with the observations of Frank (2013). Hence, Method 1 would be more conservative from a design perspective, i.e. would result in a longer estimation of the door open time.

As would be expected, apartments with more bedrooms produce a greater mean door open time and a greater standard deviation, due to the increased range of possible occupant numbers. For all apartments, the distribution mean sits between those for one and two-bedroom apartments, with a standard deviation similar to the two-bedroom apartment distribution. This observation is due to the majority of apartments having either one or two bedrooms (Figure 3d).

The 95th percentile values range from 9 to 19 s (dependent on the number of bedrooms and method adopted), but they never exceed the 20 s recommended in the latest edition of the SCA Guide (SCA, 2020). For a three-bedroom apartment, the SCA Guide recommended value represents a 96th percentile using Method 1 and is greater than the 99th percentile using Method 2.

As discussed previously, the SCA Guide recommends that the door open time be applied after 300 s, when the HRR in the apartment has reached 1 MW. The difference in the quantity of smoke which enters the corridor for a 10 s door open time, indicated as a 95th percentile for a one-bedroom apartment (Table 1), compared to a 20 s door open time could therefore be substantial (as shown in Figure 2). However, it is important to acknowledge that this quantity of smoke will also be affected by other variables and assumptions in the modelling approach, such as:

- The time that the door is first opened, where this will be influenced by the detection / alarm time and the occupant pre-evacuation time. The pre-evacuation time has been shown to vary substantially depending on whether the occupants are awake or sleeping (Gwynne and Boyce, 2016), with sleeping occupants typically having a reduced level of alertness and prolonged pre-evacuation times when compared to occupants who are awake. The pre-evacuation time can also be strongly affected by the fire safety provisions within the building, such as the specification and performance of the detection and alarm system, as highlighted in the work of Lovreglio et al. (2019b).
- The fire growth rate and the maximum HRR of the fire, with C. Hopkin et al. (2019c) identifying large variability in these parameters for dwelling fire incidents.
- The room of fire origin and whether the internal door to this room is open, impacting on the possibility of further smoke spread. Work by C. Hopkin et al. (2019d) indicates the likelihood that an internal door is open will differ depending on the room it is connected to and whether the occupants within the dwelling are awake or sleeping.
- The interaction of sprinklers with the fire, such as if they are able to maintain the HRR to a fixed value attained at the time of sprinkler activation or progressively reduce the HRR as the sprinkler continues to discharge. The interaction of sprinklers will also be affected by the thermal sensitivity parameters of the sprinkler heads. Hopkin and Spearpoint (2020) determined that standard tests for concealed residential heads can result in greater expected values for the response time index (RTI) in contrast to exposed pendent heads, ultimately producing a slower sprinkler activation time in comparison.

5. Conclusions and recommendations

Distributions of possible door open times have been determined for different apartment types, based on the number of bedrooms. The reason for determining these distributions is to help better inform fire safety engineers when they are undertaking assessments relating to smoke spread from apartments into common corridors, generally in support of the design of smoke ventilation systems.

For probabilistic assessments which involve the opening of the apartment exit door, adopting a lognormal distribution using parameters given in Table 1 would appear reasonable and conservative from a design perspective. With respect to deterministic assessments, a judgement will need to be made on an appropriate percentile in the context of the building design, other selected input parameters and the consequences of corridor smoke contamination (i.e. the number of possible occupants affected). However, the following general recommendations are made:

- Where the number of bedrooms is known, a 95th percentile door opening period could be adopted in line with the more conservative values given Table 1 (for Method 1), i.e. 10 s for a one-bedroom apartment; 14 s for two-bedrooms; and 19 s for three-bedrooms.
- Where the number of bedrooms is not known, then either a conservative value of 19 s for a three-bedroom apartment could be adopted, or alternatively the floor area could be assessed to estimate the likely number of bedrooms. C. Hopkin et al. (2019b) determined from EHS survey data that one, two and three-bedroom apartments have a mean floor area of 45 m^2, 63 m^2 and 84 m^2, respectively.
- Given the observations in this paper, while the 20 s door open time recommended in the current revision of the SCA Guide (SCA, 2020) does not appear unreasonable, it is likely very conservative in the context of most typical apartment arrangements. The SCA Guide recommended value is shown to be greater than the 99th percentile for both one-bedroom and two-bedroom apartments, and equivalent to a 96th percentile or again greater than 99th percentile for three-bedroom apartments, depending on the adopted calculation method. Therefore, the application of the door open time recommended in the SCA Guide would not be expected to directly result in an inadequate demonstration of fire safety performance.

The authors of this paper intend to undertake further work on this topic, assessing the impact of the door open time and other probabilistic input parameters on the quantity of smoke which may enter the common corridor during means of escape. This is expected to be observed in the context of the performance of typical smoke ventilation systems, expanding on previous work by D. Hopkin et al. (2019). It would also be beneficial to collect more data related to door open times for occupants evacuating from apartments, to determine whether the data from Frank (2013) is consistent with that which would be observed in a residential setting.

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