Probabilistic study of number of doors open simultaneously to fire-isolated stairs in basement carparks

- Development of CarParkEvac

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Abstract
This thesis investigates occupant evacuation in basement carparks. The thesis aims to develop a calculation model to determine the probability of different number of doors to fire-isolated stairs being open simultaneously during an evacuation scenario. Research is done on previous studies of occupant evacuation, including the pre-evacuation and evacuation phase, which is the base for a conceptual model. A probabilistic method is employed and the conceptual model is incorporated into a spreadsheet which by use of different distributions and formulas simulates the probabilities of stair-doors being open simultaneously. A case study shows the use of the spreadsheet and the results. The results and limitations of the model are analyzed in a sensitivity analysis and comparison to an existing model.

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Foreword

This thesis has been written for the Department of Fire Safety Engineering at Lund Institute of Technology (LTH), Lund University, Sweden. The thesis covers 30 credits at LTH and is the final part of my Fire Engineering Degree (BSc). The process of writing this thesis has been undertaken at Holmes Fire in Sydney, Australia. I wish to thank my supervisor at LTH, my external supervisor at Holmes Fire and the rest of my colleagues and manager at Holmes Fire for your help and support.

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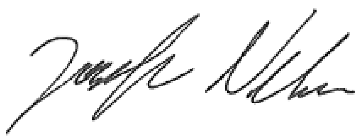
Thank you,



Josefin Nilsson
Sydney, April 2017

Summary

This thesis focuses on occupant evacuation in basement carparks. A calculation model referred to as "CarParkEvac" is developed using probabilistic methods on occupant evacuation. The calculation model can be used to determine the probability of doors to a fire-isolated stairway being open simultaneously during evacuation of the carpark.

The need for such type of model comes from the requirements for stair pressurisation systems. In Australia/ New Zealand, fire-isolated stairs in a carpark are required to be provided with a stair pressurisation system that sustains an airflow of at least 1 m/s through the doors to a fire-affected compartment. Since carparks are often connected by vehicular ramps such as it forms a single fire compartment, the stair pressurisation system is required to be designed to achieve an air flow of at least 1 m/s though the doors to the carpark when all doors are open.

Fire engineered solutions are needed regarding rationalisation of carpark stair pressurisation, to allow for a pressurisation system where the air flow of 1 m/s is achieved when less doors are open simultaneously.

How likely is it then that all doors to the stair are open at the same time in a carpark? This thesis work attempts to develop a calculation model that can determine how many doors to the fire-isolated stairs that are likely to be open simultaneously in different types of multi-storey carparks. It also shows for how long period each number of doors are likely to be open at the same time.

To develop this model, a literature review has been completed on occupant evacuation. Based on this research, random sampling methods from distributions are used to assign to each occupant an arrival time at the stair door. These arrival times are thereafter used to calculate the probability of the number of stair-doors being simultaneously open. The results will also show the aggregate probabilities, i.e. the probability of up to two doors open, up to three doors open etc.

A case study shows an example of a basement carpark, how to use the model, its results and a comparison with an existing agent-based commercial evacuation model. An exploratory sensitivity analysis measures the impact on the results of the different input values.

Acronyms

AS/NZS – Australian/New Zealand standard

NIST - National Institute of Technology

BCA – Building Code of Australia

BS – British Standard

NFPA – National Fire Protection Association

ISO – International Organization for Standardization

LNN - Law of large numbers

Contents

List of Figures

List of Tables

1 Introduction / Background

This report relates to occupant egress within basement carparks. The thesis investigates the probability of doors to fire-isolated stairways being open simultaneously during occupant evacuation in basement carparks. The motivation for this work comes from the requirements for air pressurisation in basement fire-isolated stairs.

For example, the Australian and New Zealand standard AS/NZS 1668.1-2015 (Standards Australia, 2015) requires fire-isolated stairs in a carpark to be provided with a stair pressurisation system that sustains an airflow of at least 1 m/s through the doors to a fire-affected compartment. Since carparks are often connected by vehicular ramps such as it forms a single fire compartment, the stair pressurisation system is required to be designed to achieve an air flow of at least 1 m/s though the doors to the carpark when all doors into the stair are open. It may seem onerous that all doors would be open simultaneously in a carpark, given the limited occupant load and the unlikelihood of queuing at the doors.

An alternative method for the design of buildings in accordance with the Deemed-to-Satisfy provisions in the building code in relation for fire safety measures, is to use performance-based fire engineering. A fire engineer will then be engaged to provide a performance solution (via a quantitative and/or qualitative assessment) to show that adequate fire safety is provided to the building in relation to the relevant fire safety issue(s).

There has been requests for fire engineered performance solutions regarding rationalisation of carpark stair pressurisation, i.e., to allow for a pressurisation system where the airflow of 1 m/s is achieved when less doors are open simultaneously.

Based on these grounds, this thesis will attempt to develop a simplified model (i.e. a calculation sheet), called “CarParkEvac”, which can determine how many doors from the fire-isolated stairs to the affected fire compartment that are likely to be open simultaneously in different types of multi-storey carparks. Note that the number of doors calculated will be the doors into the stair from each level, excluding the discharge door to the outside. Hence, if the stair discharges on ground level, CarParkEvac will only refer to the stair doors on the levels below ground.

This cannot be predicted with a deterministic model, since there are uncertainties associated with the variables that determine the probability of open doors. For example, different people have different pre-evacuation times, walking speeds, etc.

A stochastic approach is used to develop this calculation sheet.
A stochastic approach is intended here as a model based on probabilities. In probability theory, this is described as a method that represents a system using variables, which change is subject to a random variation. A random variable can be described as an uncertain, numerical quantity.

CarParkEvac calculates evacuation times of a basement carpark based on distributions for occupant pre-evacuation times, travel speeds, travel distances, etc. The reason for the use of distributions is that it is unknown which value a random variable X will take, however research studies are used to derive the subset of possible times in which it is known that the variable is likely to be. The random variable X could in this case for example represent the pre-evacuation time for an occupant located within the carpark, and the distribution based on a mean and standard deviation for pre-evacuation time based on research.

Based on these different distributions and a number of assumptions, the probability of different number of doors to fire-isolated stairways being open simultaneously will be determined in the calculation sheet.

1.1 Purpose and aim

The purpose of this thesis is to develop a calculation model that can be used to estimate the number of doors likely to being open simultaneously in multi-storey carparks. The thesis also includes a case study, which shows how to use the calculation model, a sensitivity study and a comparison to an existing evacuation model.

The aim with CarParkEvac is to provide results that may be useful for Fire Engineering Performance-based solutions. If the results show that it is highly unlikely for all doors to be open simultaneously, this can consequently help enable design of multi-storey carpark outside the BCA deemed-to-satisfy provisions in relation to carpark stair pressurisation rationalisation, by the use of fire engineered performance solutions. If the results show that it is relatively high probability that all doors are open simultaneously during the evacuation, the model can be used to further motivate the requirements for the stair pressurisation required airflow to be achieved while all doors are open.

1.2 Method

To determine the probability of doors to fire-isolated stairs in carparks being open simultaneously, a simplified model is developed, and implemented into a calculation sheet.

The thesis work is based on a literature review, which collects data for the definition of the conceptual model for the calculation of the probability of doors open simultaneously, and the identification of possible input numbers to be used in its implementation in a calculation sheet. Based on this, a conceptual model is developed as per the flow chart shown in Figure 1-1. As shown in the flow chart, a number of assumptions are made throughout the process.

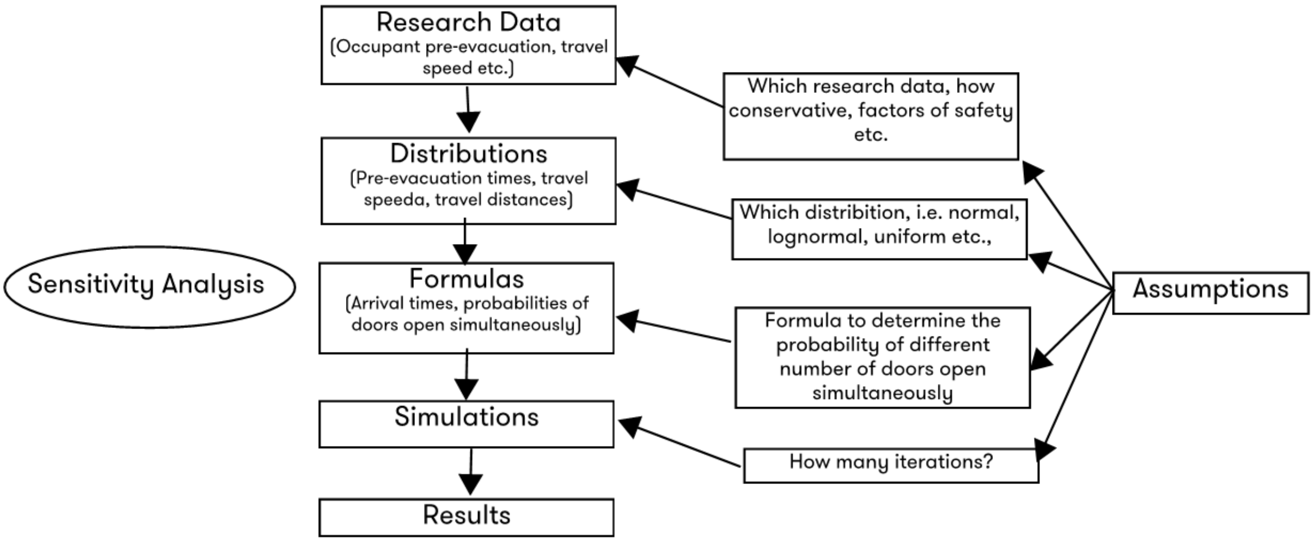


Figure 1-1: Method Flow Chart

Suitable distributions have been chosen for the different input data such as the occupant pre-evacuation times, travel speed and travel distances. The model uses a stochastic process, where the results are based on a collection of random variables based on specific formulas.

This conceptual model has been implemented in a calculation sheet, i.e. CarParkEvac, by use of Excel 2013. Random variables has been created by the use of the RAND() function. The RAND function uses a pseudo random number generation algorithm developed by B.A. Wichman and I.D. Hill, which was first implemented in Excel 2003. This algorithm has been shown to pass the DIEHARD tests and other tests developed by the National Institute of Technology (NIST) (Microsoft Support, 2011).

1.3 Limitations

The following limitations should be considered while reading the thesis:

- The thesis will be limited to multi-storey basement carparks.
- Due to lack of time and resources, the data used for input parameters is based on a literature review only; no surveys or experiments are undertaken for this thesis. Therefore, further validation for the CarParkEvac is necessary in the future.
- The conceptual model is implemented into a calculation sheet, where a number of assumptions are employed in relation to the used formulas and knowledge/limitations of the software used for implementation.
- Some of the assumptions adopted in the simplified model are based on the requirements in Australia/New Zealand, however can most likely be used in other countries as well.
- The calculation sheet is limited to a certain number of input factors, see Section 4.1.
- CarParkEvac is based on a number of assumptions, these are listed in 5.2.

1.4 Report structure

This report firstly describe the literature study, including the requirements for stair pressurisation in carparks. Thereafter, general theory on occupant behaviour and evacuation is outlined. The following section is the main section of the report, which outlines the development of the conceptual model and CarParkEvac. This section describes what input data was chosen and why, used formulas, assumptions and uncertainties, and how the results are outlined. Following this section is the case study, which by the use of a fictitious basement carpark describes how to use the model and discusses the results from this case study. Following the case study is the sensitivity analysis, which by changing one input parameter at the time, shows the impact of these parameters on the results. Thereafter the results from the case study in CarParkEvac are compared to the results from another model with the same input parameters. Finally, the last sections discusses the results, assumptions, uncertainties etc.

2 Literature review

The literature study has included investigation for previous studies on this subject. No studies have been found on the subject of the probability of doors being open simultaneously.

Limited research data has been found on evacuation studies in carparks and carparks in general. The limitation of data on carparks has required inclusion of a wider range of evacuation studies of different types of buildings. The information has been obtained by studying existing evacuation studies and reports.

2.1 Requirements for stair pressurisation

Stated below are the requirements for stair pressurisation relevant for the purpose of this thesis.

2.1.1 Australian Building Code and Australian Standards

BCA 2016 (Australian Building Codes Board, 2016) Clause E2.2(a)(i) states:

> *"A building must comply with [...] (i) Table E2.2a as applicable to Class 2 to 9 buildings such that each separate part complies with the relevant provisions for the classification"*

Table E2.2a states:

> *"A required—*
>
> *(a) fire-isolated stairway, including any associated fire-isolated passageway or fire-isolated ramp serving—*
>
> *(i) any storey above an effective height of 25 m; or*
>
> *(ii) more than 2 below ground storeys, not counted in the rise in storeys in accordance with C1.2*
>
> *[...]*
>
> *must be provided with—*
>
> *(c) an automatic air pressurisation system for fire-isolated exits in accordance with AS/NZS 1668.1; or*
>
> *(d) open access ramps or balconies in accordance with D2.5."*

The Guide to the BCA (Australian Building Codes Board, 2016) states that the intent of this Clause is to specify the requirements for minimising the smoke risks. It also states that fire-isolated exits enable the safe evacuation of occupants, and also aid fire brigade access. The Guide notes that smoke must not unduly affect the conditions in such exits during an evacuation. To minimise smoke intrusion, the exits may need to be pressurised with outside air for the entire exit route. Alternatively, the exits may be provided with open access ramps or balconies from which smoke can vent naturally.

AS/NZS 1668.1-2015 Clause 10.3(d)(i) states:

> *"For car park ventilation systems:*
>
> *(i) The fire-isolated exit pressurization system shall sustain an air velocity from the pressurized fire-isolated exit, through each doorway into the fire-affected compartment, of not less than 1 m/s averaged over the full area of each doorway while the following doors are open:*
>
> *(A) All doors from the fire-isolated exits to the fire-affected compartment.*
>
> *(B) All doors immediately above/adjacent to the fire-affected compartment.*
>
> *(C) The main discharge doors from all fire-isolated exits.*
>
> *All other doors to non-fire-affected compartments shall be closed."*

AS/NZS 1668.1-2015 Clause C10.3(d) states:

> *"In a multi-level, single-compartment car park, this Clause requires that all required fire exit doorways be open during the doorway velocity test. Further, if the adjacent compartment is also a multi-level, single-compartment car park, all required fire exit doorways in that adjacent compartment are required to be open during the doorway velocity test. Very large airflows rates are required for this Clause."*

AS/NZS 1668.1-2015 Clause 10.3(e) states:

> *"The fire-isolated exit pressurization system shall be automatically controlled so that when operation of doors or other factors cause significant variation in airflow and pressure (relative to outside the building), the system performance is restored with minimal delay, and not exceeding 10 s."*

C10.2.1 of AS/NZS 1668-2015 states that airflows in excess of 0.8 m/s through a door incorporating a transom with a depth in the order of 500 mm will minimize the spread of smoke against the direction of flow. It also states that the performance needs to be achieved against the most demanding practical situation likely to occur in the early stages of fire development.

As multistorey carparks generally form single compartments due to ramps connecting the different floors, the relief air for the stair pressurisation system is required to be designed to relieve the airflow from all doors opening into the carpark fire compartment being open at the same time.

2.1.2 International Standards

NFPA 92 Section 4.4.2.1.5 states:

"The calculations shall take into account the design number of doors to be opened simultaneously."

4.6.1* states:

"When stairwell pressurization systems are provided, the pressure difference between the smoke zone and the stairwell, with zero and the design number of doors open, shall be as follows:

(1) Not less than the minimum pressure difference specified in 4.4.2

(2) Not greater than the maximum pressure difference specified in 4.4.2.2"

Pressure Testing. 8.4.6.1.1 With the containment system activated, the pressure difference across each smoke barrier shall be measured and recorded with all interior doors closed.

8.4.6.1.2 states that if an exterior door would normally be open during evacuation, it shall be open during testing.

3 Theory on occupant behaviour and evacuation

Occupant behaviour in fire depends on several factors, such as the use of the building, the occupant characteristics, the fire safety management, and the development of the fire (Bukowski & Tubbs, 2016).

In estimating occupant evacuation, a time-line model is often applied within models, where the evacuation process is described as a list of consecutive steps. This timeline which describes the total time to evacuate can be divided into different components, namely (BSi, 2004):

- Detection time;
- Pre-evacuation time; and
- Movement time

This is a simplified time-line model of the behaviours that may occur during an evacuation process, however it has been included in international legislations and handbook, e.g.,. ISO TR16738 (International Organization, 2009), BS PD 7974-6 (British Standards, 2004), the Society of Fire Protection Engineering Handbook (Proulx, 2002) etc., and it can be useful as an easier implementation in evacuation models (Ronchi, Reneke, Peacock, 2014).

The detection time is the time from when a fire starts until the occupants in a building become aware of the fire. This time varies depending on a number of different factors but can as a worst-case scenario be considered as the time until a fire detection system activates. On the floor of fire origin occupants may become aware of the fire before the detection system activates due to visual or olfactory cues.

The pre-evacuation time is defined as the period from when people become aware of the fire until they start moving towards the exits. This time can for example include stopping of machinery, gathering family members, investigation, alerting others and fighting fire (Purser, 2001).

The movement time is the time it takes for occupants to get to a place of safety after they start to move towards an exit. This time depends on factors such as the occupant walking speed, occupant density, the location of people on the floor, the width of the doors, the slope of the floor and if the occupants are familiar with the building or not, etc. (BSI, 2004).

In multi-enclosure occupancies where the occupants are expected to be well spread out (i.e. in case of relatively low people densities), such as in hotels or residential buildings, the pre-evacuation time is often the most determining factor of the egress time, especially the pre-evacuation time of the slowest occupant. The travel distances to exits are also relatively important in these types of occupancies. In crowded occupancies, such in for example shopping centres, theatres or stadiums, the evacuation time depends more on the pre-evacuation time for the first occupant to start moving, and the movement of the whole group of occupants. The first occupant to respond will form the start of the queue and thereafter the evacuation time depends mainly on the distribution of occupants over exits and the flow capacities of the exits routes (Purser 2001).

3.1 Pre-evacuation time

The pre-evacuation time, i.e. the behaviours that take place before the occupants start moving, is often difficult to estimate, as it is individual and depends on the characteristics and choices made by the occupants within the building. The pre-evacuation time may vary significantly between the occupants within the building, between different types of buildings and different incidents depending on a number of different factors.

Pre-evacuation time can be divided into two phases; recognition time and response time (BSi, 2004).

Recognition time is the time from alarm signal until people interpret the signal as an emergency. During this period, the occupants continue with their activities as they did before the alarm, and investigate the situation.

Response time is the time from the realization of the alarm as an emergency, until the first movement towards an exit. This time includes activities such as gathering family members, fighting fire, warning others, collecting personal belongings, call the fire brigade, etc.

Once the evacuation begins, the occupants need to make a choice concerning possible evacuation routes. It is common that they choose to go towards routes and exits they are familiar with, especially the way in which they entered (BSi, 2004). If an exit or exit route is blocked by a fire, the occupants may need to turn and choose an alternative exit.

Another important aspect in occupant behaviour during the pre-evacuation time is the fire safety management within the building. This includes factors such as the provision of warnings, staff training, the fire emergency plan and the management procedures during an emergency.

The type of alarm has been shown to often have a significant impact on the pre-evacuation time. For example, the public take more notice of voice messages compared to an alarm bell/siren (Purser, 2008). A spoken message, even if pre-recorded, clearly identifies the nature of the problem and provides a clear instruction to the public. Furthermore, in buildings such as hotels when sounders are used, it is quite common to completely ignore the alarm and assume it is a false alarm (Purser, 2001)

It has been shown that pre-evacuation times in experiments can be approximated to a lognormal distribution (BSi, 2004). This means that the curve is skewed towards the faster reaction times and decreases towards the longer times. In reality, this means that the majority of the occupants will start evacuation around the mean pre-evacuation time, and a few occupants will have significantly longer pre-evacuation times (sometimes to infinity if there is people that never leave the building). This may not always be the case, however several data sets of real-life experiments have been showed to follow this pattern (Purser, 2001).

3.2 Movement time

The movement time is the time it takes for occupants to get to a place of safety after they have started to evacuate. This time depends on factors such as the occupant walking speed, occupant density, the location of people on the floor, the width of the doors, the slope of the floor and if the occupants are familiar with the building or not.

The walking speed is individual and depends on the occupant mobility. For example, elderly and disabled people are expected to have a slower walking speed.

According to the SFPE Handbook, a maximum speed of 1.19 m/s (Gwynne, Rosenbaum, 2016) can be used when the density is lower than 0.54 people/m^2.

3.2.1 Occupant Flow Rates through doors

Table 4.1.42 in Fire Protection Handbook (Bryan, 2008) states the time to negotiate a door for ambulant disabled people. This table shows that the mean time to negotiate a door for a disabled person with no aid is between 3-4.3 seconds with a push standard single-leaf door with a clear width opening of 750 mm, and 3.2-4.6 to negotiate a pull-open door.

If the population density is less than approximately 0.54occupants/m^2, occupants will move at their own pace and will not depend on the speed of other people (Spearpoint, 2008).

According to the SPFE handbook, the maximum value that can be achieved for specific flow rate through a doorway is 1.3 occupants / second / m effective width (Gwynne, Rosenbaum, 2016).

3.3 General occupant characteristics for carparks

The occupants present within carparks are expected to be made of the building's residents / staff / employees / patrons / customers etc., (depending on which type of building, i.e. residential, retail, commercial etc.) who may consist of adults, elderly and children.

Occupants can consist of people from a wide range of cultural, educational, demographic and religious backgrounds. The diversity in backgrounds can result in different behaviours and actions in the event of a fire. People with disabilities may also be present inside the carpark to the same proportion as expected within the general population. Occupants are expected to be in the carpark for short periods, typically moving to or from their vehicle.

The drivers of the vehicles within the carpark are assumed to be awake and alert (i.e., not significantly adversely influenced by alcohol or drugs). Other passengers within the vehicles are also assumed to be awake and alert, or at least capable of being alerted to an emergency situation, except small children who would be accompanied by parents or guardians.

After fire alarm notification, occupants may engage in pre-evacuation activities such as gathering family members or belongings, or investigating and possibly attempting to extinguish the fire, based on how the threat of the fire is perceived. Research for tunnels has shown that occupants may remain in their cars even if they can see fire or smoke, and that they may use their cars to move towards exits, which may also be the case in carparks (Boer, 2002).

Occupants may not be aware of all egress paths from the carpark, however the layout in carparks is generally open and it is expected that occupants will be afforded relatively clear lines of sight to see exits and/or wayfinding signage.

3.4 Occupant loads in carparks

The occupant density for a carpark is within Table D1.13 of the BCA specified as 30 m^2 per person. In the New Zealand verification method (Ministry of Business, 2013) the occupant density is specified as 50 m^2 per person. NFPA 5000-2015 Table 11.3.1.2 states that the design occupant load within a storage use in other than storage and mercantile occupancies is 46.5 m^2/person (National Fire Protection Association, 2015).

4 Conceptual Model

This section outlines the methodology used to develop the conceptual model and aims to describe certain inputs and methodological choices.

A literature review has been conducted to decide certain input parameters for occupant pre-evacuation times, travel speeds, distributions and travel distances, which are stated below. It is to be noted that these numbers are based on literature studies only, and no surveys or experiments has been undertaken for this thesis. Therefore, further validation for the calculation sheet is needed in the future.

A number of assumptions has been made for the purpose of developing the calculation model, which are listed in Section 5.2.

4.1 Input data

The following section states the input parameters used in the spreadsheet, and aims to describe the reasons why these numbers were chosen.

4.1.1 Detection time

The detection time is not relevant for the purpose of this spreadsheet as it is expected to be the same throughout the carpark levels. Therefore, the detection time is not included in the evacuation time, i.e. the arrival times are calculated from the activation of the detection system until arrival at the stair door.

4.1.2 Pre-evacuation times

The input parameters for pre-evacuation times are based on literature study of previous experimental studies. Due to lack of experimental data on evacuation in carparks, the times used for the calculation model are based on a wider range of building types.

The british standard BS 7974 (BSi, 2004) gives suggested pre-evacuation times for different behavioural scenario categories, where the times depend on the size/complexity of the building, if the occupants are awake or not, if the occupants are familiar with the building or not, and the building fire safety management systems. These pre- evacuation times has been compared to data from a range of different studies of real fires and experimental studies, which have been collected by Gwynne and Boyce (2016).

The New Zealand verification (Ministry of Business, 2013) provides data on expected pre- evacuation times based on the british standard BS 7974 (BSi, 2004), dividing the pre- evacuation times into further categories; such as if the occupants are located on the enclosure of fire origing or not, and if the building is provided with voice alarm or standard alarm signal.

It has been shown in a number of experiments that the pre-evacuation times are generally shorter in buildings where voice messages are used, compared to where bells/sirens are used. Therefore the pre-evacuation times used for the calculation model are divided into different categories for voice alarm and bell/siren.

Since a carpark is generally a relatively open area, it is likely that occupants on the floor of fire origin notice a fire upon cues such as the sight of the fire and smoke, or the smell of the smoke occurring in the carpark. These occupants are likely to have a shorter pre-evacuation time. Based on this, the calculation sheet will allow the user to choose different pre-evacuation times for different floors, where it can be decided which floor will be assumed to be the floor of fire origin.

The pre- evacuation times are also divided into different categories based on the familiarity with the building, where occupants who are familiar with the building are likely to have shorter pre- evacuation times.

Based on the reports mentioned above, numbers for pre-evacuation times has been chosen for different scenarious, shown in Table 4-1, where the mean values are the same numbers as within The New Zealand verification (Ministry of Business, 2013).

Table 4-1: Pre-evacuation times

Scenario	Awake and familiar	Min	Max	Mean	SD
1	Enclosure of origin	5	90	**30**	15
2	Remote from enclosure of origin	7	120	**60**	20
	Awake and unfamiliar				
3	Enclosure of origin (standard alarm)	5	120	**60**	20
4	Remote from enclosure of origin (standard alarm)	10	240	**120**	30
5	Enclosure of origin (voice alarm)	5	90	**30**	15
6	Remote from enclosure of origin (voice alarm)	7	120	**60**	20

The pre- evacuation times are presented as truncated lognormal distributions in the calculation sheet, which are based on the mean value and standard deviation, ranging between a minimum and maximum value. Figure 4-1 shows the distribution of occupant pre-evacuation times from approximately 5000 iterations in excel with the values of Scenario 1 in Table 4-1. These iterations were made as an example, and a different number of iterations could have been used.

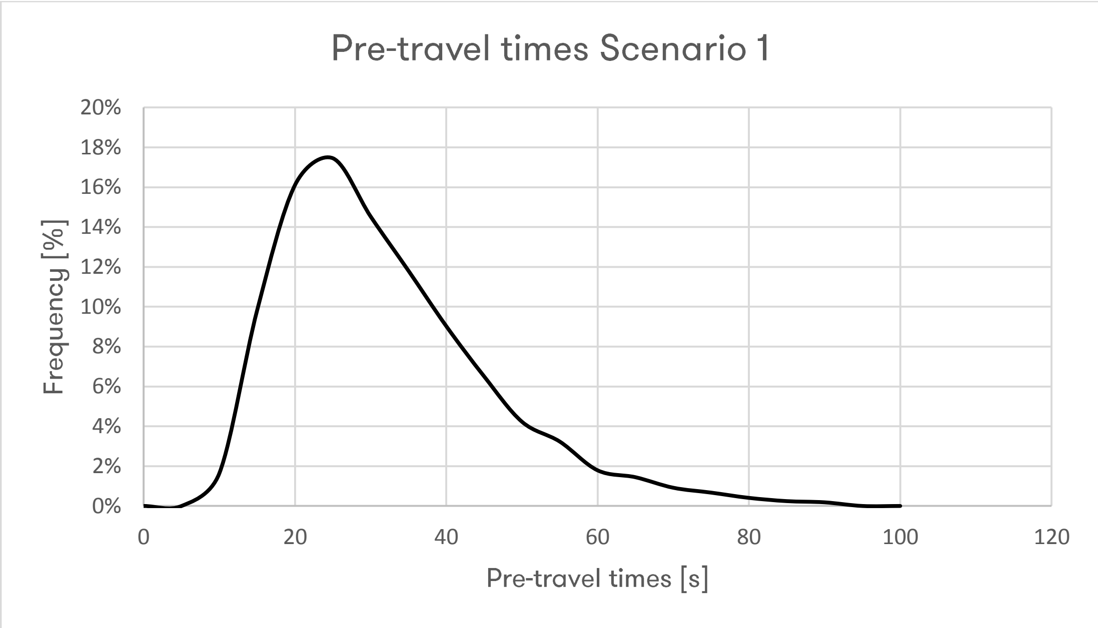


Figure 4-1: Distribution of pre-evacuation times for scenario 1

4.1.3 Occupant walking speeds

To allow for all occupants that could be present within the carpark, the occupants are divided into three categories: family group (being children/adults with children), adults and old/disabled. The mean and standard deviation for each group are based on data collected from different studies, which have been collected in Engineering Data by Gwynne and Boyce (2016).

The walking speeds for children are based on a study by V. Kholshchevnikov et al of children evacuating from pre-school institutions (Kholshevnikov, Samoshin, Parfyonenko, Belesokov, 2012) a study by J. Gates of walking speeds for pedestrian cleareance based on pedestrial characteristics (Gates, 2006), and a study by Larusdottir of walking speeds etc. in day care centres (Larusdottir, 2011). The study by Kholshchevnikov states the walking speeds for children between 0-7 years old, the study by J. Gates states the walking speeds of children assisted by adults, and the study by Larusdottir studies unimpeded speed for 3-6 year old children.

It is assumed that small children will be accompanied by adults, and that the travel speed of the adult assisting the child will depend on the childs walking speed. Therefore this group of occupants will be reffered to as “family group”. Based on the studies mentiones above, a mean value of 0.9 m/s and standard deviation of 0.25 are conservatively chosen to be used for this category in the calculation sheet.

The walking speeds of adults (excluding old / disabled, adults with children) are expected to have the highest walking speeds. A number of different studies have been looked into to determine a mean and standard derivation value (Berrou, Beecham, Kagarlis, Gerodimos, 2005), (Schulz, Schulz, Fricke, 2008), (Sime, Jonathan, 1996), (Zanlungo, Chigodo, Ikeda, Kanda, 2012), (Daamen, Hoogendoorn, 2005). These studies generally show a mean walking speed between 1.1–1.5 m/s. According to the SFPE Handbook, when the density is lower than 0.54 people/m^2, which is generally applicable to a carpark, a maximum speed of 1.19 m/s (Gwynne, Rosenbaum, 2016) can be used. Based on this, the walking speeds for adults will be using a mean value of 1.19 m/s, which is considered to be conservative.

The walking speeds for old and disabled occupants have been shown to be similar to each other, and the majority of all disabled people are also old. Therefore a mean and standard deviation has been selected for an occupant group reffered to as “disabled / old”. These values are determined from data collected in Engineering Data by Gwynne and Boyce (Gwynne, Boyce, 2016). The values selected for the spreadsheet proceed from different type of disabilities and aids such as disability with no aid, crutch, visiably impaired, wheel chair, etc (Jiang, Zheng, Yuan, Jia, Zhan, Wang, 2012), (Sorensen, Dederichs, 2012), (Jiang, 2009), (Boyce, Shields, Silcock, 1999), (Shields, 1993) and people over 65 years of age (Gates, Noyce, Bill, Ee, 2006). Based on the studies mentioned above, a mean value of mean walking speed has conservatevily been set to 0.7 m/s, with a standard deviation of 0.3.

The mean and standard deviation of walking speeds used in CarParkEvac are presented in Table 4-2.

Table 4-2: Walking speeds used for calculation sheet

Walking Speeds [m/s]	Family Group	Adults	Old / Disabled
Mean	0.9 m/s	1.19 m/s	0.7 m/s
Standard Deviation	0.25 m/s	0.25 m/s	0.3 m/s
Min	0.3 m/s	0.4 m/s	0.2 m/s
Max	2 m/s	3 m/s	2 m/s

The data used for the input parameters for the modelling are generally taken from experiments for unimpeded speed on open spaces, which would normally be the case in a carpark. Conservative values has been chosen to allow for slower moving occupants, and to take into consideration of possible inclines in carparks which could result in slightly slower walking speeds.

Since the occupant characteristics could vary between different buildings, the calculation sheet allows for the user to insert the fraction of the different occupant types.

The walking speeds are set up in the calculation sheet as normal truncated distributions. This means the most of the values will cluster in the middle of the range, and the rest of the values narrowing off towards the minimum and maximum walking speeds. Figure 4-2 shows the distribution of travel speeds for adults taken from approximately 5000 simulations in excel with the values from Table 4-2.

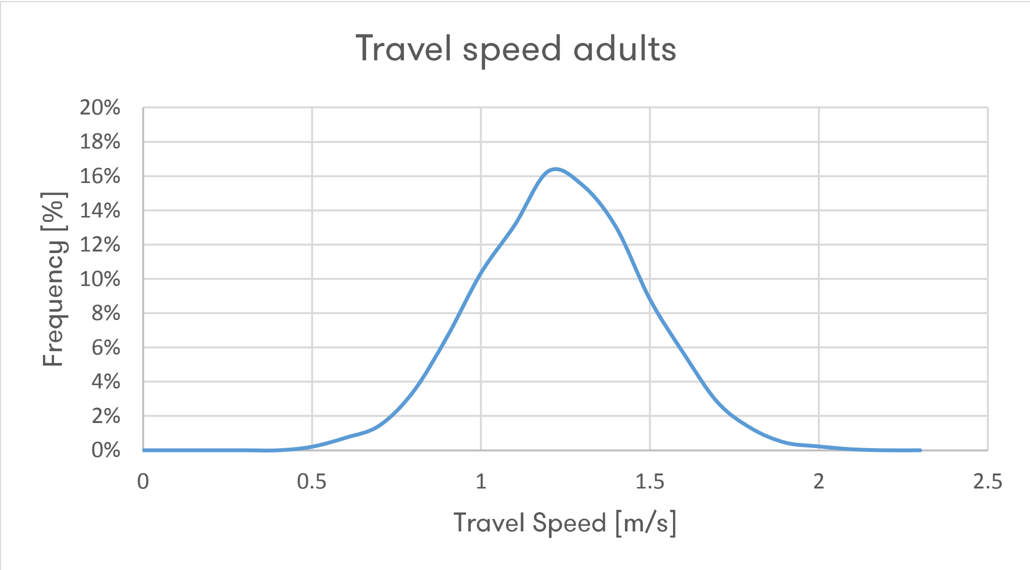


Figure 4-2: Distribution of travel speeds for adults

4.1.4 Number of occupants

CarParkEvac allows the user to insert the number of occupants located on each level of the carpark. If no information on the number of occupants that are expected within the carpark, an occupant density of 30 m^2/person may be used as per BCA Table D1.13 (Australian Building Codes Board, 2016).

4.1.5 Number of exits and distribution of occupants

CarParkEvac is developed for the purpose of calculating the probability of doors being open simultaneously within one stairway. If more than one fire-isolated stair is provided within the carpark, the user needs to decide the number of occupants using each stair. It may be reasonable to assume that the occupants are equally distributed over the stairs.

The occupants located within the carpark are expected to be distributed over the floors, such that they have different travel distances to an exit. As different carparks have different layout, it is difficult to determine a standard carpark configuration.

The maximum allowed travel distance from any point of the floor to an exit within a carpark in Australia is 40 m as per BCA Clause D1.4 (20 m if single exit). However, the occupants may not always choose the closest exit, and an exit could for example be blocked by a fire. Furthermore, greater travel distances may be allowed as part of a Performance Solution.

Based on this, the calculation sheet will allow the user to insert a maximum travel distance to the stair.

As occupants could be located anywhere on the floor, a uniform distribution is assumed. Since this is a significantly uncertain perimeter, also a normal distribution is tested in the sensitivity analysis to determine how big impact this has on the results, refer to Section 7.

5 Implementation of conceptual model into CarParkEvac

To implement the conceptual model into the calculation model called CarParkEvac, a stochastic approach is used. Random sampling from distributions has been used for different input parameters, to allow for each single occupant to be given an arrival time. Based on research, the pre-evacuation times, travel speeds and travel distances to exits, are given different distributions, refer to Section 4.1. For example the pre-evacuation time is specified as a log-normal distribution, where the mean and standard deviation are based on research (Ministry of Business, 2013), (BSI, 2004), (Gwynne, Boyce, 2016) refer to Section 4.1.2. By use of this method, every single occupant within the carpark can be given a pre-evacuation time that reflects the type of scenario under consideration.

In order to assess the impact of the probabilistic approach in the inputs and investigate the uncertainty associated with the use of probabilistic variables, the simulations are repeated adopting random sampling from the distributions described above.

CarParkEvac is developed using Excel 2013. The reason for the choice of software was to provide a user-friendly spreadsheet that is available for as many users as possible. Since Excel is a standard Microsoft Office software it is considered to have a wide usability, as the majority of users will have access to it. Microsoft Excel is also considered to be suitable for the purpose of this thesis due to the possibility of implementing probabilistic formulas.

To determine the occupants arrival times at the exit stair doors from the time of detection activation, CarParkEvac uses the following simplified formula:

$$Time\ to\ arrive\ at\ door = \\ Pre - evacuation\ time + \frac{Travel\ distance\ to\ stair\ door}{Travel\ speed}$$

The user is required to insert the specific inputs for the carpark such as number of occupants using exit stair, stair door effective width, maximum travel distance to exit, fraction of different occupants groups and pre-evacuation scenario. For the pre-evacuation scenario, the user is to select one of the six different scenario described in Table 4-1, for each level.

The pre-evacuation time, travel speed and travel distances are probabilistic formulas based on distributions as per Section 4.1. These numbers are developed by using the excel rand() function to develop random numbers. The rand function uses a pseudo random number generation algorithm developed by B.A. Wichman and I.D. Hill (Wichmann, 1982), which was first implemented in Excel 2003. This algorithm has been shown to pass the DIEHARD tests and other tests developed by the National Institute of Technology (NIST) (Microsoft Support, 2011). CarParkEvac calculates a different pre-evacuation time, travel speed and travel distance to the exit for each occupant on each floor. These numbers are for each occupant randomly taken from ~5,000 different results calculated from the probabilistically based distributions described in Section 4.1.

Based on these functions mentioned above, an arrival time for each occupant from the activation of the alarm until they reach the door, is calculated. By use of the "countif" option in excel, CarParkEvac determines how many people arrive at the door on each floor within a specific time interval. The default time interval is set as 5 seconds, however this can be modified by the user. CarParkEvac calculates the number of people arriving at the door within this time interval, and the number of people passing through the door within this time interval.

To determine the number of people passing through the door, CarParkEvac takes into account possible queuing time and the width of the door. The default specific flow rate is set to 1.3 persons / second / m of effective door width, based on the maximum specific flow rate as per the SFPE Handbook (Purser, 2008), however the flow rate value can be modified by the user.

By multiplying the effective door width with the specific flow rate and the time step, the number of people passing through the door within this time interval is calculated. Thereafter the number of people located at the door on each level during this time interval is calculated by the following formula:

$$\begin{aligned} &Number\ of\ people\ at\ door\ within\ time\ interval\ X \\ &\qquad = People\ arriving\ at\ door\ within\ time\ interval\ X \\ &\qquad + People\ located\ at\ the\ door\ within\ time\ interval\ (X-1) \\ &\qquad - People\ passing\ through\ door\ within\ time\ interval\ (X-1) \end{aligned}$$

If this number is greater than zero, the door is assumed to be open during this time interval. If this number equals zero, i.e. if no one is located at the stair within this time interval, the door is assumed to be closed. This means that the model assumes that if no queuing occurs at the door, the length of the time interval equals the time for one occupant to negotiate a door, until the door is closed behind them. This is an uncertain factor, as it depends on the occupant characteristics and the type of the door. It is assumed that the door is self-closing which generally is required to a fire-isolated stair, however the time it takes for the door to close behind the occupant may vary. Based on this, the length of the time-interval can be modified by the user. This input parameter may ideally be determined by experiment studies and/or information about the self-closing device to be used.

The default value of 5 seconds is based on studies in Fire Protection Handbook (Gwynne, Rosenbaum, 2016), which states that the mean time to negotiate a door for a disabled person with no aid is between 3-4.3 seconds with a push standard single-leaf door. It is assumed that the majority of the occupants are not disabled and will not take longer time than approximately three seconds to negotiate the door into the stair. Extra time should be added to the time interval for the door to close after the person has passed through the door; this time depends on the type of door. It is stated in BS EN 1154:1997 (Dinov, Christou, Gould, 2009) that self-closing fire doors may take between 3-20 seconds to close, depending on the type of door-closer. Based on this, the user is required to ensure what type of fire doors are used in the particular building and how long they take to close and based on this decide the length of the time interval.

By the use of Excel's "countif" option, the number of doors open within each time-interval is calculated. Hence, if people on different levels arrive at the stair door on their level within the same time interval, multiple doors to the stair will be open at the same time.

To determine the probability of each number of doors open simultaneously during the evacuation period, CarParkEvac calculates the total amount of time a specific number of doors are open, and divide this number by the maximum arrival time (time from fire alarm activation until the last occupant reaches the stair).

5.1 Number of runs

To ensure that the impact of behavioural uncertainty is taken into account, a certain number of iterations are required to investigate the convergence of results from repeated runs (Ronchi, Reneke, Peacock, 2014). For this reason, it has been assessed how the probabilities results change in relation to the number of iterations. The more iterations that are conducted, the more the probabilities are deemed to be "stable" (i.e., "correct" since they are closer to the "real probability"). This is because of the central limit theorem (reflected in the law of large numbers). The law of large numbers (LLN) is a theorem that describes the result of performing the same experiment/simulation a large number of times. The law states that the sample average of a random sample will tend to become closer to the expected value, as the size of the sample increases (Dinov, Christou, Gould, 2009). This means that a random process like the present model tends to converge towards an average probability when the number of iterations are increased.

Because of this, the uncertainty associated with the number of iterations has been assessed. To do this, the relative errors between the probabilities obtained for different numbers of consecutive iterations has been studied.

5.1.1 Acceptance criteria for number of runs

To decide an appropriate number of runs for CarParkEvac, a criterion is set for the relative errors between the results. This criterion is implemented to decide the accepted uncertainty associated with the average results obtained by multiple runs of the same scenario.

It is also required to assess an additional acceptance criteria in relation to the stability of the difference of the results, i.e. that the criterion of the relative errors is accepted for a number of consecutive iterations. This is required to ensure that the results are stable over certain pre-defined number of runs (Ronchi, Reneke, Peacock, 2014).

The acceptance criteria for the number of runs can be modified by the user, and may for example be set to 1% for 10 consecutive runs. This means that the criteria is met when:

$$\frac{avg\ Value\ until\ RunX - avgValue\ until\ Run(X-1)}{avgValue\ until\ RunX} < 1.0\%$$

$$Where\ n = X_1, X_2, \dots, X_{10}$$

This formula used to calculate the stability of the results over a number of runs. By the use of a macro, the model automatically stops running when the criteria for stability is met. Hence, when the criteria for stability is met for each of the probabilities, it is assumed that a sufficient number of runs has been made. Thereafter an average value of the probability for each number of doors open simultaneously is calculated, which are the results used as outputs. The results also shows the cumulative probabilities for the number of doors being open simultaneously.

5.2 Assumptions

The primary assumptions made for the calculation model are presented below:

- The pre-evacuation times are assumed to follow a lognormal distribution, with mean, standard deviation, min and max values as per Section 4.1.2.
- The travel speeds are assumed to follow a normal distribution, with mean, standard deviation, min and max values for three different occupant groups, as per Section 4.1.3.
- Children are assumed to be accompanied by adults, where the travel speed for the whole family group is assumed to have the slower speed of the children.
- The distribution of the occupants locations on each floor at the time of fire alarm activation is assumed to have a uniform distribution.
- All occupants are assumed to exit via the stairs, i.e. the possibility of some occupants driving out in their vehicles has been ignored.
- It is assumed that the floor of fire origin will have shorter pre-evacuation times. The fact that the floors above may also become aware of the fire earlier due to visual or olfactory cues due to smoke spread via the ramps has been ignored.
- It is assumed that the pre-evacuation times will be shorter in buildings where voice message is provided and where occupants are familiar with the building.
- It is assumed that the occupants will open the door to the stair immediately as they reach the door.
- The default number for the time-interval for occupants to pass through the door is set to 5 seconds, hence it is assumed that it takes 5 seconds for an occupant to open the door, pass through and for the door to close behind the person. However, the user can modify the time-interval.
- It is assumed that the Wichmann Hill algorithm (Wichmann, Hill, 1982) for pseudo-random sampling is deemed to be an appropriate sampling method.
- The default value for the specific flow rate through door is set to 1.3 persons/second/m of effective door width, however this parameter can be modified by the user. To consider possible queuing at the door, it is assumed that if the specific flow rate * the door width * the time-step is greater than the number of people located at the door within this time interval, a queue occurs and the rest of the occupants will be passing through the door within the next time-interval instead.

- The stair discharge door to the outside is not included in the calculation model and is assumed to be open during the whole evacuation period.

5.3 Uncertainties

The travel distance to the exits, i.e. the distributions of the occupants over the floors of each level is an uncertain factor. The occupants could be located anywhere on the floor, the majority could be located within 10 m of the exit or they could be located up to around 40 m from the exit. It is also not sure that the occupants will travel the closest path to the exit. For example, there could be obstructions at the path of travel such they have to travel further to reach the exit. The impact of the type of distribution for the travel distance has been tested in the sensitivity analysis in Section 7.2.

It is possible that in a fire scenario, one exit gets blocked by the fire. This would require that all occupants located on that floor would have to egress via the alternative exit.

The pre-evacuation times are also an uncertain factor. These distributions are based on research data and code recommendations (refer to Section 4.1.2), which is uncertain since it is taken from different evacuation studies and different types of buildings. The pre-evacuation times are individual and may vary significantly for different occupants and different events. Limited research data was find for carpark and hence the used research data may not be the most suitable for the occupants located in a carpark. Similarly, the travel speeds are also individual and may vary in reality.

The probabilistic method takes into account variations between occupants to give each occupant a different pre- evacuation time and travel speed, however the mean and standard deviation values used in the spreadsheet may vary from a real event. These uncertainties are present in all evacuation models, however to make this calculation model as valid as possible, a greater amount of research and experiments would be beneficial.

The time interval to pass through the door is one of the parameters that is the most uncertain, as not much research has been found on this. It is uncertain how long it takes a person to open and pass through the door, and it is uncertain how long it takes for the door to automatically close behind the person. If greater time and resources were available for this thesis, experiments would have been completed. As stated in BS EN 1154:1997 (BS EN, 1997), self-closing fire doors may take between 3-20 seconds to close, depending on the type of door-closer.

5.4 Presentation of results in CarParkEvac

The results are presented as the probability for each number of doors to be open simultaneously during the evacuation period (excluding the discharge door which is assumed to be open during the whole period), being the time from fire-alarm activation until the last occupant reaches the fire-isolated stair. Note that the results of the number of doors open are the doors into the stair from each level, excluding the discharge door to the outside. Hence, if the stair discharges on ground level, the calculation model will only refer to the stair doors on the levels below ground. The discharge door will be assumed to be open during the whole period, hence this door is to be added to the shown number of doors open in the calculation model.

The results show the average, min, max and standard deviation for the probabilities, based on all simulated iterations. The results are also presented as the cumulative probabilities, i.e. the probability of at least one door open, at least two doors open etc, and up to one door open, up to two doors open etc. The results also show the total time during the evacuation each number of doors are expected to be open simultaneously.

6 Case study

This section will describe a fictitious carpark with hypothetical number of floors, distances, etc. which will describe how to use CarParkEvac.

6.1 Description of fictitious carpark

As a fictitious carpark a four storey basement carpark within a retail building is chosen. These chosen input parameters are considered realistic for a basement carpark, based on a review of drawings for different carparks that a fire safety engineering company where the thesis author has been working has dealt with.

The carpark basement levels has each a floor area of approximately 2,500 m^2, served by two fire-isolated stairs. Using 30 m^2/occupant, the expected number of occupants that might be present on each floor is 84. Assuming these occupants are equally divided over the two stairs, 42 occupants are expected to be evacuating via each stair in each floor.

For this case it is assumed that the ground level is used for something other than carpark. Hence all four carpark levels are below ground level and it is assumed that everyone will egress via the fire-isolated stairs which discharge on ground level to open space. The discharge door on ground level is not included in the calculations and is conservatively assumed to be open during the whole period.

As this carpark is located within a retail building, it is assumed that the majority of the occupants are not familiar with the building. In this case study it is assumed that a fire initiate within Floor -03. Based on this, the pre-evacuation scenario will be set to scenario 5 for Floor -03 and Scenario 6 for all other levels as per the scenarios listed in Table 4-1.

The specific flow rate will be set to the default value of 1.3 persons/second/m of effective door width.

The input parameters for the fictitious carpark are listed in Table 6-1.

Table 6-1: Input parameter for fictitious carpark

Input parameter	
Number of basement carpark levels	4
Floor area [m²]	2,500
Number of occupants per stair per floor	42
Stair door width [m]	0.8
Occupant scenario (refer to Table 4-1)	5 for level -03, 6 for other levels
Min distance to exit [m]	5
Max distance to exit [m]	40
Specific flow rate through door [persons/second/m of effective door width]	1.3

6.2 Acceptance criteria for stability

The default value for the criteria of stability is 1% for 10 consecutive runs (refer to 5.1.1 for theory on the acceptance criteria).

The user may want to modify this to stricter or less strict criteria. A stricter criteria (lower value) would require a greater number of iterations and the calculation model will take longer to run.

6.3 Using CarParkEvac

CarParkEvac calculates the probability of each number of doors being open simultaneously within one fire-isolated stair. Hence, if the user wants to calculate the probability of doors open simultaneously for multiple stairs with different input numbers, the model has to be run multiple times, as it only calculates one stair at the time. The number of doors calculated will be the doors into the stair from each level, excluding the discharge door to the outside. Hence, if the stair discharges on ground level, and the user is to only insert the inputs for the floors below ground level.

The first step of using CarParkEvac is to insert the input values. The input cells are shaded in green in the spreadsheet and consist of specific flow rate through door, stair door effective width, max/min travel distance to stair, number of occupants using the stair, occupant scenario, fractions of each occupant group and criteria for stability of results. The specific flow rate through door and the criteria for stability of results already have a default value, however they can be modified by the user if a different input value is preferred.

The inputs for the pre-evacuation times and travel speeds in CarParkEvac are based on default values as per Section 4.1.2 and Section 4.1.3. It is possible for the user to change these values to instead use custom values for max, min, mean and standard deviation. To do this, the user may change the green cells in the "Pre-evac & speed input data" tab.

After inserting these input values, the user is to press the "Run Probability Results" button located under user inputs. By doing this, the calculation model starts a number of runs until the "acceptance criteria for stability" is met. After these simulations are completed, the user can press the "Run Time Results" button, which will calculate the average total time of the evacuation that each number of doors are open simultaneously. Note that "Run Probability Results" must be done *before* "Run Time Results".

6.4 Results

The results of the simulations are shown under "Results" under the "User inputs and outputs" tab. This shows the average, min and max probability and the standard deviation for the probability of each number of doors being open simultaneously. The results also show the cumulative probabilities, i.e. the probability of at least four doors open, at least three doors open etc. To show the user the results in different relevant forms, the mirror plot of the above mentioned cumulative probabilities is also provided, i.e. one or less doors open, two or less doors open etc.

Under the "Results" tab, the results for all iterations are shown. In this case, where the criteria for stability is set to 1%, 82 iterations were required to achieve the acceptance criteria. The results shown under the "User inputs & outputs" tab uses the average values for all these 82 iterations.

The results for the average probabilities for this case study are shown in Figure 6-1. This shows that it is most likely (25% chance) that four doors are open simultaneously during the evacuation period. It also shows that it is 18% probability for zero doors, 22% for one door, 14% for two doors and 21% for three doors to be open simultaneously.

The results also show the time-period each of the number of stairs are open simultaneously, refer to Figure 6-4.

Note that the number of doors open are the doors into the stair from each level, excluding the discharge door to the outside. The discharge door is to be assumed open during the whole evacuation period, hence this door is to be added to the shown number of doors open in the calculation model.

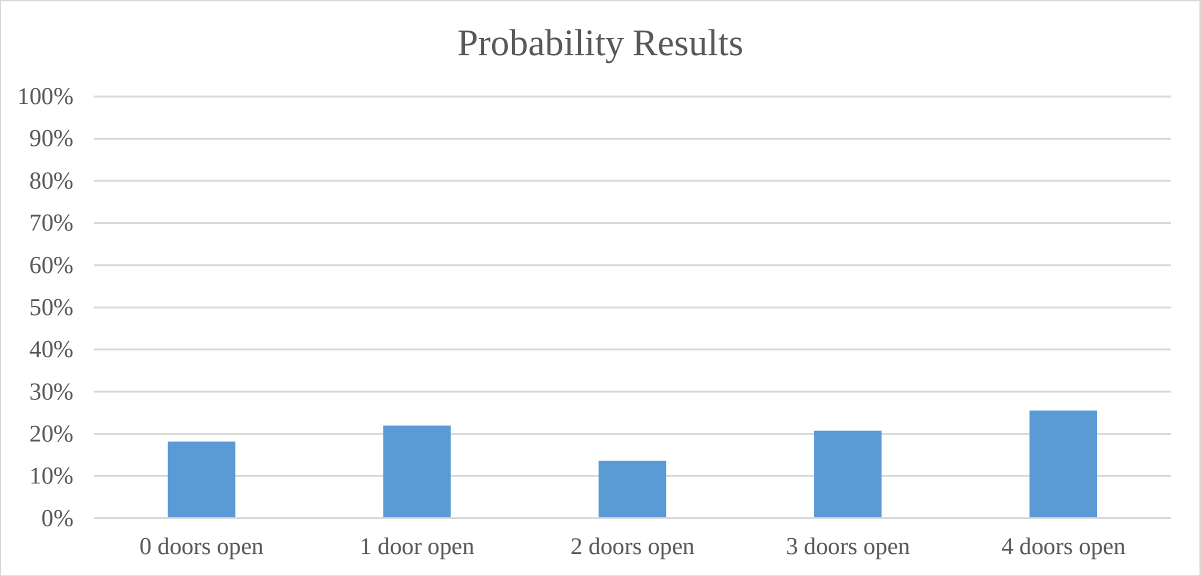


Figure 6-1: Results showing probabilities of number of doors open simultaneously

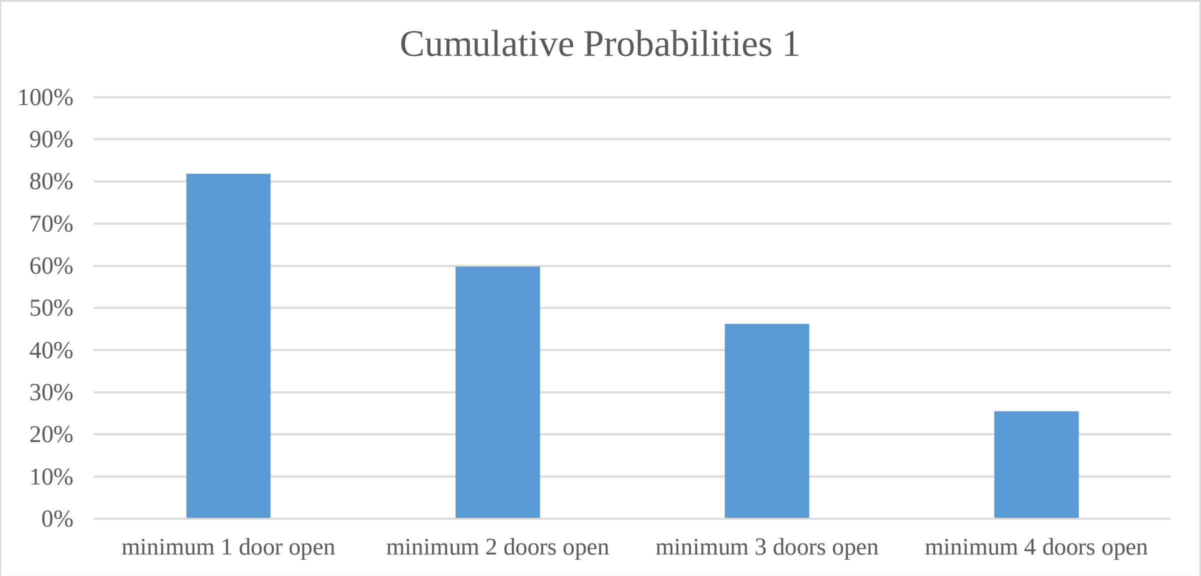


Figure 6-2: Results showing cumulative probabilities of minimum number of doors open simultaneously

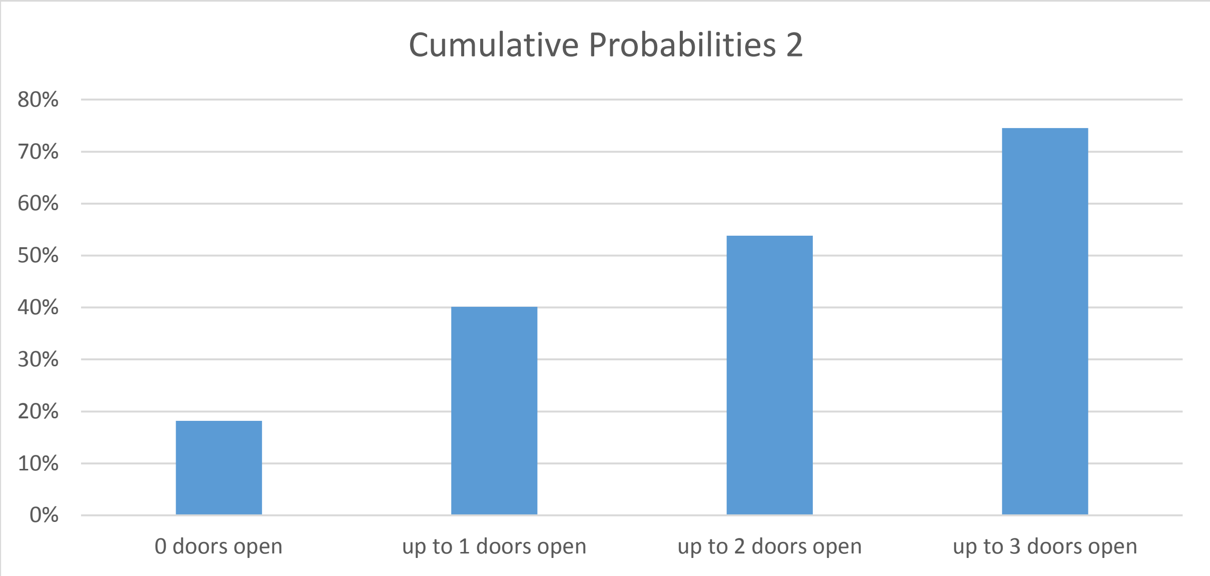


Figure 6-3: Results showing cumulative probabilities of up to number of doors open simultaneously

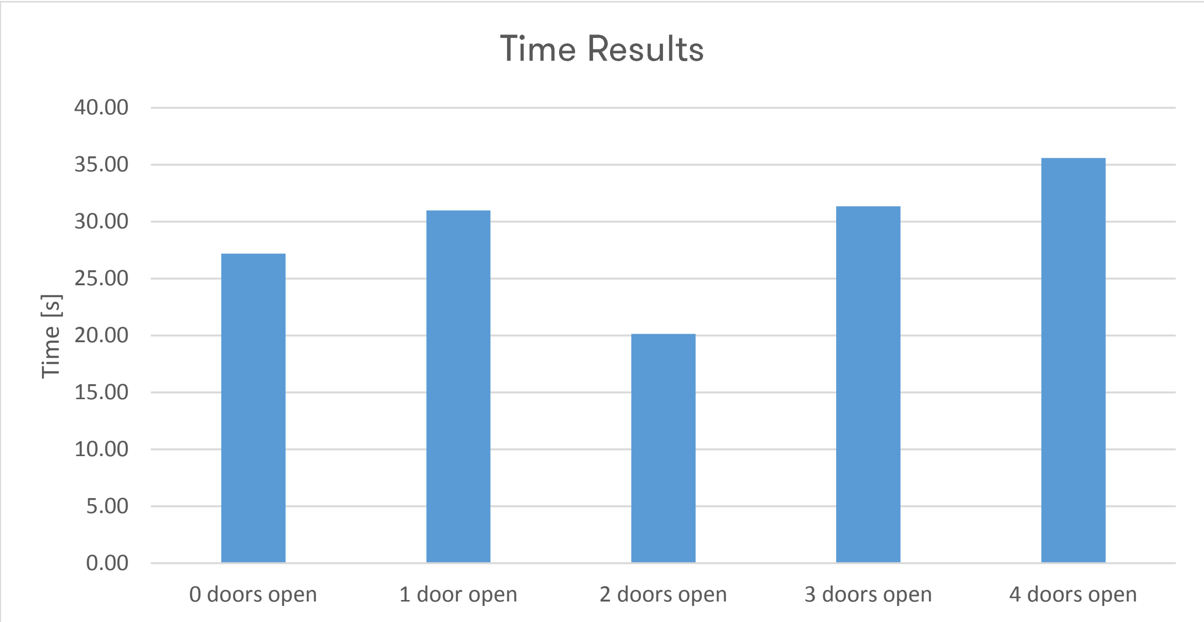


Figure 6-4: Results showing time-period each number of doors are open simultaneously

7 Sensitivity analysis

Sensitivity studies measure the impact on the results of one or more input values.

The sensitivity analysis for this model is based on the case study scenario with the input parameters as per Section 6.1. This base scenario is compared to different scenarios where one parameter at the time is changed.

The sensitivity analysis is divided into two sections; one for the user input parameters and one for the assumptions made when building the calculation model. The purpose of the first section is to give the user an idea of which input parameters have a significant impact on the results. The purpose of the second section is to validate the spreadsheet and to give guidance on what parameters may require additional future research.

7.1 Sensitivity study of the user input parameters

The following section is an explorative sensitivity study, which will attempt to show which of the user input parameters that have a significant impact on the results. To do this, a limited number of different sensitivity cases are tested, where one parameter at the time is changes while the rest are held constant. The base case scenario is as per the case study described in Section 6.1.

For this sensitivity analysis, each variable is given four different values that will be tested in the sensitivity analysis and compared to the base case. The first and the fourth values represents the assumed min and max values, and the second and third values are within this range. The assumptions for the min and max values are for the first two scenarios based on review of drawings on different basement carparks. A travel distance of less than 20 m to an exit may be reasonable in a small carpark, however this model generally is for multi-storey basement carparks which are not likely to have a maximum travel distance of less than 20 m. The maximum travel distance is allowed to be up to 40 m to an exit by the BCA (Building Codes Board 2016). Performance solutions may allow for longer travel distances and for use in other countries the requirements may be different, however greater than 80 m is not considered likely and therefore this is set as the maximum sensitivity case.

An exit door is required by the BCA to be at least 750 mm wide, which will be set as the minimum door width. The maximum door width is assumed to be 1.2 m, as double doors are not usual into a stairway.

The number of occupants per stair per level could be low if the carpark has restricted access or similar, therefore the minimum sensitivity case is set to 10 occupants per stair per floor. The maximum is set to 100 occupants, which is the maximum number allowed per stair in the BCA.

The specific flow rate is for the base case set as 1.3 persons/second/m of effective door width, based on the maximum specific flor rate as per the SPFE handbook. The sensitive analysis will test a specific flow rate between 0.9-1.5 persons/second/m of effective door width.

For the pre-evacuation scenarios, different scenarios will be tested and compared to the base case (scenario 5 on Level -03 and 6 on the other levels) being; scenario 1 on Level -03 and 2 on all levels and scenario 3 on Level -03 and 4 on all other levels. The reason for this is that only one floor will be the enclosure of fire origin. This will show how big impact it has if the building has voice alarm or not and if the occupants are familiar with the building or not. It is possible that a fire initiating elsewhere in the building (other than the carpark), require evacuation of the carpark. However in this case smoke is not expected to spread into the carpark, hence this scenario (being for example pre-evacuation scenario 6 on all levels) is not relevant, as it does not affect the occupant safety if all doors to the basement stair are open simultaneously. Based on this, only two sensitivity cases will be tested for the pre-movement scenarios.

The time-interval for passing through the door is in the base case set to 5 seconds. This means that if no queuing occurs at the stair door, it takes 5 seconds from that the occupant arrives at the door until they have passed through and the door closes behind. It is not considered likely that this time period would be any less than 3 seconds, which will be the minimum value in the sensitivity study. The maximum value will be set as 10 seconds, which is considered conservative.

The fraction of the occupant load is in the base case set as 50% adults, 30% family groups and 20% old/disabled. Four other cases are tested in the sensitivity analysis; one with predominantly adults, one with predominantly adults and old/disabled (it is not considered likely that more than 50% would be old/disabled since an aged care building would also have staff/visitors), one with predominantly family groups and one with equally divided groups.

Table 7-1: Sensitivity cases for user input parameters

Sensitivity case	**base case**	**1**	**2**	**3**	**4**
Max travel distance to stair door [m]	40	20	30	60	80
Stair door effective width [m]	0.8	0.75		1.0	1.2
Number of occupants per stair per floor	42	10	20	70	100
Specific flow rate [persons/second/m of effective door width]	1.3	0.9	1.1	1.4	1.5
Pre-evacuation scenario	5 on Level -3, 6 other levels	1 on one level, 2 on other levels	5 on one level, 6 on other levels	-	-
Time-interval for passing through door [s]	5	3	4	7	10
Fraction of occupant groups (adults/family group/old, disabled) [%]	50/30/20	80/10/10	50/0/50	20/60/20	35/35/30

Figure 7-1 shows the results of the sensitivity analysis for the user inputs. This shows that the input parameter that has the most impact on the results (where the percentages vary the most from the base case) is the number of occupants. The probability for four doors simultaneously is for the sensitivity case with 10 occupants 2% and for the case with 100 occupants 52%, compared to 25% in the base case. The pre-evacuation scenarios and the time-interval to pass through the door also have a significant impact on the results. The probability for four doors to be open simultaneously varies to 10% for pre-evacuation Scenario 3 and 4, compared to 25% in the base case. The probability for four doors to be open simultaneously varies to 15% for 3 seconds and 36% for 10 seconds time interval to pass through door, compared to 25% in the base case. The rest of the parameters appear to have a low impact on the results, as in all these cases the results are relatively close to the base case scenario, being in the order of a couple percent units greater or smaller than the base scenario.

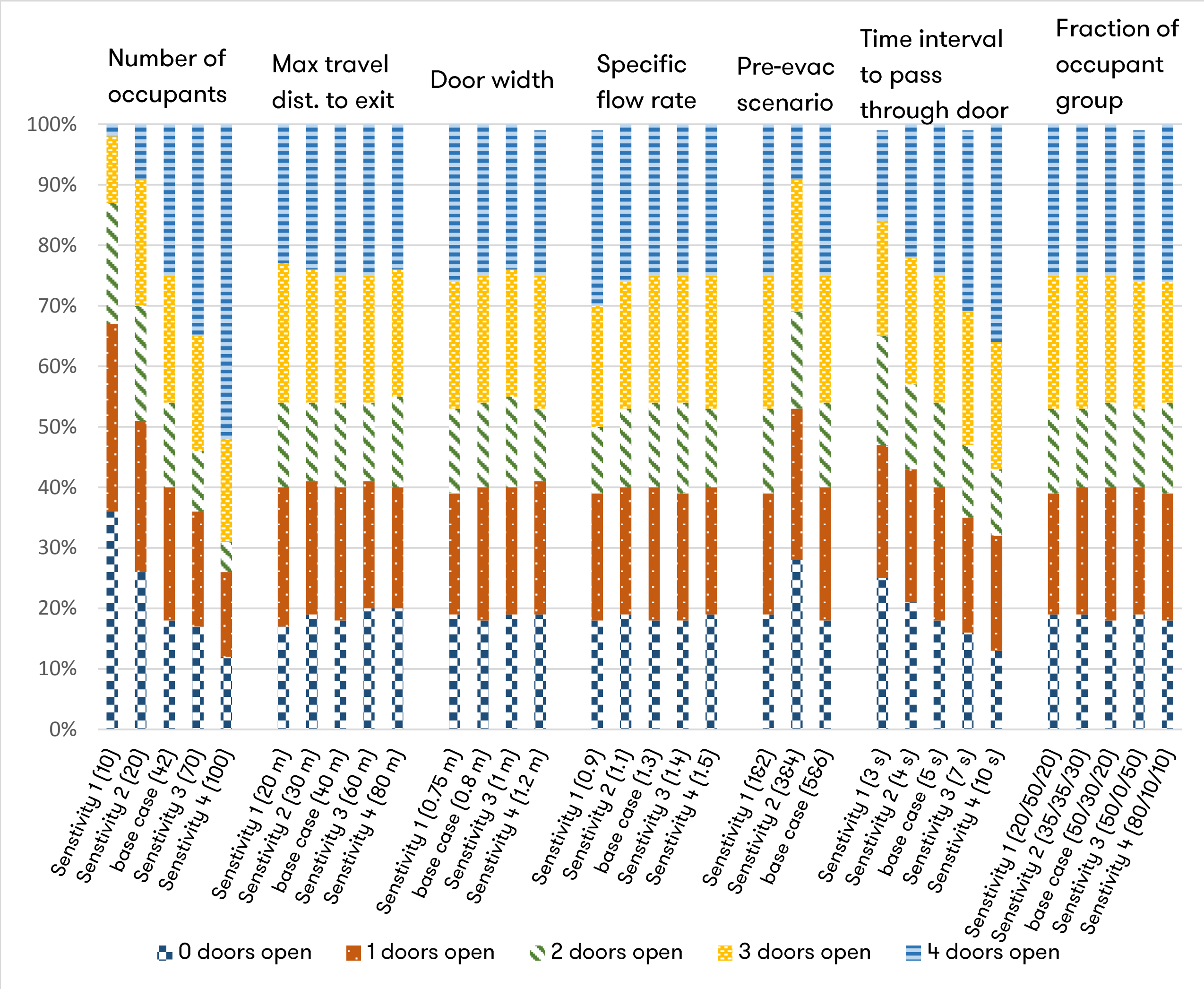


Figure 7-1: Sensitivity Analysis Results User Inputs

7.2 Sensitivity study for calculation model assumptions

To develop CarParkEvac a number of assumptions were made. These are generally in relation to the pre-evacuation and travel speed values, refer to Section 4 for information about the chosen input data. The sensitivity analysis below is to determine how much input these assumptions has on the result. This can give guidance on where additional research may be required in the future to reduce the uncertainty.

For the pre-evacuation times, the distributions used in the calculation model are based on a mean value and standard deviation. The mean value for pre-evacuation in the base case is 30 seconds for Scenario 5 and 60 seconds for Scenario 6. These variables are tested between 15-60 seconds for Scenario 5 and 30-120 seconds for

Scenario 6. The maximum pre-evacuation values are tested between 45-180 seconds for Scenario 5 and 60-240 seconds for Scenario 6.

The travel distance is in the base case set as a uniform distribution. A scenario where the travel distances instead follow a normal distribution has been tested in the sensitivity analysis. This is because it is unknown where the occupants are located over the floors.

The sensitivity analysis also test the assumptions for the travel speeds mean values and standard deviation. The mean values are tested from 0.7 to 1.5 m/s for adults, 0.6 to 1.1 m/s for family groups and 0.5-0.9 m/s for old/disabled. These sensitivity parameters are chosen based on the research data described in Section 4.1.2.

Table 7-2: Sensitivity cases for calculation model assumptions

	Base case	Sensitivity 1 (min)	Sensitivity 2	Sensitivity 3	Sensitivity 4 (max)
Pre-evacuation mean value (scenario 5/6) [s]	30/60	15/30	22.5/45	45/90	60/120
Pre-evacuation max value(scenario 5/6) [s]	90/120	45/60	67.5/90	120/180	180/240
Pre-evacuation standard deviation(scenario 5/6) [s]	15/20	7/10	10/15	22.5/30	30/40
Travel speed mean value (adults/family/old disabled) [m/s]	1.19/0.9/0.7	0.7/0.6/0.5	1.0/0.75/0.65	1.35/1.0/0.8	1.5/1.1/0.9
Travel distance distribution type	Uniform	Normal			
Travel speed standard deviation	0.25	0.1	0.175	0.35	0.5

The results from the sensitivity analysis for these parameters are shown in Figure 7-2. This shows that the pre-evacuation mean times have the biggest impact on the results, followed by the pre-evacuation standard deviation and pre-evacuation maximum value. For the pre-evacuation mean times, the probability of four doors open simultaneously varies between 1%-38% for the cases investigated in the explorative sensitivity analysis. In comparison for the pre-evacuation standard-deviation sensitivity cases, the probability of four doors open simultaneously varies between 23-29%, and for the pre-evacuation maximum value between 26-33%. The change of the travel speed and travel distance distribution appears to have low impact on the results, where the variation in the probability results is only a couple percent units from the base scenario. Based on this, it is considered that future additional research should focus on the pre-evacuation values, and significantly the mean pre-evacuation times.

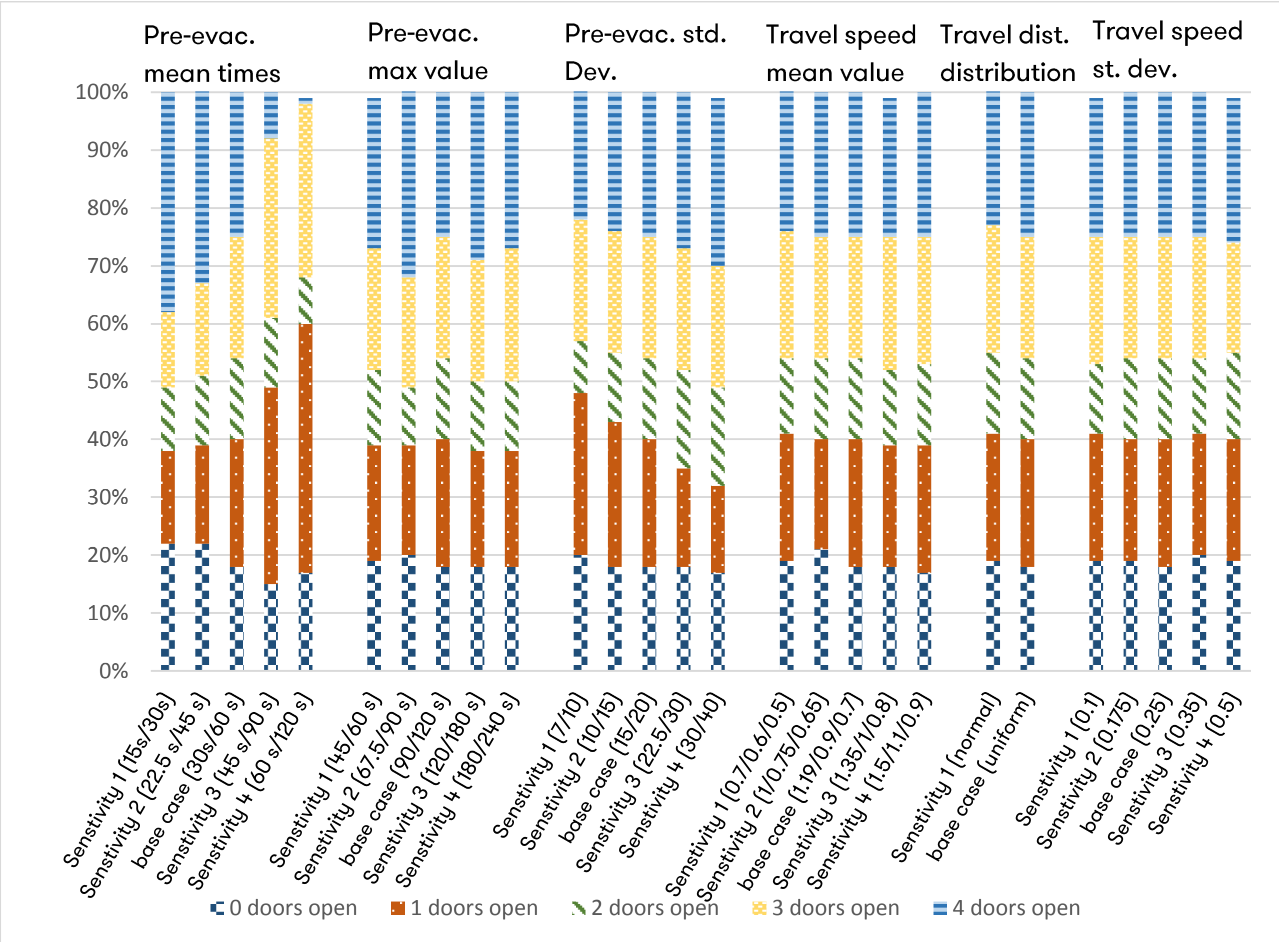


Figure 7-2: Sensitivity Analysis Results Mode Assumptions

8 Comparison of calculation model with evacuation simulations

To assess the results obtained from the CarParkEvac, the case study results are compared to an existing evacuation simulation model, namely Pathfinder 2015 (Thunderhead, 2015).

In Pathfinder the same input parameters as in the case study are used, refer to Section 6.1. Four floors with the same area are set up with 42 occupants on each floor and two doors per floor, with a maximum travel distance of 40 m to the closest exit. The occupants are given pre-evacuation times with the same distribution, mean and standard deviation as per the case study. Thereafter the simulations is ran in Pathfinder, which gives an arrival time at the door for each occupant on each floor. These simulations are done multiple times to ensure the results are relatively stable using the same principle adopted in the developed calculation spreadsheet.

These results for the arrival times are thereafter inserted into an excel sheet and the same method as for CarParkEvac is used to determine the probability of each number of doors open simultaneously. i.e., it is calculated how many people arrive at the door within each time interval of five seconds, and assumed that during the time intervals where no one arrives at the door, the door is closed, as explained in Section 5.

The results are shown in Figure 8-1, where the blue columns are the results from the CarParkEvac and the orange columns are the results from the Pathfinder simulations.

To be noted is that it is only the arrival times at the door that are simulated in Pathfinder (i.e. the pre-evacuation times, the travel distances and the travel speeds), thereafter the same method is used to determine the probabilities of doors open simultaneously. Since the results are relatively similar, the method to determine the pre-evacuation times, distribution of occupants over the floors and the travel speeds are considered to be in line with the results from current evacuation simulation tools.

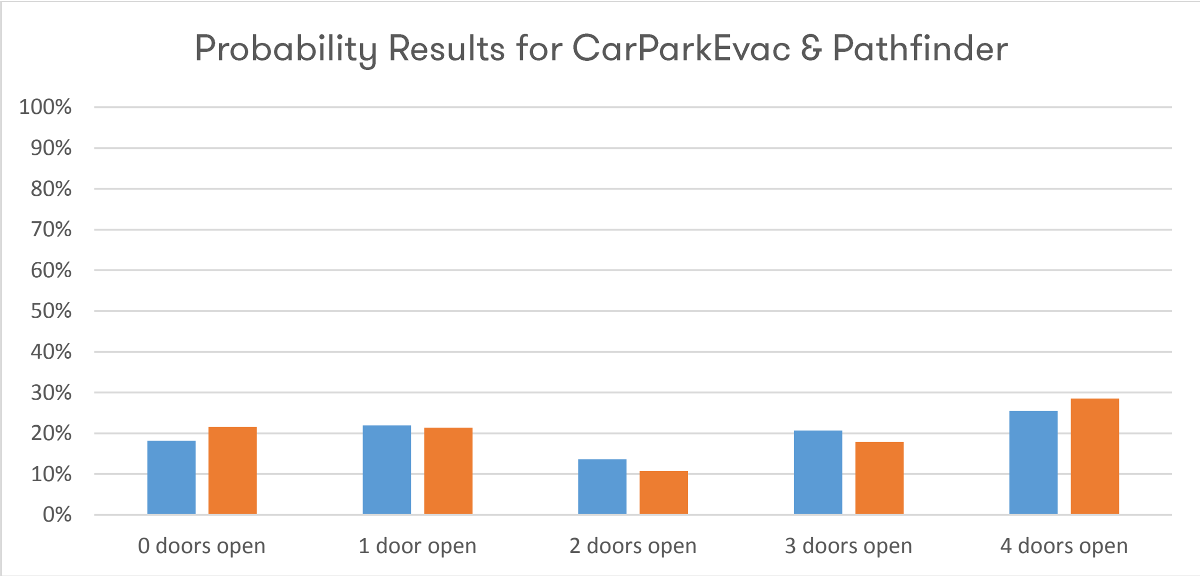


Figure 8-1: Results from Pathfinder compared to CarParkEvac

9 Discussion

CarParkEvac can be used to determine the probability of different number of doors being open to a fire-isolated stairway in a basement carpark during an evacuation scenario. The results show the cumulative probabilities of up to a certain number of doors open, and also at least one door open, two doors open etc. The results also show for how long time in total each number of doors are likely to be open simultaneously.

The request for such type of model comes from the requirements for stair pressurisation in basements, which requires an airflow of 1 m/s, tested when all doors to the fire compartment are open. Since carparks usually are connected by ramps, they are considered as one fire compartment, and therefore all doors to the fire-isolated stair in the carpark are required to be open when the airflow is tested. CarParkEvac was developed with the intention to find out how likely it is that all doors/a certain number of doors will be open simultaneously.

If the results show that the probability of for example more than three doors open simultaneously is very low during an evacuation, this may be used to show that the airflow of 1 m/s is only necessary when tested with 3 doors open simultaneously. If the results on the other hand show that it is likely for all doors to be open simultaneously, CarParkEvac can instead be used to further motivate the requirement of 1 m/s airflow when all doors to the stair are open. These results can be used for risk assessments in carparks. The results will give an idea of how many doors are likely to be open at the same time and for how long. This information can be useful to determine the risk of smoke entering the stair via the doors being open, which can be helpful for design choices.

It is to be noted that these probabilities are calculated only during the evacuation period of the carpark, which in this model is from the time of detector activation, until the last occupant is within the fire-isolated stair (which is considered a "safe place"). The discharge door from the stair to the outside is not included in the calculations and is conservatively assumed to be open during the whole period.

The detection time is not considered relevant for this calculation model, as the actual evacuation of the occupants is assumed to start after the activation of the detection system, and the detection system is assumed to be connected such that it activates for the whole carpark at the same time. If results of the probability of number of doors open simultaneously during a full fire scenario would be requested, the use of fire modelling would be required.

This report includes a case study of a fictitious basement carpark with four levels. The results for the average probabilities for the case study (refer to Section 6) are shown in Figure 6-1. This shows that it is most likely (25% chance) that four doors are open simultaneously during the evacuation period. It also shows that it is 18% probability for zero doors, 22% for one door, 14% for two doors and 21% for three doors to be open simultaneously. It is to be noted that this is just a fictitious carpark, and the results may vary significantly between different carpark layouts depending on its size, number of occupants, the use of the building etc.

The results show that for the case study carpark, all four doors are likely to be open for approximately 35 seconds during the evacuation period, which is considered relatively low in relation to the full fire scenario, which could last for hours. An experiment shown in Sardqvist (Sardqvist, 1993) shows that a small vehicle burned for approximately 1.5 hours. For example, during a one-hour long fire scenario, these 35 seconds are less than 1% of the whole fire scenario. If the carpark is provided with a sprinkler system, the fire is likely to be controlled or extinguished earlier in the fire scenario, however this will also reduce the amount of smoke that can spread into the stair. During the time from fire ignition until the detection system activates, it is expected that all doors are closed for the majority of the time since the movement of occupants to and from the carpark is expected to be low most of the time.

AS/NZS 1668.1-2015 Clause 10.3(e) states that the minimum time for the system performance to be restored is 10 seconds. Hence, the airflow is allowed to vary for 10 seconds, and it is assumed that no significant amount of smoke will spread into the stair during these 10 seconds. Based on this, it may be argued that if the pressure is slightly too low during the time that all doors are open this is not expected to affect the occupant safety. In the case study all four doors are shown to be open for 35 seconds simultaneously, however in a different carpark the results may show that all doors are likely to be open for less than 10 seconds (for example if there is a lower occupant load in that carpark). This may be a reason to show that 1 m/s airflow when all doors are open is not necessary in the basement fire-isolated stair in that building.

If for some reason a user wanted to determine the probability of doors open to a stair in a basement used for something other than carparking, it would be possible to use the calculation model. However, the pre-evacuation times are based on research data where occupants are assumed to be awake and alert, hence these may not be appropriate to use in for example a residential building.

The sensitivity analysis (refer to Section 7) shows that the user input parameter that has the greatest impact on the results is the number of occupants located in the carpark. Therefore, it is important for the users to give great thought to this number. Some buildings may have a restriction of occupant numbers such that it is known what the exact maximum number of occupants will be on each floor, however for most buildings this number is expected to be relatively uncertain. The BCA may be used as a guide, which states an occupant load of 30 m^2 per occupant within a carpark. If the basement has more than one fire-isolated stair, the user is also required to make an assumption of how many occupants will use each stair. It may be reasonable to assume that the occupants on each floor will be equally divided between the stairs. However, it is recommended for the user to also include a sensitivity analysis where one of the exits is blocked, hence all the occupants on that floor will use the alternative exit. The reason for this is to include the worst-case scenarios.

It is expected that some occupants may drive out from the carpark, instead of using the emergency egress stairs in the event of a fire. This has not been accounted for in the spreadsheet, i.e. all occupants within the carpark are assumed to egress via the stairs. This is considered conservative as due to this reason, in reality, less people may be walking towards the stairs and open the stair doors.

The time interval to pass through the door is one of the parameters that is the most uncertain, as not much research has been found on this. It is uncertain how long it takes for a person to open and pass through the door, and it is uncertain how long it takes for the door to automatically close behind the person. If greater time and resources were available for this thesis, experiments would have been completed. As stated in BS EN 1154:1997 (BS EN, 1997), self-closing fire doors may take between 3-20 seconds to close, depending on the type of door-closer. Based on this, the user is required to ensure what type of fire doors are used in the particular building and how long they take to close. Consideration is also to be made to the building use, for example if the building has a great amount of old or disabled occupants, it may take them longer to pass through the door. It is also possible that occupants may hold open the door to the next person arriving. However, in a fire scenario it is expected that the majority of the occupants will walk straight out through the stair without holding the door open to other occupants unless they arrive just a few seconds after.

The pre-evacuation also has a significant impact on the results, as shown in the sensitivity analysis the chance for four doors to be open simultaneously is twice as high for Scenarios 1&2 than for Scenarios 3&4 and 5&6 (refer to Table 4-1 for the scenarios). The difference between Scenarios 1&2 compared to the others is that the occupants in this case are assumed to be familiar with the building. This generally results in shorter pre-evacuation times, which results in a greater amount of people arriving at the door within similar time periods, hence it is more likely for all doors to be open simultaneously. It is expected that the user knows what their building is used for and hence which occupant pre-movement scenario is the most relevant.

Section 7.2 in this report analyses the impact on the results by different assumptions made while developing CarParkEvac. These are parameters that has been used to build up the model, and in comparison to Section 7.1, these numbers are not changeable by the user. Figure 7-2 shows that the assumptions that has the greatest impact on the results are the pre-evacuation mean times and standard deviations. With mean pre-evacuation times as low as 15 seconds for Scenario 5 and 30 seconds for Scenario 6, the probability of all four doors open is 38% chance. In comparison, for the sensitivity cases 3 and 4 (with longer mean values), the probability of all four doors open simultaneously is 8 and 1% respectively. Based on research (refer to Section 4.1.2) mean pre-evacuation times as low as 15 or 30 seconds are not likely, however possible. Due to the lack of experimental evacuation studies in carparks, these numbers are uncertain. Even with evacuation studies in carparks these numbers would be uncertain, as this is an individual parameter that varies for each occupant. The pre-evacuation times also depend on the fire scenario, for example if there is a significant fire causing smoke spread between the levels, the occupants are expected to start moving towards the exits sooner.

As stated within Section 3.3, occupants within a carpark are expected to be awake and alert, and being in the carpark for relatively short periods of time. Therefore, the pre-evacuation times are considered to be relatively short compared to experiments/real fire incidents in for example retail portions of buildings. For example, in retail buildings, it has been shown that people may be reluctant to leave because they did not want to leave food they had paid for, or they spent time on gathering family members etc. In a carpark, a family group is expected to be together, either in a vehicle or walking to / from their vehicle. As the occupants are only expected to be located in the carpark for short periods of time regardless of a fire scenario, they are expected to start walking towards the exit after a relatively short period of time (since there are not many reasons to stay in the carpark as it might be for example in a restaurant). The pre-evacuation activities that can be expected in a carpark include generally to gather family members / belongings (mainly from their vehicle), and investigate the situation / fight fire. Possibly some people would spend time on parking their car, buying parking tickets and looking for egress routes etc. before they evacuate.

Based on the above, the chosen pre-evacuation mean times used in CarParkEvac are considered realistic; however as they are uncertain, further experimental research is needed in the future to fully validate the model and improve its reliability. It is to be noted that CarParkEvac enables the input parameters for max, min, mean and standard deviation for pre-evacuation times to be changed by the user. Hence the user can use their own experimental research to decide the most suitable input values for these parameters for their particular building.

The travel speeds are also individual and may vary significant between different occupants, hence this is also an uncertain parameter. However, as shown in the sensitivity analysis, changing the travel speed mean values or standard deviations has low impact on the results.

The travel distance distribution is also an uncertain factor as it is unknown where on the floor the occupants are located. However, changing the distribution from uniform to normal has been shown in the Sensitivity Analysis to not change the results significantly. Dedicated validation studies for this parameter are needed in the future to ensure that the most appropriate distribution is being used.

Based on the sensitivity analysis of the calculation model assumptions, if further research was to be done to improve the model, this should focus on the pre-evacuation mean and standard deviation values.

When developing CarParkEvac, a number of assumptions and simplifications had to be done due to restrictions with the software, knowledge, time and resources etc. This has resulted in restrictions and limitations with the model.

The part of the model that is considered the biggest limitation is the assumption of when the doors are open or not. CarParkEvac assumes that if anyone is located at the door within a certain time interval, the door is open. The model assumes that if anyone arrives within the time interval the door will be open during the whole time interval, independent of when during the time interval the person arrives. This means that the model does not take into account if the person arrives the first or the last second of the time interval. Ideally, further enhancement of the model would have given a delay time for the door to be open based on when each person arrives. The assumptions about the time interval is however considered reasonable (especially since the user can modify the length of the time interval).

One advantage with CarParkEvac is the simple usability compared to other models. To get results the user only need to insert the input parameters that are highlighted in the “User inputs and outputs” sheet and press “Run model” and the outputs will be shown in the same sheet.

For the four-storey case study fictitious carpark described in Section 6, the results have shown that the probability of all doors open simultaneously during an evacuation scenario is approximately 25%. This is considered relatively high and the requirements for all doors being open while the testing of the air pressure for the stair pressurisation system is considered necessary in this scenario. However for a different carpark the probability and time may be lower and the model could be used to show that the requirements of all doors open during the test is not necessary. It has been shown that the number of occupants and the pre-evacuation times have a great impact on the results and hence the results may vary significantly between different types of carparks. For CarParkEvac to be as valid as possible, further research is desired, with focus on pre-evacuation times.

10 References

1. Standards Australia, Standards New Zealand, AS/NZS 1668:1-2015, *Australian/New Zealand Standard, The use of ventilation and air conditionings in buildings, Part 1: Fire and smoke control in buildings*, 2015.

2. Microsoft Support, Article: "*Description of the RAND function in Excel*", Article ID: 828795, 9/18/2011, https://support.microsoft.com/en-au/kb/828795

3. Australian Building Codes Board, *National Construction Code Series 2016, Volume 1, Building Code of Australia, Class 2 to Class 9 Buildings.* Australian Building Codes Board, CAN, Australia, 2016.

4. Australian Building Codes Board, *National Construction Code Series 2016, Guide to Volume 1, Building Code of Australia, Class 2 to 9 Buildings.* Australian Building Codes Board, CAN, Australia, 2016.

5. Bukowski, R.W, Tubbs J.S., *The SFPE Handbook of Fire Protection Engineering:* Chapter 56: *Egress Concepts and Design Approaches*, 5th Edition, Springer, New York, USA, 2016.

6. BSi, *PD 7974-6:2004, The Application of Fire Safety Engineering Principles to Fire Safety Design of Buildings – Human Factors: Life Safety Strategies – Occupant Evacuation, Behaviour and Conditions*, July 2004.

7. Ronchi, E., Reneke, P. A., & Peacock, R. D. (2014). A Method for the Analysis of Behavioural Uncertainty in Evacuation Modelling. *Fire Technology*, *50*(6), 1545–1571. https://doi.org/10.1007/s10694-013-0352-7

8. D.A. Purser, M. Bensilum, *Quantification of behaviour for engineering design standards and escape time calculations*, Fire Engineering Centre, Building Research Establishment, Garston, Watford, UK, 2001.

9. Purser, D., *Comparison of evacuation efficiency and pre-travel activity times in response to a sounder and two different voice alarm messages*, 2008.

10. Gwynne, S.M.V. and Rosenbaum, E.R., *The SFPE Handbook of Fire Protection Engineering*, Chapter 59: *Employing the Hydraulic Model in Assessing Emergency Movement.* 5th Edition, Springer, New York, USA, 2016.

11. Bryan J.L, *Fire Protection Handbook:* Chapter 4.1: *Human Behaviour in Fire, 20th Edition, National Fire Protection Association*, Quincy, Massachusetts, USA, 2008

12. Spearpoint, M, *Fire Engineering Design Guide*, Chapter 11: *Means of Escape*, Third Edition, 2008.

13. Boer, L. C., 2002, *Behaviour of Motorists on Evacuation of a Tunnel*, TNO, Soesterberg, Netherlands, 2002.

14. Ministry of Business, Innovation & Employment, *Commentary for Building Code Clauses C1-C6 and Verification Method C/VM2*, New Zealand, 2013.

15. NFPA 5000-2015: *Building Construction and Safety Code.* National Fire Protection Association. 2015 Edition.

16. BSi, PD 7974-6:2004, *The Application of Fire Safety Engineering Principles to Fire Safety Design of Buildings – Human Factors: Life Safety Strategies – Occupant Evacuation, Behaviour and Conditions*, July 2004.

17. Gwynne, S.M.V, and Boyce, K.E., *The SFPE Handbook of Fire Protection Engineering:* Chapter 64: *Engineering Data*, 5th Edition, Springer, New York, USA, 2016.

18. Kholshevnikov VV, Samoshin DA, Parfyonenko AP, Belesokov IP (2012) *Study of children evacuation from pre-school education institutions.* Fire Mater. 36:349-366. DOI: 10.1002/fam.2152, John Wiley and Sons Ltd.

19. Gates T.J., Noyce D.A., Bill A.R, Van Ee N, *Recommended walking speeds for pedestrian clearance timing based on pedestrian characteristics,* Paper No. 06-1826 Transportation research record journal of the transportation research board, 2006.

20. Larusdottir AR, Dederichs A (2011) Evacuation dynamics of children – walking speeds, flows through doors in day-care centres. In: Peacock et al (eds) Pedestrian and Evacuation Dynamics, Springer Science and Business Media, DOI 10.

21. Berrou JL, Beecham P, Kagarlis MA, Gerodimos A (2005) *Calibration and validation of the Legion simulation model using empirical data.* In: Waldau N et al (ed) *Pedestrian and evacuation dynamics.* Springer Science and Business Media, pp 167-181.

22. Schulz M, Schulz C, Fricke H (2008) *Passenger dynamics at airport environment.* In: Kingsch WWF, Rogsch C, Schadschneider A, Schreckenberg M (eds) Pedestrian and evacuation dynamics. Pp 381-396

23. Sime, Jonathan D., *Assessing Occupant Response Time: A Key Issue for Fire Engineering,* In R. Barham (ed) Fire and Emergency Planning: Research and Applications, E & F N Spon, London (48, pp442-449), 1996.

24. Zanlungo F, Chigodo, Y. Ikeda, T., and Kanda, T. (2012) Experimental study and modelling of pedestrian space occupation and motion pattern in a real world environment, Paper presented at 6th Pedestrian and evacuation dynamics symposium 6th-8rh June 2012, Zurich.

25. Daamen W, Hoogendoorn SP (2005) *Free speed distributions – based on empirical data in different traffic conditions*, In: *Waldau N et al (eds) Pedestrian and evacuation dynamics* 2005. Springer Science and Business media pp 167-181.

26. Jiang CS, Zheng SZ, Yuan F, Jia HJ, Zhan ZN and Wang JJ (2012) *Experimental assessment on the moving capabilities of mobility-impaired disabled*

27. Sorensen JG, Dederichs AS (2012) *Evacuation characteristics of blind and visually impaired people: walking speeds on horizontal planes and descending stairs.* In: *Proceedings of fifth international symposium on human behaviour in fire*, Cambridge, England.

28. Jiang CS (2009) *Study on self-evacuation capability of the disabled as well as its impact on evacuation capability of healthy population.* Final Report on Projects Supported by National Natural Science Foundation, China.

29. Boyce KE, Shields TJ, Silcock GWH (1999) *Toward the characterization of building occupancies for fire safety engineering: capabilities of disabled people moving horizontally and on an incline.* Fire Technol.

30. Shields TJ (1993) *Fire and disabled people in buildings.* Building Research Establishment Report.

31. Wichmann BA, Hill ID (1982). "Algorithm AS183: An Efficient and Portable Pseudo-Random Number Generator." Applied Statistics, 31(2), 188-190.

32. Dinov I.D., Christou N, Gould R (2009), J Stat Educ, *Law of Large Numbers: the Theory, Applications and Technology-based Education:* https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3095954/#

33. Ronchi, E., & Nilsson, D. (2016). Basic Concepts and Modelling Methods. In A. Cuesta, O. Abreu, & D. Alvear (Eds.), *Evacuation Modeling Trends* (pp. 1–23).

34. BS EN 1154:1997, *Building hardware. Controlled door closing devices. Requirements and test methods*, 1997.

35. Thunderhead, *Pathfinder, 2015 User Manual*, 2015.

36. Sardqvist, S. *Initial Fires*, Lund Univeristy, Sweden, 1993.

APPENDIX A USER GUIDE CARPARKEVAC

Background:

CarParkEvac is used to determine the probability of each number of doors to a fire-isolated stair (excluding the discharge door from the stair to the outside) that are open simultaneously during evacuation of a basement carpark. The spreadsheet randomly assigns each occupant a travel distance, pre-movement time and walking speed, and determines what time they arrive at the exit. This data is thereafter used to determine the probability of number of doors to the stair to be open simultaneously.

Instructions:

Insert input numbers for stair door width, maximum travel distance to stair door, number of occupants using the stair for each level in rows 6-11 (if less than 6 floors, ignore the rest of the rows). The number of doors calculated will be the doors into the stair from each level, excluding the discharge door to the outside. Hence, if the stair discharges on ground level, the inputs are only to be inserted for the levels below ground.

The input cells are shaded in green.

- A2: Maximum Specific flow rate: The default value is 1.3 as per SFPE handbook.

- C6:C11 Max travel dist: If more than one fire-isolated stair it may be reasonable to assume that occupants choose the closest exit.

- D6:D11: If more than one stair it may be reasonable to assume that the total number of occupants on each floor are equally divided over the number of stairs.

- E6:E11 Occupant pre-movement: choose between Scenario 1-6 (see A22-A29) for each level.

- B13 Time interval to negotiate through door: The time for one occupant to negotiate a door, until the door is closed behind them. Default value is 5 seconds.

- B15 Minimum travel distance to exit

- C19-E18 Fraction of occupant group: Insert the fraction of each occupant group in row 18 that can be expected in the carpark. This is used to determine the travel speed of each occupants (as children and old/disabled occupants are likely to have slower travel speeds than adults).

- B20 Criteria for stability: This relates to the number of runs that are required to achieve stability in the results. To decide an appropriate number of runs for this calculation sheet, a criterion is set for the relative errors between the results. This criterion is implemented to decide the accepted uncertainty associated with the average results obtained by multiple runs of the same scenario. The default value is set to 1% for 10 consecutive runs. The iterations will stop when the acceptance criteria is met. Hence a lower (stricter) input value will require a greater number of runs.

Custom pre-evacuation and travel speed values:
If the user wish to use different values for the pre-evacuation and travel speed min, max, mean and standard deviation values, this may be done by changing the green shaded cells in the "Pre-evac and speed input data" tab. Note that only the numbers for the particular pre-evacuation scenarios that are choosen (between Scenarios 1-5) needs to be updated.

To run model, first press "Run probabilities results", and after the results are shown, press "Run time results" to recieve the results for how long time the doors are open.

Output:
The results of the simulations are shown under sults", and after the results are shown, press "Run time results" to recieve the results for how long time the doors are open.cells in the "Pre-evac and speed input data" tab. Note that only the num simultaneously. The results also show the cumulative probabilities, i.e. the probability of at least one door open, at least two doors open etc.