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Investigating Evacuation Behaviour in Retirement Facilities: Case Studies from New Zealand

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Abstract

Ageing populations are generating new challenges for the safe design of buildings and infrastructure systems in communities around the world. Elderly building occupants are more likely to have mobility impairments, and in turn, require longer times and increased assistance to evacuate buildings compared with able-bodied adults. To date, only a few studies have been carried out to assess the evacuation performance of elderly evacuees in retirement homes. Therefore, it is necessary to collect critical evacuation data, such as pre-evacuation times and evacuation speeds, for these occupancy types.

This work investigates the evacuation behaviour of elderly evacuees and caretaking staff using video recordings of evacuation in retirement facilities. The paper presents three case studies. The first case study includes *unannounced* drills, which took place in communal areas of retirement homes during a live music exhibition and in a kitchen. The second case study is a series of *unannounced* drills, which took place in independent living apartment buildings of a retirement facility. The last case study is of a single *announced* evacuation drill, which took place in a communal area of a retirement building. Qualitative results indicate that the occupants' behaviours depended on their role (i.e. resident or staff) and on the type of monitored area (i.e. apartment building or communal area). Pre-evacuation times measured in this study are in accordance with values stated in the literature, and walking speeds fall in the range of values reported in past studies of these types of building. Finally, results revealed that the use of fundamental diagrams from the SFPE Handbook of Fire Protection Engineering to assess the gap between the data provided in this work and the design curves used for buildings having mainly of adults with not walking impairments.

Keywords – Retirement facilities, fire drill, evacuation, pre-evacuation time, walking speed, human behaviour, elderly.

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1 Introduction

The ageing world population is rapidly increasing due to decreasing mortality (Mamun *et al*., 2020, Folk *et al*., 2020). An ageing population increases the challenges when evacuating built environments (Peacock and Averill, 2011; Spearpoint and MacLennan, 2012; Pichler *et al*., 2015; Folk *et al*., 2020). Conducting an effective, safe and timely evacuation in some buildings, such as retirement facilities, can be challenging, as building occupants are elderly and may have reduced mobility (Pichler *et al*., 2015; Folk *et al*., 2020). This means that a large percentage of occupants may be reliant upon staff assistance in order to evacuate in case of a fire emergency. Hence, fire safety codes require higher safety standards for retirement facilities than for standard buildings where most occupants are likely to be younger and able-bodied (Cartwright, 2006).

In order to evaluate the effectiveness of evacuation strategies in retirement facilities, fire drills can be employed. These drills can also be used to collect evacuation data for evacuation modelling tools calibration and validation (Zhao *et al*., 2020; Lovreglio *et al*., 2014, Lovreglio *et al.*, 2019b). Data collected from evacuation drills can be qualitative (e.g. observations or narratives of evacuee behaviours, route and exit choice, etc.) or quantitative (e.g. data on pre-evacuation times, walking speeds, evacuation times, etc.). It is important that the limitations of these drills are documented alongside the data presented to ensure data validity and reliability (Gwynne and Boyce, 2016; Rahouti *et al*., 2020; Folk *et al*., 2020). Data collection during the evacuation of retirement facilities is rare, and of those studies that collected evacuation data in these facilities, most collected qualitative data. Possible reasons for this lack of data include the physical challenges associated with evacuating vulnerable populations, and ethical considerations (Rahouti *et al*., 2020).

The main purpose of this paper is to add to the existing evacuation data for retirement facilities through the analysis of evacuee behaviours during a series of *announced* and *unannounced* fire drills. These drills were run in retirement facilities located in Auckland, New Zealand. Behavioural analyses were conducted to study resident and staff behaviours and interactions during the evacuation process in each building. In addition, quantitative analyses were carried out in order to estimate residents' pre-evacuation times, the impact of staff behaviour on the pre-evacuation times, and unimpeded walking speeds (in uncongested situations). Where congestion was observed, the relationships between the walking speed and local density, and between the specific flow and local density (here termed fundamental diagrams) were derived. Finally, the collected data were compared with existing data from the literature.

This paper is organised as follows. Section 2 provides background information about existing evacuation studies with a focus on those studies focused on retirement facility analyses. The authors have attempted to highlight the individual context from which the data was derived in order to allow readers to understand the existing datasets, their applicability and their limits. Section 3 presents the method employed in the present experimental study. This includes information about the monitored facilities, the drills settings, the observed case studies and the methods used for data collection and analysis. The results will be reported in Section 4. Finally, Sections 5 and 6 close this paper with a discussion of the results and conclusions.

2 Background

Several papers have shown the potential of using video recording of evacuation drills to investigate evacuation behaviour. For instance, Rahouti *et al.* (2020) investigated drills in healthcare facilities, Hamilton *et al*. (2017) in schools, Kuligowski *et al*. (2014) in office and residential buildings, and Kholshchevnikov *et al*. (2012) and Larusdottir *et al*. (2012) in day-care centres. While there is an extended body of literature focusing on pre-evacuation times, walking speeds and fundamental diagrams for children and adult evacuations (Lovreglio *et al.*, 2019a; Bosina and Weidman, 2017; Gwynne and

Boyce, 2016), data relating to elderly evacuees or evacuees requiring assistance are limited. This section aims at providing an overview of the existing studies on retirement facilities and assisted living facilities.

Shields *et al.* (1999) analysed videos of two *unannounced* evacuation drills carried out in two residential care premises in Northern Ireland. Most of the observed residents were mobile, which means they did not require assistance from the staff to evacuate. At the time of the drills, all residents were located in their bedrooms with the exception of a few. This study focused on the qualitative description of resident behaviours, but also generated quantitative data, such as pre-evacuation and evacuation times. A commonality between both observed buildings is that residents needed information and confirmation of fire and used familiar routes for evacuation. It was also noticed that several residents evacuated without direction or help from others. In residence 1, pre-evacuation times ranged from 58 seconds to 360 seconds, while the evacuation times ranged from 210 seconds to 371 seconds. However, it should be noted that only a limited number of residents (3 out of 10) participated in the drill, and all of those were male residents. In residence 2, pre-evacuation times ranged from 6 seconds to 160 seconds, while evacuation times ranged from 24 seconds to 270 seconds. The main limitations of the study by Shields *et al*. (1999) are the limited sample size (13 observations) and the focus on able-bodied residents (i.e., people with mobility impairments were excluded from the drills for safety and ethical concerns).

Pichler *et al*. (2015) observed and analysed an *announced* evacuation drill at a Canadian retirement facility. Observers collected the data by hand. The drill involved staff working in the facility along with three residents, all of whom were ambulant, and did not receive assistance from staff members during their evacuation. Many staff (i.e. approximately 15 nursing staff) responded to the fire alarm, however, most of them seemed unsure of what to do in case of evacuation and stood near or behind the exit doors of the wing.

Other drills have been carried out in Canada by Folk *et al*. (2020). They analysed nine *announced* fire drills carried out at six Canadian retirement facilities. The first four were monthly drills in which resident participation was not mandatory, while the latter five drills were legally required annual fire marshal-observed drills. During these drills, staff and resident behaviours were collected by observers. Out of these observations, pre-evacuation times and evacuation movement data (e.g. walking speeds) were quantified where possible. The drills involved 37 staff members and 56 residents. The results of this study demonstrated that, overall, the evacuation outcome in such environments is highly dependent on the staff performance as most residents may require the full assistance of staff at all stages of the evacuation process. Regarding the quantitative measurements, residents' pre-evacuation time ranged from slightly more than 1 minute to approximately 14 minutes, while residents' horizontal travel speed ranged from 0.02 m/s to 1.81 m/s, with an average speed of 0.33 m/s.

Kuligowski *et al.* (2013) documented stairwell movement speeds and behavioural data for 45 residents evacuating a six-story assisted-living facility in the United States during an *announced* drill. The building contained 133 living units for residents and three stairwells that exited to the ground floor. In this study, only two of the three stairwells were video monitored, however the majority of residents evacuated through Stairwell 2 (which was monitored). The building's population comprised of a diverse array of elderly adults and disabled residents descending the stairwells by the following methods: self-evacuation without assistance, assistance using a cane, assistance from another occupant or firefighter, or assistance using a stair chair. Overall, residents evacuating the building had an average speed on stairs of 0.22 ± 0.10 m/s with a range from 0.07 to 0.54 m/s. Occupants evacuated at low population densities within this building; therefore, the stair movement data presented in this work should be considered as occurring during unimpeded movement conditions. Encompassing the data from Kuligowski *et al.* (2013), Peacock *et al.* (2017) compiled evacuation data from two US assisted living facilities or elderly housing. From a sample of 170 evacuees, they observed that the delay time (i.e. the time from the initial alarm until the occupant was seen entering the stair to evacuate the building) for these facilities ranged between 398s and 1708s. Overall, residents evacuating the buildings had an average speed on stairs ranging from 0.07 to 0.94 m/s.

Data regarding elderly movement were also collected using experiments. For instance, Boyce *et al.* (1999) ran several experiments in Northern Ireland to study the capabilities of people with mobility impairments (including elderly people) to move on horizontal and inclined planes. However, the results of this study are aggregated, and in turn, do not allow users to extract that data only applicable to elderly people. Fujiyama and Tyler (2014) ran an experiment with 18 elderly people to measure their average speeds on stairs. The results indicate that the ascending speeds ranged from 0.41 to 0.76 m/s while the descending speeds were between 0.46 and 0.80 m/s.

In summary, various past studies have investigated retirement home evacuations or movement of elderly in a lab setting. These studies were all carried out in Canada, the US and North Ireland, which potentially limits their generalizability. Thus, the collection of evacuation data in other countries is necessary to verify the reliability of the existing data. The present study addresses this limitation by collecting a new evacuation dataset in retirement facilities located in Auckland, New Zealand.

From a sample viewpoint, the existing datasets show that there is a relatively high sample size when focusing on movement on stairs while the sample size for pre-evacuation time and horizontal speed is relatively small. Previous studies also acknowledged that the observation and recording methods would have resulted in some information being missed and suggested consideration of other methods in future investigations. To provide more accurate data, video recordings are used in the present study. Finally, most of the drills analysed in previous studies were *announced* drills. This may influence the external validity of the results (Gwynne and Boyce, 2016). To overcome this last limitation, the present study mainly relies on *unannounced* drills where/when possible, i.e. only one drill out of the 16 performed fire drills is *announced* and only used to investigate fundamental diagrams for elderly evacuees.

3 Methods

This section provides information about where the evacuation data was collected (Section 3.1), the drills settings (Section 3.2), the investigated case studies (Section 3.3) and how the data was collected and analysed (Section 3.4).

3.1 Buildings

The evacuation drills analysed in this work were recorded in six buildings belonging to three retirement facilities located in Auckland, New Zealand. For ethical reasons, the names of these facilities are not reported in this paper, and the geometry of the evacuated areas are represented only schematically. As such, in the following parts of the paper, three retirement facilities are labelled as Facility A, Facility B and Facility C (See Table 1). The facilities are designed using fire compartments, allowing the occupants to evacuate horizontally from one compartment affected by the fire to an adjacent non-fire affected compartment. These facilities include different areas:

A1 - Areas with independent living apartments connected by corridors. In these areas, fire compartments consist of several apartments and the corridor connecting them to stairs, elevators and an exit. These areas are occupied by the elderly (≥65 years old) who do not require any assistance in their day and night activities.

A2 - Retirement care areas having a set of bedrooms connected by corridors. In these areas, fire compartments consist of several bedrooms connected by corridors. These areas are occupied by people (≥65 years old) who require assistance for their day and night activities.

A3 - Communal areas consisting of big rooms for dining and recreation. In these areas, fire compartments consist of one room and the corridors connecting the room with the remaining parts of the building. These areas are occupied by the people staying in A1 and A2.

Drills in A2 areas were not carried out given the vulnerability of building occupants as these drills might put them at risk.

3.2 Drills settings

Data were collected from 16 drills carried out in A1 and A3 areas belonging to different buildings. Fifteen of the drills were *unannounced* drills while one was *announced*. These drills were focused within single fire compartments, and none of these drills prompted a full evacuation of the entire building. As such, during these drills building occupants and staff were supposed to evacuate horizontally from one fire compartment to its adjacent fire compartments. Once this goal was achieved, the drill was ended.

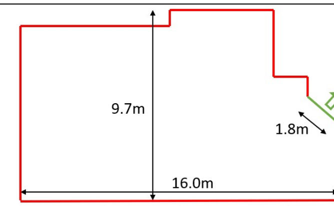
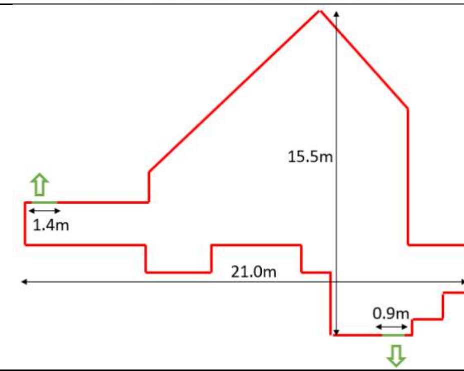
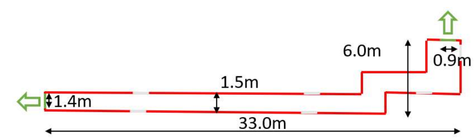
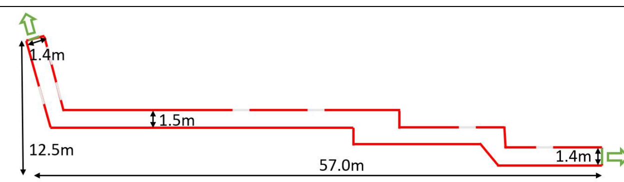
The *unannounced* drills were run by activating one of the smoke detectors in the drill area. The smoke detector started a local fire alarm (only in the room where the smoke was detected) and sent an alert message to the operations desk of the retirement facility. One staff member was supposed to check the room where smoke was detected and start the evacuation procedure. As a next step, the staff member went to the manual fire point in the fire compartment to activate the alarm in the entire compartment. The manual call point activated both the fire compartment alarm and triggered the closure of the fire doors connecting the fire compartment to its adjacent compartments. The alarm provided a voice message telling occupants to evacuate the building immediately using the nearest exit. Once the alarm was activated, the staff member started informing building occupants and other staff to evacuate by either knocking on their doors in A1 areas or informing them in person in A3 areas. Once the building occupants were informed, all the staff started assisting them to evacuate by helping occupants with mobility impairments, opening the fire doors for the occupants, etc. In these drills, residents were not aware of the drills prior to the activation of the alarm while some staff were aware of the drills for residents' safety considerations.

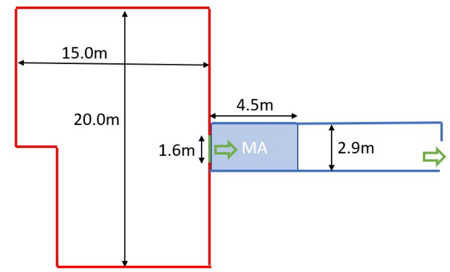
This study also includes one *announced* drill, where staff and building residents were informed of the drill ahead of time. In this case, the fire compartment alarm was activated by the evacuation consultant running the drill. The building residents and staff were asked to move from the current fire compartment where the alarm was sounded, to the adjacent fire compartment.

3.3 Case studies

The data collected in the 16 drills are here divided into 3 case studies. The first case study includes data from *unannounced* drills which took place in A3 areas of two retirement facilities: one drill took place in a recreation room during a live music exhibition and the other in a kitchen. The monitored kitchen consists of an open space with a dining table where residents were having lunch when the alarm sounded. The second case study includes data from a series of *unannounced* drills which took place in A1 areas. The last case study consists of a single *announced* evacuation drill which took place in an A3 area of a retirement facility: the drill took place in a recreation room where staff and building occupants attended a fire safety class. Table 1 provides a summary of these case studies, including the number of building occupants, the number of staff members involved in the drill, type of area, geometry scheme of the evacuated area, and type of drill (*announced* or *unannounced*).

Table 1 Characteristic of the case studies

Case Study	Facility	Building	Floor	# of occupants	# of staff	Area type	Drill Type	Geometry
1	A	1	2	28	>17 (13*)	A3-recreation	unannounced	
	B	4	Ground Floor	6	1	A3-kitchen	unannounced	
2	B	1	Ground Floor	1	1	A1	unannounced	
	B	1	1	1	1	A1	unannounced	
	B	1	2	3	1	A1	unannounced	
	B	1	3	6	1	A1	unannounced	
	B	1	4	2	1	A1	unannounced	
	B	2	1	4	1	A1	unannounced	
	B	2	2	6	1	A1	unannounced	
	B	2	3	4	1	A1	unannounced	
	B	2	5	7	1	A1	unannounced	
	B	3	1	3	1	A1	unannounced	

	B	3	2	2	1	A1	unannounced	
	B	3	3	6	1	A1	unannounced	
	B	3	4	5	1	A1	unannounced	
3	C	1	3	34	>27 (7*)	A3-recreation	Announced	 *(MA: Measurement Area)*

*** number of staff who was observed to help residents**

3.4 Data collection and analysis methods

Data collection techniques commonly used in human behaviour in fire research can be broadly categorised as observations, interviews, focus groups, and questionnaires. In the present study, we are using observations to obtain information on the evacuation behaviours of the participant samples. There are a number of observations equipment commonly used to collect evacuation data. They include stationary video cameras (CCTV/security cameras or specially located cameras), roving video cameras, still cameras, human observers, electronic sensor/Automated measurement (such as mobile and GPS data) /RFID technology and scanners (Gwynne and Boyce, 2016). Each of these means has strengths and limitations. In the current study, strategically located stationary video cameras were utilised. The cameras were fixed on walls in areas of interest in each analysed building on the days of the drills.

Once the drills were recorded, the videos were analysed in order to conduct behavioural analyses (i.e. observing the staff and residents' behaviours and interactions) and estimate quantitative data, such as pre-evacuation times of residents, their (un)constrained horizontal walking speed, and local density where required. The pre-evacuation time of an individual is defined as the time between the first activation of the alarm in the monitored fire compartments and the time when the individual started to move towards a place of safety (an adjacent fire compartment). This approach has been widely used in previous studies such as Rahouti *et al.* (2020), Hamilton *et al*. (2017), Kuligowski *et al*. (2014), Kholshchevnikov *et al*. (2012), and Larusdottir *et al*. (2012). Evacuee horizontal walking speed is defined as follows:

$$S = \frac{d}{t_{out} - t_{in}} \qquad \text{(Eq. 1)}$$

Where

S is the walking speed in m/s

d is the distance between two reference points (in m).

t_{in} is the time at which the individual enters the first reference point (in seconds).

t_{out} is the time at which the same individual enters the second reference point (in seconds).

This approach is consistent with previous studies such as Rahouti *et al.* (2020), Hamilton *et al*. (2017), and Cuesta and Gwynne (2016). The distances between the reference points were determined during inspections (or visits) of the monitored buildings or using the CAD drawings of those facilities.

Local density in corridors and its impact on movement speed was estimated as part of this work. This was done by monitoring the number of occupants located in front of each occupant as they entered the first reference point in a specific corridor. It is assumed that only occupants who stayed between the first and second reference points when the selected occupant arrived at the first reference point impacted the occupants' speed. The calculation of local density was, therefore, performed as follows: the number of other occupants (O_J) in front of the selected occupant (O_I) was determined by counting only those occupants, such that the times, t, are such that $t_{enter,I} \leq t_{exit,J}$ in line with past studies such as Rahouti *et al.* (2020) and Kuligowski *et al.* (2015). Finally, local density was measured only for Case Study 3 to estimate the fundamental diagrams. This was measured by dividing the number of evacuees in the MA area highlighted in Table 1 by the walkable area. The density was measured for each participant at the moment they entered the MA area.

There was additional data collected for the participating residents using the videos. This included whether a resident was using walking aids during the evacuation, and whether he/she received staff assistance/guidance. No data was collected on stairs as the facilities under investigation run evacuation drills evacuating residents from a fire compartment to the adjacent fire compartments located on the same floors.

4 Results

In this section, the results of this study are reported. These include qualitative and quantitative results. Section 4.1 reports the qualitative results which consist mainly of observed behaviour in the monitored drills. Section 0 reports the quantitative results. These include pre-evacuation times, unimpeded horizontal walking speeds for unconstrained scenarios, and the walking speed-local density and specific flow-local density for constrained scenarios.

4.1 Qualitative results

The observed occupants of the retirement homes in the study showed a range of behaviours. These mainly depended on whether they were staff members or elderly residents, and the area type where the drill was carried out (i.e., either A1 or A3). For instance, in an area of type A1, staff member responses to the alarm signal consisted of performing sweeps of the area in order to alert residents who stayed inside this area in spite of the alarm. They also directed residents who were hesitating or waiting for staff evacuation orders towards the nearest exit. Moreover, where assistance was needed (i.e. a resident with reduced mobility requiring external help), staff members or another resident helped the individuals requiring assistance to evacuate the fire compartment.

In some areas of type A3 (e.g. the music exhibition room), a large number of staff members gathered. However, because so many were present, no one was certain of his/her role in the evacuation; and therefore, were observed waiting in a corner or behind the room door for further instructions from the fire warden (or the chief nurse). For example, many of these staff members evacuated the music exhibition room without aiding residents. This observation is consistent with observations made in previous studies such as Pichler *et al.* (2015) and Folk *et al.* (2020). In effect, high numbers of staff do not necessarily result in a quick evacuation, but rather seems to increase the feeling of hesitation of staff or result in a diffusion of responsibility (Latané and Darly, 1970; Fischer *et al*., 2005). However, staff members who were seen to act in areas of type A3 responded effectively to the alarm. They directed residents who were able to walk to the adjacent fire compartment. They also helped residents with reduced mobility to evacuate using wheelchairs and wheeled armchairs. Additionally, they walked with some residents who were able to move with little external help from the staff. These actions required the staff members to walk with the residents until they had reached a place of safety. Another observation was that staff members had to assist more than one resident, in turn, re-entered the fire compartment several times. This was due to the low assistant-to-resident ratio.

The residents of type A1 areas showed a range of behaviours. Some evacuated immediately and headed towards the nearest exit without receiving staff evacuation orders. While a large percentage stayed inside their apartment until alerted by a staff member or another resident knocking on their apartment door. This means that the staff role in such buildings is critical for safe and efficient evacuation in case of fire. Another observed behaviour was that some individuals looked around (i.e. situation assessment) for a few seconds to seek more information before heading towards an adjacent fire compartment. This means that people may still hesitate about what is happening even when hearing a clear voice alarm telling them to evacuate the building immediately using the nearest exit. This also suggests that the behaviour of those individuals might result from their being unfamiliar with the evacuation procedures for the residence, which may have influenced their behaviour. Many individuals evacuated on their own, while a few cared for others. Data indicated that a few residents knocked at the doors of their neighbours' apartments in order to warn them, held the door of another apartment open to allow the occupants to exit, or collected a transportation device (e.g. a wheelchair) to transport an individual with walking impairments to an adjacent fire compartment. Individuals living in the same apartment evacuated in groups. This means that affiliation has an impact in such environments as some individuals were observed to evacuate with others who were familiar to them. However, more evidence is needed in order to confirm this trend. Another interesting observation is that some residents were not capable of opening fire doors. Thus, they waited in front of the door until they received help from staff. Finally, some residents talked with staff or other residents, stood in corridors, walked barefoot, fixed footwear, entered another apartment, or even returned back to the apartment to close doors, all of which can delay movement to safety during evacuation

In areas of type A3, all residents stayed inside the premises after the alarm sounded until they were prompted to evacuate by staff members. Those who were able to move on their own with/without personal walking aids, such as canes, walking frames, etc., evacuated themselves even if they waited for staff confirmation before starting to move towards adjacent fire compartments. Some residents also collected their walking aids before evacuating, which delayed their evacuation. Conversely, residents with reduced mobility waited in their initial locations until they were assisted by a staff member.

4.2 Quantitative results

Several quantitative data were collected and analysed. Section 4.2.1 provides the results regarding the pre-evacuation times while Sections 4.2.2 and 4.2.3 show the results regarding the unimpeded horizontal speed and fundamental diagrams respectively. In the following sub-sections, we will refer to residents' pre-evacuation times as pre-evacuation times and to residents' walking speeds as walking speeds to allow easier reading.

4.2.1 Residents' pre-evacuation times

Pre-evacuation times were collected in all drills, except the drill within Case study 3, since the building occupants were aware of the evacuation.

Figure 1 shows boxplots of pre-evacuation times for Case study 1 measured in two communal areas of facilities A and B: a gathering room in facility A during a live music exhibition and a kitchen in facility B. Table 2 reports descriptive statistics. Figure 1 and Table 2 present also the boxplot of the combined data (i.e. All) and associated descriptive statistics.

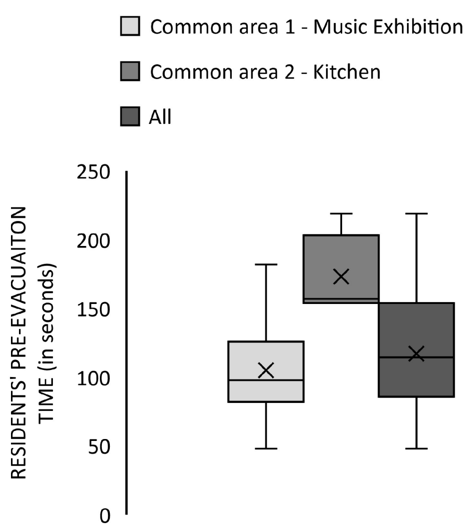


Figure 1 Residents' pre-evacuation time distributions in communal areas of retirement homes

Table 2 Descriptive statistics of residents' pre-evacuation time distributions in communal areas of retirement homes

Communal area	Sample size	Minimum	Maximum	Mean	S.D.	25th Percentile	Median	75th Percentile
1	28	48.0	182.0	105.2	35.6	82.3	98.0	126.0
2	6	154.0	219.0	173.2	28.3	154.0	157.0	203.3
All	34	48.0	219.0	117.2	43.0	86.0	114.5	154.0

In the music exhibition room, the mean pre-evacuation time was 105.2 ± 35.6 seconds, while, in the kitchen, the mean pre-evacuation time was 173.2 ± 28.3 seconds. It is clear that the pre-evacuation times measured in the monitored communal areas are different. The Mann-Whitney U-test confirmed that the pre-evacuation times measured in the above-outlined communal areas are statistically different (p-value = 0.002 < 0.05). The mean pre-evacuation time for the communal area data was 117.2 ± 43.0 seconds.

From the video footage, it was observed that the staff assisting residents located in the kitchen of facility B started to act late (122 seconds after the fire alarm sounded) compared with the staff that assisted the residents located in the music exhibition room of facility A (44 seconds after the fire alarm sounded). Therefore, we normalised the measured pre-evacuation times from the time when staff started to act in order to investigate if the normalised values are comparable. This was done by calculating the difference between the measured residents' pre-evacuation time and the time at which the first staff member started to act. The objective here is to investigate whether the action of staff influenced residents' pre-evacuation times in those facilities. Figure 2 shows the normalised distributions of pre-evacuation times measured in communal areas of facilities A and B, while descriptive statistics are reported in Table 3.

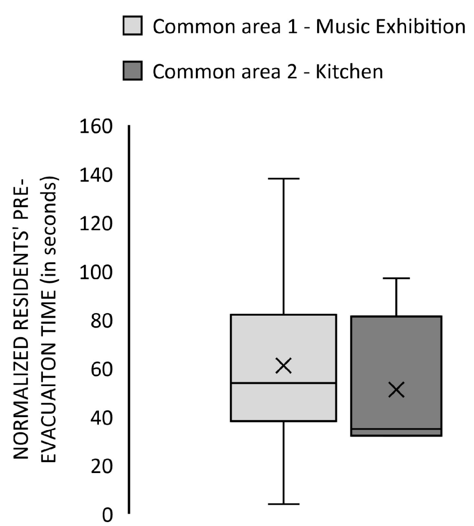


Figure 2 Normalised residents' pre-evacuation time distributions in communal areas of retirement homes

Table 3 Descriptive statistics of normalised residents' pre-evacuation time distributions in *communal* areas of retirement homes

Communal area	Sample size	Minimum	Maximum	Mean	S.D.	25th Percentile	Median	75th Percentile
1	28	4.0	138.0	61.2	35.6	38.3	54.0	82.0
2	6	32.0	97.0	51.2	28.3	32.0	35.0	81.3

Figure 2 and Table 3 reveal that there is no notable difference between the distributions of the normalised pre-evacuation times measured in either facility. The Mann-Whitney U-test confirmed that the normalized pre-evacuation times are not statistically different (p-value = 0.442 > 0.05). This highlights the importance of quick staff response on the outcome of the evacuation. The earlier staff members respond, the earlier residents can start their evacuation. That is, the success of an evacuation in retirement facilities is highly dependent upon the staff response. It is, therefore, necessary that the staff acts quickly and efficiency and are regularly trained on how to respond in emergency situations.

Figure 3 shows the boxplots of pre-evacuation times for Case study 2 measured in three apartment buildings of facility B. Table 4 reports their descriptive statistics. Figure 3 and Table 4 present also the boxplot of apartment buildings of facility B for grouped data, as well as its descriptive statistics.

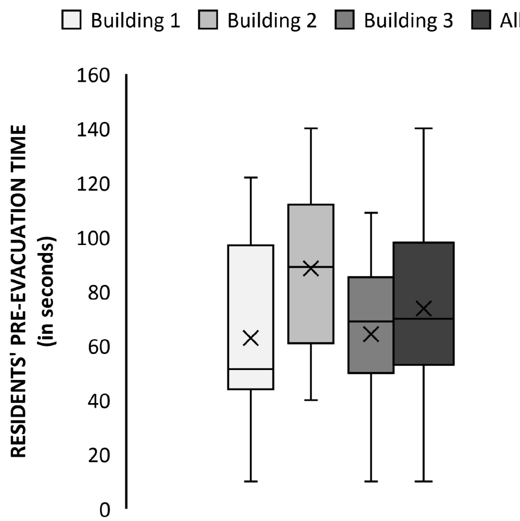


Figure 3 Residents' pre-evacuation time distributions in apartment buildings of facility B

Table 4 Descriptive statistics of residents' pre-evacuation time distributions in apartment buildings of facility B

Building	Sample size	Minimum	Maximum	Mean	S.D.	25th Percentile	Median	75th Percentile
1	12	10.0	122.0	62.8	36.5	44.0	51.5	97.0
2	19	40.0	140.0	88.5	27.8	61.0	89.0	112.0
3	16	10.0	109.0	64.3	27.8	50.0	69.0	85.3
All	47	10.0	140.0	73.7	32.0	53.0	70.0	98.0

The mean pre-evacuation time is 62.8 ± 36.5 seconds, 88.5 ± 27.8 seconds, and 64.3 ± 27.8 seconds, in buildings 1, 2 and 3, respectively. It is clear that the pre-evacuation times measured in building 2 are different from those measured in buildings 1 and 3. This difference is statistically significant as confirmed by a one-way independent ANOVA analysis ($F(2, 44) = 3.835$, p-value = 0.029). Post-hoc analysis, using Fisher's protected t-test, revealed (1) a significant difference (p-value = 0.026 < 0.05) between the pre-evacuation times in buildings 1 and 2; and (2) a significant difference (p-value = 0.023 < 0.05) between the pre-evacuation times in buildings 2 and 3. The difference between the pre-evacuation times in buildings 1 and 3 did not reach significance (p-value = 0.899 > 0.05). From Figure 3 and Table 4 results, it can also be noted that the mean pre-evacuation time in apartment buildings of facility B for the grouped data (i.e. All) is 73.7 ± 32.0 seconds.

Figure 4 shows the boxplot of the pre-evacuation time combining the data of Case studies 1 and 2. Table 5 reports the descriptive statistics. The mean residents' pre-evacuation time in retirement homes is 92.0 ± 42.7 seconds. Figure 5 represents the cumulative probability of pre-evacuation time measured during the observed fire drills for Case studies 1 and 2, and combining the data from both case studies. This figure also shows the estimated pre-evacuation distributions, which are commonly used type of distributions in computer modelling (Lovreglio *et al.*, 2019a; Rahouti *et al.*, 2020) including Gamma, Lognormal, Loglogistic and Weibull distributions. The estimated parameters of these distributions are reported in Table 6.

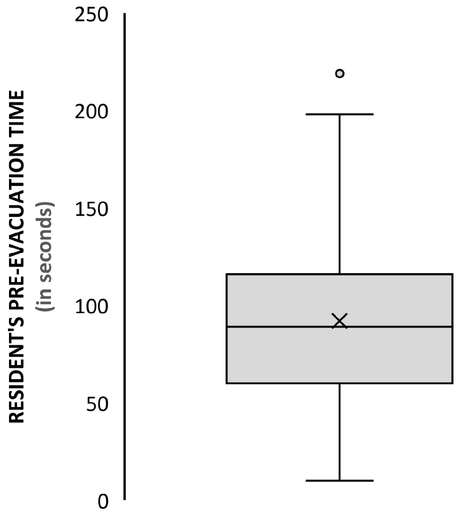
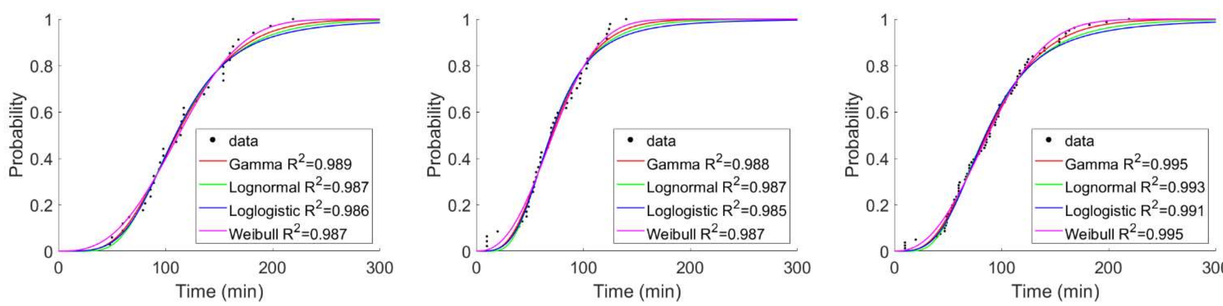


Figure 4 Residents' pre-evacuation time distribution in retirement homes (Case studies 1 and 2 combined data)1

Table 5 Descriptive statistics of residents' pre-evacuation times distribution in retirement homes (Case studies 1 and 2 combined data)

Sample size	Minimum	Maximum	Mean	S.D.	25th Percentile	Median	75th Percentile
81	10.0	219.0	92.0	42.7	60.0	89.0	116.0



Case Study 1 Case Study 2 Case Study 1 and 2

Figure 5 The cumulative probability of residents' pre-evacuation time in retirement homes

The most probable pre-evacuation time in the monitored retirement homes is between 60 seconds (or 1.00 minute) and 116 seconds (or 1.93 minutes). Moreover, Figure 5 cumulative probability distribution shows that about 96% of the data will most likely to be 168 seconds (or 2.80 minutes) or less.

Table 6 Estimated parameters of pre-evacuation distributions

Case Study	Distribution	Parameters in seconds		Data points	R^2
		a	b		
1	Gamma	6.3	-18.5	34	0.989
	Lognormal	4.7	0.4		0.987
	Loglogistic	4.7	-0.2		0.986
	Weibull	127.8	2.8		0.987
2	Gamma	5.2	14.6	47	0.988
	Lognormal	4.2	0.4		0.987
	Loglogistic	4.2	0.3		0.985
	Weibull	83.1	2.5		0.987

1 & 2	Gamma	4.6	-20.1	81	0.995
	Lognormal	4.4	-0.5		0.993
	Loglogistic	4.4	-0.3		0.991
	Weibull	101.7	2.4		0.995

4.2.2 Unimpeded residents' horizontal walking speeds

Unimpeded horizontal walking speeds were collected in Case study 2 where the density of residents was smaller than 0.54 persons/m². According to Gwynne and Rosenbaum (2016), if the population density is less than approximately 0.54 persons/m², building occupants are assumed to move at their unimpeded walking speed. Figure 6 shows the walking speeds measured in the corridors of facility B's apartment buildings: from 1 to 3. It also shows the boxplot of the grouped data (i.e. All). Table 7 reports the descriptive statistics of these distributions. It should be noted that the data presented in this section represent free-flow (or uncongested) scenarios as the measured local density values were lower than 0.54 persons/m².

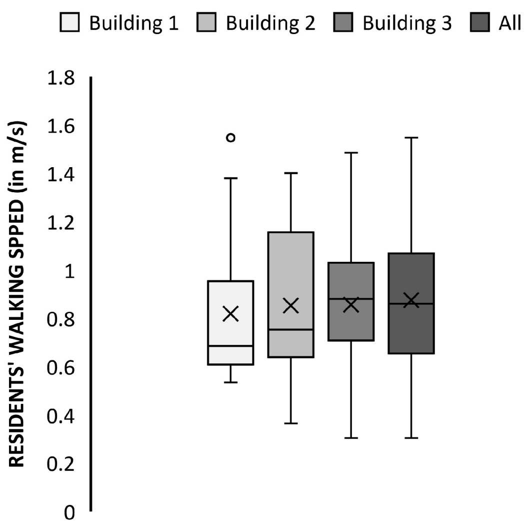


Figure 6 Residents' horizontal walking speed distributions in apartment buildings of facility B

Table 7 Descriptive statistics of residents' horizontal walking speed distributions in apartment buildings of facility B

Building	Sample size	Minimum	Maximum	Mean	S.D.	25th Percentile	Median	75th Percentile
1	10	0.5	1.6	0.9	0.4	0.6	0.7	1.1
2	19	0.4	1.4	0.9	0.3	0.6	0.8	1.2
3	12	0.3	1.5	0.9	0.4	0.7	0.9	1.1
All	41	0.3	1.6	0.9	0.3	0.7	0.9	1.1

The mean walking speed in corridors was 0.86 ± 0.35 seconds, 0.88 ± 0.30 seconds, and 0.89 ± 0.36 seconds, in buildings 1, 2 and 3, respectively. It is clear that the walking speeds measured in the three buildings are similar. The lack of significant differences between the walking speeds across the three buildings was confirmed by a one-way independent ANOVA analysis ($F(2, 38) = 0.037$, p-value = 0.964). From Figure 6 and Table 7, it can also be noted that the mean walking speed in apartment buildings of facility B for the grouped data (i.e. all) was 0.89 ± 0.33 seconds.

Figure 7 shows the walking speed distributions in apartment buildings of facility B depending on whether the resident was using walking aids (such as rollators, walking sticks, and wheelchairs) during the evacuation movement, while Table 8 reports descriptive statistics.

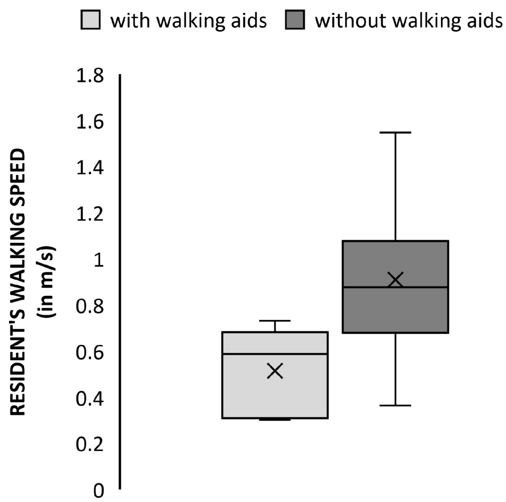


Figure 7 Residents' horizontal walking speed distributions in apartment buildings of facility B depending on the residents' movement abilities

Table 8 Descriptive statistics of residents' horizontal walking speed distributions in apartment buildings of facility B on the residents' movement abilities

Residents ability	Sample size	Minimum	Maximum	Mean	S.D.	25th Percentile	Median	75th Percentile
With walking aids	5	0.3	0.7	0.5	0.2	0.3	0.6	0.7
Without walking aids	35	0.4	1.6	0.9	0.3	0.7	0.9	1.1

Figure 7 and Table 8 reveal that residents in retirement facilities move at different speeds depending on their abilities. Residents who used walking aids during evacuation moved at an average speed of 0.51 ± 0.19 m/s, while those who did not use walking aids moved at an average speed of 0.91 ± 0.29 m/s.

4.2.3 Fundamental diagrams

This section provides the estimated relationships between walking speed and local density and specific flow and local density in congested and uncongested scenarios. According to Gwynne and Rosenbaum (2016), the relationship between walking speed and local density is assumed to be: (1) constant if the population density is less than approximately 0.54 persons/m². In corridors, this constant speed is approximately 1.20 m/s; and (2) if the population density exceeds 0.54 persons/m², this relationship is assumed to be a linear function. The equation that defines this linear function is the following:

$$S = k - a \cdot k \cdot D \qquad \text{(Eq. 2)}$$

where

S is the walking speed along the line of travel in m/s
D is the population density in persons/m²
k and *a* are constants that are equal to 1.40 persons/m² and 0.266 m/s, respectively.

The relationship between the specific flow and local density is defined as follows (Gwynne and Rosenbaum, 2016):

$$F_s = S \cdot D = (1 - a \cdot D) \cdot k \cdot D \qquad \text{(Eq. 3)}$$

The above-outlined relationships are plotted in Figure 8 (i.e. SFPE) along with the experimental data collected in the present study. The data points reported in Figure 8 with a density equal to 0.00 persons/m² are estimated in facility B, while the remaining data points are estimated in facility C.

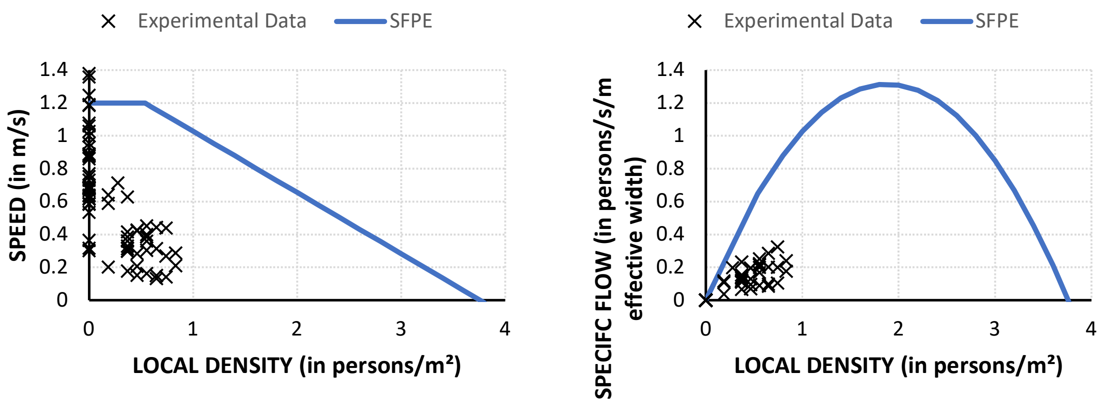


Figure 8 Fundamental diagrams: Speed versus local density (*left*); specific flow versus local density (*right*)

A large variance is observed in Figure 8. The walking speeds ranged from 0.13 to 1.55 m/s, the local density ranged from 0.00 to 0.83 persons/m², and, the specific flow ranged from 0.00 to 0.33 persons/s/m of effective width. One should be aware that the SFPE relationships are often used for the design of buildings having mainly adults with not walking impairments and might not be appropriate for specific cases such as retirement homes design. This is confirmed in our study as most experimental data points fall below the SFPE relationships. This means that the usage of SFPE relationships in the modelling of retirement homes evacuations or the design of these buildings will result in overly optimistic results and will underestimate the required evacuation time.

The experimental data presented in this study are, however, limited and only represent low values of local density (i.e. < 1 person/m²). Therefore, it is suggested to undertake further investigations with a higher sample size and higher values of local density in order to represent the full relationships between walking speed and local density, and specific flow and local density in congested scenarios that may occur in retirement homes. This will allow the generalizability of the newly estimated evacuation data set for retirement homes.

5 Discussions

This study provides new insights on how residents (i.e. elderly people) and staff behave while evacuating in retirement facilities. This was possible by running qualitative and quantitative analyses of several evacuation drills carried out in New Zealand.

From a qualitative viewpoint, the study shows that both staff and residents showed various behaviours depending on their role in the building – i.e. staff or resident; and the type of the monitored area – i.e. A1 or A3 (see Section 3.1 for definitions). Even if staff response was not in all cases immediate, staff showed expected behaviours such as (1) sweeping the fire compartments in order to alert residents, (2) opening the door of the apartment and looking inside if residents did not respond, (3) providing evacuation orders, (4) directing residents towards the nearest place of safety (typically an adjacent fire compartment or an emergency exit), and (5) assisting residents and helping them to reach an adjacent safe compartment. Not all of these behaviours were observed in both areas (i.e. A1 and A3). In the A3 area, for example, only behaviours 3 to 5 were observed.

Residents showed various behaviours such as evacuating immediately, staying inside the premises regardless of the alarm, waiting for evacuation orders, seeking more information and assessing the situation, warning or taking care of others, affiliative behaviour, evacuating in groups, talking with staff and other residents, standing in corridors, entering another apartment, returning back to the apartment to close the door, collecting walking aids before evacuating, and waiting for assistance due to their physical status (i.e. people with walking disabilities). Resident behaviours in retirement homes depended on their abilities and locations within the buildings during the fire emergency.

Pre-evacuation data of residents revealed that residents' pre-evacuation time highly depends on the type of observed area and the physical ability of residents. In areas of type A1, residents' pre-evacuation time ranged from 10 seconds to 2 min 20 seconds, while it ranged from 48 seconds to 3 min 39 seconds in areas of type A3. Residents of areas of type A3 took longer to initiate their evacuation because many of them were assisted by staff to move towards an adjacent fire compartment. This is typical in healthcare facilities where a large number of people with mobility impairments might be present, as discussed by Rahouti *et al.* (2020). Another interesting observation emerged when considering the normalised residents' pre-evacuation time distributions (see Figure 2), namely that faster staff response leads to a better evacuation outcome, i.e., earlier resident evacuation. When analysing residents' pre-evacuation times in apartment buildings, it was shown that there are statistically significant differences between the measured data in building 2 compared with buildings 1 and 3. This can be explained by the fact that building 2's corridors are much longer and more complex than the two other buildings (see Table 1), which may have influenced the way a single staff member in charge of alerting residents informed them. Thus, two or more staff members may be required in this building instead of a single staff member in order to enhance the pre-evacuation response of residents.

Pre-evacuation data measured in the present study can be compared with values from the literature. The residents' pre-evacuation times measured in apartment buildings can be compared with values reported by Shields *et al.* (1999), while the values measured in communal areas can be compared with those of Folk *et al*. (2020). Shields *et al*. (1999) reported residents' pre-evacuation times ranging from 6 seconds to 6 minutes, while in the present study residents' pre-evacuation times in apartments ranged from 48 seconds to 3 min and 39 seconds. The estimated data fits within data collected by Shields *et al.* (1999) and aligns with values on the lower end of the study range. This could be explained by the fact that in the present study there was a staff member warning the residents, which might have led to a reduction in pre-evacuation times, unlike in Shields *et al.'s* (1999) study where no warning was provided to residents in either monitored residence. Folk *et al*. (2020) reported residents' pre-evacuation times ranging from 1 minute to about 14 minutes, while in the present study, residents' pre-evacuation times ranged from 10 seconds to 2 min 20 seconds in communal areas of retirement homes. There is a notable difference between the data measured in the present study and those reported in the literature for retirement homes. This can be explained by the fact that, in the communal areas observed in the present study, even though larger numbers of staff may have caused some delay (see Section 4.1), residents' pre-evacuation times were shorter when compared with Folk *et al*.'s (2020) scenarios representing night shift staff-to-resident ratios.

This study also focused on the measurement of residents' walking speeds. We assumed that the staff members had some capability to evacuate the building at a quick pace, unlike the residents who may have had physical and mental disabilities. Also, it was only possible to measure residents' walking speeds in apartment buildings. It can be noted that the residents using walking aids moved at an average speed which is about half of the average speed of the remaining residents. This is consistent with values from the literature such as Rahouti *et al.* (2020), Boyce *et al*. (1999) and Shields *et al.* (1997). Slower movement is one of the characteristics of residents in healthcare facilities such as retirement homes and hospitals, which should be considered when carrying out evacuation simulations of these environments.

It is noted that the unimpeded speeds of residents measured in the present study fall within the values reported in Folk *et al.* (2020).

The analysis of the fundamental diagrams has shown large scatter of the measured data. However, most of the experimental data points fall below the SFPE fundamental diagrams. This suggests that the usage of SFPE fundamental diagrams when dealing with scenarios simulating retirement homes may not be a conservative assumption. This may lead to optimistic designs which underestimate the actual required evacuation time in such environments and, in turn, lead to disastrous consequences in the event of an actual fire event. The experimental data reported in the present study are, however, limited and further investigations are needed in order to confirm the above-outlined observations.

6 Conclusions

This work presents the results of 16 evacuation drills carried out in three retirement facilities in New Zealand. These drills involved 61 staff members and 118 residents.

The qualitative analysis has shown that even though staff action is known to be critical for the efficiency of the evacuation in case of fire in retirement buildings, staff response was not immediate in all observed drills because of diffusion of responsibility. Some residents hesitated about what was happening even when hearing a clear voice alarm telling them to evacuate the building immediately using the nearest exit. It was also observed that affiliation has an influence in such buildings on residents' behaviour as some residents were observed to evacuate with others who were familiar to them. The analysis showed that some residents with walking disabilities were not capable of opening fire doors and waited for staff assistance before initiating their evacuation towards a safe area. This showed the fundamental role of staff during the evacuation process.

The quantitative analysis revealed that residents' pre-evacuation time range from 48s to 219s in communal areas and from 10s to 140s in areas with independent living apartments. The comparison of the pre-evacuation data measured in the present study has shown consistency between the generated dataset and data values found in the literature for similar building occupancy when considering the data for areas with independent living apartments. The collected pre-evacuation data from communal areas are instead lower than the one provided in the literature as in the present study there were many more staff members assisting in the evacuation were present in communal areas

This work provides new data for horizontal walking speeds. The results range from 0.3m/s to 0.73m/s when using walking aids and from 0.37 to 1.55 when not using walking aids for uncongested situations. Finally, the comparison of the proposed fundamental diagrams and the ones from the SFPE Handbook highlights that most experimental data points fall below the SFPE design curve as expected.

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