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Investigating office buildings evacuations using unannounced fire drills: the case study of CERN, Switzerland

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Abstract

The main objective of this paper is to explore evacuees' behaviour during an unannounced fire drill using data collected in two office buildings located at CERN, in Switzerland. Overall, a total of 142 pre-evacuation time measurements, 121 evacuee walking speed measurements in staircase configurations, and 336 evacuee walking speed measurements on floor configurations are included in the dataset. These data were compared with the existing evacuation data for office buildings. This comparison revealed that the pre-evacuation times measured in the present study are significantly lower compared to existing data from the literature for the same type of occupancy. Walking speed data collected in corridors in the present study is within the range of the values reported in previous studies. Further, walking speeds on descending stairways measured in the present study were significantly higher than those available in the literature. However, the novel dataset presented in this study is in accordance with the values recommended in well-known guidelines (such as the SFPE Handbook) and could be used in the future to simulate evacuations of office buildings.

Keywords Pre-evacuation time; fire drill; evacuee walking speed; human behaviour; fundamental diagram; corridors; stairs; office buildings; evacuation.

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1. Introduction

Multiple types of hazards such as fires, earthquakes, and terrorist attacks, can threaten a building population's safety. As such, different building codes have been developed to ensure occupants' safety throughout the life of the building. Such codes can be classified as prescriptive-based codes, performance-based codes, and objective-based codes [1,2]. These codes define the minimum requirements to ensure the safety of all building occupants in case of an emergency.

Prescriptive-based codes consist of a set of rules that, if followed, produce a design deemed to be safe even if its level of safety is not always quantified clearly [3-5]. Conversely, performance-based and objective-based codes are based upon the use of analytical or numerical models that require the designer to quantify the level of safety provided by the building [2,6]. Performance-based design involves the comparison of ASET, the available safe egress time, and RSET, the required safe egress time. RSET is therefore one of the key criteria of safety assessment of a building and can be estimated using computer evacuation models. Evacuation models can simulate the evacuation process using different approaches including agent-based ones as well as coarse network alternatives, among others [7,8]. However, existing evacuation models require users to supply inputs to account for occupant behaviour such as pre-evacuation time, exit choice and evacuation movement speed [9]. These inputs are generally based on the available data or engineering judgement if data is not available [10-13].

While data from actual fire evacuations is the most applicable and more likely to accurately represent occupant evacuation behaviour, it is not as readily available as other data types [14]. For example, data from fire drills are often used as an alternative to data from real events [15-18]. A key assumption is that drill data can be used to approximate the response of evacuees in an actual fire emergency, especially when these drills are unannounced. For that reason, a number of studies have collected evacuation drill data from a number of different building types with different population demographics. However, they are not exhaustive. There are some building types or scenarios for which data are lacking. For instance, pre-evacuation data from some building types (e.g., airports and transportation terminals) are not available, or, if available, sample sizes are relatively small. In addition, data collected from office building evacuations in countries other than the US, UK or Canada are rare [10]. As such, generating new evacuation data is still an ongoing need for use in performance-based design to identify if there are any differences in pre-evacuation and evacuation movement [18,19].

The goal of this work is to better understand how people behave during office evacuations, and more specifically to understand if pre-evacuation and evacuation movement data collected from office buildings in Switzerland are similar to data collected from other countries. Similarities and differences among datasets will be identified, as well as possible reasons for differences, where possible. This is achieved by collecting new evacuation data through an unannounced drill carried out in two office buildings. This was done by recording the drill using video cameras and analysing the video data to estimate pre-evacuation times, walking speeds, specific flow and local density. From there, SFPE relationships (i.e. fundamental diagrams) were plotted alongside the collected experimental data in order to judge whether the SFPE relationships could be used as design curves for office occupancy. Finally, this work aims at performing a comparison between the new empirical data and the data presented in the literature showing the need for new evacuation investigations in the future.

2. Background

This section provides a review of the existing studies investigating office building evacuations, where possible, dividing them into studies focusing on the pre-evacuation (Section 2.1) and the evacuation movement (Section 2.2) phases. The pre-evacuation phase starts when occupants are notified (e.g. recognise the alarm signal), and it ends when they begin purposive movement towards a place of safety (e.g. out of the building or an adjacent safe compartment), and the evacuation movement ends once the occupants have reached a place of safety [5].

2.1 Pre-evacuation studies

Several previous studies, such as [10, 20 and 21], have presented databases of pre-evacuation times. These studies highlighted that pre-evacuation times could largely be dependent on the type of occupancy, e.g., office buildings, apartments, restaurants, mercantile buildings, etc. Table 1 summarizes pre-evacuation times collected from 13 case studies related to office buildings. Those evacuations took place in buildings ranging from 4 to 110 floors located mostly in the US and Canada.

Table 1 *pre-evacuation data for business occupancy (P-UD= Partial Unannounced Drill, UD=Unannounced Drill, AD=Announced Drill, FI=Fire Incident, PV=Pre-recorded Voice notifications, T3=T3 fire alarm systems, AL=sirens, bells and horns, No AL=No Alarm)* [10]

Reference	Country	Nature	Alarm	Floors	Number of occupants	Pre-evacuation time Mean ± SD (min)	Cluster
1	US	P-UD	PV	11	72	2.355 ± 1.060	1
2	US	UD	T3	4	348	1.693 ± 0.841	
3	US	P-UD	PV	12	132	1.233 ± 0.562	
4	Canada	UD	AL	13	458	1.398 ± 1.436	
5	Canada	UD	AL	6	92	0.573 ± 0.385	
6	Canada	UD	AL	7	161	1.196 ± 0.827	
7	Finland	AD	AL	7	33	2.722 ± 1.151	
8	Finland	AD	AL	4	9	2.017 ± 0.850	
9	UK	UD	AL	6	19	0.467 ± 0.183	
10	Denmark	UD	PV	12	70	0.961 ± 0.600	
11	Australia	FI	No AL	14	106	5.415 ± 1.547	
12	US	FI	No AL	110	85	11.300 ± 58.489	2
13	US	FI	No AL	110	46	28.400 ± 43.490	

From Table 1, it can be noticed that the first 10 studies have similar mean pre-evacuation times. All mean pre-evacuation time values of these studies are below 3 minutes. On the other hand, the mean pre-evacuation times estimated in the remaining studies are greater than 3 minutes. One of the reasons that could explain these observed differences is the fact that the data analysed in the first 10 studies come from drills, while data analysed in the remaining studies come from actual events. Another reason could be that data values of the latter two studies (i.e. 12 and 13) come from the WTC towers.

Lovreglio et al. [10] identified two clusters of existing pre-evacuation data for office buildings. They carried out a clustering analysis to investigate whether it was possible to subdivide the case studies into clusters and thus identify candidate factors that may segregate the datasets. They employed the mean and standard deviation (SD) of the pre-evacuation times as input values for the clustering analysis. Therefore, the resulting clusters included case studies sharing similar mean and SD of pre-evacuation time. Readers can refer to [10] for more detail about the clustering method employed.

In addition, Lovreglio et al. [10] have considered four possible pre-evacuation distributions defined by two parameters (i.e. a and b in Table 2): gamma (Equation (1)), lognormal (Equation (2)), loglogistic (Equation (3)) and Weibull (Equation (4)), to approximate the selected pre-evacuation data for either identified cluster. These distributions were selected as they are defined only for positive values of the random variable (i.e. x), but also because these distributions have a skewed shape which is typical for pre-evacuation data [10]. Another reason is that they are implemented in many well-known computational evacuation models [10] and can be used by practitioners in performance-based design. The fitting of the above-outlined distributions with pre-evacuation data is assessed using the R^2 parameter. The a and b parameters and the R^2 values of these distributions are reported in Table 2. It is worth noting that the R^2 parameters given in Table 2 must not be used as a criterion to select between clusters but need to be only used to select a distribution within the same cluster.

Gamma: $F(x|a,b) = \frac{1}{b^a\Gamma(a)}\int_0^x t^{a-1}e^{\frac{-t}{b}}dt$ (Equation 1)

Lognormal: $F(x|a,b) = \frac{1}{b\sqrt{2\pi}}\int_0^x \frac{\exp\left(\frac{-(\ln(t)-a)^2}{2b^2}\right)}{t}dt$ (Equation 2)

Loglogistic: $F(x|a,b) = \frac{1}{1+\left(\frac{x}{a}\right)^{-b}}$ (Equation 3)

Weibull: $F(x|a,b) = \int_0^x ba^{-b}t^{b-1}\exp\left(-\left(\frac{t}{a}\right)^b\right)dt$ (Equation 4)

Table 2 *estimated parameters of pre-evacuation distributions for the business clusters* [10]

Cluster	Distribution	Parameters in seconds		Data points	R^2
		a	b		
1	Gamma	1.291	103.901	2597	0.564
	Lognormal	381.651	0.967		0.548
	Loglogistic	4.592	0.587		0.548
	Weibull	139.285	1.195		0.566
2	Gamma	0.557	1419.096	10	0.942
	Lognormal	36.131	1.613		0.949
	Loglogistic	5.905	0.958		0.950
	Weibull	672.010	0.664		0.944

2.2 Movement Studies

In an engineering context, crowd movement is usually quantitatively specified using three key characteristics. These are density, speed and flow. Population density is generally expressed as the number of persons in a unit area of measured space [22]. Speed is the distance covered by a moving person in a unit of time [22]. Flow is the number of people who pass a reference point in a unit of time [22].

Past observations and experiments have shown that the speed of a group or an individual in a group is a function of the population density. Similarly, the flow of evacuating persons passing a certain point in the exit route is a function of the local population density. These relationships are described in fundamental diagrams and have been empirically as well as theoretically evaluated in previous studies. These diagrams are used in designing facilities and in evaluating bottleneck capacities as well as their overall capacity. The shape of the fundamental diagrams and capacity, which is characterized by the maximum flow, are largely dependent on various factors, such as the geometry of the facility, type of the facility and user characteristics [23]. Comprehensive reviews on pedestrian flow characteristics are presented in several previous studies, such as [24] and [25].

Several other studies also presented reviews on fundamental diagrams on staircases [26,27]. Staircases are critical components of buildings, particularly in evacuation situations, and therefore, fundamental diagrams of staircases are included in well-known planning handbooks, such as [28,29], and the SFPE Handbook of Fire Protection Engineering [22,30]. Gwynne and Rosenbaum [31] derived relationships between speed and density, and between flow and density, while Zhang [23] compared different fundamental diagrams with different geometries. However, none of them focused, particularly on office buildings data.

Walking speed is also a key factor when calculating evacuation time. This parameter could be influenced by many factors, such as characteristics of occupants (e.g., age and sex), and type of building. For example, young people walk faster compared to the elderly, and males walk faster compared to females (see **Table 3**). Thus, it is important to consider such aspects when designing and planning buildings (including office buildings). Moreover, people may walk faster in horizontal configuration compared to staircase configuration. Therefore, several other studies focused on descending walking speed (see **Table 4**).

It can be noted that different building and occupant types have been considered in these previous studies. However, no comprehensive studies have been carried out for office buildings. In addition, the cultural difference also affects the occupants’ behaviour and decision-making during emergencies [55]. Therefore, the data collected at a specific facility at a certain geographic location or country might not represent the behaviours of occupants at another location. This means that additional data are required to enrich the databases on occupants’ behaviours during fires.

3. Material and Methods

Data on occupant pre-evacuation time and movement on staircases and in corridors were collected during unannounced evacuation drills at two office buildings of CERN, in Switzerland. The buildings involved in this study ranged from four to five storeys in height. The following sub-sections discuss the details of drill settings, the geometry of the buildings, and data collection and extraction.

3.1 Drill settings

The drill was carried out during normal business hours (circa 10.30 am). It was a rainy day in June, and the observed population was *unaware* that the drill was to take place. Occupants in each building were located on various floors, and the elevators were not available during the drill.

3.2 Buildings Geometry

In this study, video data were collected in two buildings (named building 1 and building 2 for the purpose of this study) located at Meyrin, Switzerland. Geometries of these buildings are briefly described in the following sub-sections.

Table 3 *occupants' horizontal walking speeds summarized in previous studies*

		Walking speed Mean ± SD (m/s) or range	Reference
Occupants' characteristics	Male	1.51	[32]
		1.41 ± 0.04	[33]
		1.41 ± 0.29	[34]
		1.30	[35]
	Female	1.41	[32]
		1.35 ± 0.03	[33]
		1.28	[34]
		1.24	[35]
	Young	1.46 ± 0.03	[32]
		1.36 ± 0.07	[34]
	Elderly	1.20 ± 0.04	[32]
		1.15 ± 0.16	[34]
	Male elderly	1.05	[35]
	Female elderly	1.04	[35]
	Children	1.08	[35]
		1.46±0.58	[36]
		1.09	[37]
		1.2 – 1.9	[38]
Building type	Indoor commercial	0.98 (free flow)	[39]
	Indoor shopping	0.80 (free flow)	[39]
		0.92	[40]
	Train station (concourse and platform)	1.30	[39]
	High-rise apartment	0.56-1.2	[41]
	A vocational high school	0.49 – 0.73	[38]
	A factory	1.1 – 1.6	[38]

Table 4 *Occupants' descending stair walking speeds summarized in previous studies*

Reference	Number of storeys	Slope (°)	Speed Range or $Mean \pm SD$ (m/s)	Density Range or $Mean \pm SD$ (p/m²)
[42]	25	-	0.62 ± 0.15	-
	25	-	0.74 ± 0.12	-
	25	-	0.62 ± 0.15	-
[43]	24	32.5	0.72 ± 0.25	1.67 ± 0.55
	10	32.5	0.59 ± 0.23	1.83 ± 0.23
	62	38.2	0.61 ± 0.12	1.01 ± 0.48
	18	36.9	0.48 ± 0.20	1.89 ± 0.69
	30	33.1	0.44 ± 0.15	1.72 ± 0.61
[44]	-	-	0.78 ± 0.17	-
	-	-	0.93 ± 0.27	-
[45]	13	-	0.66 ± 0.25	1.56
	13	-	0.40 ± 0.17	1.60
	13	-	0.57 ± 0.21	1.58
	13	-	0.66 ± 0.31	1.60
[46]	13	-	0.70 ± 0.16	1.25
	13	-	0.61 ± 0.10	1.30
	13	-	0.57 ± 0.12	2.05
	13	-	0.72 ± 0.09	1.00
[47]	53	-	16 s/floor	$Dmax = 3$
[48]	7	27	Median = 0.64 95% fractile = 1.04	-
[49]	-	24.6 – 38.8	0.56 ± 0.23 – 1.49 ± 0.43	-
[35]	-	-	0.38 ± 0.09	$0.0 - 0.72$
[50]	-	26.4	$0.38 - 0.68$	$0.7 - 2.3$
[51]	9	28.6	$0.6 - 1.3$	$0.2 - 1.45$
[52]	50	32.5	0.74 – Female 0.83 - Male	Individual speed
[53]	-	-	0.82 – 0.91 1.0	2.2 – 2.5 One-by-one
[54]	-	27.3	0.5 – 0.9	0 – 1.8

3.2.1 Building 1

Building 1 is a five-storey office building (i.e., from R-1 to R+3), equipped mainly with auditoriums, laboratories, as well as office spaces. The floor-to-floor height in this building is 3.15 meters. The floor layouts are shown in appendix A. The basement (R-1) contains two emergency exits, i.e., Exit A in Fig. A.1 and Exit B (which is a staircase) in Fig. A.1. The ground floor (R0) contains two emergency exits, i.e., Exit C in Fig. A.2 and Exit D in Fig. A.2.

The upper floors (R+1 to R+3) contain two egress means, i.e., stairs 1-205 in Fig. A.3 and stairs 1-204 in Fig. A.3. A commonality between the upper floors (R+1 to R+3) is that they have a similar layout.

One of the primary data collected for this study was the timing of the evacuee movement traversing the straight staircase number 204 during evacuation. The geometry of this staircase is shown in Fig. 1 including the distance travelled on the staircase flights and landing, the staircase width and the landing size. These measurements were carried out to calculate walking speed, density and flow between two floors. The staircase 204 tread and riser measure 30 cm and 19.7 cm, respectively. The slope of each flight of stairs in this staircase is 33.3°.

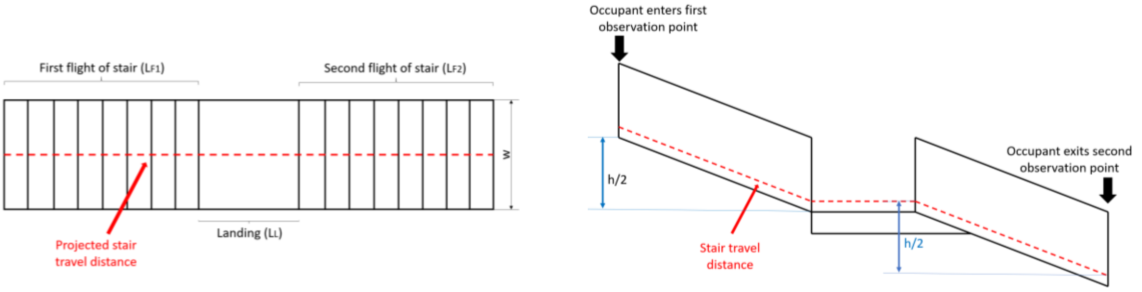


Fig. 1 *overview of straight flights of staircase 204 between two floors, its landing, staircase travel distance and width*

Travel distance within staircase 204 is calculated as follows:

$$L_{S204} = \sqrt{\left(\frac{h}{2}\right)^2 + {L_{F1}}^2} + L_L + \sqrt{\left(\frac{h}{2}\right)^2 + {L_{F2}}^2} \qquad \text{(Eq. 4)}$$

where

L_{S204} is the travel distance between two floors in staircase 204 (= 6.74 m);
h is the height between two floors (= 3.15 m) ;
L_{F1} is the projected travelled distance within the first flight of staircase 204 (= 2.40 m) ;
L_L is the travelled distance within the landing (= 1.00 m) ;
and L_{F2} is the projected travelled distance within the second flight of staircase 204 (= 2.40 m).

3.2.2 Building 2

Building 2 is adjacent to building 1. It is a four-storey office building (i.e., from R-1 to R+2). The floor-to-floor height in this building is also 3.15 meters. The building is equipped with meeting rooms and office spaces, among other rooms. Further details are provided in appendix A. Overall, the basement (R-1) contains two emergency exits leading to the outdoors labelled as Exit 1 and Exit 2, plus an emergency staircase (i.e., staircase S-209) leading to the ground floor. The ground floor (R0) contains one emergency exit leading to the outdoors labelled as Exit 3 and four emergency stairs (i.e., those close to R-030, R-403, R-027, and R-003 on the floor plans). The first floor (R+1) contains multiple emergency stairs; however, only three of them are observed in this study. Those are labelled as 1-201 and staircases close to 1-101 and 1-022. Finally, the second floor (R+2) also contains multiple emergency stairs; however, only three of them are observed in this study (i.e., 2-201, and staircases close to 2-101 and 2-021).

Similar to building 1, the timing of the evacuee movement traversing the stair was obtained. In this case, stair 210 is a dog-legged staircase. Fig. 2 illustrates the configuration of staircase 210 between two floors. The staircase tread and riser measure 32 cm and 19.7 cm, respectively. The slope of each flight of stairs in this staircase is 31.6°.

Fig. 2 *overview of dog-legged flights of staircase 210, its landings, staircase travel distance and width*

Travel distance between two floors within staircase 210 is calculated as follows:

$$L_{S210} = \sqrt{\left(\frac{7h}{16}\right)^2 + {L_{F1}}^2} + L_{L1} + \sqrt{\left(\frac{3h}{16}\right)^2 + {L_{F2}}^2} + L_{L2} + \sqrt{\left(\frac{6h}{16}\right)^2 + {L_{F3}}^2} \qquad \text{(Eq. 5)}$$

where

L_{S210} is the travel distance between two floors within stairs 210 (= 10.09 m) ;

16 is the total number of steps in staircase 210 (7 for the first flight, 3 for the second, and 6 for the third);

h is the height between two floors (=3.15 m) ;

L_{F1} is the projected travelled distance within the first flight of stairs 210 (= 2.24 m) ;

L_{L1} is the travelled distance within the first landing (= 2.03 m);

L_{F2} is the projected travelled distance within the second flight of stairs 210 (= 0.96 m) ;

L_{L2} is the travelled distance within the second landing (= 2.05 m) ;

and L_{F3} is the projected travelled distance within the third flight of stairs 210 (= 1.92 m).

In this study, we assumed that evacuees walk in the centre of staircases. Uncertainties could be estimated by assuming other possible travel paths along the inside or the outside of the stair like it was done in [56]. This is out of the scope of this study but could be a future development.

3.3 Video recording

In this study, video data were collected by positioning video cameras at strategic locations, i.e., on corridors and on staircases. These camera placements captured the time occupants were seen leaving a specific room, the times they were seen moving past a stair landing as well as the time they were seen moving into corridors and staircases.

Fig. 3 demonstrates an example of a camera view at building 1. In this particular camera view, the time that an occupant entered the corridor (at the doorway as shown by the highlighted red line and the time that an occupant exited the corridor (highlighted green line in Fig. 3) were recorded for each occupant that travelled between the entry and exit observation points shown in Fig. 3.


[redacted]

Fig. 3 *typical corridor showing camera view with entry and exit observation points for occupant movement timing in-plane configuration for building 1*

Fig. 4 shows an example of two camera views that were used to estimate evacuees' walking speeds on stairs. In the first camera view (Fig. 4-a), the time that an occupant entered the staircase was recorded, while, in the second camera view (Fig. 4-b), the time that an occupant exited the staircase was recorded.

a- entry (R+1) b- exit (R0)

Fig. 4 *typical staircase showing camera view with entry (a) location for occupant movement timing in the stair, and exit (b) location in the staircase for building 2*

The locations of all cameras throughout each building floor are reported in appendix A. It can be noticed that all the areas and routes out of the buildings are not covered by the cameras. This is one of the limitations of this research study. However, both buildings were inspected and a meeting with the facility manager was organised prior to the date of the drill in order to identify areas with high occupancy loads. All these areas were covered by cameras.

3.4 Video Analysis

From video recordings, timestamps were recorded for each occupant at each time during the evacuation drill that the occupant was seen at a specific floor location (e.g., corridors) or in the stairs (depending on the locations of the cameras). This was typically when occupants left a specific room, when they entered and left a specific corridor, and when they entered and left a staircase. To allow for comparison and calculation, the collected times were converted to times relative to the building fire alarm defining the beginning of the drill. The converted times were used in all subsequent analyses.

Pre-evacuation time was estimated for each occupant as the time from the initial alarm until the occupant was seen starting to travel towards a place of safety (typically an exit or an emergency stair). Readers must be aware of the limitation of this approach as cameras were not located throughout the observed buildings (such as within offices). In other words, estimated pre-evacuation times likely include part of the evacuation movement time in cases where evacuees started the evacuation movement phase from their offices, or an area not covered by the cameras. In line with previous studies such as [5], [57] and [58], corridors and stairs movement speeds were determined from the total time that the occupant took to pass by two pre-defined observation points and the distance travelled during that time span. Typically, in corridors, the first observation point was a line drawn at a specific position within the corridor; while, in staircases, this was a line drawn at the first step of the staircase (see Figs. 3 and 4). The second observation point was a line drawn at a specific position within a corridor, while it was a line drawn at the last step of the staircase. Data regarding the travelled distances and widths of corridors and staircases were taken from CAD files of the monitored buildings. Another method that can be used to estimate the speed with accuracy is the one used in [54]. However, this is out of the scope of the present study and could be a future development.

In line with past studies such as [5] and [58], density in the stairs and corridors was estimated (in persons/m^2) to investigate the impact on walking speeds. As each occupant entered the first observation point in a specific corridor or stair, there may have been a number of occupants in front of the occupant potentially impacting his/her speed of movement. Thus, the calculation of density was 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 $t_{enter,I} \leq t_{exit,J}$ (here we assume that occupants who leave the second observation point before an occupant arrives are only indirectly impacting the occupant entering the first observation point by slowing the other occupants still on the area comprised between the first and second observation points).

Additionally, there were other data collected for each occupant (overall) during the evacuation drill. These included the following information:

- Gender: Occupants were classified as being female or male.
- Floor of origin. For building 1, it was possible to report the floor of origin for only a proportion (i.e. approximately 79%) of the total observed population after the alarm sounded; i.e., 105 occupants. This was due to the locations of the cameras (e.g., some areas where 28 occupants were located at the time of the alarm, were not observed by

the cameras); whereas, for building 2, it was possible to report the floor of origin of all building occupants (i.e. the 70 individuals).

- Whether they were carrying anything (YES or NO). It was assumed that a person identified as carrying an object did so throughout the evacuation. There was no distinction made for the size of object or how it was being carried. Objects included small objects held in one hand (such as a laptop or a cell phone), bags on either a shoulder or held in one hand, a vest or jacket carried in one hand, etc.
- Whether they were in a group at any time during the drill (YES or NO). In this study, a group is defined as a collection of more than two evacuees located in a specific area of the building who are walking in close proximity.
- Whether they were helping someone at any time during the drill (YES or NO).
- Whether they were travelling in the opposite direction of the evacuating occupants, here termed counterflow.

4. Results

In total, 203 people (133 from building 1 and 70 from building 2) were observed during the drill. Of the 203 people, 171 were males (116 from building 1 and 55 from building 2) and 32 were females (17 from building 1 and 15 from building 2).

The types of behaviours observed during the drill are reported in Section 4.1 while the pre-evacuation times are reported in Section 4.2. Finally, walking speeds and experimental data alongside SFPE fundamental diagrams are reported in Sections 4.3 and 4.4, respectively.

4.1 Behavioural observations

45.9% (i.e., 61 individuals) of the observed occupants in building 1 were observed carrying an object during evacuation. Objects included vests, bags, cell phones and laptops. In building 2, 68.6% (i.e. 48 individuals) of occupants were carrying similar types of objects. In addition, a few individuals travelled in the opposite direction of the flow during evacuation (i.e., counterflow); 9% (i.e., 12 individuals) in building 1 and 4.3% (i.e., 3 individuals) in building 2. Group behaviour was also observed in both buildings: 33.1% (i.e. 44 individuals) of occupants in building 1 and 71.4% (i.e. 50 individuals) of occupants in building 2 were observed to walk in groups. In addition, a few people were designated as emergency guides: 3.8% (i.e. 5 individuals) in building 1 and 7.1% (i.e. 5 individuals) in building 2. These individuals were distinguishable from others because they were wearing a yellow or orange vest. They encouraged others to leave the building and directed them to exits allowing for a rapid evacuation of either building.

4.2 Pre-evacuation time

Fig. 5 shows the boxplots of pre-evacuation times for buildings 1 and 2. For building 1, the mean pre-evacuation time of the observed occupants is 29.3 s ± 22.9 s, while, for building 2, the mean pre-evacuation time for the observed occupants is 34.8 s ± 20.3 s. The Mann-Whitney U-test confirmed that the difference between pre-evacuation times observed in either building is statistically significant (p-value = 0.011 < 0.05). Moreover, a few outliers can be observed in Fig. 5, and these can be attributed to emergency guides who spent additional time sweeping the floors to ensure that no one was left behind.

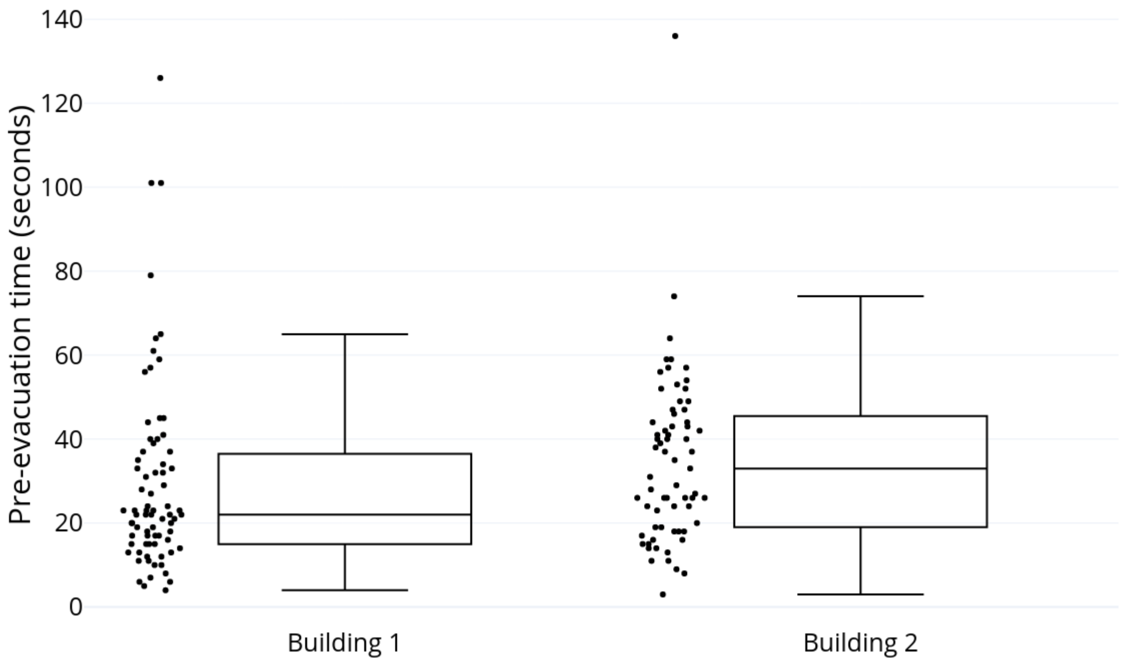


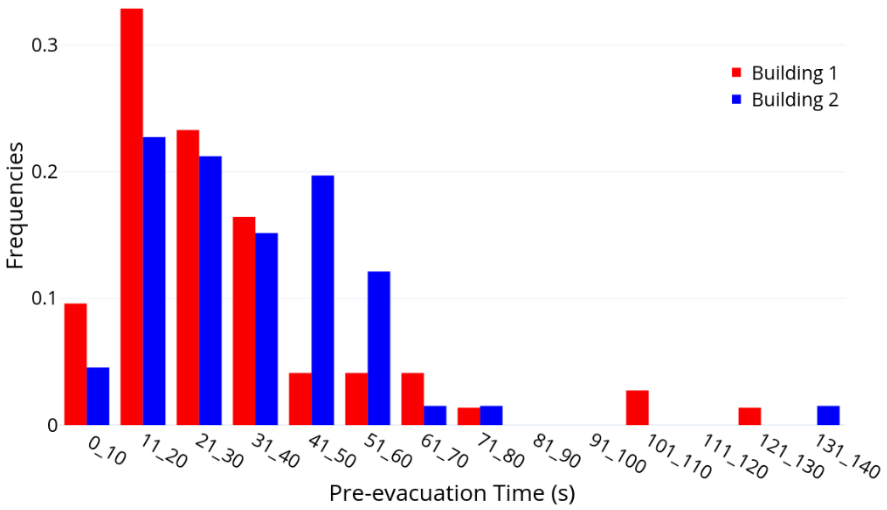
Fig. 5 *Pre-evacuation times (in seconds) recorded during an unannounced fire drill evacuation at CERN in buildings 1 (left: N=75) and 2 (right: N=67)*

Fig. 6a represents the distributions of the observed pre-evacuation data from buildings 1 and 2. We assume that data falling between the 25th and 75th percentiles are the most probable. Therefore, the most probable pre-evacuation times in building 1 occur between 15s and 37s, whereas in building 2, the most probable pre-evacuation times occur between 19s and 46s. Moreover, the cumulative distribution plots show that about 95% of the data will most likely occur before 65s for building 1 while about 97% of the data will most likely occur before 64s for building 2. Using the data, we estimated the well-known pre-evacuation distributions available in evacuation models [10]: Gamma, Lognormal, Loglogistic and Weibull. The results are provided in Fig. 6b and Table 5. These distributions can be used by practitioners conducting performance-based designs for office buildings. However, they must be aware of the context of data and verify whether they can be applied to their specific purpose.

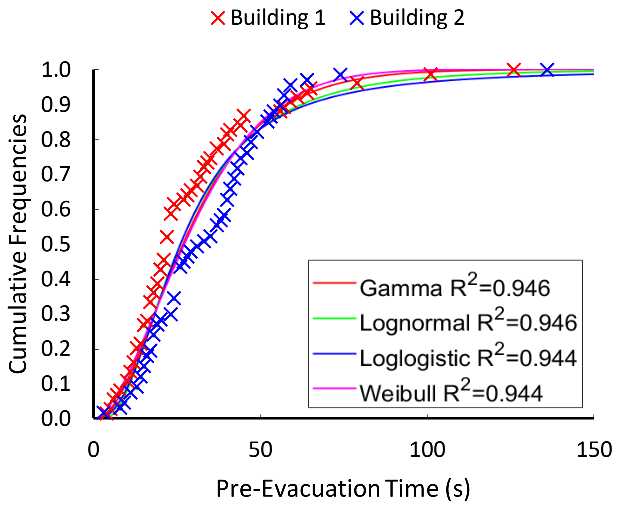
According to Fig. 6-b and Table 5 results, it can be observed that Gamma and Lognormal distributions provide the best fit for both buildings' pre-evacuation times.

Table 5 estimated parameters of the pre-evacuation times distributions

Distribution	Parameters in seconds		Data points	R^2
	A	b		
Gamma	-2.338	13.229	142	0.946
Lognormal	3.253	-0.687		0.946
Loglogistic	3.254	-0.414		0.944
Weibull	33.864	1.637		0.944



a- Frequencies



b- cumulative frequencies and estimated distributions

Fig. 6 Distributions of the observed pre-evacuation times during an unannounced fire drill evacuation at CERN in buildings 1 and 2

4.3 Walking speeds

Before we describe the estimated data, it is worth noting that all estimated local density values fall below 1 person/m². Thus, the described speeds can be considered as unimpeded speeds.

Fig. 7 reports the boxplots of corridors walking speeds in buildings 1 and 2. For building 1, the mean speed of occupants was estimated as 1.17 m/s ± 0.32 m/s (N = 249), while, for building 2, the mean speed was estimated as 1.28 m/s ± 0.31 m/s (N = 87). It seems that the estimated walking speeds are different between the two buildings. The Mann-Whitney U-test confirmed that the difference between walking speeds observed in either building is statistically significant ($p\text{-value} < 0.001$). From the above-mentioned results, it can be noticed that, on average, occupants of building 1 moved slightly slower in comparison to occupants of building 2. In addition, in both buildings, a few outliers existed, which represent evacuees who were observed running in the corridors.

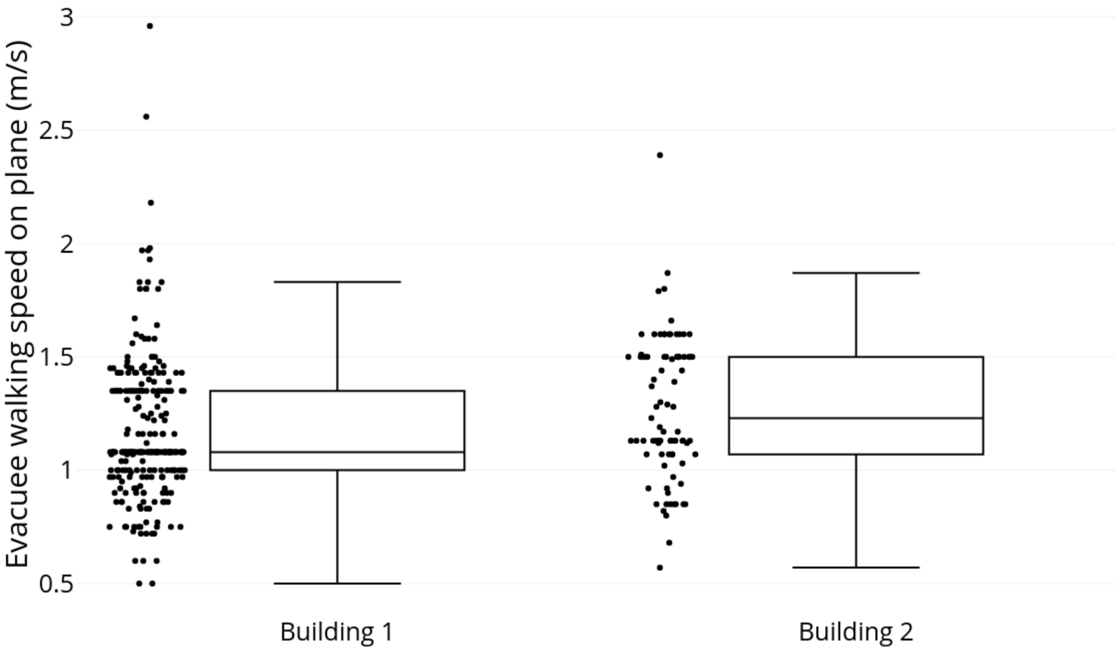
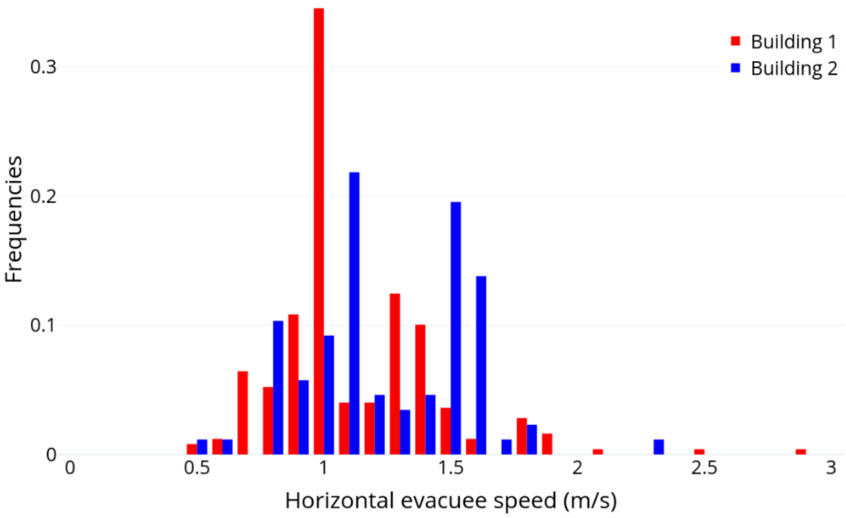


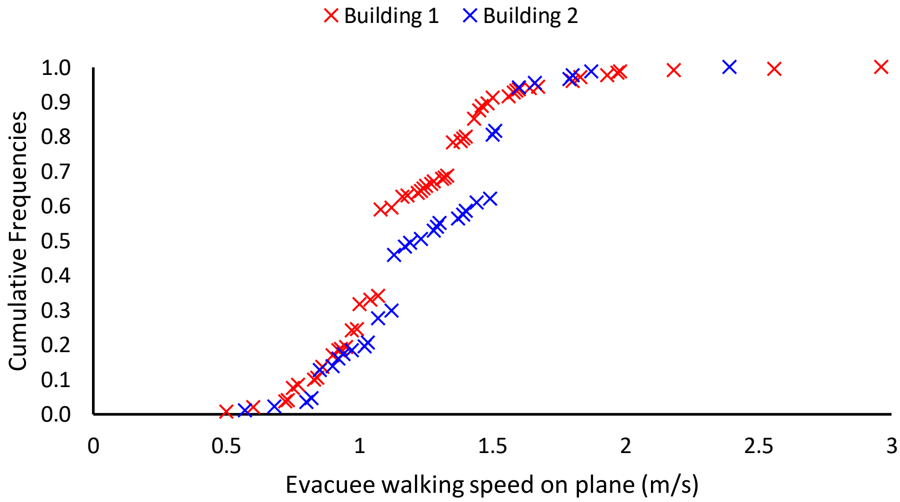
Fig. 7 *Boxplots of corridors travel speeds in buildings 1 (left: N=249) and 2 (right: N=87)*

The frequencies and cumulative frequencies of walking speeds in Fig. 8 represent a compilation of each observed evacuee's speed in corridors for buildings 1 and 2. For building 1, there was about 35% of occupants travelled in corridors with speeds between 1.0 m/s and 1.1 m/s; while, for building 2, there was approximately 22% of occupants who travelled in corridors with speeds between 1.1 m/s and 1.2 m/s. It can also be observed that in both buildings, the distributions seem to be bimodal. Even if this suggests that there are two clusters in data (i.e. representing "slow" and "fast" walkers), the recordings do not provide any evidence regarding this. Further investigations (or drills) are needed to confirm this observation. The cumulative distribution plots show that, for building 1, a walking speed of 1.98 m/s or less captures approximately 99% of the occupants; whereas, for building 2, a speed of 1.87 m/s or less captures approximately 99% of the occupants.

Fig. 9 displays the boxplots of walking speeds on stairs for buildings 1 and 2. For building 1, the mean speed on stairs was estimated as 0.88 m/s ± 0.19 m/s (N = 113), while, for building 2, the mean speed was estimated as 0.88 m/s ± 0.12 m/s (N = 17). It seems that the estimated walking speeds are not different between the two buildings. The Man-Whitney U-test confirmed that there is no statistically significant difference in walking speeds on stairs observed between buildings 1 and 2 (p-value = 0.946). Higher variability of speeds is observed for occupants of building 1 compared with the variability of speeds observed for occupants of building 2 (Levene's test for equality of variances results: F = 11.403 and p-value = 0.001). The observed configurations of the stairs in both buildings are different as, for building 1, the monitored staircase is a straight staircase with two flights of stairs and an intermediate landing, whereas, for building 2, the monitored staircase is a dog-legged staircase with three flights of stairs and two intermediate landings. Such factors might have led to the observed differences in variability of speeds. Another factor could be the fluctuation of density in stairs over time. Unfortunately, we had not the possibility to verify this assumption because of the location of the cameras. For example, if people started their travel on the second floor of building 1 or 2 and then used the observed stair to reach the ground floor, we only measured their speeds between the first and ground floors.



a – Frequencies



b – cumulative frequencies

Fig. 8 *Distributions of corridors movement speeds in buildings 1 and 2 during fire drill evacuation*

The frequencies and cumulative frequencies of movement speeds in Fig. 10 represent a compilation of each observed evacuee's speed across buildings' 1 and 2 staircases. For building 1, there was 24% of the occupants descending the stairs who walked with speeds between 1.2 m/s and 1.3 m/s; while, for building 2, there was 35% of the occupants descending the stairs walked with speeds between 0.8 m/s and 0.9 m/s. Moreover, for building 2, the results tended to accumulate around the highest frequency range from 0.7 m/s to 1.2 m/s; while, for building 1, the results are more dispersed. Finally, the cumulative distribution plot shows that, for building 1, a speed of 1.12 m/s or less captures approximately 98% of the occupants' walking speeds on stairs, whereas, for building 2, a speed of 1.01 m/s or less captures approximately 88% of the occupants.

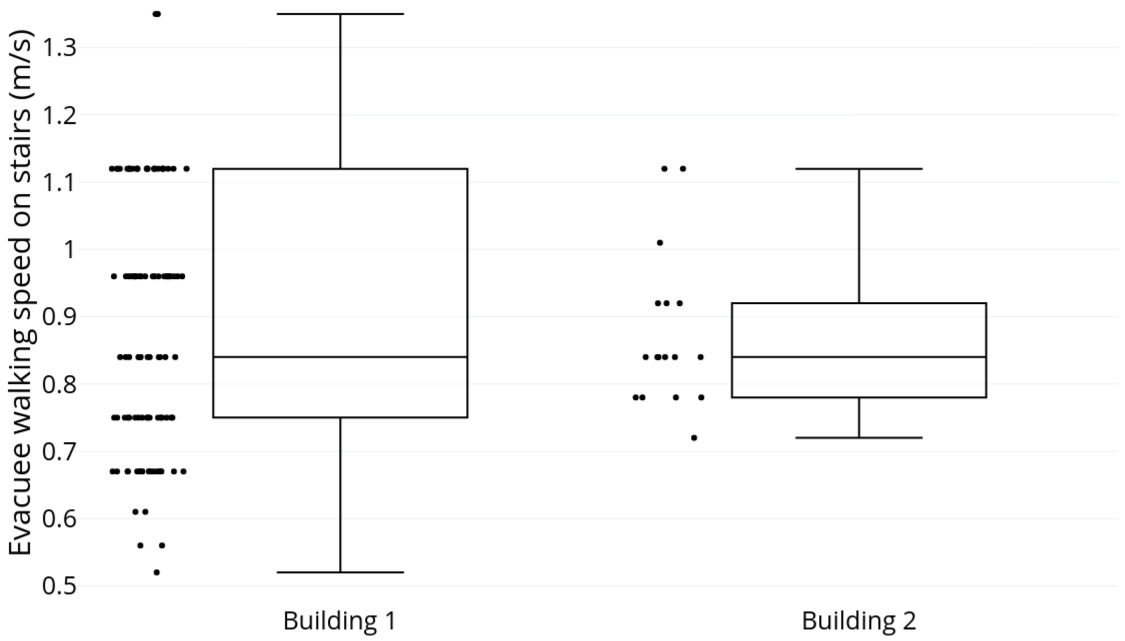


Fig. 9 *Boxplots of stairs walking speeds in buildings 1 (left: N=113) and 2 (right: N =17) fire drill evacuation*

4.4 Fundamental Diagrams

4.3.1 Horizontal Fundamental Diagrams

The SFPE hydraulic model relationship between speed and density assumes that: (1) if the population density is less than approximately 0.54 persons/m² on an exit route, individuals will move at their own pace, independently from the speed of others; and (2) if the population exceeds about 3.8 persons/m², no movement will take place until enough of the crowd has passed from the crowded area to reduce the population density. Between the population density limits of 0.54 and 3.8 persons/m², this relationship is assumed to be a linear function. The equation of this function is:

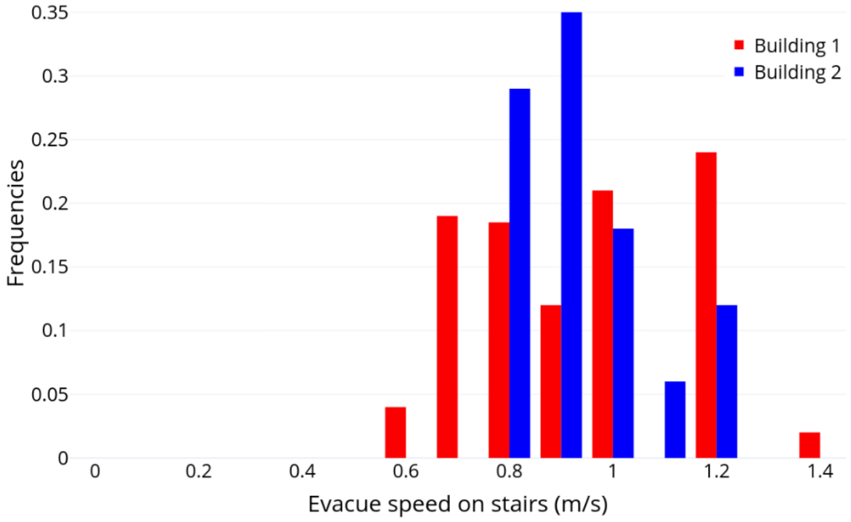
$$S = k - a \cdot k \cdot D \qquad \text{(Eq.1)}$$

where

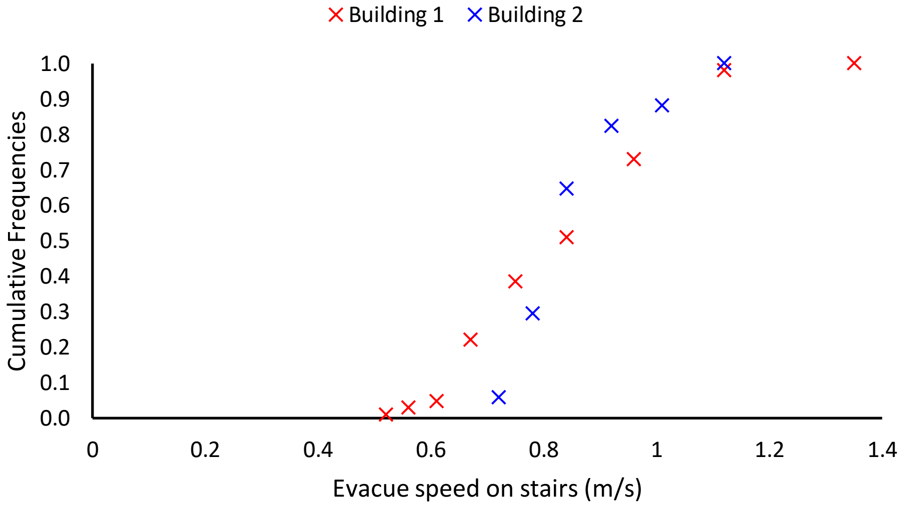
S is the walking speed along the line of travel,

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 speed is assumed to be constant if the population density is less than 0.54 persons/m². In corridors, this speed is approximately equal to 1.20 m/s.



a – Frequencies



b – cumulative frequencies

Fig. 10 *Distributions of stairs walking speeds in buildings 1 and 2 during fire drill evacuation*

The experimental data representing the relationship between the speed and population density in corridors for buildings 1 and 2 are plotted in Fig. 11 alongside the SFPE hydraulic model relationship [31].

High scattering of data is observed in both buildings as can be understood from Fig. 11. In both buildings, evacuee walking speed in corridors ranged approximately from 0.50 to 3.00 m/s. The density ranged approximately from 0 to 1.00 persons/m². It can be noted that only free-flow and uncongested conditions (Density < 1 p/m²) were observed in this study. If we assume that people will move at their own pace in corridors for densities equal to or less than 0.54 persons/m², the mean walking speed in corridors derived from the collected experimental data, for densities equal to or lower than this population density, is equal to 1.20 ± 0.32 m/s, which is equivalent to the design value suggested by the SFPE hydraulic model [31].

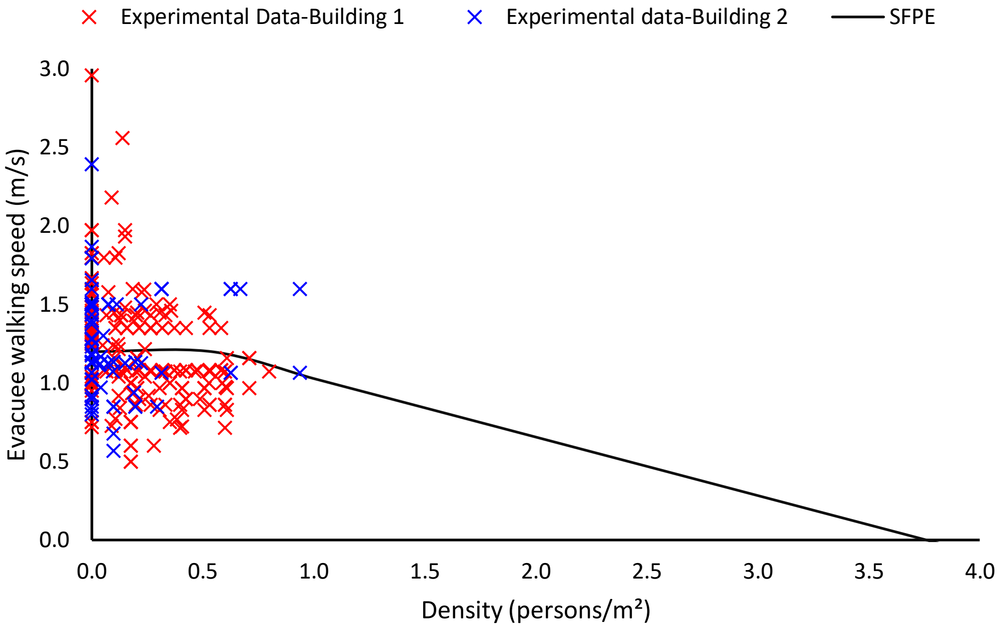


Fig. 11 *Speed versus density data in-plane configuration for buildings 1 and 2 as well as the original SFPE hydraulic model relationship*

Similarly, the specific flow is defined as follows:

$$F_s = S \cdot D = (1 - a \cdot D) \cdot k \cdot D \tag{Eq.2}$$

The specific flow-density empirical data observed in corridors are plotted in Fig. 12 alongside the original SFPE hydraulic model relationship [31].

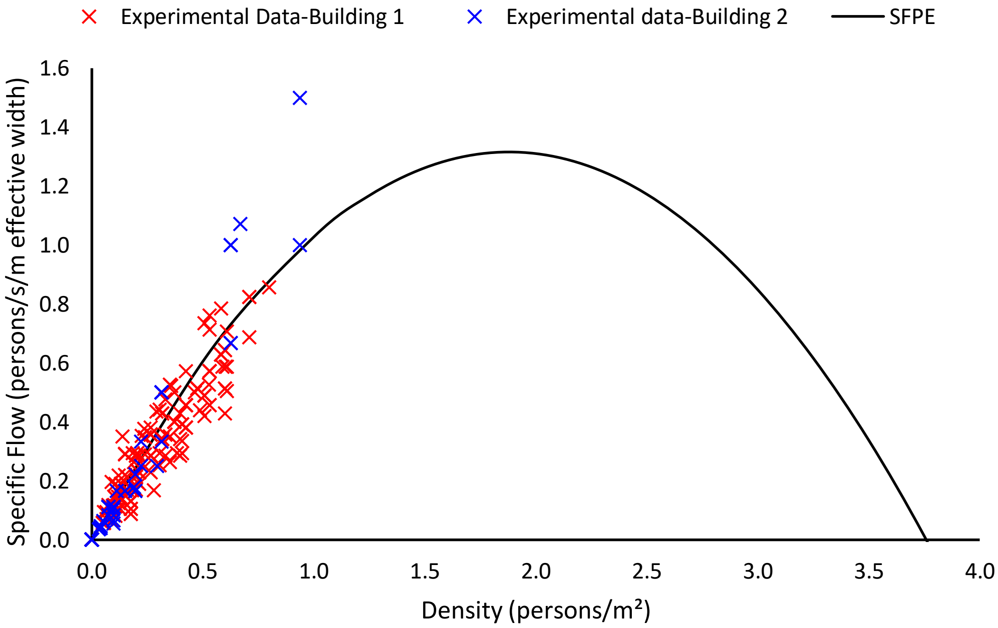


Fig. 12 *specific flow versus density data on plane configuration for buildings 1 and 2 as well as the original SFPE hydraulic model relationship*

For only the small density range (i.e. between 0 and 1 person/m²) within which data were collected, it can be understood from Fig. 12 that, the parabolic shape of these data is consistent with the SFPE hydraulic model relationship [31].

Overall, only free-flow and uncongested conditions are captured in corridors as can be understood from Figs. 11 and 12. Thus, further investigations with higher population densities are necessary to explore capacity and congested conditions in buildings 1 and 2.

4.3.2 Vertical Fundamental Diagrams

Speed-density and specific flow-density relationships are plotted in Figs. 13 and 14, respectively, for buildings 1 and 2 stairs. Since none of the SFPE riser and tread dimensions matches those of the stairs in the monitored buildings, all four SFPE relationships [31] are included here. They are drawn using Equations 1 and 2 by using varying values for the parameter *k* (see Table 6).

***Table 6** constant k value for Equations 1 and 2 for varying riser and thread dimensions of stairs* [31]

Stairs	Riser (mm)	Tread (mm)	k (persons/m²)
SFPE_1	190.50	254.00	1.00
SFPE_2	177.80	279.40	1.08
SFPE_3	165.10	304.80	1.16
SFPE_4	165.10	330.20	1.23

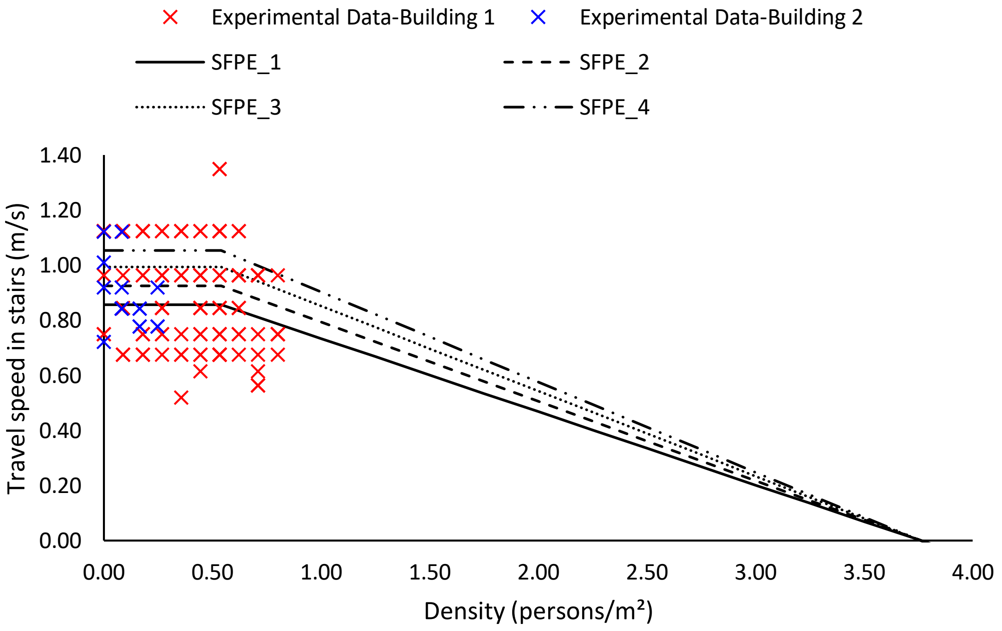


***Fig. 13** Speed versus density data on stairs for buildings 1 and 2 as well as the original SFPE hydraulic model relationships*

Again, it can be noted that only free-flow and uncongested situations (Density < 1 p/m²) in stairs are captured during the evacuation drills ran in buildings 1 and 2. Nevertheless, the empirical data are consistent with the models presented in the SFPE Handbook (i.e. [31]) for densities lower than 1 person/m². The mean walking speed for unimpeded movement on stairs is 0.90 ± 0.18 m/s, based on the data collected in this study.

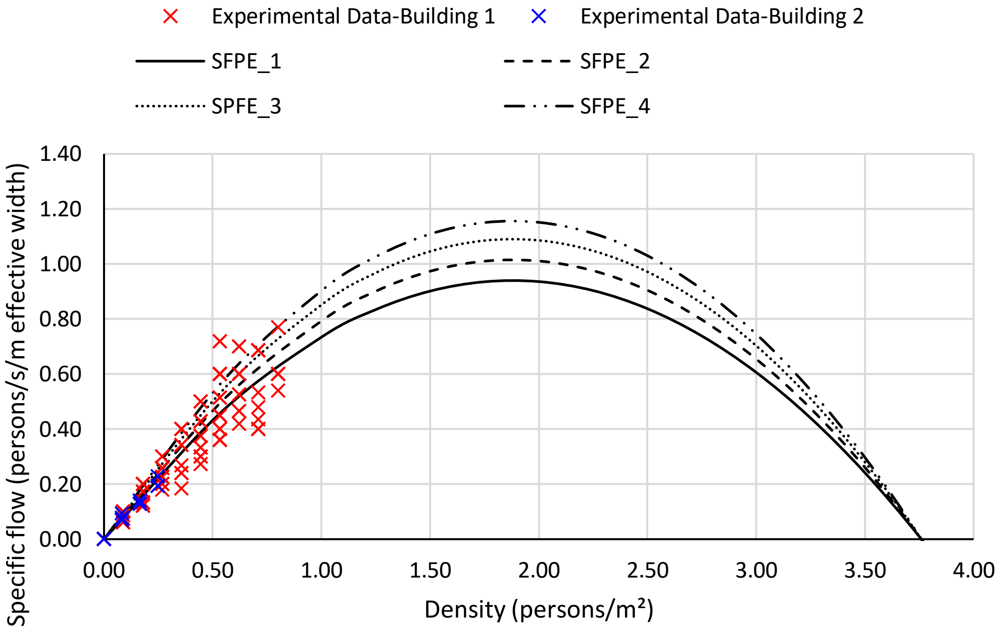


Fig. 14 *specific flow versus density data on stairs for buildings 1 and 2 as well as the original SFPE hydraulic model relationships*

6. Comparison with literature values

Both community disaster and building evacuation research provide evidence that people do not immediately react to verbal warnings or physical cues [58]. Instead, in order to assess and confirm the initial cues, people delay their attempts to take protective actions [58]. The same behaviours were observed in the monitored buildings. Therefore, we compare pre-evacuation data measured in the present study with published pre-evacuation data available in the literature for business or office occupancy. Fig.. 15 and 16 report the pre-evacuation times from this study and those extracted from previous studies. From these figures, it can be observed that, mostly, occupants of buildings 1 and 2 reacted faster compared to data from previous studies. This difference is potentially exacerbated by the fact that the estimated pre-evacuation times in this study are likely to include part of evacuees' evacuation movement time due to the placement of the cameras within both buildings. The data collected in this study represent the lowest pre-evacuation times compared with values collected from similar building occupancies. This quick pace could be attributed to the relatively quick action of emergency guides as well as to regular training. Further, it should be noted that the data in the present study represented an unannounced fire drill, while some of the literature values were observed during actual fire events, which may also explain the observed differences.

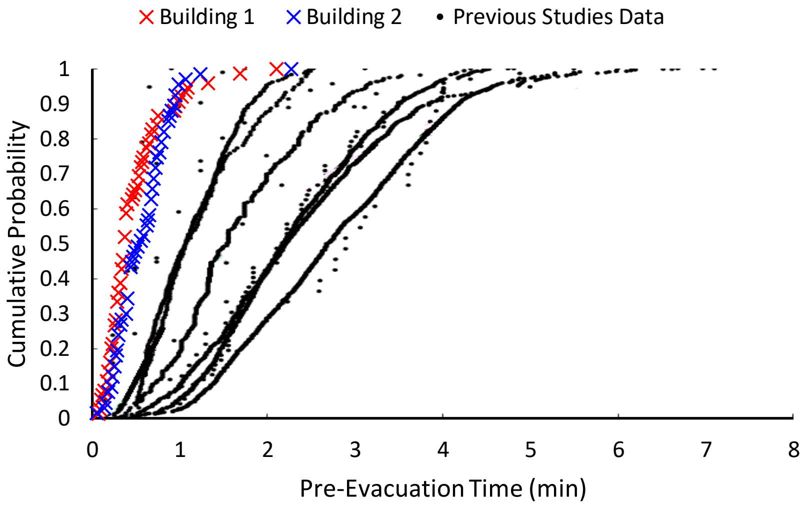


Fig. 15 Comparison of the collected pre-evacuation data in buildings 1 (in blue) and 2 (in orange) with the existing data (in black) published in the literature

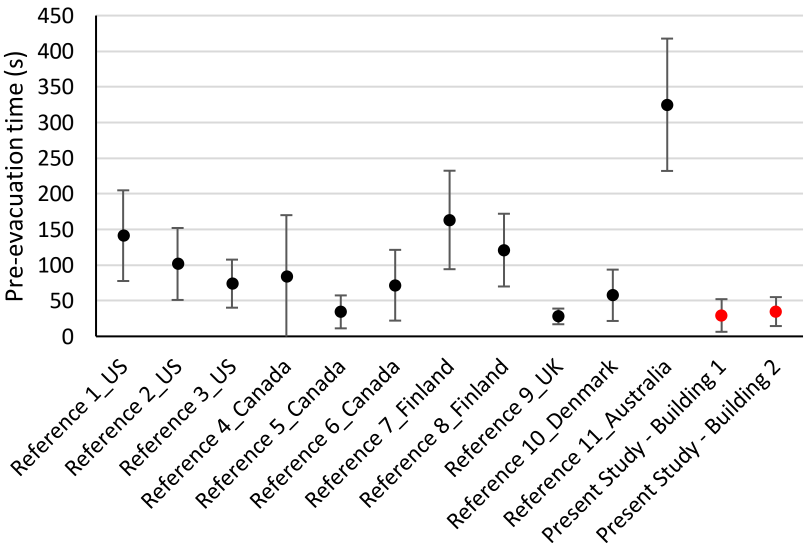


***Fig. 16** Comparison of the collected pre-evacuation data (Mean ± SD) in buildings 1 and 2 (in red) with the existing data (in black) published in the literature*

On the one hand, horizontal walking speed values measured in the present study fall within the range of values reported in the literature (see Fig. 17). The mean walking speed measured in corridors is equal to 1.17 m/s and 1.23 m/s for buildings 1 and 2, respectively. These values are consistent with the values reported by Fritzpatrick et al. [32], Bohannon and Andrews [33], Young [34] and Yeo and He [35]). Moreover, the range of encompassing observations in this study overlaps with the walking speeds found in previous studies.

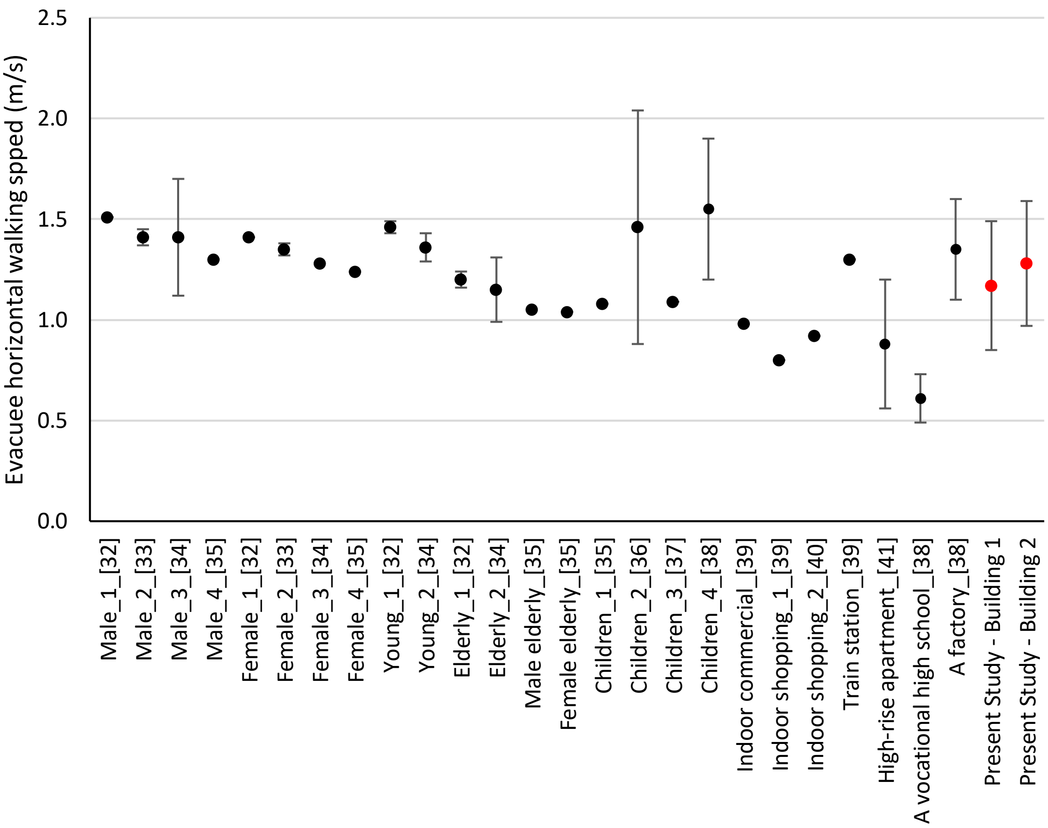


Fig. 17 *Comparison of the collected horizontal walking speed data (Mean ± SD) in buildings 1 and 2 (in red) with the existing data (in black) published in the literature*

On the other hand, descending walking speeds values measured in the present study fall within the upper range of values reported in the literature (see Fig. 18). This suggests that, mostly, the occupants of buildings 1 and 2 walked at higher speeds as compared to the values reported in previous studies. This may be explained by the fact that occupants of the monitored buildings received regular training and in turn, may have been more familiar with the evacuation procedures. Further, the data in the present study represent an unannounced fire evacuation. Occupants' behaviour during an unannounced fire drill could be closer to the behaviour during an actual fire evacuation situation compared to an announced fire drill. Another reason for the difference can be the low densities observed in stairs in this study, since the maximum observed density was lower than 1 person/m², essentially allowing for unimpeded flow. This may also explain why there are differences between the collected data in the current study and literature values. Finally, the SFPE Handbook [22, 30, 31] suggests speeds between 0.85 – 1.05 m/s with varying tread dimensions and our results agree with the handbook.

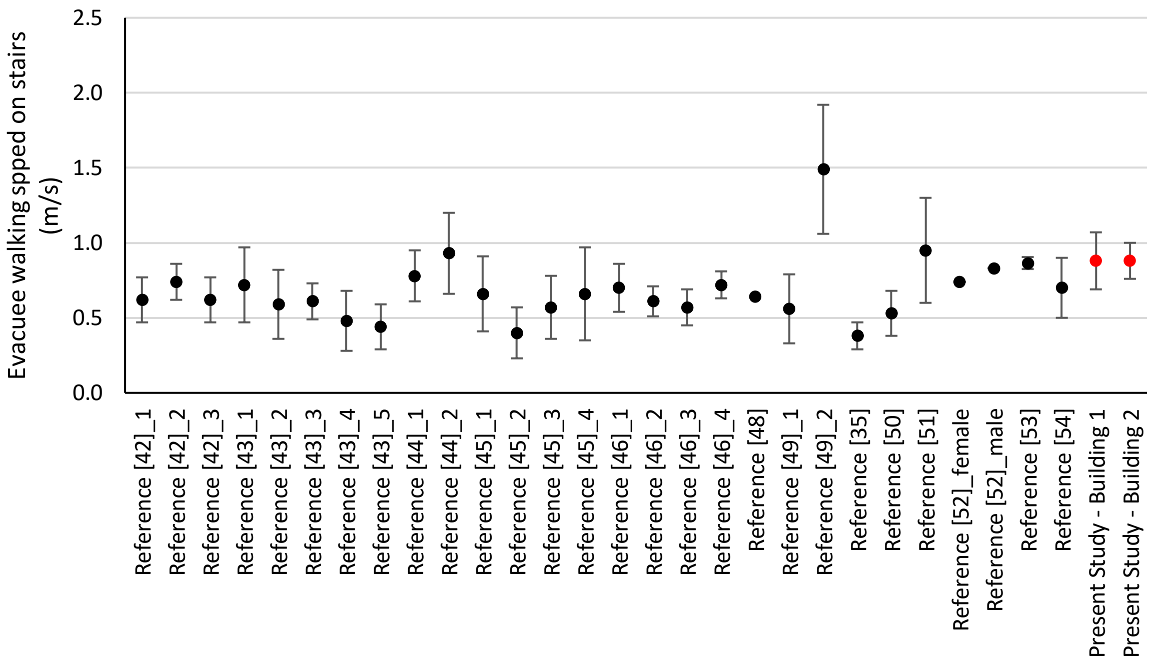


Fig. 18 *Comparison of the collected walking speed on stairs data (Mean ± SD) in buildings 1 and 2 (in red) with the existing data (in black) published in the literature*

7. Discussion and conclusion

This study presents data collected during unannounced evacuation drills in two office buildings located at CERN, in Switzerland. This was done by collecting videos during the drill and performing a video analysis aimed at extracting the following data: pre-evacuation times; and walking speeds, flows, and occupant densities in corridors and stairs. In addition to these quantitative measurements, qualitative observations regarding evacuee behaviour were also carried out, showing the common behaviours observed during the drill.

From the qualitative observations, it was noticed that more than half of the observed population of the monitored buildings (i.e., 58.1% of occupants in building 1 and 68.6% in building 2) carried personal objects. It was also observed that a few evacuees travelled in the opposite direction of the flow and a proportion of occupants evacuated in groups. Finally, a few individuals notified others about the emergency.

Pre-evacuation results showed that occupants of the monitored buildings responded quicker compared with data from previous studies. Lower pre-evacuation times were observed in both buildings compared with existing business occupancy data. This could be attributed to the buildings' training schemes. In effect, the training program of CERN contains a variety of channels through which the staff is trained to respond effectively to an emergency. These include online courses about evacuation procedures, regular fire drills, and the assignment of "emergency guides" throughout the building.

The observed horizontal walking speeds were compared with previous research values and were consistent with data from the literature. However, only uncongested conditions were observed in the current study as the evacuation did not generate any significant bottlenecks. Future developments are, therefore, needed to conduct drills in the same buildings with higher population densities.

Regarding evacuee movement in stairs, results show that occupants from buildings 1 and 2 moved at a similar speed (mean = 0.88 m/s) regardless of the different geometry of the stairs; however, the variability in speeds is higher in building 1 as compared with building 2. The monitored staircase in building 1 is a straight staircase with two flights of stairs and an intermediate landing, whereas the monitored staircase in building 2 is a dog-legged staircase with three flights of stairs and two intermediate landings. This could also be a factor that led to the travel speed variability. The observed walking speeds in stairs were also compared with previous data and seemed to fall within the upper range of values reported in the literature. Differences between the previous data and data from the observed drill could be related to various factors. For instance, the observed drills were unannounced, which is not always the case in previous studies. Another reason could be that the density values observed in this study are lower than 1 person/m^2, which represents only free-flow (or uncongested) conditions which is not always the case in previous studies. Finally, the comparison of the observed experimental data with SFPE relationships showed that the collected data are consistent with the SFPE hydraulic model.

Overall, it is important to recognize the limitations of the current study. This study only provides the results on a single evacuation drill for the two buildings under investigation. As such, future studies are necessary to investigate multiple drills of these two buildings. Multiple trials would provide answers on how representative these evacuation data are. Further, having data from multiple drills would make the dataset suitable for future model validations using the methods proposed in [19]. Another limitation of this study lies in the assumptions made to calculate density. Since density is a continuous function at all locations in a stair or corridor, including those not directly monitored by cameras, the employed calculation methods are simplifications of real-world phenomena. In addition, density is inherently a local function, so there may be higher or lower densities at positions not monitored by cameras. It is also worth noting that, with this definition, it is possible to have a density of zero since the density count does not include the occupant being considered; in effect, the counted density is the one seen by occupants as they enter the first observation point. Another limitation of this study is that it does not include data from people with reduced mobility which may influence the evacuation dynamics in office buildings. Further investigations are, thus, necessary to better understand the performance of more heterogeneous populations during office evacuations. As higher density conditions were not observed, only a portion of the fundamental diagrams is applicable in this study. Therefore, future investigations with higher population density are required.

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References

[1] Hadjisophocleous, G.V., Benichou, N. and Tamim, A.S., 1998. Literature review of performance-based fire codes and design environment. *Journal of Fire Protection Engineering*, *9*(1), pp.12-40.

[2] Meacham, B.J., 2010. Risk-informed performance-based approach to building regulation. *Journal of Risk Research*, *13*(7), pp. 877-893.

[3] Wolski, A., Dembsey, N.A. and Meacham, B.J., 2000. Accommodating perceptions of risk in performance-based building fire safety code development. *Fire Safety Journal*, *34*(3), pp.297-309.

[4] B. Van Weyenberge, X. Deckers, R. Caspeele and B. Merci (2018). Development of an Integrated Risk Assessment Method to Quantify the Life Safety Risk in Buildings in Case of Fire. Fire Technology, https://doi.org/10.1007/s10694-018-0763-6

[5] Rahouti, A., Lovreglio, R., Gwynne, S., Jackson, P., Datoussaïd, S., and Hunt, A., (2020), Human Behaviour during healthcare facility evacuation drills: investigation of pre-evacuation and travel phases, Safety Science, *In Press*.

[6] Bergeron, D., Desserud, R.J. and Haysom, J.C., 2004. The Origin and development of Canada's objective-based codes concept. In Proceedings of the CIB Triennal Congress, Toronto, Canada.

[7] Kuligowski, Erica D. "Computer evacuation models for buildings." *SFPE Handbook of Fire Protection Engineering*. Springer, New York, NY, 2016. 2152-2180.

[8] Lovreglio, Ruggiero, Enrico Ronchi, and Michael J. Kinsey. "An Online Survey of Pedestrian Evacuation Model Usage and Users." *Fire Technology* (2019): 1-21.

[9] Gwynne, Steve MV, et al. "Pros and cons of egress drills." *Interflam 2016* (2016).

[10] Lovreglio, R., Kuligowski, E., Gwynne, S. and Boyce, K., (2019-b). A pre-evacuation database for use in egress simulations. *Fire Safety Journal*, 105, pp. 107-128.

[11] Shi, Long, et al. "Developing a database for emergency evacuation model." *Building and Environment* 44.8 (2009): 1724-1729.

[12] Fahy, Rita F., and Guyléne Proulx. "Toward creating a database on delay times to start evacuation and walking speeds for use in evacuation modeling." *2nd international symposium on human behaviour in fire*. Boston, MA, USA, 2001.

[13] Gwynne S.M.V., Boyce K.E. (2016) Engineering Data. In: Hurley M.J. et al. (eds) SFPE Handbook of Fire Protection Engineering. Springer, New York, NY

[14] Kuligowski, E., 2013. Predicting human behavior during fires. *Fire Technology*, *49*(1), pp.101-120.

[15] Gwynne, S. M. V., L. M. Hulse, and M. J. Kinsey. "Guidance for the model developer on representing human behavior in egress models." *Fire technology* 52.3 (2016): 775-800.

[16] Gwynne, S., Galea, E.R., Parke, J. and Hickson, J., 2003. The collection and analysis of pre-evacuation times derived from evacuation trials and their application to evacuation modelling. *Fire Technology, 39*(2), pp. 173-195.

[17] Ramirez, M., Kubicek, K., Peek-Asa, C. and Wong, M., 2009. Accountability and assessment of emergency drill performance at schools. *Family & community health, 32*(2), pp.105-114.

[18] Lovreglio, R., et al. "The need of latent variables for modelling decision-making in evacuation simulations." *IX Int. Work. Plan. Eval., Bari* 10 (2015).

[19] Lovreglio, Ruggiero, Enrico Ronchi, and Dino Borri. "The validation of evacuation simulation models through the analysis of behavioural uncertainty." *Reliability Engineering & System Safety* 131 (2014): 166-174.

[20] Fahy, R.F. and Proulx, G., 2001, March. Toward creating a database on delay times to start evacuation and walking speeds for use in evacuation modeling. In *2nd international symposium on human behaviour in fire* (pp. 175-183). Boston, MA, USA.

[21] Proulx, G. and Fahy, R.F., 1997. The time delay to start evacuation: review of five case studies. *Fire Safety Science, 5*, pp.783-794.

[22] Hurley, M.J., (2016) SFPE Handbook of Fire Protection Engineering, Fifth Edition, Springer. Doi: 10.1007/978-1-4939-2565-0

[23] Zhang, J., 2012. *Pedestrian fundamental diagrams: Comparative analysis of experiments in different geometries* (Vol. 14). Forschungszentrum Jülich.

[24] Gupta, A. and Pundir, N., 2015. Pedestrian flow characteristics studies: A review. *Transport Reviews*, *35*(4), pp.445-465.

[25] Vanumu, L.D., Rao, K.R. and Tiwari, G., 2017. Fundamental diagrams of pedestrian flow characteristics: A review. *European transport research review*, *9*(4), p.49.

[26] Burghardt, S., Seyfried, A. and Klingsch, W., 2013. Performance of stairs–fundamental diagram and topographical measurements. *Transportation research part C: emerging technologies*, *37*, pp.268-278.

[27] Klingsch, W. and Seyfried, A., 2014. *Fundamental Diagram of Stairs: Critical Review and Topographical Measurements* (No. FZJ-2014-03280). Jülich Supercomputing Center.

[28] Predtechenskii, V.M. and Milinskiĭ, A.I., 1978. *Planning for foot traffic flow in buildings*. National Bureau of Standards, US Department of Commerce, and the National Science Foundation, Washington, DC.

[29] J.J. Fruin, Pedestrian Planning and Design, Elevator World, New York (1971).

[30] H.E. Nelson, F.W. Mowrer, Emergency movement, SFPE Handbook of Fire Protection Engineering (third ed.), National Fire Protection Association, Quincy, MA (2002), pp. 367-380

[31] Gwynne, S.M.V., and Rosenbaum, E.R., (2016). Employing the Hydraulic Model in Assessing Emergency Movement, in: SFPE Handb. Fire Prot. Eng., Springer New York, New York, NY, pp. 2115–2151. doi:10.1007/978-1-4939-2565-0_64

[32] Fitzpatrick, K., Brewer, M.A. and Turner, S., 2006. Another look at pedestrian walking speed. *Transportation research record*, *1982*(1), pp.21-29.

[33] Bohannon, R.W. and Andrews, A.W., 2011. Normal walking speed: a descriptive meta-analysis. *Physiotherapy*, *97*(3), pp.182-189.

[34] Young, S.B., 1999. Evaluation of pedestrian walking speeds in airport terminals. *Transportation Research Record*, *1674*(1), pp.20-26.

[35] Yeo, S. K., & He, Y. (2009). Commuter characteristics in mass rapid transit stations in Singapore. *Fire safety journal*, *44*(2), 183-191.

[36] Hamilton, G. N., Lennon, P. F., & O'Raw, J. (2017). Human behaviour during evacuation of primary schools: Investigations on pre-evacuation times, movement on stairways and movement on the horizontal plane. Fire Safety Journal, 91, 937-946.

[37] Ono, R., Valentin, M., & Vittorino, F. (2012). Walking speed data of fire drills at an elementary school. In Proceedings of 5th International Symposium: Human Behaviour in Fire.

[38] Rinne, T., Tillander, K., & Grönberg, P. (2010). *Data collection and analysis of evacuation situations* (p. 46). Espoo: VTT.

[39] Tanaboriboon, Y., Hwa, S.S. and Chor, C.H., 1986. Pedestrian characteristics study in Singapore. *Journal of transportation engineering*, *112*(3), pp.229-235.

[40] Lam, W.H. and Cheung, C.Y., 2000. Pedestrian speed/flow relationships for walking facilities in Hong Kong. *Journal of transportation engineering*, *126*(4), pp.343-349.

[41] Proulx, G. (1995). Housing evacuation of mixed abilities occupants in highrise buildings. National Research Council Canada, Institute for Research in Construction.

[42] Kadokura H, Sekisawa A, Sano T, Yajima M, Masuda S (2012) Study of Congestion in Stairs During Phased Evacuation in a High-Rise Building – Analysis based on the Observational Data of a Real Total Evacuation Drill, in Proceedings 5th International Human Behaviour in Fire Symposium, Cambridge, England, pp 171-181.

[43] Hoskins BL (2011) The effects of interactions and individual characteristics on egress downstairs. PhD Dissertation, University of Maryland – College Park. Available on-line at http://drum.lib.umd.edu/handle/1903/12515

[44] G. Proulx, A. Kaufman, J. Pineau, Evacuation Time and Movement in Office Buildings - NRCC Technical Report, (1996).

[45] Proulx G, Bénichou N (2010) Photoluminescent stairway installation for evacuation in office buildings. Fire Technol. 46: 471–495.

[46] Proulx G, Bénichou N, Hum JK, Restivo KN (2007) Evaluation of the effectiveness of different photoluminescent stairwell installations for the evacuation of office building occupants. Research Report 232. National Research Council of Canada, Ottawa, Canada.

[47] Kagawa M, Kose S, Morishita Y (1985) Movement of people on stairs during fire evacuation drill - Japanese experience in a high-rise office building. In: Grant CC, Pagni PJ (eds) Fire safety science: proceedings of the first international symposium Gaithersburg, Maryland. International Association, Fire Safety Science, pp. 533–540.

[48] S. Hostikka, T. Paloposki, T. Rinne, J. Saari, T. Korhonen, Evacuation Experiments in Offices and Public Buildings, VTT Technical Research Centre of Finland, Espoo, Finland, 2007

[49] Fujiyama, T. & Tyler, N. 2004. An Explicit Study on Walking Speeds of Pedestrians on Stairs. 10th International Conference on Mobility and Transport for Elderly and Disabled People. Hamamatsu, Japan. 10 p.

[50] Yang, L., Rao, P., Zhu, K., Liu, S., & Zhan, X. (2012). Observation study of pedestrian flow on staircases with different dimensions under normal and emergency conditions. *Safety science*, *50*(5), 1173-1179.

[51] Huo, F., Song, W., Chen, L., Liu, C., & Liew, K. M. (2016). Experimental study on characteristics of pedestrian evacuation on stairs in a high-rise building. *Safety science*, *86*, 165-173.

[52] Choi, J. H., Galea, E. R., & Hong, W. H. (2014). Individual stair ascent and descent walk speeds measured in a Korean high-rise building. *Fire Technology*, *50*(2), 267-295.

[53] Yin-qing, L.I., (2005). Performance Design for Building Fire Protection, Chemical Industry Press., Beijing,141-171

[54] Ono, R. et al. Method for collecting data of children descending movement on stairs in schools, Fire and Materials, DOI:10.1002/fam.2833

[55] Almejmaj, M., Skorinko, J. L., & Meacham, B. J. (2017). The effects of cultural differences between the us and saudi arabia on emergency evacuation—Analysis of self reported recogntion/reaction times and cognitive state. *Case Studies in Fire Safety*, *7*, 1-7.

[56] E.D. Kuligowski, E.D. Peacock, P.A. Reneke, C.R. Hagwood, K.J. Overholt, R.P. Elkin, J.D. Avrill, E. Ronchi, B.L. Hoskins, M. Spearpoint, Movement on stairs during building evacuation, NIST Technical note 1839, 2015, http://dx.doi.org/10.6028/NIST.TN.1839

[57] Peacock RD Hoskins BL, Kuligowski ED (2012) Overall and local movement speeds during fire drill evacuations in buildings up to 31 stories. Saf. Sci. 50:1655–1664.

[58] Kuligowski, E., et al. (2015). Movement on Stairs During Building Evacuations, NIST Technical Note 1839, doi: http://dx.doi.org/10.6028/NIST.TN.1839

Appendix A

Buildings 1 and 2 floors layouts, the locations and orientations of cameras, and the locations of emergency exits

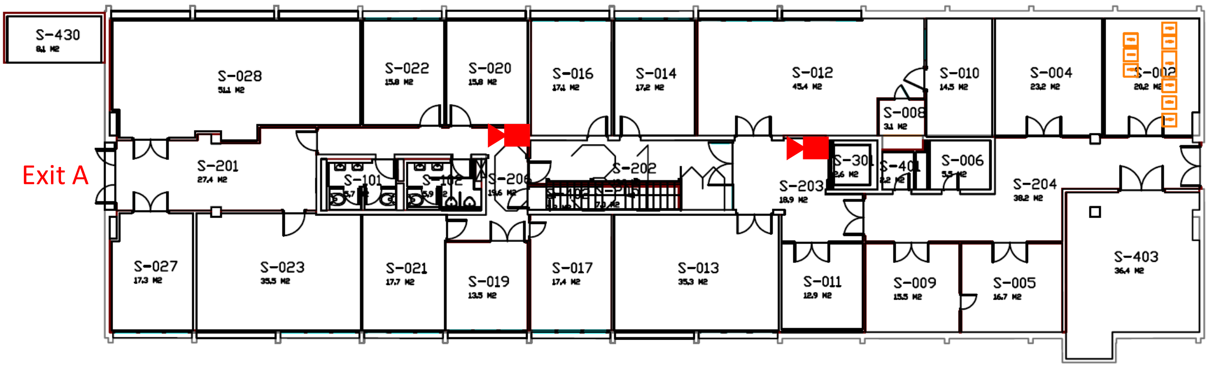

Fig. A.1 floor R-1 layout, the locations and orientations of cameras, and the locations of emergency exits within this floor – building 1

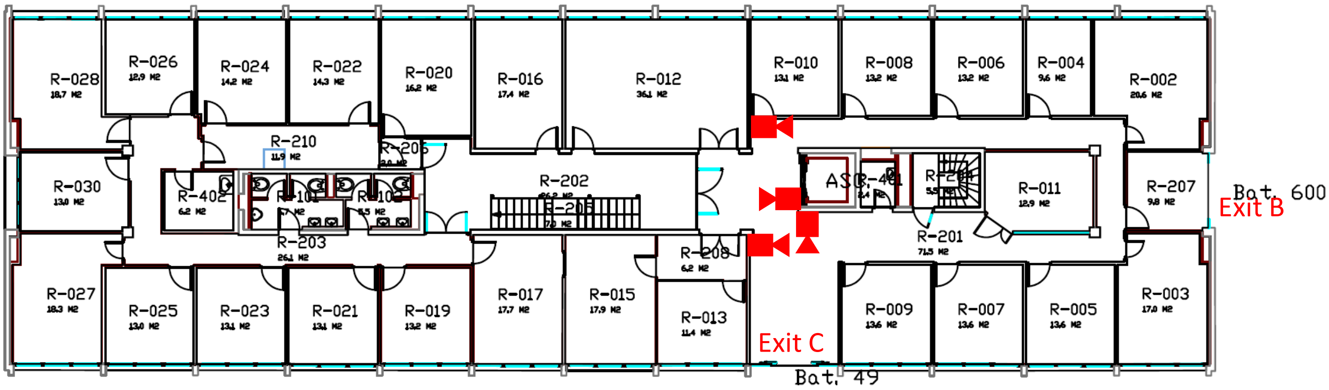

Fig. A.2 floor R0 layout the locations and orientations of cameras, and the locations of emergency exits within this floor – building 1

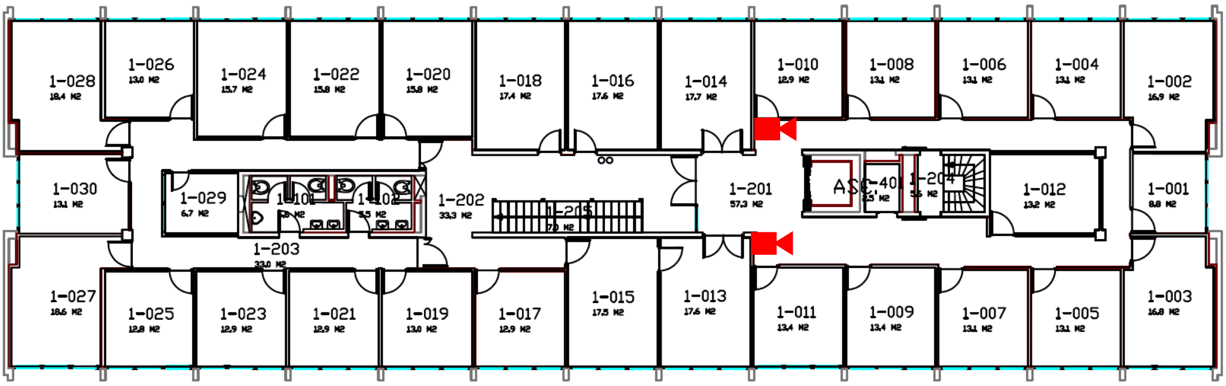

Fig. A.3 floor R+1 layout as well as the locations and orientations of cameras within this floor – building 1

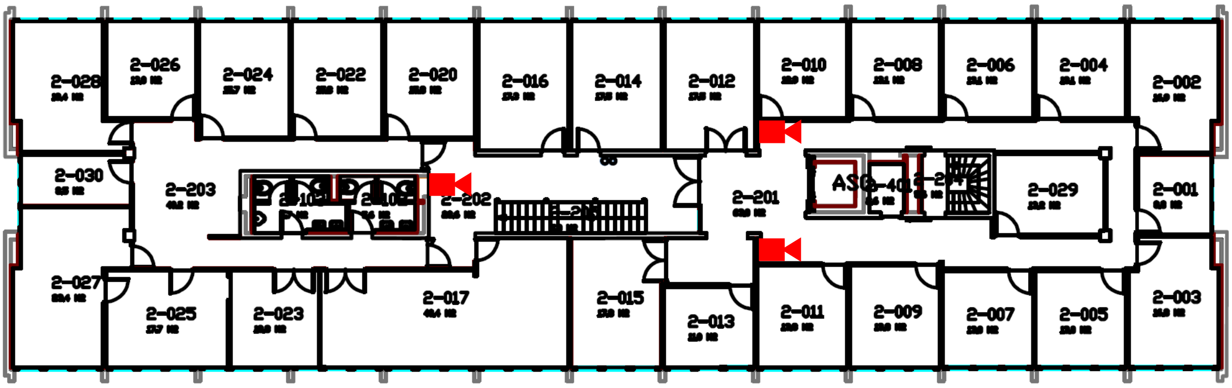

Fig. A.4 floor R+2 layout as well as the locations and orientations of cameras within this floor – building 1

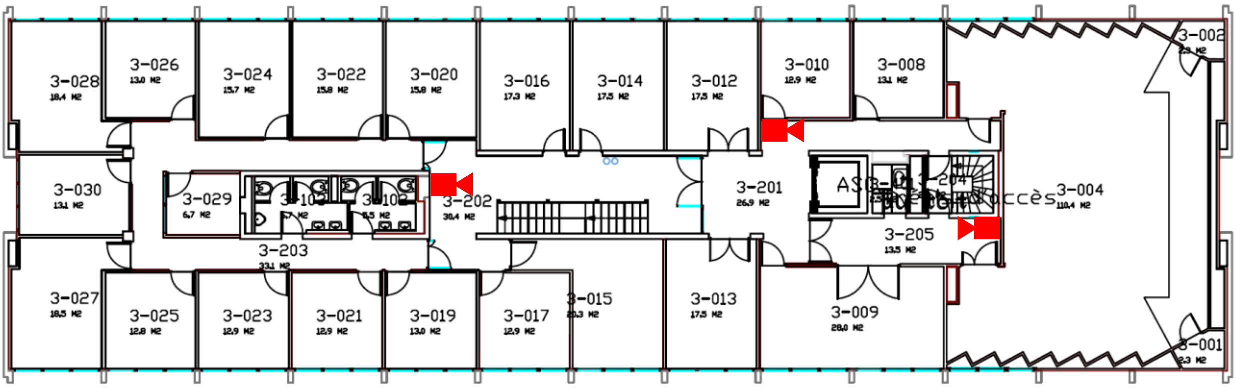

Fig. A.5 floor R+3 layout as well as the locations and orientations of cameras within this floor – building 1

Fig. A.6 floor R-1 layout, the locations and orientations of cameras, and the locations of emergency exits within this floor – building 2

Fig. A.7 floor R0 layout, the locations and orientations of cameras, and the locations of emergency exits within this floor – building 2

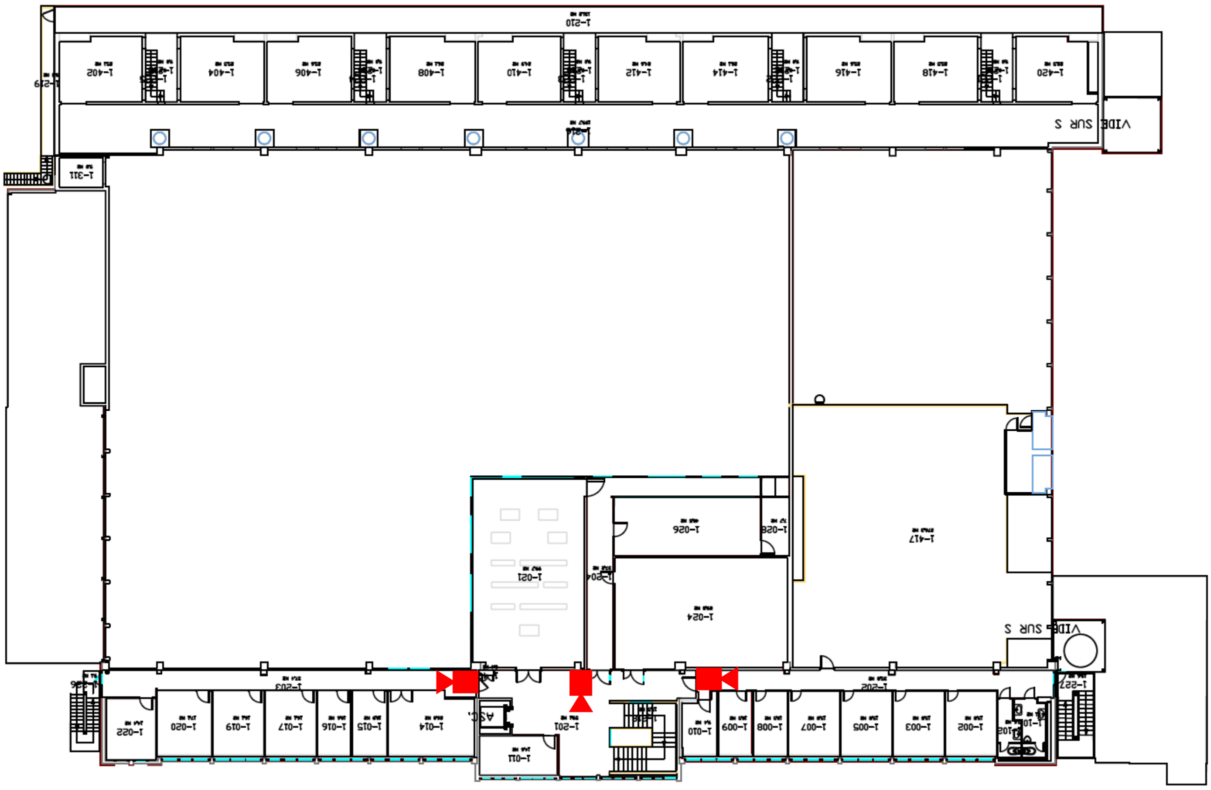

Fig. A.8 floor R+1 layout as well as the locations and orientations of cameras within this floor – building 2

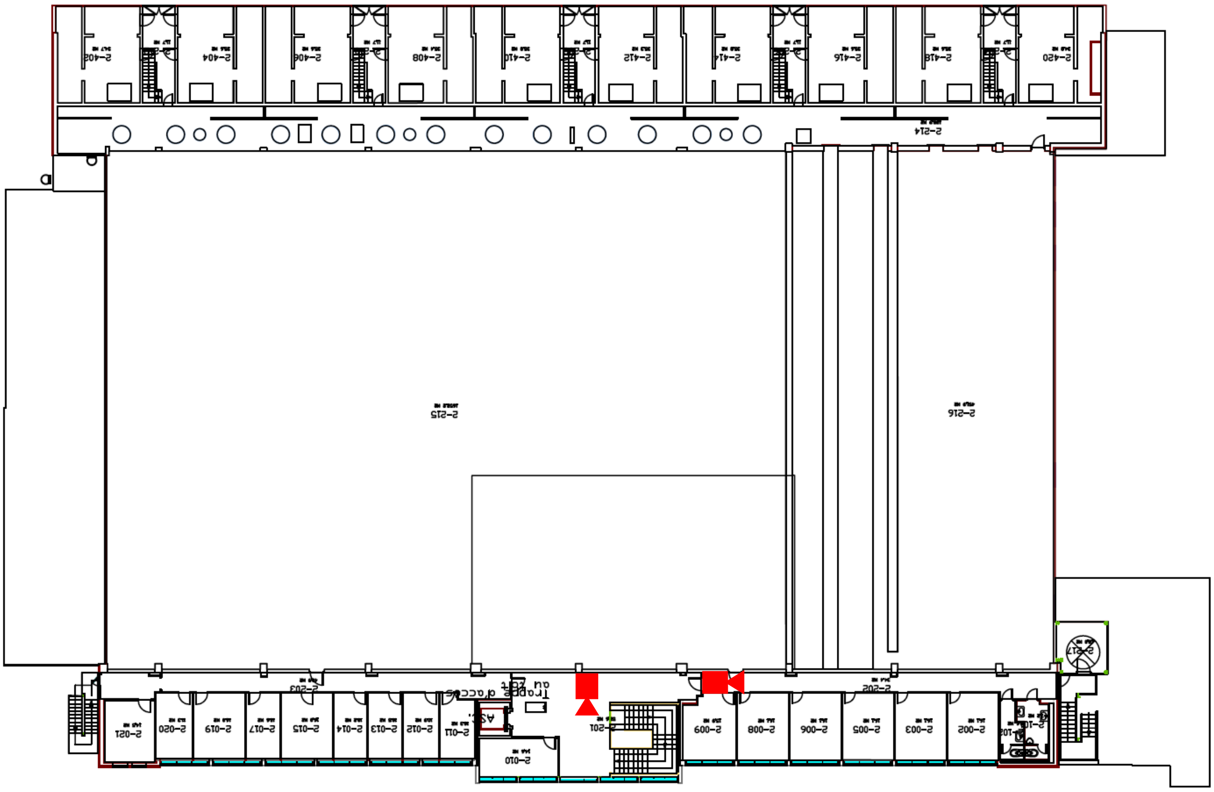

Fig. A.9 floor R+2 layout as well as the locations and orientations of cameras within this floor – building 2