Design and experimental evaluation of an interactive system for pre-movement time reduction in case of fire

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Abstract

After hearing a fire alarm, people continue to carry out activities not directly connected to the evacuation procedure: this pre-movement phase could be very long, especially when people are involved in carrying out their working activities and in using their electronic devices. Starting from this problem regarding safety, our study proposes a system for reducing pre-movement time that is based on an interaction with the people being evacuated. The system, composed of individual wearable devices, is organized in two modules: the first is the Zig-Bee-based localization module which identifies people's positions after the alarm and understands whether they are evacuating; the second is an interactive module which gives a personal stimulus to latecomers. This system was tested for university building evacuation. A case study has been analyzed, which also compared experimental results to those of simulation software. The simulator was able to reasonably reproduce the real phenomenon. The effectiveness of the system was investigated through simulations by considering different individual responses. Our results demonstrate that up to 30% reduction in total evacuation time can be obtained.

1. Introduction

Several studies in the past have been conducted on social and environmental factors that influence the "evacuation time" of a building during a fire [1—7]. In particular, real accident analyses have shown how the first evacuation phase influences the total evacuation procedure [1,3]: this so-called pre-movement phase [8] delays the start of evacuation and can often lead to numerous losses of life [8—10], especially when people are involved in carrying out their work activities or in using their personal devices. The correct designing of architectural spaces is an essential element for aiding evacuation [5], but it becomes very important to efficiently project devices that are able to help people in the evacuation process and especially in the pre-movement phase [5, 11]. Similar systems can be composed of personal devices [12] based on the recognition of wrong and time-wasting behaviours: they can interact with people in order to effectively reduce the egress time whereby increasing the level of safety of the building itself [13]. The definition of such an interactive system for reducing pre-movement time involves two main factors. The first factor concerns behavioural aspects and human phenomena during evacuation especially in the premovement phase [8,11,14]. In this work, the attention is focused on buildings where people were involved in working and studying activities and in using their personal electronic devices (i.e., university) [14]. The second factor involves defining a system that is able to identify wrong behaviours and to interact with people in order to increase their level of safety.

Regarding the first factor, the pre-movement phase [15–18] starts after fire is detected and the occupants are alerted. In this phase, people do different things before moving out [8,19]. For instance, they take time trying to interpret any information announced about dangers, interact with other individuals around them [6,8,13], wait for other people such as their friends or relatives or other people they know ("attachment to people" phenomenon) [6] and try to collect their belongings ("attachment to things" phenomenon) [20]. The quantitative and qualitative characterization of this phase is analyzed for different buildings and situations: offices [21], stores [22], hotels [11], cinemas and theatres [13], schools [14,23—25], flats [26], and care homes [18]. As far as quantification of time is concerned, the maximum pre-movement time measured is equal to 3.92 min for a theatre (after an announcement) [8]. However, these numerical data show wide dispersion, depending on the type of building and activities in which people are engaged [25, 27]. As such, different proposals of time probability distributions have been provided [4,8]. Nevertheless, "attachment" behaviours [16] have not been investigated in detail, and there is a lack of organized data about important conditions in buildings, such as the use of personal electronic devices by occupants of schools, and universities [14]. In this case, people can be easily inclined to waste time by behaving wrongly like when trying to save their data and personal belongings: the pre-movement time in this situation is very significant, and so its reduction becomes essential in order to improve the whole evacuation process in terms of safety.

As such, some authors have suggested the need to interact with people during an indoor fire evacuation in order to effectively reduce egress time in both pre-movement and motion phases [28]. Consequently, the second factor concerns defining an interactive system for supporting evacuation. Various systems composed of modern and wearable devices have been proposed [12,29—32]; in addition, multi-sensor approaches are provided [33]. Similar technologies have also been proposed for outdoor evacuations [34]. These devices can also be part of complex systems for monitoring evacuation and aiding the occupants [32,34,35]. In particular, a direct and personal stimulus can be introduced and given to individuals that do not move immediately after the communication for evacuation (e.g., the sound of the fire alarm) has been made. Similar systems can be composed of a localization module and an interactive module [12]. Different wireless technologies are often used for the localization module [12,33,36—38]. Wi-Fi location tracker is able to develop fast flow control algorithms for real-time emergency evacuation [39]; modifications in network robustness can be introduced [40, 41]. Recently, CPSs (cyber physical systems) have been proposed as tools to further develop interactions between the physical and virtual world, such as location tracking and road information sensing [42]. The introduction of ERISs (Emergency response information systems) has been suggested to enhance emergency response operations [43]. Another system in real-time building monitoring technologies concerns sensor units and communication network based on wireless Zig-Bee which can also be used in evacuation situations [44—47], such as those for construction elevator security system [48] or patient localization and environmental monitoring [49]. Localization data can be elaborated by different algorithms [32] in order to give information or stimuli to people evacuating (e.g., appropriate evacuation routes) [50—54]. The interactive module effectively returns information and stimuli to the occupants based on algorithm results. The interactive module can be included into common elements, such as way-finding components [31,32] or decision nodes [29], or personal and portable devices [12,32]. The testing phase usually consists in technology effectiveness analysis and in validating the system by using evacuation simulation software.

However, a limited number of studies have used similar systems for aiding evacuation, and only few of them are interactive; finally, there has not been any further development in interaction with people during pre-movement time.

On the basis of the above observations, this work proposes an interactive system for aiding evacuation in a real situation, and in particular, for pre-movement time reduction. An interactive system has been designed: the system can be worn by each person who can take advantage of a wireless network by using Zig-Bee technology. System requirements were experimentally analyzed which concerned localization problems and the response of the system for recognizing wrong behaviours and for interacting with individuals through a direct and personal stimulus. The attention is focused on a possible application of the system in the context of universities and schools where people are usually busy using their electronic devices for learning activities. Experimental students' evacuations from classrooms were analyzed, and quantitative and qualitative behavioural data have been provided; one of the experimental evacuations was recreated through simulation software and results were then compared, demonstrating the possibility to simulate a real case through the software. Finally, the effectiveness of the system in terms of technological aspects, such as possible interferences, has been evaluated; then, the evacuation time reduction by using the simulator is analyzed.

2. Phases and Methods

2.1. Phases

The study was organized in the following four phases:

1. The interactive wearable system was designed for pre-movement time reduction and evaluation of technological requirements.
2. Experimental evacuations of university classrooms were carried out while personal electronic devices were being used.
3. The correspondence between experimental evacuations results and simulations using software was tested.
4. The system was evaluated in terms of evacuation time reduction by means of simulation software.

In the first part of the study, the interactive system for premovement time reduction was defined, including module characterization. The system was capable of recognizing defined "wasting-time" behaviours and was able to interact with students in order to reduce the fire evacuation time. The evaluation of technological requirements has been provided.

Since a particular environment for testing our proposed system was needed, the evacuation of a school building was chosen, and in particular, university classrooms [14], keeping a special eye on the pre-movement phase. In these classrooms, students were using their personal electronic devices (laptops, tablets) during their regular educational activities: the use of these devices can modify their evacuation behaviours and consequently, the students' evacuation time. For these reasons, pre-movement time could be very high with respect to other building types. The second part involved various evacuation experiments: in these cases, students did not use our system. Experimental data have been provided in order to classify people in terms of their behaviours during evacuation, define time-wasting behaviours, and to quantify students' pre-movement time.

Then, the goal was to evaluate the effectiveness of our system in the selected environment. A series of real devices was not actually assembled, and consequently simulations for this testing phase were used. Since a validation test of the simulation software was required, at first, one of the experimental evacuations was recreated through simulation software. Later, results were compared to those of the real evacuations. The correspondence between the real phenomena and the simulated ones is positive, and so it is possible to use the simulation software for the testing phase.

Finally, in the fourth phase, the effectiveness of the proposed system is verified through an evaluation of the effective reduction of the evacuation time in the case study using the simulation software.

2.2. *Methods*

2.2.1. *Interactive system architecture*

The architecture of our interactive system is designed with the purpose of recognizing the "wrong" pre-movement behaviours that are experimentally noticed and of giving a direct stimulus to them by means of some wearable device. The general characteristics of the system have been roughly determined on observations of previous literature. The proposed system is composed of a *localization module* for tracking the positions of individuals and an *interactive module* with a vibration motor for interacting with people through a direct and personal stimulus. The hardware platform used was the CC2431DK platform produced by Chipcon [55]. This platform uses a wireless network based on the ZigBee-2006 standard. The CC2431 chip includes a location detection hardware module that can be used in the so-called blind nodes (i.e., nodes with unknown location) to receive signals from nodes with known location. The location engine calculates an estimate of the blind node's position that is based on the value of Received Signal Strength Indicator (RSSI). Through an appropriate configuration of the 21 general I/O CC2431 pins and a programming activity, the system is able to evaluate CO2 levels, air temperatures, people's movements and positions all at the same time. Moreover, the chip can produce direct stimulus with the vibration motor.

2.2.2. *Evaluation of technological requirements of the interactive system*

The technological requirements of the proposed system are evaluated through an experimental analysis. The SmartRF04EB of the CC2431DK is use as monitoring system for collecting data on a laptop. The requirements correspond to two aspects.

2.2.2.1. *Experimental analysis of the localization module.* Firstly, the localization module analysis involves the evaluation of possible interferences with other wireless devices present and the estimation of the localization distance error. 10 different experimental tests are conducted according to Table 1 with still and/or people in motion. Some setups were defined in order to describe different scenario configurations; one or more experiments were performed for each setup in different still and motion cases. Tests were conducted in three different setups, in different rooms, of the main building of "Università Politecnica delle Marche". A series of experimental analysis on the CC2431 localization system [56] shows that Wi-Fi devices could potentially interfere with ZigBee communication when their carrier frequencies overlap. For this reason, investigations concerned the presence of any possible interference (setup 1) and the variation of interference during time through a 24 h test, leaving the node in the same position (setup 2). At the same time, the influence of the blind node height from the floor was also considered. The analysis of the results of these activities allowed us to identify rooms with a lower level of interference during time (setup 3). Table 1 resumes the different setups and single proof for each setup. A significant amount of sample data was collected in order to define a threshold value of position error and the related probability that could occur.

Fig. 1a shows setup 1. It is composed of a big classroom with a lot of students and Wi-Fi devices, useful for investigating interferences. Fig. 1b shows setup 2. It is composed of a medium-sized classroom with nobody except for some Wi-Fi networks which are useful for analyzing the correlation between time and interference in a 24-hour testing period. In the following pictures, the reference nodes are the grey circles, while the blind node is the black circle.

Fig. 2 shows setup 3. It is composed of 2 small classrooms and a corridor with just a few people and some Wi-Fi networks which were useful to simulate four evacuation routes. The number and position of reference nodes for every setup, such as the calibration parameters (Received Signal Strength Indicator value measured one metre from the sender, Signal propagation coefficient), were determined according to the manufacturer's guide [57]. In movement tests, the blind node was moved along the evacuation routes with a speed of 1.5 m/s, and the activities were repeated 20 times for each route. The localization error (E) was considered as the distance between the real position and the calculation result of the blind node which was recorded every 0.5 s. The number of data locations collected for every test is reported in Table 1.

2.2.2.2. *Evaluation of system response time.* Secondly, the response time of the proposed system was evaluated in order to understand whether the activation time required is satisfactory. In order to establish the effectiveness of the proposed system, the response time R_{time} (s) that the proposed system needs for detecting a wrong behaviour and to transmit the stimulus was calculated as in Eq. (1):

$$R_{time} = 2 \cdot E/V + T_S + 2.5s + 3.5s \qquad [1]$$

where E (m) is the localization error threshold value (it is found on experimental analysis and brings a certain probability), V (m/s) is the average of the walking speed recorded in the evacuation experiment (140/5 classroom), T_s (s) is the time needed for the sit-to-walk (STW) activity [58]. In Eq. (1), it was assumed that 2.5 s were required for acquiring the 5 new locations, and 3.5 s for giving a direct stimulus. Potential latecomers are identified if the pre-movement time of the individuals is higher than R_{time}; the system will interact with them through a personal stimulus.

2.2.3. *Analysis of evacuation and pre-movement phase behaviours*

The second and third phases of this work are based on the analysis of the evacuation in two classrooms and in the library of the Faculty of Engineering at “Università Politecnica delle Marche” (Ancona, Italy); experimental evacuation was carried out by previous activities [14]. In these classrooms, students usually attend lectures and do exercises that require them to use personal electronic devices (laptops, tablets): in particular, 93% of the students involved in experiments use personal electronic devices. The experimental database is related to both quantitative and qualitative analyses of the pre-movement phase, and involves students from 19 to 24 years. Data were obtained by using both questionnaires concerning hypothetical behaviours in evacuation and experimental evacuation results in the two classrooms [14]. The test included 200 students to answer the questionnaire and 104 students in the experimental evacuations; no one with disabilities was involved in the evacuation. The maximum distance during evacuation for the experimental proofs was the same.

Experimental data were used for different work steps. The second part of the work analyzes them in order to highlight the presence of time-consuming pre-movement phenomenon. Organized behaviours were defined by the set of actions and attitudes of individuals during the pre-movement phase, including interaction with the surrounding environment (belongings, objects) and other people; attention was focused on the “attachment” phenomenon [6,14,16]. Pre-movement behaviours noticed had to be present in at least 30% of the cases and/ or were significant in terms of high time-consumption (more than 10s); “wrong” (especially time-wasting) behaviours are stressed and evaluated in quantitative terms. Regarding the numerical inquiry of motion, recordings made with fixed cameras were analyzed, and numerical values (average value, maximum, standard deviation) on pre-movement time, movement time, total egress time, and speeds were obtained. The organized experimental results have been compared to the simulated ones in the third part of the work in order to evaluate whether the simulation software can actually recreate the real phenomenon effectively.

Table 1

Characteristics of localization testing.

Setups	Number of test	Type of test			Height of the blind node	Number of samples
		Still test	Movement test (1.5 m/s)	24 h still test		
1	1	x			0.5	150
	2	x			1.0	150
	3	x			1.8	150
	4		x		1.0	394
2	5			x	0.5	67,369
3	6	x			0.5	7,705
	7		Road 1		1.0	686
	8		Road 2		1.0	546
	9		Road 3		1.0	685
	10		Road 4		1.0	585

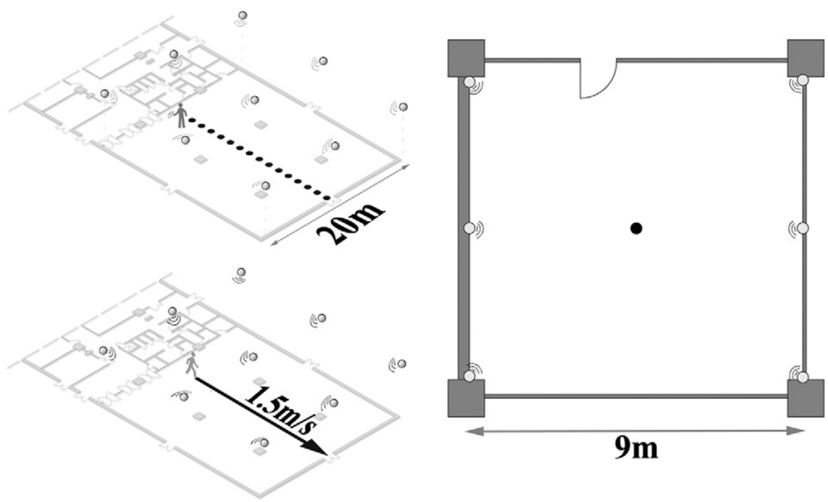

Fig. 1. Setups 1 and 2. A-left: Setup 1, in still test (up) and movement test (bottom). B-left: Setup 2, a 24-hour testing period with the nodes in the same positions.

2.2.4. Possibility to use the simulation software and evaluation of system interaction

The Pathfinder simulation software was used for simulation in a free trial licence. Pathfinder is an agent-based egress simulator that uses steering behaviours to model occupants' motion [59,60]. A previous large validation of the simulator is offered [61].

The experimental evacuation conducted in the 140/5 classroom was repeated using this simulation software. Obviously, input values concerning classroom geometry and the parameters of students (number, position, pre-movement time, walking speed) were the same as those of the experimental evacuation. Fig. 3 shows a 3D-frame of the environment that was tested in the simulation, which shows obstacles (white spaces), people (grey cylinders) and the exit (black triangle).

Firstly, a comparison between experimental evacuation and simulation results has been made in terms of numerical and qualitative data. It was noticed that the numerical values (egress time, pedestrian flow rate at the exit doors) and behaviours of the people evacuating in the simulation are very close to the experimental results. The number of people who exited the room was analyzed during the evacuation time, and two curves were obtained: one for experimental results and the other one for simulation results. The areas under the two curves were calculated. The area under the curve was considered proportional to a sort of general speed during evacuation for the whole evacuation group. The difference between them was divided by the area connected to the experimental curve. This value, offered using the percentage notation, is the “Difference between the graphic Areas Under the experimental and the simulation Curves” (DAUC).

A specific condition for verifying the numerical results was that the simulator had to not produce underestimated results, especially the ones connected with egress time. In other words, a positive DAUC value is required: in this case, the experimental area was higher than the simulated one. As a result, the real evacuation is “faster” than the simulated one. Moreover, a maximum value of 20% in the total difference between the experimental and simulation results would be generally accepted when it is connected to demonstrable conditions. If this verification is positive, the software can also be used to evaluate the proposed system.

Secondly, after this phase, the simulator was used to evaluate the influence of the interactive system in a case study. The same 140/5 classroom scenario was selected for simulation analysis; in this case, each student had his/her interactive wearable device. The aim was to understand whether using this system could improve evacuation. In this possible real-case scenario, the effective individual time of reaction to the stimulus was assumed higher than the R_{time} value of the system; moreover, not all the latecomers would respond to the stimulus positively.

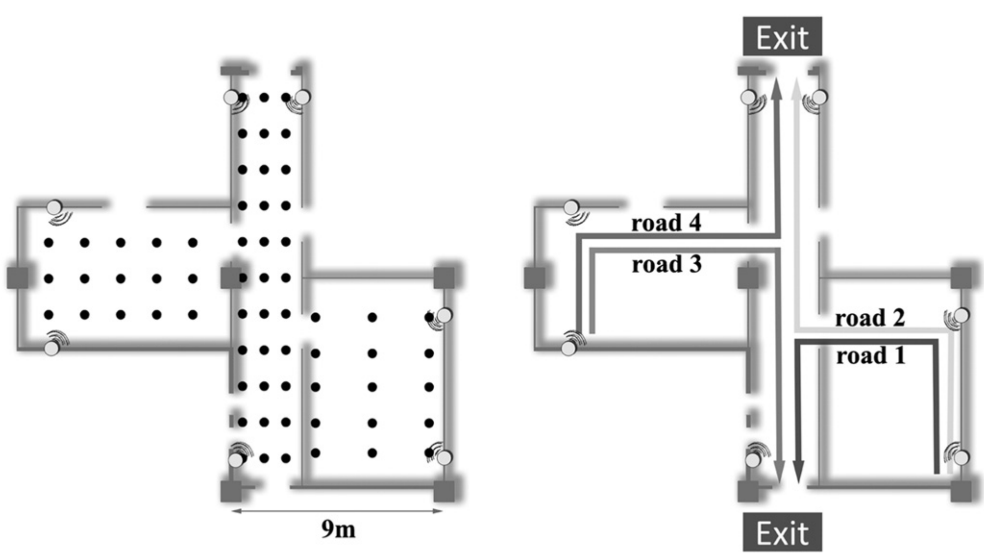

Fig. 2. Setup 3: in still test (left) and movement test (right).

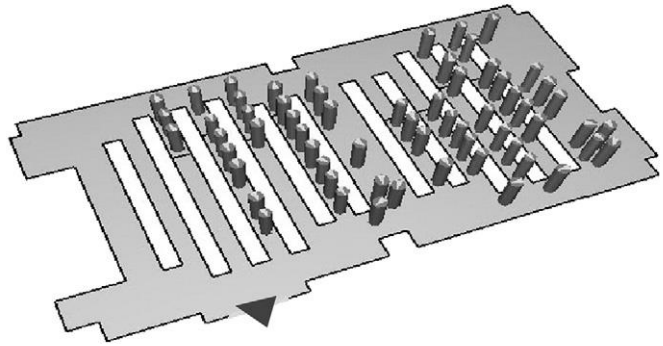

Fig. 3. Reconstruction of the evacuation experiment (140/5 classroom) in the simulation software.

For this reason, each of our simulation setups firstly considered a different individual effective reaction time (R_{ind}), which is included in a range between the R_{time} value and two times the R_{time} value, with intermediate steps every 5 s. The chosen R_{ind} denotes the maximum premovement time for the related simulations. By considering two times the R_{time} value, it was supposed that the device would interact with two stimuli. Moreover, for each of these setups, the simulations considered a series of sub-setups, with a variation in the percentage of the positive reactions of the latecomers to the stimulus, starting from 10% to 100%; stimulated latecomers were randomly chosen.

Evacuation time at the 54th individual was analyzed in each simulation: the pedestrian flow rate at the door was investigated for each setup and each sub-setup as an index of the evacuation speed. The random choice of *latecomers* with positive response also implied the possibility to have *latecomers* with a negative response to the stimulus: these individuals would have high pre-movement time and, consequently, high total evacuation time and low pedestrian flow rate. For this reason, analysis involved the evacuation time at the 54th student and not at the last individual. Finally, the total evacuation time of the real evacuation experiment was compared to the simulation results including the use of the interactive system.

3. Results

3.1. Interactive system

3.1.1. System design

Previous studies have evidenced the presence of individuals with high time-consuming behaviours in the pre-movement phase (*latecomers*). Therefore, it is necessary to define a system that was capable of identifying the *latecomers* and to interact with them by using an appropriate stimulus in order to reduce their pre-movement time so as to improve the whole evacuation process. These activities are possible if the localization and interaction are provided in a personal way. Fig. 4 shows an overview of our proposed interactive system, which is composed of wearable devices.

Each person in the building owns a device in order to allow a personal and direct stimulus if needed. The components of the device could be put together on a badge, or on a pager or on a bracelet. The first solution is the easiest and more preferable in public spaces or offices: in many cases, an identification badge is distributed to each occupant when she/he enters this kind of building. Generally, the badge is also required to access specific areas and/or services. The idea is to include the proposed interactive device in this badge.

Fig. 4-A shows that each device is based on two main modules: the *localization module* and the *interactive module*. An overview of this system has been described previously (*Interactive system architecture*). The *location module* is able of detecting the position of people during the fire alarm as well as in the evacuation process and, in this way, it can recognize their motion behaviours (so as to understand whether the people are actually moving toward the exits or whether they are just loitering). Fig. 4-B and -C shows the general operational sequence for each wearable device. Individual localization (Fig. 4-B, top) is carried out through communication between the blind node and the reference nodes in the wireless network based on the ZigBee-2006 standard, as described previously (*Interactive system architecture*), and by using trilateration-based techniques.

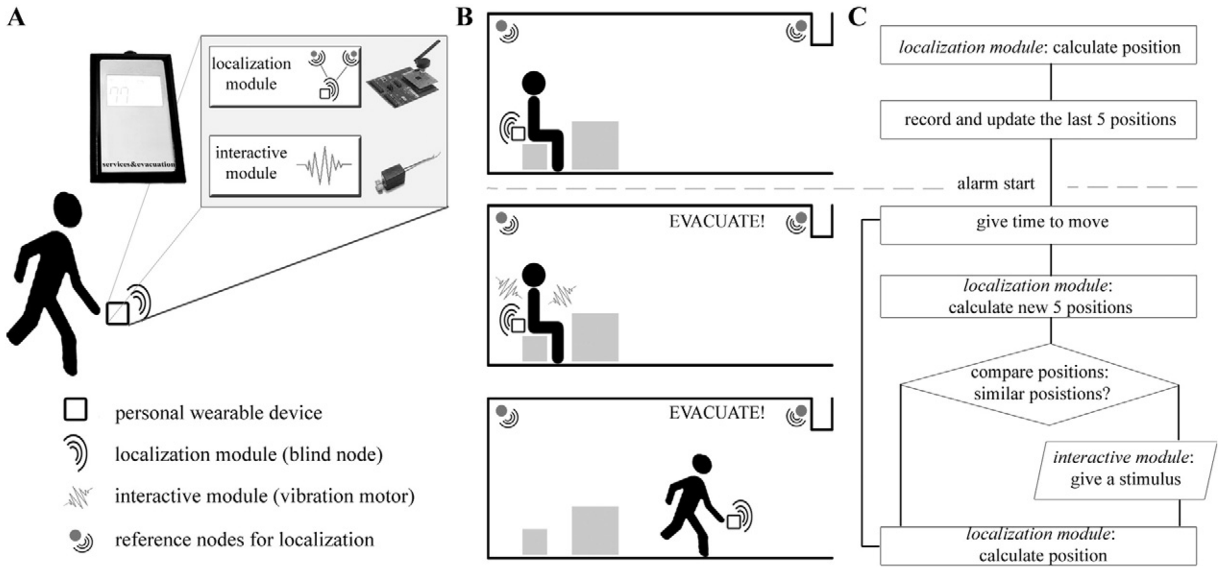

Fig. 4. Interactive wearable system design: on the left, the composition of the system (A); in the centre, a graphical representation of the three main operating phases of the system (B); on the right, the summary flowchart (C), with blocks placed next to the related graphical representation.

This localization is active at all times, in normal conditions: the *location module*, owned by the wearable device, calculates the position continuously and records the last 5 locations. When the fire alarm goes off, evacuation is carried out (Fig. 4-B, middle). The device stops calculating the position of the individual and gives some time to the person to stand up and to cover a distance that is equal to two times the location system error distance. Later, it records 5 new locations and compares them with the previous locations. This approach enables the system to consider a threshold value of the position error and the probability that may occur. If the positions are close, the system detects a possible wrong behaviour and considers that the occupant is not moving (*latecomer*): the *interactive module* gives him a personal stimulus through its integrated vibration motor. The direct stimulus is given for about 3.5 s. Moreover, the *localization module* can also control the rest of the person's motion in a recursive way, and additional stimuli could be given in case of other eventual stops during the evacuation procedure (Fig. 4-B, bottom).

Table 2 operatively synthesizes the components of the system and the related characteristics and requirements. The system requirements connected to the chosen architecture are explored below. In particular, the system is influenced by the characteristics of the localization module which is founded on localization errors and response *time*, which is the time needed to detect the time-wasting behaviour and to interact with the *latecomers*. Actually, the latter factor could influence the efficiency of the whole system.

3.1.2. *Localization system error*

Table 3 shows minimum, mean and maximum localization errors in setup 1. In this classroom, many Wi-Fi devices are used by students. The possible interferences that could take place between these devices and the blind nodes were investigated; the influence of interferences in relation to the height of the blind node was also considered. The average location error was higher than 2 m as described in literature [62]; the minimum error of 0.3 m confirms that some interference occurred, as found in previous studies [56].

Fig. 5 shows the result of a 24 h-period test in setup 2. It is interesting to note that at the university's closing time the average error (1.38 m) appears to be lower than at the opening time (6.91 m). Analyzing the setup of the experiment (closed classroom with no students), it is possible to note that the interferences were caused by the Wi-Fi network activity in the building, as found in previous studies [56].

Fig. 6 shows a map of location error values in setup 3 environment, obtained by test number 6. The location error is lower than the ones in the previous experiments, with a maximum of 13.4 m confined in small areas.

Table 4 shows the minimum, mean and maximum localization errors and their probabilities, for all the tests in setup 3. Although some Wi-Fi networks are still present during the experiment, the average error is almost in line with the values found in previous studies [62].

Table 2

Description of the interactive system.

Module	Components	Position	Main issue	Main requirements
Location	Reference node	In fixed positions in the rooms, near the ceilings	Interaction in the radio range (X/Y location of the reference node and RSSI)	More than one per room
	Blind node	In the wearable device		One per device
	Location engine	In the wearable device	Estimates the blind node position on the RSSI value and records it	
Interactive	Interaction engine	In the wearable device	Calculates the necessity to activate the vibration motor if the individual is not moving	
	Vibration motor	In the wearable device	Gives a direct and personal stimulus to the *latecomer*	Has to be activated within 20 s from when the alarm goes off

Table 3

Localization error in setup 1.

Setup	Number test	Localization error [m]		
		Min	Mean	Max
1	1	0.530	4.325	14.128
	2	1.893	6.484	27.583
	3	1.167	7.700	19.852
	4	0.300	7.099	45.000

3.1.3. *Response time of the proposed interactive system*

Fig. 7 shows the various activities of the proposed interactive system in the course of time. A total time of 18 s is needed to receive and elaborate information, and to give a direct stimulus to the person. The total system time is calculated by using Eq. (1) and the operations in Fig. 4-C. The first system activity (*time for standing up and treading* 10 m) is operatively defined by evaluating the localization error and average student speed; this activity is carried out by the *location module*. In order to evaluate the localization error, collected data in the motion tests of setup 3 were used because setup 3 offers the condition that is more similar to the real situation. A threshold of error of 5 m was chosen: this threshold corresponds to a probability of 83% of the cases, as shown in Table 4. Furthermore, the results were influenced by the individuals' speed: for calculation, the used average student speed was the one recorded in the 140/5 classroom (about 0.94 m/s). This activity time (R'_{time}) is mathematically expressed in Eq. (2); T_s value is equal to 1.46 s according to previous studies [58]:

$$R_{time} = 2 \cdot E/V + T_S = 2 \cdot 5m/(0.94m/s) + 1.46s \approx 12s: \qquad [2]$$

For this reason, the R_{time} is equal to 18 s according to Eq. (1). The *interaction module* involves the second (*time for acquiring 5 new locations*) and third activities (*time for giving a direct stimulus*): they are previously defined in terms of the length of time.

3.2. *Experimental evacuation and pre-movement phase behaviours*

This system so designed could be applied in real-life situations in order to evaluate its positive influence on the evacuation phenomena and, in particular, to evaluate a possible reduction in pre-movement time. The chosen case study is connected with university rooms. Firstly, experimental evacuations were carried out [14] with the purpose of defining the activities that are performed when people are evacuated, especially during the pre-movement phase. Both behavioural and numerical data were investigated. Table 5 shows the list of noticed premovement behaviours, giving special attention to the “attachment” phenomena [14,16]: behaviour keywords, short description, statistical frequency referred to both hypothetical (from questionnaires) and experimental (from the analysis of evacuations, when a direct comparison is possible), and the direct visible consequences of the behaviours have been provided for each one. Data obtained confirm the typical behaviours described in previous studies concerning organization of actions during evacuation and first movement decisions [6,16,63].

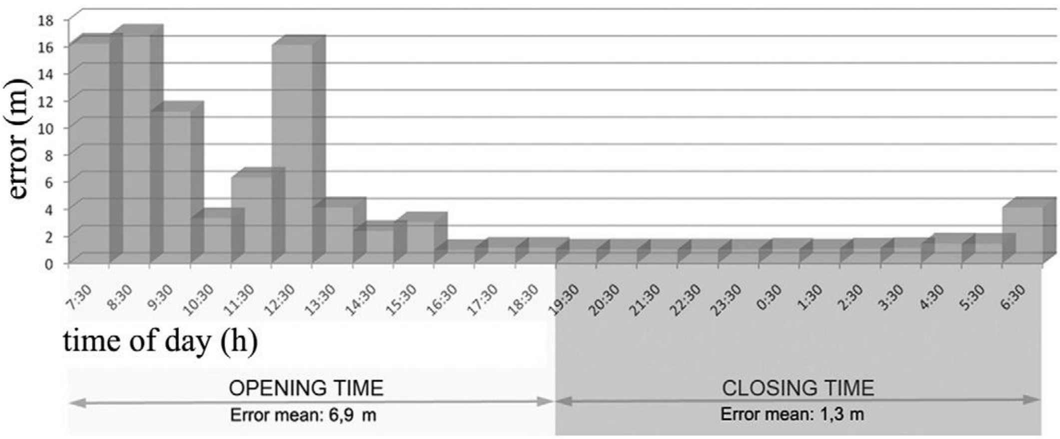

Fig. 5. Localization error in setup 2 (24 h test).

Fig. 8 synthesizes the two main phenomena during the pre-movement and evacuation phases. The first phenomenon is the sense of belonging to a group ("*herd Behaviour*", *attachment to people*), which is confirmed in 80% of the hypothetical cases. In fact, Fig. 8 shows interaction between three people in the same group (the ones marked by a black arrow and two black triangles). After the alarm goes off, the people spend a lot of time on exchanging information [5], as showed in the frame with time +0 s. The group then decides to evacuate (time +3 s). Some individuals hasten to evacuate the room compared to the other people: they then stop and decide to wait for the latecomers (time +8 s). This phenomenon creates high pre-movement time for a group of people. Moreover, during the real movement procedure, the group gets bigger by the arrival of other individuals (marked by a black ellipse) who interact with each other (underlining the presence of "Herd behaviour" [63]) (time + 24 s).

The first phenomenon in Table 5 is the most important one: the "attachment to belongings" behaviour [14,16] has high statistical influence, essentially due to the large number of students who use their personal electronic devices while in the university classrooms.

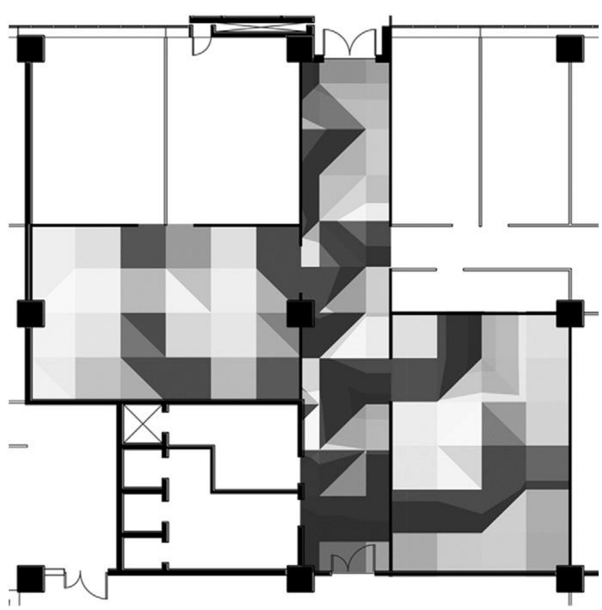

Fig. 6. Location error map in setup 3, experiment 6: areas with the same greyscale colour have the same error range (0–5 m for white, 5–10 m for light grey, 10–13.4 m for dark grey).

Fig. 8 shows how some of the students in the black rectangle are still interacting with their laptops even after the alarm has gone off and other individuals have already started evacuating. In fact, in such cases, students would not leave these objects in the classroom because of their importance and due to the data stored in them for future use. This phenomenon implies a related high pre-movement time. However, some students, who are engaged in these extremely slow data-rescue operations and in the collection of their belongings, can cause a slowing down of the evacuation process and can also oblige other students to leave from the opposite side of the room. In addition, the *coming-andgoing* phenomenon is another wrong behaviour connected with collecting one's belongings. Movement time starts when the individual effectively starts the exiting process. For this reason, the time spent by an individual on the *coming-and-going* behaviour is considered as premovement time.

Table 6 summarizes the statistical analysis of evacuation quantities. Pre-movement time is significantly greater than movement time. Maximum values correspond to the students that are strongly attached to their belongings [16], and as such, to *coming-and-going* or *attachment to belongings* (in particular for the long time taken for saving data) behaviour. This phenomenon has a big influence due to the very high percentage of students who use their personal electronic devices at the time of evacuation.

In addition, Fig. 9 shows the evacuation speed and pre-movement time distributions. Statistical tests on our experimental data (Kolmogorov—Smirnov, Anderson—Darling, Chi-square) suggest to adopt the 3 parameter gamma distribution, but Weibull distribution reported by Purser e Bensilum cannot be rejected [8].

Finally, concerning evacuation speeds, the average value obtained is lower than the results found in previous studies [64] in terms of "normal" conditions, but it is high if compared with average speed values reported for educational buildings (0.25—0.33 m/s) or public places in general (0.5—0.7 m/s) [65]. These results depend on the influence of characteristics of the occupants, such as age, gender, grouping, clothing and physical ability [66].

3.3. *Comparison between experimental and simulationresults*

Experimental evacuation was recreated using the Pathfinder simulation software. Experimental results were compared to simulation results with the purpose of verifying the possibility of reproducing similar evacuation phenomena in terms of pedestrian behaviours and numerical quantities of motion. Fig. 10 compares the results of simulations (grey line) and experiments (black line) concerning the number of people that left the room during the time of evacuation.

Table 4

Localization error in setup 3.

Number test	Localization error [m]			Localization error probability (99% confidence degree)		
	Min	Mean	Max	<4 m	<5 m	<6 m
6	0.09	3.17	13.39	77.99% ± 1.30%	85.11% ± 1.04%	93.98% ± 0.70%
7	0.15	2.78	12.00	72.58% ± 2.30%	83.57% ± 1.91%	92.33% ± 1.37%
8	0.06	3.95	13.97			
9	0.46	3.95	13.11			
10	0.19	3.09	8.62			

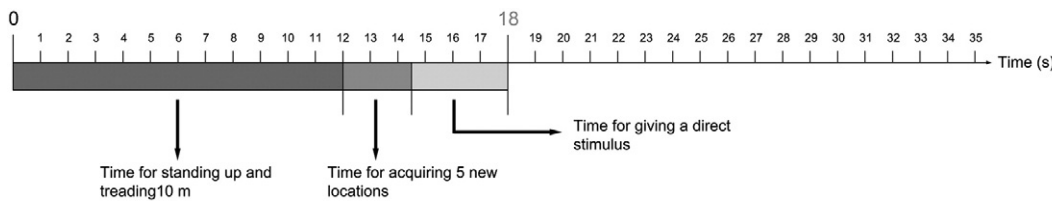

Fig. 7. Temporal bar of the proposed system response time.

The minimum value in pre-movement time is fixed (equal to about 17 s) in the software by using the experimental evacuation results. The first part of the graph (from 0 s to 30 s) underlines the perfect correspondence between the results of the simulation software and those of experimental evacuation. The students who left the room in this period of time were the ones who were sitting on the outside row of seats, which was analogous to the real case. Fig. 11 shows the initial position (Fig. 11-A) of the students; then, there is the comparison between the frame from the experimental (Fig. 11-B) and the simulation (Fig. 11- C) videotapes which confirms the same movement phenomena and the arrival to the exit door.

Starting from 30 s to 74 s, differences in the number of evacuated pedestrians for each evacuation time step were due to the experimental pre-movement phenomenon. In particular, the most influencing factor is the *coming-and-going* behaviour. This phenomenon cannot be carried out in the Pathfinder model: people can delay the start of the evacuation process but they cannot choose to come back. This case could be simulated by increasing the pre-movement time. Again, the simulation model does not consider the possibility that people can stop collecting their personal devices thereby allowing other people to continue the evacuation process; the Pathfinder model is programmed in such a way that if a person is involved in pre-movement activities it will completely block the way for other people to evacuate.

However, according to the chosen evaluation criteria, simulation results can be considered close to the real ones. In order to confirm this statement, the aforementioned DAUC values for the time range between 30 s and 74 s were analyzed. The related percentage difference was calculated to about 14%. This demonstrates that, in general terms, the experimental evacuation process is, on average, 0.14 times faster than the simulated one, from 30 s to 74 s. Moreover, simulation results do not overestimate the evacuation phenomenon with respect to the experimental ones, and so it is also possible to consider these precautionary values valid.

Finally, starting from 74 s, simulation and experimental results are identical. This phase involves the evacuation of students who are highly influenced by the *attachment to belongings* behaviour, just like the one observed in Fig. 12. They spend a very long time in saving their data and collecting their belongings, as in Fig. 12-B: this phenomenon was also recreated by the simulation software in Fig. 12-A from both numerical (egress time) and behavioural (qualitative frames analysis) points of view.

Finally, the pedestrian flow rate at the doors was compared. Table 7 resumes the comparison between experimental and simulation values; evacuation data at the 54th individual are useful for the next step concerning the evaluation of the effectiveness of the system. Each value is compatible with the limit fixed by the proposed evaluation criteria.

3.4. *Effectiveness of the proposed system*

The Pathfinder simulation software can be considered a valid tool for recreating evacuation conditions in the chosen environment, as verified previously. For this reason, the simulator was used for system effectiveness analysis in our case-study (140/5 classroom). According to the aforementioned criteria, Fig. 13 compares the pedestrian flow rate at the doors considering the egress time of the 54th evacuating individual: this flow is a function of different percentages of individuals with a positive response. For each simulation, it was assumed that the selected percentage of people decreased their pre-movement time: for this reason, the R_{ind} value decreases, with a minimum that is equal to the R_{time} of the proposed system.

Table 5

Observation regarding pre-movement behaviours.

Behaviour keywords	Short description	Frequency (%)		Consequences
		Hypoth.	Exper.	
Attachment to belongings	People first collect their belongings and then go to the exit	29%	55%	Queuing phenomenon High individual pre-movement time
"Herd behaviour"	People's movements and velocity depend on their neighbours' movements and velocity	48%	(−)	Group motion
Attachment to people	People first wait for other people and then go to the exit	36%	(−)	Queuing phenomenon Group motion Increasing collective pre-movement time
Coming-and-going	People apparently start evacuating, but rapidly return to the initial point to collect their belongings, and then go to the exit	(−)	21%	Queuing phenomenon Counterflow movement High individual pre-movement time

Fig. 8. Frames from the 140/5 classroom evacuation recording, numbered by time, showing an example of the sense of belonging to a group (black arrow, two black triangles, black ellipse) and of attachment to belongings behaviours (student in the black rectangle); time + 0 s is arbitrarily fixed after the alarm goes off.

Table 6 Basic statistics for the variables Pre-movement time, Movement time, and Evacuation speed in the two experiments and only in the 140/5 classroom evacuation. "Two experiments" columns refer to the whole data sample (two evacuations from the two different classrooms) while the "Single experiment" columns refer to a single classroom evacuation 140/5 classroom [14].

	Two experiments			Single experiment (140/5 classroom)		
Data	Pre-movement time [s]	Movement time [s]	Evacuation speed [m/s]	Pre-movement time [s]	Movement time [s]	Evacuation speed [m/s]
Minimum	5.6	4.6	0.35	12.9	4.6	0.35
Maximum	71.4	34.2	2.17	71.4	34.3	2.17
Median	21.6	14.2	0.84	32.3	13.4	0.85
Arithmetic mean	25.9	15.5	0.92	34.3	14.6	0.94
St. deviation	15.8	6.7	0.33	15.1	6.7	0.36

In general terms, no improvements in the evacuation procedure are due to a percentage lower than 40%; in all these cases, the pedestrian flow rate at the 54th individuals is obviously the same as that in Table 7. Moreover, when the R_{ind} value increases, a reduction in evacuation time (resulting in an increased flow rate) can be noticed: this phenomenon is naturally more evident for the high percentages of individuals with a positive reaction. For $R_{ind} = 2\ R_{time}$, an increase in the flow rate by about 10% is reached. Over this time, the improvement in evacuation seems to be not so important. In addition, the R_{ind} value also influences the inferior limit of efficiency for the system in terms of the percentage of reactive individuals. Analyses involved the evacuation procedure in detail by assuming the maximum level of improvement, and as such R_{ind} = 18 s was chosen. Fig. 14 shows the total evacuation time required by the 54th student in 10 different simulation sub-setups; the total evacuation time includes both the pre-movement and movement phases. Every setup considers a different percentage of positive reaction of the *latecomers* to the stimulus, starting from 10% to 100%. Fig. 14 shows that our response time (equal to 18 s) requires a percentage of positive reaction to the stimulus above 30% in order to have the first benefits. Finally, Fig. 15 compares the time in the evacuation experiment (without devices), the simulation with a null percentage (0%) of positive responses to stimulus, and the simulation with a full percentage (100%) of positive response.

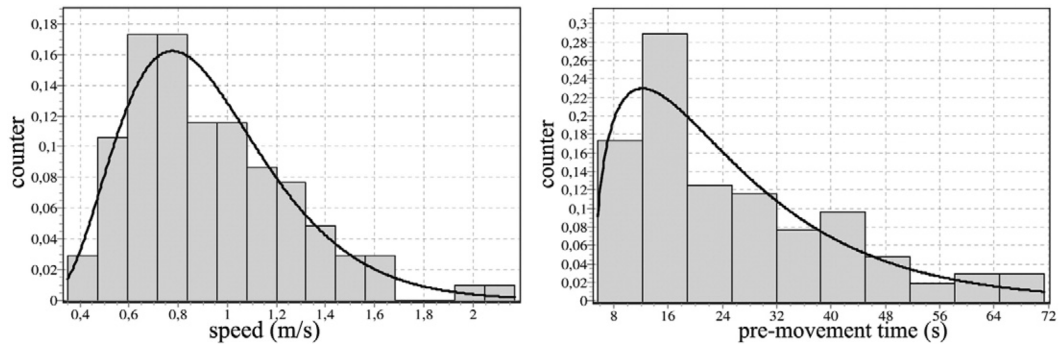

Fig. 9. Evacuation speeds and pre-movement time distributions in experimental evacuations.

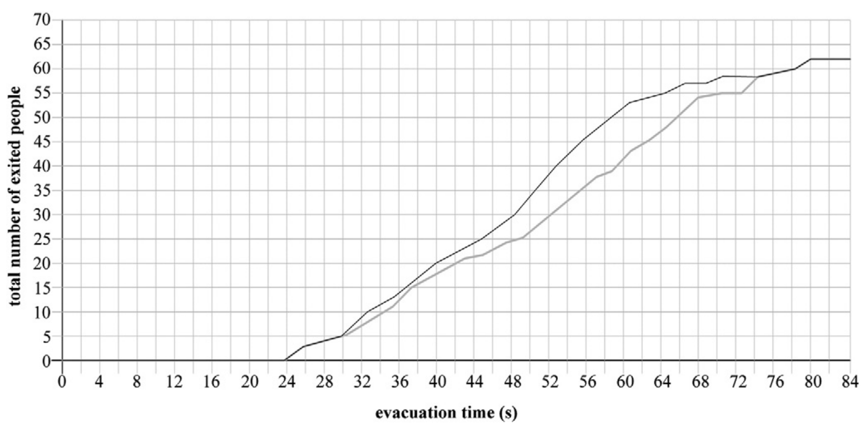

Fig. 10. Number of people that exited 140/5 classroom during the time of evacuation: comparison between the results of the simulation (grey line) and experimental evacuation (black line).

Fig. 11. A plan of the evacuation phase for the students leaving first (numbered people): on the left, the students' initial positions at the sounding of the fire alarm (A), in the middle, a frame of the experimental evacuation videotape, about 22 s from the sounding of

the fire alarm (B); on the right, a plan of the related simulation frame (C); students' positions are evidenced with numbers in every figure, and each number corresponds to the same student in the different figures A, B and C.

The evacuation experiment line and 0% system interaction line describe same evacuation conditions: the premovement time is influenced by no stimulus and its related distribution is similar to the one proposed in Fig. 9. In addition, according to Table 7, the minimum experimental egress time is a little higher than the simulator value (+3%). In this case, the simulator overestimates the total egress time, and so the experimental line has to be under this superior limit. Differences between the experimental evacuation and the 0% positive response simulation are essentially due to the numerical definition of some particular phenomena in evacuation, as explained in the previous paragraph. On the contrary, the 100% system interaction line implicates a maximum pre-movement time of about 18 s. For this reason, this line represents the inferior limit in egress time reduction due to the effective device interaction. Fig. 15 shows how it is possible to reduce the total evacuation time up to 30%: total evacuation time decreases from 81.56 to 57.00 s, with 24.56 s of benefit.

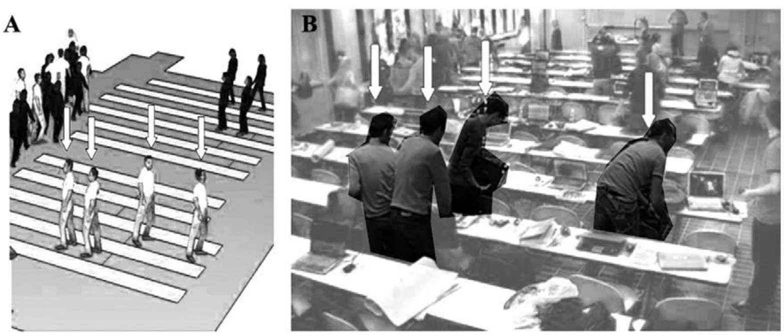

Fig. 12. Frames showing the presence of so-called *attachment to belongings* phenomenon: on the left, a simulation frame (A); on the right, the experimental videotape frame involving the same students (B).

Table 7

Evacuation quantities in experimental activity and simulation, including percentage differences between the values.

Quantity	Unit of measurement	Experimental value	Simulation value	Difference (%)
Maximum egress time	s	81.56	81.64	<−0.01%
Minimum egress time	s	24.88	24.20	3%
Pedestrian flow rate at the door at the last individual	Person/s	0.76	0.76	0%
54th pedestrian's egress time	s	61.64	68.00	−10%
Pedestrian flow rate at the door at the 54th individual	Person/s	0.88	0.79	10%
DAUC	%	–	–	14%

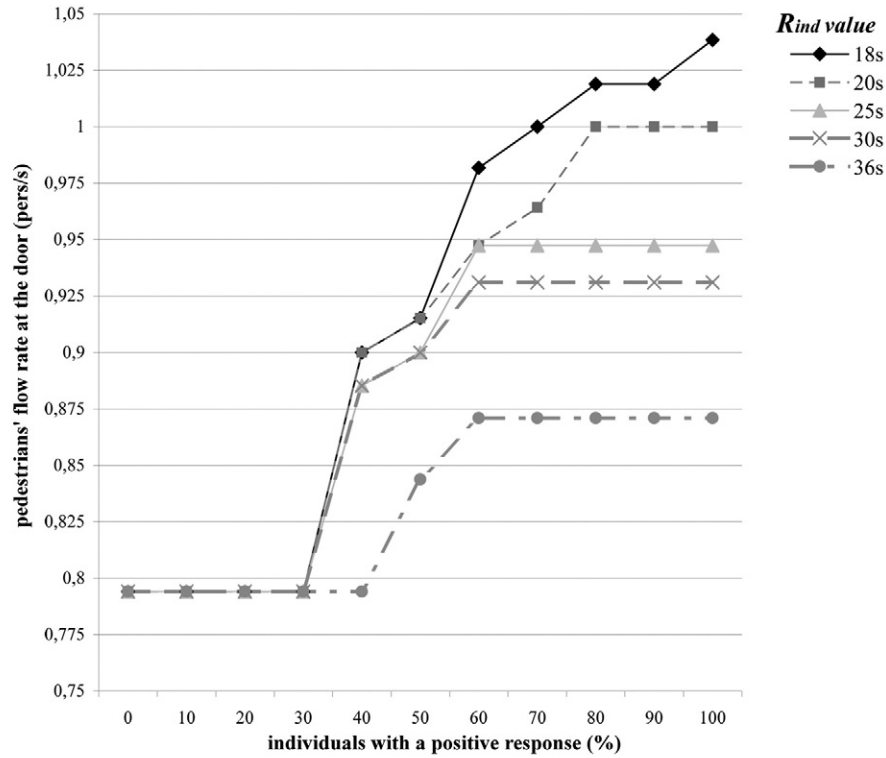

Fig. 13. Pedestrian flow rate at the doors by varying the positive reaction percentage of individuals and different R_{ind} values.

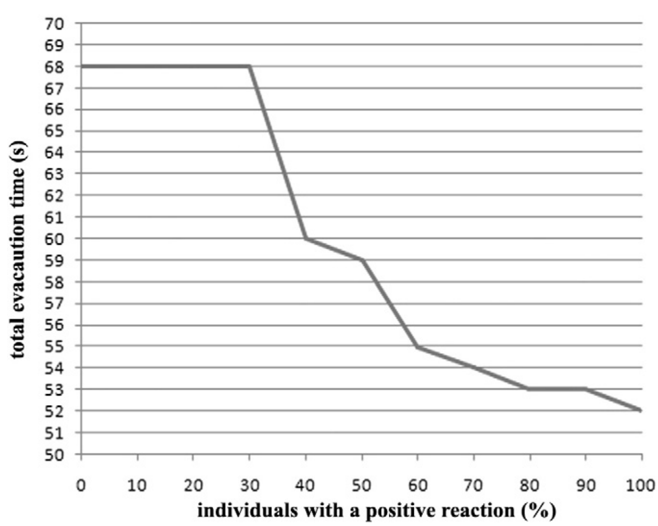

Fig. 14. Evacuation time at the 54th student in 10 different simulation setups of percentages of reaction.

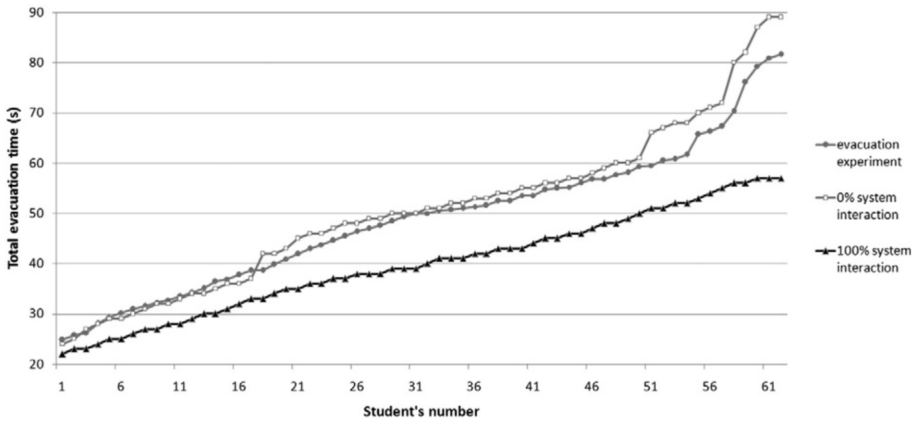

Fig. 15. Comparison between the evacuation experiments, the simulation of system interaction with a null positive reaction to the stimulus, the simulation of system interaction with a total (100%) positive reaction to the stimulus.

4. Conclusions

The development of information technology has led to a large diffusion of electronic devices in many activities, and no data is currently available which relates to interaction between individuals and these devices during an evacuation procedure. People who use personal electronic devices (laptops, tablets) can be easily inclined to waste time in wrong behaviours in an emergency situation, such as saving data and packing up devices, which result in spending a lot of time on these activities. On the one hand, these activities lead to very high premovement time, thereby generating high individual total evacuation time. On the other, they can create a general queuing phenomenon during evacuation by blocking some evacuation routes. In order to improve the whole evacuation process, it is essential to introduce an interactive system for identifying latecomers and giving them a personal stimulus for avoiding these kinds of behaviours.

Our work has designed a system for reducing pre-movement time, based on interactive individual wearable devices, which can also be applied to a person's badge or pager. The device is able to determine a person's position in order to understand whether the person is involved in any wrong evacuation behaviour, so as to give a personal stimulus to him through the wearable device he is wearing. The system uses ZigBee network for determining the individual's position (*location module*) and a microchip for interacting with him/her (*interactive module*) by means of a vibration motor. The technological requirements are evaluated. Firstly, the time required to identify the *latecomer* and interact with him/her through a stimulus (*response time*) is equal to 18 s: this value implies that our system can effectively operate if the individual's pre-movement time is equal or higher than 18 s. Moreover, these kinds of systems can be influenced in determining an individual's position if other Wi-Fi networks are present; however, the threshold of error (5 m) for our system was considered in the *location module* for assigning people's positions and for evaluating their response time.

This system was applied to a case study which was an evacuation of university classrooms. Firstly, the attention was focused on the premovement time in a similar environment. In particular, investigations involved the presence of fire in the classrooms where students were interacting with their personal electronic devices. A comparison between the results of an experimental evacuation and its reproduction using simulation software was carried out. The simulator was able to reasonably reproduce the real evacuation phenomenon, and therefore, it was used for analyzing the effectiveness of the system in our case-study. According to our evacuation simulations, the use of our interactive system can significantly reduce pre-movement time and consequently total evacuation time. Different reaction times for the individuals were investigated. It was able to achieve up to 30% reduction in total evacuation time.

The effectiveness of the proposed system was investigated by means of a simulation method. Therefore, it would be better to physically create evacuation devices in order to provide a series of real experiments. These experiments would also determine the effective requirements for the type of stimulus to be given by the *interactive module*. Moreover, different localization systems could be compared using different technologies in order to obtain the most efficient system that provides the lowest interference level.

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