Cognitive Buildings for Increasing Elderly Fire Safety in Public Buildings: Design and First Evaluation of a Low-Impact Dynamic Wayfinding System

Gabriele Bernardini, Lucio Ciabattoni, Enrico Quagliarini, and Marco D'Orazio

Abstract The progressive population ageing increases the participation of autonomous Elderly to the community life and their presence in public buildings. Such complex spaces are generally characterized by high occupants' density, with different users' types (including elderly) that additionally own a scarce familiarity with the emergency layout. Emergency safety levels (i.e.: fire) are significantly affected by man-environment interactions, especially for the hosted autonomous Elderly. Here, they tend to choose well-known paths, while group behaviours can provoke overcrowding and, hence, an increasing of the evacuation time. Cognitive Buildings can solve this issue, because they can suggest to people how to behave in relation to the monitored surrounding conditions. This study proposes a Cognitive Wayfinding System (Co-WayS) to be applied in such scenarios, with a low impact level. Co-Ways is composed by: individuals' badges for their wi-fi tracking; building components including wi-fi tracking system and electrically-illumined signs (to dynamically address correct paths to evacuees); central processing unit to solve a density-based guidance algorithm for sign activation. Co-WaysS addresses the egress paths depending on monitored queueing conditions. A first validation in a significant public building is performed through egress drills. When using Co-WayS, the evacuation time decreases (−28%) while correct path choices (+17%) and individuals' sign confidence (+58%) increases, with respect to standard signage.

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1 Introduction

The population average age is progressively increasing by provoking a sensible rising in the number of Elderly: only in Italy, from 2007 to 2017, the number of individuals with 65 years and more has been increased of about 2 millions, by leading to an incidence of this age class of 22.3% in respect to the overall National Population.[1] In such a scenario, allowing the Elderly to remain independent and socially included in their daily life is a key challenge. Ambient Assisted Living (AAL) solutions could solve this issue by supporting a person's daily life in both normal and risk (emergency) conditions, and increasing the individual's social connection and independence also into old age [1–3].

To this end, the Built Environment (both indoor and outdoor scenarios) should be designed to include intelligent and Cognitive Building-oriented systems (i.e. implemented in their Building Components and devices) with the aim to [4–6]: (1) detect human activities and behaviours within the situational context of the Built Environment (and so the environmental conditions), by preferring low-impact (for the hosted users and for the Built Environment) solutions; (2) recognize behavioural patterns and users' needs; (3) provide support to the users by means of direct assistance to them (i.e., to autonomous occupants) or by invoking external aid.

Such AAL solutions can ensure independent fruition of the Built Environment by the autonomous Elderly, by hence increasing their quality of life [1, 7, 8]. In this sense, Elderly safety is one of the most challenging topics, especially in relation to possible emergency conditions that they can cause particular stresses to them and so possible additional threads [2, 3, 9].

This work applies this concept to autonomous Elderly's safety issues in buildings, by focusing on the first critical phases of an emergency: the building evacuation process. In fact, the evacuation process for them is critical, especially in case of complex buildings like public ones [2, 3]: in addition to critical conditions due to high occupants' density and the possibility that spaces are not well designed for Elderly's use, such occupants can have scarce familiarity with emergency layout and procedures. These circumstances can lead them to adopt improper and risky behaviours also in terms of evacuation choices and direction (i.e. missed identification of the "best" evacuation path") [2]. To solve these issues, this study proposed a Cognitive Building-oriented System for their support in the evacuation process, which suggests occupants how to behave and where to move in relation to the monitored surrounding conditions. The system is tested by means of a wide-scale drill in a significant public building, by actively involving the Elderly in the experiments.

The structure of the paper firstly offers the literature background adopted to develop the Cognitive Building-oriented System and to set up the experiments (Sect. 2). According to the methodological outline (Sect. 3), results provide the proposed system architecture and its preliminary validation in a significant case

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[1] Source: ISTAT, 2016 https://www.istat.it/it/files/2017/03/Indicatori-Demografici.pdf (in Italian - last access: 01/04/2019).

study application, by comparing egress drills conditions with and without the system itself (Sect. 4).

2 Literature Overview

The current lifestyle of the Elderly makes them frequent public spaces with a possible high density of occupants which are in their informal care networks, such as museums, city halls, 3rd age universities [8]. Allowing autonomous Elderly to be independent in such Architectural Spaces use will additionally help healthcare assistants and other staff members to focus their attention on not-autonomous individuals, by increasing the overall Elderly participation to the community social life and then the life quality for all of them.

To support them in these buildings also in emergency and evacuation conditions, it is essential to focus on three main topics: the general paradigms to be adopted to developing Built Environment-integrated solutions for Elderly's support in such architectural spaces; the factors affecting their safety in emergencies; the solutions that can be adopted to improve their safety during the emergency.

2.1 Paradigms for Built Environment-Integrated Solutions

Cognitive Building-oriented approach [4] moves towards such goal, in proactive and reactive manners [6]. In fact, it firstly analyzes the data collected by the sensors implemented in the building (including the ones on the hosted occupants), and it learns how users behave according to joint man-environment interactions models. Then, it automatically predicts possible critical scenarios and preventively acts (proactive), or it detects incoming anomalous situations and then adapts the implemented components to manipulate the current situation (reactive) thus proceeding to the possibility of implementing alarm signals and improvement measures.

Different paradigms can be merged in this approach to improve their capabilities, and mainly [10–14]:

- Internet-of-Thing (IoT) criteria to effectively interconnect the embedded devices by sharing data, model to analyze them, and computational resources to be used (i.e. also to provide local low-level computations);
- user-centered and behavioural design-based approaches to actively include users' behaviour modeling and understand their effective needs against different environmental drivers, especially in relation to most vulnerable users' categories (i.e. Elderly). In such a way, it could be also possible to develop interactive solutions that can suggest people how to properly behave;
- supporting digital technologies for environment representation, data sharing and storage, by using e.g. Building Information Modeling techniques, also to improve

the management of the facilities in relation to the users' changing needs (i.e. different kind of Elderly hosted within the building).

2.2 Safety-Affecting Factors for Elderly in Buildings

Elderly's safety in public buildings is generally affected by [2, 3, 15–20]:

- low level of familiarity with spaces and safety strategies to be adopted (including the evacuation plan), because of occasional fruition of the buildings itself. By this way, emergency wayfinding activities can be oriented towards well-know spaces (i.e. the path used to enter the building), by leading to risky overcrowding conditions;
- sensory, perceptual, cognitive and communication abilities, as well as motor skills, that can worsen in emergency conditions (e.g. delays in reaction and evacuation start) and, mainly, in case of high occupants' densities and overcrowding (e.g. additional reduction of evacuation speed in groups because of Elderly with lower motion speeds);
- social identification effects, that can affect group choices in the evacuation process (including direction and evacuation target) and lead individuals to support each other by provoking possible group evacuation delays (e.g. people remain in risky conditions to help the Elderly);
- intrinsic features of space layout, that can be not designed to be easily used by them in relation to their motion abilities (especially in case of historic buildings).

As a result, possible evacuation delays and wrong choices (including the ones in wayfinding activities) can expose the Elderly to additional risks. In particular, in case of fires in buildings, they can be affected by serious consequences because of smokes (including irritants), carbon monoxide and fire (burns) exposure [21]. In such conditions, the occupants' safety depends on a rapid building evacuation: this goal can be achieved by suggesting the "best" paths and exits to all the evacuees who can autonomously move, through guidance systems [2, 17].

2.3 Solutions to Support the Elderly in Evacuation

Literature works show the effectiveness of wayfinding signage systems in egress time reduction [2, 18, 22, 23]. In general terms, signage systems can be distinguished between collective (placed in the built environment, so as that more than one individual can be supported by them) or individual (each occupant is supported by his/her personal devices, e.g. a smartphone) [12]. Moreover, they can be:

- "passive" [2, 18, 24]—the evacuation direction addressed by the sign is predetermined; they are the common "standard" evacuation signs currently included in the buildings according to the current fire regulation. They can be reflective, photoluminescent or luminous;

- "active" [12, 22, 23, 25, 26]—the evacuation direction addressed by the sign dynamically varies depending on the surrounding conditions thanking to a combined sensor-control-actuator system. They are composed of luminous signs connected with a common network to the control unit.

"Active" signage systems move towards a Cognitive approach, since they address the "best" paths to evacuees in terms of environmental conditions (e.g.: fire and smokes) and/or human motion and egress process by monitoring check-points conditions. In particular, the individuals' motion is monitored by using personal devices such as badges or electronic devices, CCTV control systems or motion detection devices [12, 22, 26]. Then, these data are used as input by the central control unit, which runs a software control that, step-by-step, assesses the best evacuation paths according to the defined evacuation route calculation algorithms [12].

Different path selection algorithms can be adopted, starting from a route graph of building spaces/paths, such as [12, 22, 27]: threshold-based to evidence blocked paths; Dijkstra's algorithm-based on evacuation path risk; travel distance or evacuation time-based. The guidance algorithm could also take advantage of supervision systems (by means of a safety staff member) or of (quasi) real-time evacuation simulators, which use the input monitored data to evaluate the egress process timing and evolution [22].

Finally, the directional information assessed by the central control unit is displayed to occupants by means of electrical-illumined signs, by including directional and prohibition information [12, 22]. Previous drills demonstrated how "continuous" evacuation signs (at least 1 directional sign per 5 m of paths) can improve the evacuation speed, especially for Elderly, in respect to punctual solutions (on doors, directional changes, etc.) [2, 18]. Sound alarms can be also included in order to help people with visual impairments [26].

However, the effectiveness of wayfinding signage systems are also related to "group phenomena", due to social-shared identity within the hosted individuals or among a "group leader" [16, 19, 20]. Such phenomena affect the whole duration of the evacuation, during both the pre-movement time (i.e. people spend time waiting for other groups members before starting the evacuation) and the motion process. During the evacuation motion, people in the same social group (e.g. family) prefer to move together towards the evacuation target, by sharing the same evacuation direction and adjusting their motion speed to the ones of the other group members. Studies also point out the support given to the most vulnerable individuals (i.e., elderly) within the same group, by also provoking "Coming-and-going" behaviours along the evacuation time to reach or to wait for those individuals [20]. Such behaviours are relevant in public spaces and public buildings, for the interaction between different groups and the creation of macro-groups sharing the same evacuation target. It could be also possible to identify a leader within the evacuation group, which is generally responsible for wayfinding activities for their followers (the group) [19, 20, 25].

"Active" wayfinding signage systems could take advantage of such phenomena to monitor group activities.

"Active" wayfinding signage systems were provided for different public buildings (e.g. train and underground stations, theatres, offices, multi-storeys buildings)[12, 22, 26], and commercial systems have also been developed.[2] Anyway, real-world experiments carried out to evaluate the system effectiveness are still limited in terms of involved number of participants, and, mainly, in terms of elderly participation [22, 26].

3 Phases, Materials and Methods

The current work is organized according to the following two phases:

1. definition of the Cognitive Wayfinding System (Co-WayS), by taking advantages of previous literature researches, and mainly focusing on occupants' evacuation behaviour (i.e. group behaviours) detection. Both behavioural-based (Sect. 3.1) and technological (Sect. 3.2) requirements are shown;
2. experimental drills in a significant case study to evaluate how Co-Ways can improve the evacuation process with respect to the current scenario conditions (standard evacuation signage systems). The case study, the tests methodologies and the Key Performance Indicators (KPIs) adopted for drills results comparison are described in Sect. 3.3.

Drills were performed by involving 49 volunteers, by including autonomous Elderly, as follows: 10 to 24 years-old = 10%; 25 to 38 years-old = 60%; 39 to 52 years-old = 10%; 53 to 75 years-old = 20%). All people involved in the test confirmed having a normal or corrected-to-normal vision, and had no motion impairments. All people also confirmed to be unfamiliar with the architectural spaces used in the test.

3.1 Behavioral-Based Requirements for Co-WayS Definition

In this study, the attention is focused on the individuals' motion as key factor for the "best" path choice. According to a Density-based approach for the "best" path identification [12], the Cognitive Wayfinding System (Co-WayS) should check possible overcrowding conditions in specific areas. Such factor affects the evacuation time by provoking evacuation slowing down or even pushing phenomena between evacuees,

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[2] E.g.: EVACLITE Dynamic and Adaptive Emergency Evacuation Signage: https://www.evaclite.com/ (last access 20/04/2019); Q. Li, T. Plocher, Time-dependent classification and signaling of evacuation route safety, US 7,683,793 B2, 2010 https://www.google.com/patents/US7683793 (last access 20/04/2019).

and then related individuals' injuries, regardless of the considered disaster conditions (e.g. fire, earthquake, general-purpose, terrorist acts) [12, 26].

Firstly, group motion behaviours are considered according to common fruition conditions of public buildings. The Elderly and the other occupants generally prefer entering the building in groups [2] and, according to the social shared identity phenomena described in Sect. 2, they try to gather together also during the evacuation process [16, 20]. Co-WayS can take advantage of this evacuation behaviour, by considering the optimization of the motion monitoring through a related sensor associated with the group leader, instead of each component [19, 25]. The monitoring device given to the group leader is associated with the group dimension. Although the possible simplification of this operational choice, the proposed solution can: (1) reduce the number of monitoring devices to be used by improving the computation timing; (2) lead to a consistent representation of the phenomena especially in case of small groups; (3) encourage evacuees to stay close during the whole process by avoiding "coming-and-going" behaviors and reduce individual-individual interactions along egress paths.

Secondly, the group motion can be monitored by mainly considering specific areas of the Built Environment (called "*control areas*") like geometrical bottlenecks (doors; intersections between corridors, and between corridors and staircases), that can be seriously affected by overcrowding conditions. Co-WayS should count the number of people in such areas to evaluate the occupants' density within them [persons/m^2]. A certain evacuation path could be "unavailable" when the pedestrians' density at the related entrance "*control area*" is higher than 3 persons/m^2 [12]: in this condition, hazardous physical contacts among people can occur and the evacuation flows slows down. When all the possible routes are marked as unavailable, the one with the lower pedestrians' density can be considered as opened.

Finally, Co-Ways has to address the "best" evacuation paths to pedestrians:

- moving along a path or inside a room, by using "continuous" wayfinding signs. The presence of constant directional information can speed up the motion process also for the Elderly, as shown by previous works (up to +54%) [2, 18, 26];
- arriving near a decision point by including doors, by using green/red lights or not marked/red X-marked signs to define the direction to choose/to avoid [12, 22, 23]. Such elements allow individuals to choose the proper evacuation direction.

Electrically-illumined signs can be used to be visible both in lighting and blackout conditions, by placing them also near to the floor (at least along the path) to be visible also in smoke conditions [12, 26].

3.2 Co-WayS Technological Requirements

Co-Ways should adopt wireless communication to detect the individuals' positions and to support the evacuees through the signs. By this way, it ensures rapid application and adaptation, system modularity and improved efficiency of the communication network also in emergency conditions [25, 26].

Hence, group monitoring was performed by using a Wireless Mesh by Apio (https://www.apio.cc/eng/platform/apio-mesh; last access 18/04/2019), that uses the IEEE 802.15.4 (2.4 GHz) standard. In particular, the Apio Gateway was connected to the Apio Dongle to ensure the mesh operation and the connection with the Apio General devices. These were used as monitoring nodes for both the ones with a known (reference nodes, placed in the building in fixed positions) and unknown (blind nodes, given to the individuals) position. The main system controller (hosting the path selection algorithms) connected to the gateway was a Raspberry Pi (operating system ApioOS). In this system, the location engine estimates the blind node position by using the value of Received Signal Strength Indicator (RSSI) [dBm] between the Apio General devices. Preliminary tests are carried out in the drill environment (described in Sect. 3.3) to define the values of RSSI depending on the distance between fixed and movable nodes, to classify critical values for counting the number of individuals inside each *control area.* Tests were carried out by moving a blind node, for 20 times, along a 10 m-long linear path, with a speed of 1 m/s, which is consistent with evacuation speed by previous works [2, 15]. Average RSSI-distance couples were calculated, and results should can be acceptable only if they showed a monotonously decreasing trend. Linear regression was also performed.

Finally, the electrically illumined signs are connected to Gateway by wireless communication. Depending on the path selection algorithm results, the status of the signs is changed. The dimension of the sign (i.e. directional arrows) can be assessed by means of correlation between the dimension and the identification distance. For instance, according to UNI EN 1838:2013 (current standard for evacuation signage in Italy), the identification distance l [m] of each directional sign for internally illumined elements is calculated as $d = 200h$, where h [m] is the sign (arrow) height.

3.3 Evacuation Drills

Co-WayS is applied to a significant scenario: a classroom in the Faculty of Economics at the Università Politecnica delle Marche, placed in Ancona. The classroom can represent a general indoor public space with possible high density of occupants, frequented by Elderly, like 3rd age universities, small theatre or city hall, and where the attention of the occupant attention is directed on a single focal point [8, 12]. The building fire safety requirements on wayfinding signage and emergency plan are designed according to the National Regulation (i.e. D.M. 81/2008). Figure 1 shows the scenario application layout, by also defining the conditions of the stepped classroom where the participants were placed at the evacuation starting (i.e. the position of the participants).

Two building exits are considered in the experiments, as sketched by Fig. 1: the entrance door $\mathrm{U_E}$ (Fig. 1A); the fire compartment door $\mathrm{U_A}$, placed at the first floor (it can be considered as a building exit since it leads to another fire compartment where

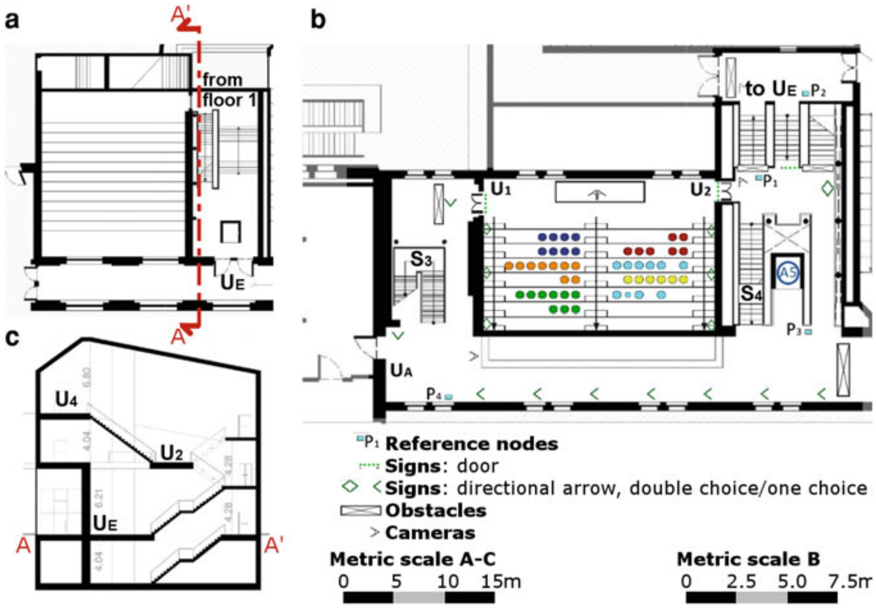

Fig. 1 The scenario characterization: **a** ground floor layout; **b** first floor layout, by including symbol explanation (dots are the individuals' positions in both the tests; each colour refers to a group); **c** section view of the building

people could be considered as safe, and then to the outdoor by means of a secondary evacuation staircase). Furthermore, the stepped classroom has 4 exits: two downside door U_1 and U_2 (directly on the first floor, as shown in Fig. 1B) and two upside door U_3 and U_4 (connected to the first floor by means of dedicated staircases S_3 and S_4 in Fig. 1B). Figure 1C resumes the related section view for the building.

Figure 2 shows the evacuation paths according to the building emergency plan: standard reflective signs are punctually placed at the door and at the intersection between corridors and between corridors and staircases, to point out the evacuation direction define in the plan. Table 1 resumes the possible main paths that can be used to exit the classroom and reach one of the exits. It can be noticed that the main evacuation path links the room to the fire compartment door U_A instead of to the entrance door U_E, by exiting the room from U_1 or U_3. Figure 1 also shows the position of Co-WayS elements (including signs) in the test environment. Video cameras were placed inside the classroom and at the intermediate doors/paths intersections, and at the exits, to monitor the drills. Either the tests (without and with Co-Ways application) were performed during a short seminary in order to reproduce real cases conditions. The test without Co-WayS (original scenario) were performed before the one with Co-WayS implementation. Since no information about evacuation paths was given to the participants when entering the building (as in normal fruition conditions), this choice could support the fact that people were not affected by the knowledge of secondary evacuation paths [12].

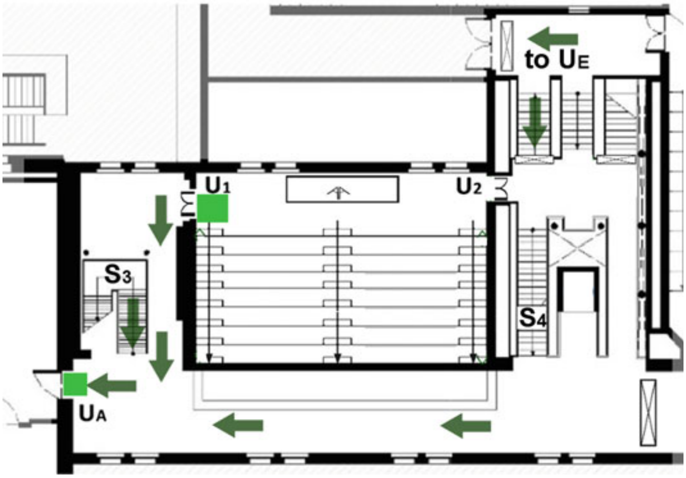

Fig. 2 Evacuation plan (arrows are the paths) implemented in the original scenario. Standard signs are placed at the door (green squares) and at paths intersection. The metric scale is the displayed by Fig. 1b

Table 1 Possible paths to be used by stepped classroom occupants. – means none. Elements codes refer to Fig. 1 localization. CO-WayS control areas are also stressed. Paths 3 and 5 are the paths considered in the emergency plan (original scenario, without Co-WayS application)

Path code	Classroom exit	Staircase to first floor	Intermediate point	Exit	Control area in Co-wayS
1	U_2	–	P_1 then P_2	U_E	P_1 then P_2
2	U_4	S_4	P_1 then P_2	U_E	P_1 then P_2
3	U_1	–	P_4	U_A	P_4
4	U_2	–	P_1 then P_3 then P4	U_A	P_1 then P_3
5	U_3	S_3	P_4	U_A	P_4
6	U_4	S_4	P_1 then P_3 then P4	U_A	P_1 then P_3

In the two tests, the whole sample entered the university building in groups by the main entrance, and then they occupied the seats in the room on the first floor. Individuals' positions were randomly chosen by each group, by considering that all the group members had to seat close one to each other, and by taking account a homogenous distribution for the room. Occupants' positions during the first drill (without Co-WayS) were exactly replicated in the second drill (with Co-Ways), as shown by Fig. 1.

During the seminary, the fire alarm rang and the voice alarm announced: "Please, the evacuation drill is started. The audience is invited to not hurry and to exit the building by following the wayfinding systems". Each evacuation drill ended when the last occupant reached the considered exits in Fig. 1 (U_A or U_E). After each drill, persons were asked to fill out a questionnaire. Questions concern the evacuation way-finding system appreciation (according to a likelihood scale 0 to 4: for all the participants “Did you find the system helpful in evacuation choices?”, and, for Elderly, “Was the sign visible and easy to be understood?”) and the individuals’ perception on group motion assumption (yes or no response; “Did you perceive that you move together with your group?”).

Video cameras were used to monitor the evacuation conditions in each drill from a qualitative (adopted behaviours, by focusing on the main Elderly-related ones in relation to the group; use of evacuation signs) and quantitative (individuals’ and groups path selection, number of exited occupants against the time, group evacuation time) standpoint. Adopted approximation was 1 s for the evacuation time-related quantities. Since the effectiveness of continuous wayfinding signs on individuals’ choices and speed were assessed by previous works [2, 18], Key Performance Indicators (KPIs) used to assess the evacuation conditions were focused on the overall effects of Co-WayS on the evacuation conditions, by outlining: evacuation paths choices (e.g. exits usage) [persons], overall evacuation time [s], evacuation flows at the exits (by using linear regression on the number of exited occupants against the time; the flows are the coefficient multiplying the x variable) [persons/s]. For each of these quantities A (including questionnaires results), percentage differences dA [%] were calculated between Co-Ways supported (subscript *Co-WayS*) and original (subscript *Orig*) scenario according to Eq. 1:

$$dA = \frac{A_{Co-WayS} - A_{Orig}}{A_{Orig}} [\%] \tag{1}$$

4 Results

According to Sect. 3 phases, results are organized in two parts: (1) Co-WayS definition and implementation to the case study (see Sect. 4.1); (2) evacuation drill results in the original scenario conditions and in case of Co-WayS application, by comparing the two systems according to Sect. 3.3 KPIs, and analyzing the individuals’ confidence in respect to the Co-WayS, through questionnaires to the involved volunteers (see Sect. 4.2).

4.1 Co-WayS Definition and Implementation in the Case Study

Co-Ways is composed as shown by Table 2. The main device is a wearable one for each group (hold by the group leader) in the environment, which is the blind node of

Table 2 Co-Ways components characterization

Components	Main task	Main requirements
Reference node	Interaction with the blind node; known position	At least one for each “control area” entrance
Blind node	Interaction with the reference node	One for device, given to the individual (i.e. leader of the group, while entering the building)
Gateway	Ensure the communication between the system elements	At least one, to create a unique mesh for building/building part
Main controller	Estimation of the number of blind nodes (by using the RSSI value) for each “control area”; evacuation path solving	One for building/building part
Wayfinding sign (door)	Addressing paths to be used and paths to be prohibited	One for door/control area access, by using LED-strip portals (green/red light)
Wayfinding sign (directional arrows)	Pointing out the direction along a path	At least 1 per 5 m of path (continuous wayfinding signs)

the localization system (Apio General). The blind node is delivered when the group enters the building, by associating the related number of people in a database.

When the alarm rings and the evacuation starts, the main controller collects the positions of the blind nodes. It uses the Density-based solving algorithm described in [12], which address open paths with less than 3 person/m^2 in the entrance *control area*. The group is considered to be in the control area when the related RSSI value is higher than a certain experimental threshold. Figure 3 shows the average RSSI values against the distance between blind and reference node in the considered testing scenario. For each distance, the percentage RSSI-related standard deviation is lower than 10%. Experimental pairs confirm a monotonously decreasing trend of data, which can be associated with the following linear regression: $RSSI\ [dBm] = -2.9\ dBm/m * distance\ [m] + 40\ dBm$ (R^2 of about 0.5). In the drills, the frequency of sampling for RSSI values was set equal to 1.5 s. According to the dimension of the scenario in Fig. 1, a control area of about 4 m of radius (centered on the reference node) is considered, so as to: avoid the overlapping between the nearest control areas; ensure at least 2 position localization inside the *control area* also in case the evacuees move at high speed (about 2 m/s); measuring, at least, the identification of 3 groups of about 10 individuals inside the *control area* in critical conditions, except for physical obstacles (3 persons/m^2). This choice also fits with confident Fig. 3 results, by taking advantages of the significant decreasing of RSSI between 2 and 3 m. Hence, all the blind nodes with RSSI $\geq$ 30 dBM in relation to a specific reference node were considered inside the related *control area*.

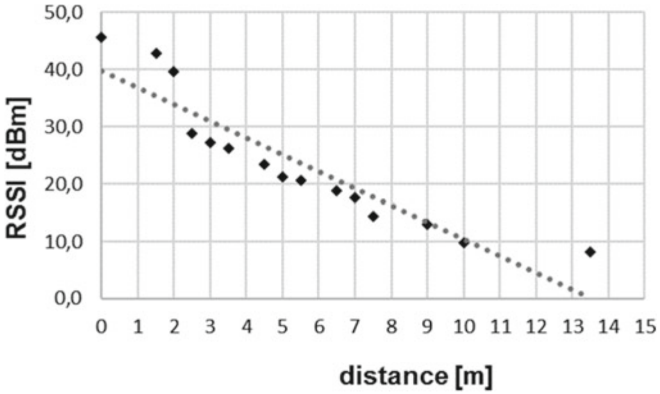

Fig. 3 RSSI against the distance between the blind and the reference node. Points are experimental pairs (average values), the dotted line is the adopted linear regression

Fig. 4 View of the Co-WayS application in the testing scenario: **a** stepped classroom (directional sign and, on the top, the U3 door sign); **b** door sign (prohibited access, red; to be used, green); **c** along the corridor (directional arrows)

Co-WayS reference nodes and signs are implemented as shown by Fig. 1b. The reference nodes are assigned to the *control areas* described in Table 1, so as to define if a path can be open or not. Finally, Fig. 4 shows some relevant views of the Co-WayS signs application in the building (by using RGB LED strips, Lm/LED: 12, Lm/m:800, 60 LED/m). The directional arrows are 17 cm high to be seen at about 30 m of distance (maximum length of a corridor within the building), according to Sect. 3.3 requirements. LED strips at the door are 1 m long.

4.2 Drill Evacuation Results

In general terms, the use of Co-WayS improves the emergency conditions according to the defined KPIs. In fact, it firstly allows an overall reduction of the egress time of about 15 s, that means -28% in percentage terms, as shown by Fig. 5. In both the drills results, it is possible to distinguish two evacuation parts: the first one related to

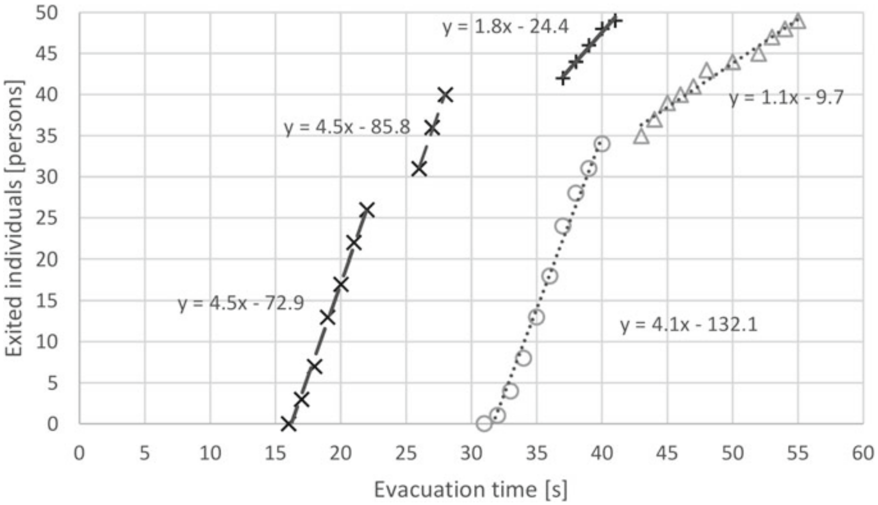

Fig. 5 Number of exited individuals versus the evacuation time for the original scenario (light grey pairs: circles refers to U_A exit and triangles to U_E exit) and the Co-WayS scenario (black pairs: X refers to U_A exit and + to U_E exit). Linear regression for each group of individuals is offered to evidence people moving in groups, and the related equation is offered (R^2 always greater than 0.97): here, the flows are the coefficient multiplying the x variable [persons/s]

the use of U_A related paths (people who arrived first, or rather before about 40 s in the original scenario, and before about 27 s in the Co-WayS scenario) and the second one related to the use of U_E related paths. Choosing to move towards U_E implies higher evacuation times, mainly because of the path length. Anyway, the evacuation flows at each exit improve while using the Co-WayS, as shown by the linear regression in Fig. 5, according to Sect. 3.3 definition: the flows increase of + 63% for U_E (from 4.1 to 4.5 persons/s) and +10% for U_A (from 1.1 to 1.8 persons/s).

These results can be obtained because of the optimization of the evacuation path use by means of their control in terms of density at related bottlenecks (*control areas* in Table 1). Meanwhile, the use of U_A (which is connected to the recommended evacuation path) is increased of +17% in Co-WayS use conditions in comparison to the original scenario (from 27 to 40 persons using U_E and the related paths).

Figure 6a shows the paths used in the original scenario drill for each group. Paths identified by the codes 1, 3 and 5 were used (see Table 1). Hence, the evacuation plan is partially followed by the individuals. In general terms, the occupants moved towards the nearest classroom exit, regardless of the overall evacuation layout. Then, they move towards the nearest identifiable exit. In particular, the choice of using U_E related paths (path code 1 in Table 1) can be related to the familiarity with the entrance route in combination to group phenomena (social-shared identity combined to leader–follower effects) [19]. All the Elderly follow their group leader by adopting this behaviour. The groups similarly arrived at the doors, so only two linear regression are noticed in Fig. 5.

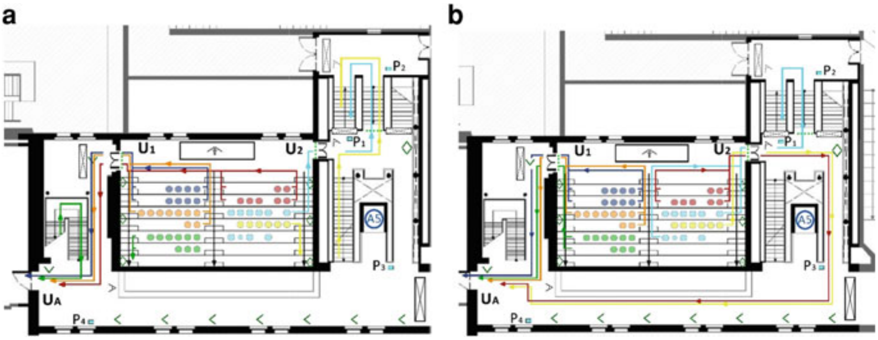

Fig. 6 Evacuation paths followed by the groups in: **a** original scenario conditions; **b** Co-WayS scenario. The initial group members' positions are the colored dots; each color is associated to a different group, and the related path has the same color

Figure 6b shows the paths used in the Co-WayS drill for each group. In this condition, most of the occupants used paths 3 and 4, while path 1 was used only by a group (see Table 1). In this conditions, the "cyan" group members arrived at the decisional point after "red" and "yellow" groups, as shown by the RSSI values over the evacuation time in Fig. 7, concerning the control area P_1 (which refers to U_2, compare to Table 1). Meanwhile, path 4 reaches critical conditions of density at the *control area* P_3 because of the arrival of "red" and "yellow" groups. Hence, path 4 is considered as blocked and the signs changed their status, by suggesting the "cyan" group to move towards path 1 and U_E.

Finally, questionnaires results to the involved individuals evidenced an increased satisfaction towards the Co-WayS with respect to the standard signs. About the question "Did you find the system helpful in evacuation choices?", the modal value for the likelihood-scale vote was 2 for standard signage (31% of people; vote 4: 25% of people) and 4 for Co-WayS (83% of people). The 75% of Elderly also stated that

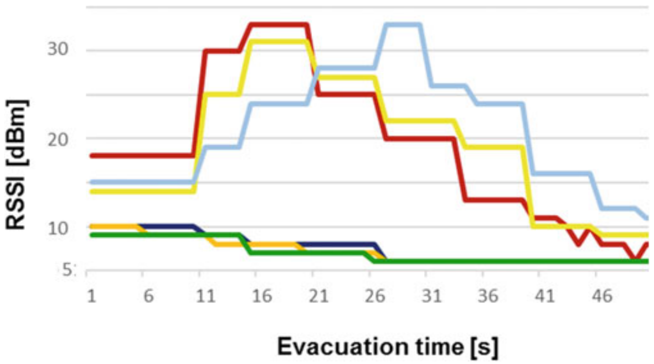

Fig. 7 RSSI values for the control area P_1, by evidencing the previous arrival of "red" and "yellow" groups in respect to the "cyan" one. The group colors are the same of Fig. 6

Co-Ways was visible and easy to be understood (vote 4), while only 50% stated the same for the standard signage. Finally, 89% of the individuals perceived to move together with their group in the original scenario, feeling themselves safe within their group. This value rises to 95% for Co-WayS use. The safety perception based on group motion assumption increases too.

5 Conclusions

In case of emergency in buildings, the safety of people is connected to their possibility to exit the building as quick as possible, by using the "best" evacuation path. Wayfinding activities are essential in this term for all the individuals who can autonomously move. The identification of the "best" evacuation path can reduce the overall time and so to prevent hazardous conditions to occupants (e.g.: prolonged exposure to toxic smokes; burns; risky crowding conditions). Vulnerable people, such as Elderly, should be considered with particular attention in this sense, especially when they are placed in an unfamiliar built environment. Public buildings represent for Elderly a critical scenario since they are additionally characterized by complex layout and high occupant densities.

To this assistance purpose, wayfinding systems can enhance the safety conditions for the occupants, including the Elderly. Anyway, they should be able to address the "best" evacuation direction depending on the effective evacuation conditions of the various building parts. Cognitive Building-oriented solutions can face this issue since they are able to monitor the conditions of the architectural space (referring to: building environment, disaster effects spreading in it, occupants' behaviours) to understand their related performance levels (referring to safety) and support individuals' choices by directly interacting with them (i.e. addressing the "best" path or which "safe" behaviours should be adopted). Moreover, they are integrated within the building components and take advantages of sensors placed in the environment to ensure the occupants' assistance.

This work proposes a Cognitive Wayfinding System (Co-WayS) to support evacuation tasks according to the effective users' needs and behaviours. The proposed system firstly detects the occupants' positions to evidence possible risky conditions for them (i.e. overcrowding leading to unacceptable pushing phenomena and to evacuation slowing down). The detection takes advantages of spontaneous gathering behaviours of people in evacuation, and so it is performed by assigning a detection element for each group of individuals in the building. Data on the localization of groups are collected by a central solving unit, and the main controller uses a density-based guidance algorithm to select the fastest and less crowdy paths. Electrically illumined signs with a dynamic status are connected to the controller, and they dynamically address the path to be followed according to the algorithm results. Signs are placed at the directional changes (i.e. doors), along corridors and stairs. The proposed system is also easy-to-apply and easy-to-remove, as well as it is modular.

The application of the system in a representative case study is offered in order to verify the proposed system effectiveness with respect to current wayfinding signage. Wide-scale drills involving the Elderly are performed. Results show how evacuation the time significantly decreases while occupants are guided by the proposed system, because the path choice (and so the related exits flows) is optimized. Advantages are essentially due to the adoption of the density-based algorithm, which reduces the motion time by leading people to move towards the clearest paths. The same results descend from both motion quantities evaluation and analyses on questionnaires to attendees, especially to the Elderly, who pointed out a very high appreciation of the system in terms of visibility and intelligibility. The system effectiveness is demonstrated although each individual's localization is checked according to his/her belonging group. The possibility to monitor each occupant would surely improve the system reliability but computational issues should be solved to ensure the (quasi) real-time system operation, especially in case of large and complex buildings.

Study outcomes recommend applying such intelligent wayfinding systems to existing buildings to help occupants during the evacuation (especially autonomous older ones). For instance, they could be installed in hospitals and Care Homes to reduce the possible evacuation interferences between autonomous and not-autonomous (i.e. assisted by healthcare assistance and safety staff members) Elderly. Anyway, further studies should extend the validity of the results, by using different spaces configurations (e.g. individuals placed in different parts of a building) and by massively involving silver age individuals. Moreover, it could be combined also to alarm solutions which could be able to guarantee the alert of occupants and their support also at the begin of the emergency (i.e. to reduce the pre-movement phase). Finally, the inclusion of additional control of the conditions of the architectural spaces within the system, i.e. disaster-induced effects during the time (e.g. smoke production), would better prepare the "path" selection algorithm to risky environmental factors.

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