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Intelligent evacuation guidance systems for improving fire safety of Italian-style historical theatres without altering their architectural characteristics

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Abstract.
Fire risk in Architectural Heritage represents a fundamental problem for occupants' safety. Italian style historical theatres are one of the most interesting examples because of their historic and artistic value, high fire vulnerability, fire sources and occupants' features (many people are not familiar with the architectural spaces). Current fire safety regulations approaches for similar Architectural Heritage generally suggest massive and irreversible interventions in order to improve the occupants' level of safety: main related solutions concern with interventions on building layout (e.g.: introduction of fire-proof elements; increasing dimension and number of evacuation paths and exits). This really implies a conflict in preserving original architectural characteristics. Besides, experiments demonstrate how these adopted solutions can be insufficient in improving the individuals' safety level, especially in case of high occupants' density and people who are unfamiliar with the building itself, because of individuals' behaviours in emergency conditions. An efficient emergency evacuation layout can be able to help evacuating occupants, especially in smoke or black-out conditions. "Intelligent Evacuation Guidance Systems" (IEGS) could monitor human behaviours (how people move) and related criticisms in the evacuation process (e.g.: slowing down along paths, paths blockage). Then, they could elaborate these data through smart inducing algorithm so as to suggest dynamic evacuation paths to occupants. In this way, IEGS can effectively suggest the "best" evacuation path to occupants depending on the effective human behaviours. In this paper, an IEGS is firstly defined by introducing suggested low impact environmental components and their related requirements. In particular, occupants' behaviours are associated to evacuees' density along egress paths, doors and exits, by using indoor individuals' tracking systems (e.g.: RFID, Wireless localization). A density-based algorithm based on Level-of-Service conditions is adopted for evaluating possible overcrowding phenomena and identify the best evacuation paths. Directional electrically-illumined signs are used so as to indicate the proper direction to occupants. Wireless communication between the system elements is required. Each element is provided with backup power supply. Then, the proposed IEGS is evaluated by applying it to a significant case study (the "Gentile da Fabriano theatre" in Fabriano, AN). Interactions between occupants and IEGS are reproduced within a validated fire evacuation simulator (FDS+EVAC), and the system effectiveness is evaluated by performing evacuation simulation for the whole building. Comparisons of evacuation times between the original scenario and the IEGS-related one are proposed. Total maximum egress time is reduced down to 26% in the IEGS scenario (40% for levels with 3 or more different possible paths). The number of people using secondary paths (that are also the less crowded ones) raises to 88%. IEGS elements correctly and fully interact with people by understanding their evacuation behaviour and suggesting them the most appropriate (clearest) path: hence, the overall evacuation efficiency can be so increased by virtue of this "behavioural design" approach. Besides, it is strongly important to underline how IEGS elements provide no architectural modifications.

Keywords. building heritage safety; historical theatres fire safety; evacuation in historical buildings; human behaviors in evacuation; reversible systems for human safety; intelligent evacuation guidance systems

1 Research aim

Building heritage is affected by significant risk levels because of intrinsic features (structures vulnerability), presence of different hazards (e.g.: fire sources; localization in earthquake or flood prone areas), high exposure (mainly due to: occupants' density and characteristics; cultural and architectural value). Fire emergency represents a significant topic, especially in case of wooden structures and when occupants are unfamiliar with the building layout (e.g.: historical theatres). In these conditions, "correctly" evacuating the building (in a short time, by using the proper path) widely depends on individuals' spaces perception, architectural layout and presence of adequate wayfinding systems.
This work extends our previous researches on tools for individuals' risks evaluation in historical buildings and low-impact interventions design aimed at jointly increasing the safety level for building occupants and preserving the original heritage features [1]. These solutions are based on a "behavioral design" approach [2,3]: not-invasive solutions

for occupants' safety on the building heritage will be proposed where they are effectively needed and by considering their effects on users. Thus, investigations of man-environment interactions during the evacuation are performed. Easy-to-apply building components can be designed so as to interact with evacuating pedestrians and introduce no architectural modifications to the original building layout and features.

Starting from this point of view, this study concerns with fire evacuation safety in significant historical buildings (historical Italian-style theatre), and offers an evaluation about innovative concepts of emergency wayfinding systems.

2 Introduction

Researches about individuals' safety in buildings during a fire [1,3–5] demonstrated how the occupants' evacuation is widely influenced by behavioral aspects, architectural spaces features (including their layout) and evacuation wayfinding systems. Many interferences affect the evacuation process especially in historical building [1,6,7], where people move in mostly unfamiliar architectural spaces and high occupants' density are coupled with reduced places [1,8,9].

Individuals' safety criteria are essentially founded on evacuating the building in the shortest time [4,10]. According to this evidence and to "empirical" investigations about evacuation times in different buildings [11,12], "traditional" approaches in current regulations adopt an hydrodynamic point of view [13,14]. Hence, regulations generally establish:

- geometrical criteria for reducing the egress time, mainly limited to the increasing number and width of exits and the reduction of traveling distances, e.g.: between two exits [15–17], and by e.g.: introducing fire stairs, opening new doors/exits so as to increase their number/dimension;
- a minimum fire-resistance rating criterion (as a measure of time), so as to limit the fire effect and spreading during the time, by e.g.: defining different fire zones, building fire-proof walls.

Hence, Architectural Heritage highly suffers from this quite fire safety schematic approach and is affected by several related problems. Massive and invasive modifications to original building heritage layout and features could be introduced to respect these regulations, by also ignoring the minimal intervention criterion. In addition, regulations bases are "out of times": related schematic models are generally based on too old experiments (from the '50s to the '80s of the last century) [18]. During the time, building occupants have been changed, and also their relationships with architectural spaces. Hence, similar investigations and related regulations risk to be really obsolete! Besides, many studies on real fire accidents [19–22] and experiments [1,9,23] underline how the majority of traditional solutions are not able to effectively increase the occupants' safety level. This is mainly due to a lack of effective human behavioral aspects while proposing risk-reduction solutions [1,3], as well as responses of both not-disable/disable individuals and vulnerable occupants [24–26].

Previous works demonstrate how using wayfinding systems can improve the occupants' safety by suggest people the evacuation path during the egress process and then reducing the required time [1,5,27,28]. Current regulations include similar systems (including safe condition signs and exit signs [29,30]) in addition to the aforementioned layout solutions, by providing their characterization, positioning, distances between elements (e.g.: [31–33]). Signs systems can be distinguished: reflective [34], photoluminescent (PLM) [1,5,27], electrically-illumined [34], interactive wayfinding systems and Intelligent Evacuation Guidance Systems [35,36], acoustic wayfinding systems [37], individual portable devices [38,39]. According to their possible interaction with the individuals, they can be "active" (or rather, "intelligent" [40]) or "passive" since they are able to suggest the evacuation direction depending on the surrounding environment conditions (e.g.: presence of fire, smoke [36] or slowing down in evacuation motion [35] along paths), or not (e.g.: fix arrow direction on PLM signs [5,41]). The influence of "passive" signs on occupants' evacuation was widely investigated by including real-world and virtual reality experiments [5,28,42,43], and by applying them on Architectural Heritage [1].

"Intelligent" Evacuation Guidance Systems (IEGS), generally applied to new buildings, could represent a relevant frontier in occupants' evacuation solutions in Architectural Heritage. They are composed of a central evacuation guidance algorithm solver (e.g.: a computer), the detecting (or measurement) devices and the wayfinding and alarm signs (e.g.: electrically-illumined, sound and light alarm, personal devices) [35,38,41,44–46]. A complete review of these systems was previously offered [40].

The detecting devices acquire input for the central algorithm solver, which uses "an intelligent inducing algorithm based on multi-parameters to get dynamic evacuation routes" (e.g.: smoke, human behavior, building layout) [35]. Some solutions do not take into account human behaviors detection [45], while others include similar behavioral factors by detecting different quantities through several devices (e.g.: wearable devices including badges and Wi-Fi communications [39,41,47], environmental sensors for presence and/or motion [35,48] detection in relation to the environment dimension and of indoor/outdoor conditions [35,41,49–52]). An overview of instruments for this purpose was offered [48]. Behavioral aspects could surely increase the system effectiveness, especially where pedestrian density-related effects are significant (e.g.: narrow paths or complex layout such as the one of building heritage). However, it is necessary that the measurement devices are (always) connected to the central solver in real-time, so as to allow the system to collect data, elaborate by solving the guidance algorithm and return the directional indications to signs.

Finally, the algorithm solution is sent to connected signs ("collective" ones, that are building components [35,45,53]; individual ones, including smartphone, for direct personal stimuli [38,39,41]) so as to address the proper evacuation choice to individuals. Building spaces are represented according to a wired system, composed by nodes and links with different levels of related static (e.g.: length, width, local hazard) and dynamic (the ones from input sensors) characterizing data [38,46,53]. The main approaches about algorithms for occupants' guidance include basic (e.g.: shortest path [39,54], Dijkstra's algorithm [38,53]) and advanced (e.g.: detection of "traffic jam" by pedestrians' density or other motion quantities such as speed [35,38,44]). Comprehensive reviews of models and algorithms that can be applied to similar evacuation problems are provided by previous literature works [55,56]. The efficiency of these evacuation guidance systems are generally investigated through simulation software [44,53], by demonstrating the importance of occupants' density in the building and initial positions in overall time reduction. Nevertheless, real world experiments [35] evidence a high acceptance of IEGS by evacuees in terms of signs and directional information perception and use, also in smoke conditions. In some experimental drills with thousands of people [35], a total reduction of evacuation time of about -25% in case of short distance between exit signs along the path (≤3m). A limited number of commercial systems and patents were also developed [57,58][1], but no application to building heritage seems to be provided up to now.

Hence, IEGS could be able to "dynamically" interact with occupants in emergency conditions while jointly considering their behaviors and surrounding environment conditions. However, these systems should be designed by avoiding current approaches simplifications and related shortcomings, such as the ones connected to the potential effect of a fire[2], and by taking advantages of previous wayfinding studies [1,3–5,28]. The "behavioral design" (BD) approach would help in developing similar systems by founding the building components definition on human behavioral aspects, providing not-invasive solutions while preserving architectural characteristics, and also using innovative design solutions and tools [1,3].

Considering what is reported above, Italian-style historical theatres represent a good example of high fire risk historical buildings needed to be studied for decreasing their safety risk in respect to their architectural values [1,59], for example by introducing innovative wayfinding systems. They are characterized by:

- a very particular architectural shape and spaces distribution (mainly characterized by a wide principal door and narrow secondary exits; all the audience is placed in the same "room", because tiers, galleries and foyer all face the stage: people ca be considered as placed in the same fire zone);
- high occupants' density during shows and other performances (people occasionally spend times in this building by moving along strict entrance directions in order to reach their seat; they are so generally unfamiliar with spaces different from the main hall, the parterre and the foyer);
- typical wooden structures of particular historic and artistic value (e.g.: the upper circle box and its slabs, the overhead scenery and the unusual roofing trusses);
- the possibility of massive and invasive modifications due to fire regulations [15,16].

In this study, an innovative IEGS for individuals' safety in building heritage is defined and evaluated in an historical Italian-style theatre. The proposed occupants' Density-based IEGS (*DensIEGS*) considers as main input values the occupants' density along egress paths, doors and exits, so as to evidence slowing down or bottlenecks in evacuation [13,60]. "Collective" signs will address the best evacuation path in terms of pedestrians' density (and so overcrowding probability) to incoming occupants. According to the "behavioral design" approach and previous studies about wayfinding systems evaluation [2,41,45,61], an initial system effectiveness evaluation can be performed by using validated microscopic evacuation simulators [62–64], which are able to reproduce human interactions in emergency evacuation in an accurate way [63]. One of the most powerful approaches is represented by the Social Force Model [63]: experimental-based individuals' interactions with both other building occupants and environmental elements are represented by assigning evacuation rules (defined in mathematical terms by a series of "invisible" Social Forces) to each person. The overlapping of these interactions evidences the same macroscopic phenomena noticed in real world events [62,63,65]. Analyses on risk-reduction interventions could easily take advantages of this approach also in order to reduce the impact of implementation problems connected to organization of a real-world evacuation drill, creation of the IEGS and application to a case study [2,46].

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[1] E.g.: Siemens® "Total Building Solution": https://www.youtube.com/watch?v=ycp6k5zDtF0 (last access 12/12/2015)

[2] For example, regulations do not discouraged the application of signs near to (at) the ceiling: nevertheless, during a fire, the ceiling level is the first one that suffers from smoke presence: signs could briefly become invisible!

3 Methods

This work is divided into three main phases (in round brackets, sections about the phase descriptions (P) and the related results (R) are summarized):

1. Defining a significant case-study application (P:3.1);
2. Defining an "efficient" intelligent evacuation guidance system (called Density-based Intelligent Evacuation Guidance System, *DensIEGS*) by taking advantages of the BD-approach and implementing *DensIEGS* in a fire evacuation simulator (P:3.2; R:4);
3. Evaluating the *DensIEGS* effectiveness on the selected case-study in respect to the existing wayfinding system, by using the fire evacuation simulator (P:3.3; R:5).

3.1 The tested scenario

The historical Italian-style theatre “Gentile da Fabriano” (Fabriano, Italy), was chosen as the case-study. Built during the 19th century, it is a typical Italian horseshoe-shaped theatre with more than 700 seats on 4 tiers and a gallery, as shown by Figure 1. Table 1 summarizes the considered seats number for each level and the emergency exits according to the theatre evacuation plan, as shown by Figure 1. The existing traditional Punctual Wayfinding System (PWS) [1], shown by Figure 2, is composed by PLM standard directional signs (a person running and a triangle with tail) [32,66], hung at the wall (minimum height from the floor: about 200cm) placed at directional intersections. The current theatre emergency and evacuation layout configuration (including evacuation exits and paths, wayfinding system) respects Italian regulations about fire safety [16,32,67,68]. The theatre was involved by previous experimental activities of our research group [1] involving the parterre and 1st tier fire drill.

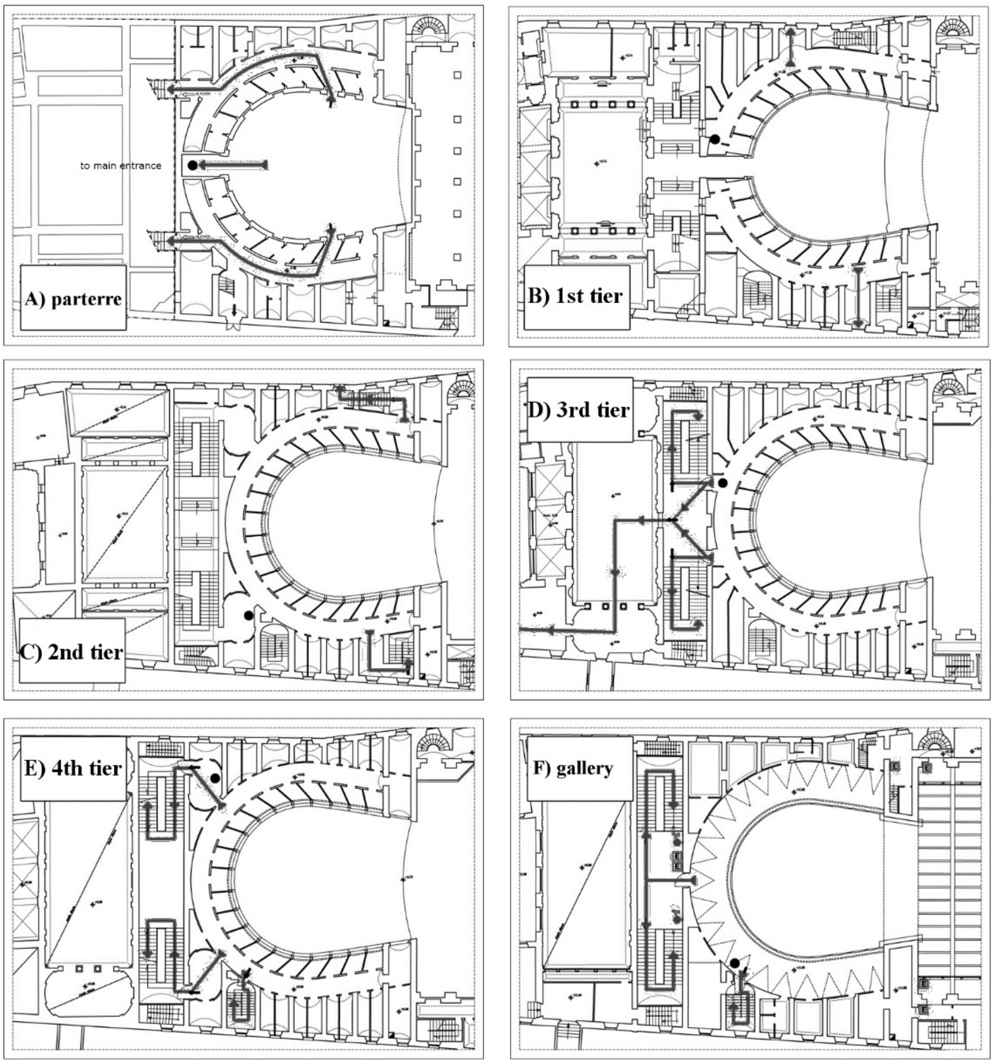

Figure 1. Theater level plans: A-parterre; B- 1st tier and main entrance; C- 2nd tier; D- 3rd tier and foyer; E-4th tier; F-gallery. Evacuation paths (gray arrows) according to the theatre evacuation plan and position of the main evacuation maps hanged on building walls (black dots) are evidenced. The left side of the theatre is the bottom part of each figure.

Level	Seats	Level (floor) height (m)	Exits [code] (specifications)
parterre	200	0	main entrance [ME] (on the floor, composed by three doors)
1st tier	120	2.6	main entrance [ME], 1st tier left [1L] and right [1R] sides (on the floor)
2nd tier	126	5.2	main entrance [ME], 2nd tier left [2L] and right [2R] sides
3rd tier	126	7.7	main entrance [ME], foyer [F] (on the floor)
4th tier	106	10.3	main entrance [ME], 4th tier left [4L] side
gallery[3]	>80	12.8	main entrance [ME], 4th tier left [GL] side

Table 1. Number of seats for each level. About exits, "on the floor" means that no stairs are used while exiting from the related door; elsewhere, motion along stairs is needed. Codes univocally identify each exit. 4th tier and gallery share a staircase exit on the left side, as graphically evidenced by Figure 1.

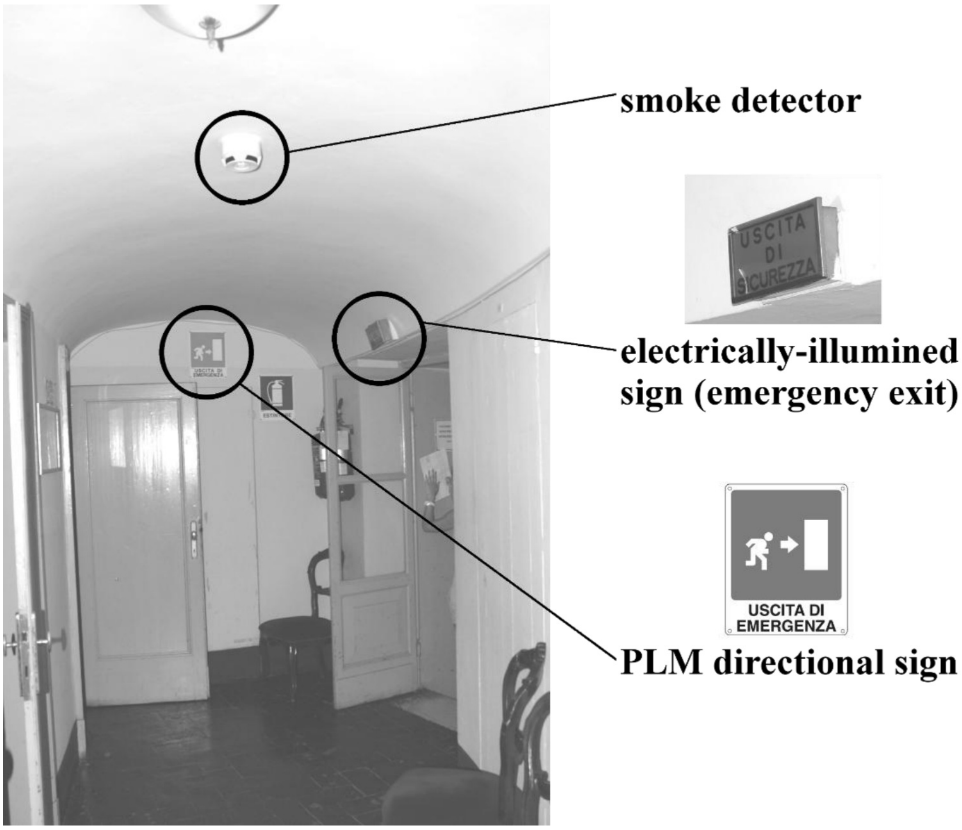

Figure 2. View of the 1st tier corridor (right side), including the current wayfinding sign and other elements within evacuation facilities.

3.2 BD approach-based intelligent wayfinding system definition: Dens-IEGS

The IEGS has to address the most performing evacuation paths to pedestrians arriving near a decision point by considering the surrounding environmental conditions [35,45]. One of the most important aspects to be considered is represented by understanding how men are moving in the environment. Mainly, overcrowding phenomena due to high pedestrians' level could affect the evacuation time and so should be resolved. For this reason, the proposed IEGS should be based on the identification of pedestrians' densities in critical environment points (such as geometrical bottlenecks, doors, intersections between horizontal distribution spaces or between corridors and staircases). The density level is considered as significant for describing the pedestrians' speed and flow according to the Fundamental Diagrams [60]. At the same time, the pedestrians' density can be calculated as a function of pedestrians' flows too.

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[3] Not numbered seats.

3.3 Implementation of DensIEGS and validation

The IEGS algorithm and IEGS effects on occupants (in terms of choices, mainly) are implemented in the freeware FDS+EVAC fire evacuation simulator [64][4] so as to provide a first effectiveness assessment of the system. FDS+EVAC is based on the Social Force Model [63] and merges pedestrians' motion with the fluid-dynamics representation of fire and smoke spreading during the time. In this microscopic approach, experimental-based individuals' interactions with both other building occupants and environmental elements are represented by assigning evacuation rules (defined in mathematical terms by a series of "invisible" Social Forces) to each person. The overlapping of these interactions evidences the same macroscopic phenomena noticed in real world events [62,63,65].
FDS+EVAC is composed by: a modulus simulating the fire development during the time through a fluid-dynamic solver (FDS)[5]; a modulus simulating pedestrians' evacuation according to the Social Force Model (EVAC) [63,64]. The two modules can be separately used. Different occupants characteristics can be modeled inside EVAC by the user in terms of physical quantities (e.g.: individual's dimension, speed) and evacuation choices (e.g.: "herding" behaviors, familiarity with architectural space, knowledge of a limited number of exits through a "known door probability" index[6]). Specific parameters variations are allowed by statistical distributions, in order to define differences in individual's behavioral aspects, as in real tests [11]. The simulator is widely used for fire safety engineering evaluations [69], allows modifications to the source code in order to include further modifications[4], and was already validated by many tests (including the ones from international guidelines and real world experiments) [64,70,71].

3.3.1 Hardware and software

Simulations were performed by using:

- Hardware: HP ProDesk 400 G1 MT; Intel ® Core™ i5 -4570 CPU @ 3.20Ghz; RAM: 8GB; SO: Windows 7 Professional 64-bit.
- Software package used for numerical modelling: Complete suite FDS+EVAC (including Smokeview) and related source codes (in Fortran90); FDS v6.0, EVAC v2.5.0[7]. Smokeview is the graphical interface of solver results about both fire, smoke and pedestrians' motion;
- Software package used for serve FDS+EVAC simulator:
  - Pyrosim® software (by Thunderhead Engineering) for rapid FDS input files definition through a specified 2-D and 3-D design environment; six months free academic license[8]. However, input files can be created directly using a txt processor by following the software input file guidelines;
  - ECLIPSE, Open Source IDE (version Luna)[9] combined with the PHOTRAN plug-in[10] for Fortran language. This is used for modifying the EVAC source code and inserting the simulation of the Dens-IEGS;
  - a Fortran compiler for creating the final executable file for FDS+EVAC simulation.

3.3.2 EVAC source codes modifications

Modifications to FDS+EVAC about human behavioral algorithms (rules for occupants' motion) are provided in *evac.f90* file. ECLIPSE was used to develop the modifications and test them in a stand-alone environment. When modifications are completed within *evac.f90*, a Fortran compiler should be used so as to run the *makefds* file and generate the executable final program. The new executable file replaces the original one in order to perform FDS+EVAC simulation by considering the performed modifications. Inputs and outputs for *DensIEGS* are "virtually" connected to individuals' evacuation data from the FDS+EVAC simulator, in real time.

3.3.3 Criteria for DensIEGS effectiveness evaluation

Two sets of simulations are performed for effectiveness evaluations as shown by Table 2. 8 simulations are carried out

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[4] http://firemodels.github.io/fds-smv/ (last access 12/06/2015)

[5] http://www.nist.gov/el/fire_research/fds_smokeview.cfm (last access 12/06/2015)

[6] The "known door probability" goes from 0 (unknown door) to 1 (known door). A similar parameter concerns exits. In this way, familiarity with particular building parts can be simulated.

[7] Download from http://firemodels.github.io/fds-smv/ (last access 12/06/2015)

[8] Download from http://www.thunderheadeng.com/pyrosim/ (last access 12/06/2015)

[9] Download from http://www.eclipse.org (last access 12/06/2015)

[10] Download from http://www.eclipse.org/photran/ (last access 12/06/2015)

for each simulation set, as for the simulator validation process, and average results are compared. Both the two simulations set will involve 756 individuals, according to the maximum occupants' number in Table 1. For the gallery, it is supposed to have 85 occupants. The theatre geometry is faithfully reproduced in FDS+EVAC with an approximation of about 20cm.This approximation is also compatible with individual's radius within FDS+EVAC and Social Force Model [64,72]. No smoke conditions are simulated in order to underline the algorithms components directly connected to human behaviors as themselves. Moreover, no pre-movement time is considered for the scenarios simulations.

The first set concerns with the evacuation of the whole theatre in the current conditions (*scenario 0*, without the Dens-IEGS system). This can be considered the "worst" conditions in terms of wayfinding help to people who have no familiarity with the building [1]. The second set involves the application of the Dens-IEGS on the theatre (*scenario IEGS*). This scenario represents the "best" evacuation conditions, where all individuals should positively react to the IEGS system stimuli. Conditions of individuals' familiarity with the theatre are considered according to real-world behaviors examined by our previous drill in the same theatre [1]. All the simulated occupants know the main entrance (in FDS+EVAC, the main entrance will have a maximum "known door probability" equal to 100%), while a percentage of occupants $p_{path,sec}$ also knows secondary paths and exits. According to previous results concerning with the number of people using the traditional punctual system during this drill [1], experimental $p_{path,sec}$ was about 10% of people in the parterre and about 50% for the 1st tier. However, we consider $p_{path,sec}$ =10% as the most significant value in order to err in the side of caution and to stress the influence of unfamiliarity conditions. The simulator randomly chooses people who know these secondary paths.

Comparisons of these two scenarios allow to detect how safety level increases by considering the following aspects [1,5,41,64]:

- number of exiting pedestrians versus evacuation time (graphical representation);
- average and maximum evacuation time (s) with an approximation of 5s;
- use of exits by occupants (number of people);
- pedestrians' flow at the exit (pp/s);
- average evacuation speed (m/s).

Previous works about IEGS effectiveness analysis through simulators [41] underline how the random selection of occupants' characteristics (i.e.: by defining $p_{path,sec}$) could introduce secondary evacuation phenomena (e.g.: random path choices) while estimating the total evacuation time. For this reason, the analyses involve the maximum evacuation time when the 95% of occupants exit the building (or the level), and not when the last individual reaches the exit.

For each quantity, percentage differences will be calculated in respect to *scenario 0* according to the following Equation 1:

$$\Delta x(\%) = \frac{x_{IEGS} - x_0}{x_0} \cdot 100 \qquad (1)$$

where x is a general parameter (e.g.: the evacuation time), and the subscripts refer to *scenario 0* (*0*) and *scenario IEGS* (*IEGS*) simulations values, respectively. Finally, main path choices are placed when people is on the floor (e.g.: choice of the exits from the parterre), while along the foyer, the main entrances, the staircase and the following corridors, any evacuation exit choice can be directly performed (the path can be defined as "obliged"). At the same time, the horizontal progressive building evacuation [15] can be used so as to evacuate multi-story buildings (such as the theater). For these reasons, an analysis of evacuation time from each level is shown in a separate way. Finally, for each individual, speeds are evaluated as the ratio between the evacuation path length and the related evacuation time. Hence, the average whole sample value for each exit is calculated. Comparisons of average motion speed with previous emergency drills [12] in normal visibility conditions is performed in order to validate the motion process from a general point of view.

Scenario	**Preferred speed**	**Exit choice criteria**
Scenario 0	Adult type for FDS+EVAC simulator, standard configuration [64]	everyone knows the main entrance; a $p_{path,sec}$ (10%) of occupants also knows the floor secondary exits defined in Table 1
Scenario IEGS		everyone follows the path direction suggested by evacuation signs

Table 2. "*Scenario 0*" and "*Scenario IEGS*" description: the main entrance refers to Table 1 and corresponds to main [EM] exit.

4 Definition of the DensIEGS by a BD approach in historical heritage application

The proposed Density-based Intelligent Evacuation Guidance System (*DensIEGS*) uses the pedestrians' density as representative parameter for describing human behaviors and possibility to move along an indoor path.

4.1 DensIEGS characterization

Figure 3 resumes the overall proposed system by including both the system blocks (on the left) and their related operations within the path choice algorithm (on the right).

Detection of fire evolution can be performed by fire detectors. They are currently applied to building heritage in order to quickly detect possible fire sources and causes for evacuation, as also suggested by fire regulations [10,15,16,73], fire maps guidelines (e.g.: pr EN 54-14; UNI9795:2010 for Italian applications) and shown by Figure 2. Smoke detectors should be added so as to identify the optical density of smoke and evaluate the visibility distance in the space [m]. In this way, it should be possible to monitoring fire propagation (addressing unavailable building parts because of fire, flames and gas toxicity [45]) and smoke propagation (evidencing smoke-man interferences especially in motion speed [74]) within the building.

Occupants' indoor positioning detectors can define “where” individuals are and “which” are the pedestrians' densities along the paths or in critical areas. “Where” involves presence of people in rooms with raising hazardous conditions (e.g.: because of raising smoke or heat levels). Pedestrians' densities are direct indicators of possibility to move along the evacuation paths [60]. Related critical areas are “hot-spots” in the building layout, such as bottlenecks, spaces in front of doors and exits, and are called “control areas”. In this way, overcrowded paths can be evidenced and related inputs can be addressed to the central processing unity (algorithm solver). Involved detector could be:

- PIR sensors for detecting if anyone is moving in a space/room [48];
- PIR array sensors for detecting motion speed and direction along the path; applied on the ceiling or on the walls [75,76];
- RFID sensors (e.g.: gates) for determining individuals crossing particular passages, such as door, and so determining flows of pedestrians during the time and number of people along the path stretch between two consecutive passages [39,51,77]; active and passive RFID would implies the distance between the crossing pedestrians and the detectors;
- Wi-Fi indoor tracking positioning [41,78].

Furthermore, real time image analysis by fixed cameras could be also performed [36,79,80], but has many disadvantages, such as time-consuming in data interpretation. These systems are often applied to building heritage and generally have a low impact on the construction (in terms of supplier and building modifications).

Detection systems are connected to an *evacuation central manager* in a real-time way [35]. The manager is composed by a central processing unit for data collecting, including the evacuation guidance algorithm solver (e.g.: a computer). Depending on the input data from environmental and behavioural detectors, the algorithm solver mainly would take into account the presence of smokes, of pedestrians' densities conditions so as to avoid an additional arrival of occupants in critical areas.

Figure 3 includes the general scheme for the path decision algorithm. These series of actions are performed for each “control area” and for each calculus time step. Different best path choices can be proposed by combining all the data about pedestrians' density for the whole path or for a single stretch of path (or for a single room).

Finally, *electrically-illumined signs* allow to interact with pedestrians by suggesting them the "correct" and "safe" evacuation path in a dynamic way during the time. They are often applied to building heritage according to current fire safety regulations [15,16,32,33], as also shown by the case-study Figure 2. According to the algorithm solution, signs are able to directly bring suggested paths to evacuating individuals' attention. From an operative point of view, the signs could be composed by: punctual elements placed at least at the path variations (including doors and “control areas”) with different arrows (one for each possible path direction) or open/close sign (e.g.: green or red colour); continuous elements such as LED stripes placed along the paths. In the second case, their dimension should be minimized and they should be applied as removable elements (e.g.: within baseboards or handrails), so as to maintain a low-impact criteria point of view in these historical scenarios. In particular, near ground applications (e.g.: within baseboards) are really useful in case of smoke presence [1,35].

All sensors and signs should be removable, connected by Wi-Fi and supplied by portable batteries[11], in order to avoid massive cables and related installation interventions on buildings. Existing electrically-illumined signs (often placed in building heritage) could be shared with IEGS. Furthermore, another fundamental topic is represented by the fire resistance of elements composing the system (e.g.: electric devices should be hosted by fireproof or fire retardant boxes). At the same time, the electrical equipment should be tested in fire conditions.

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[11] With both good durability and low level of maintenance. Communication could be also guaranteed by “power over Ethernet” technologies in no blackout and no fire damages emergency conditions.

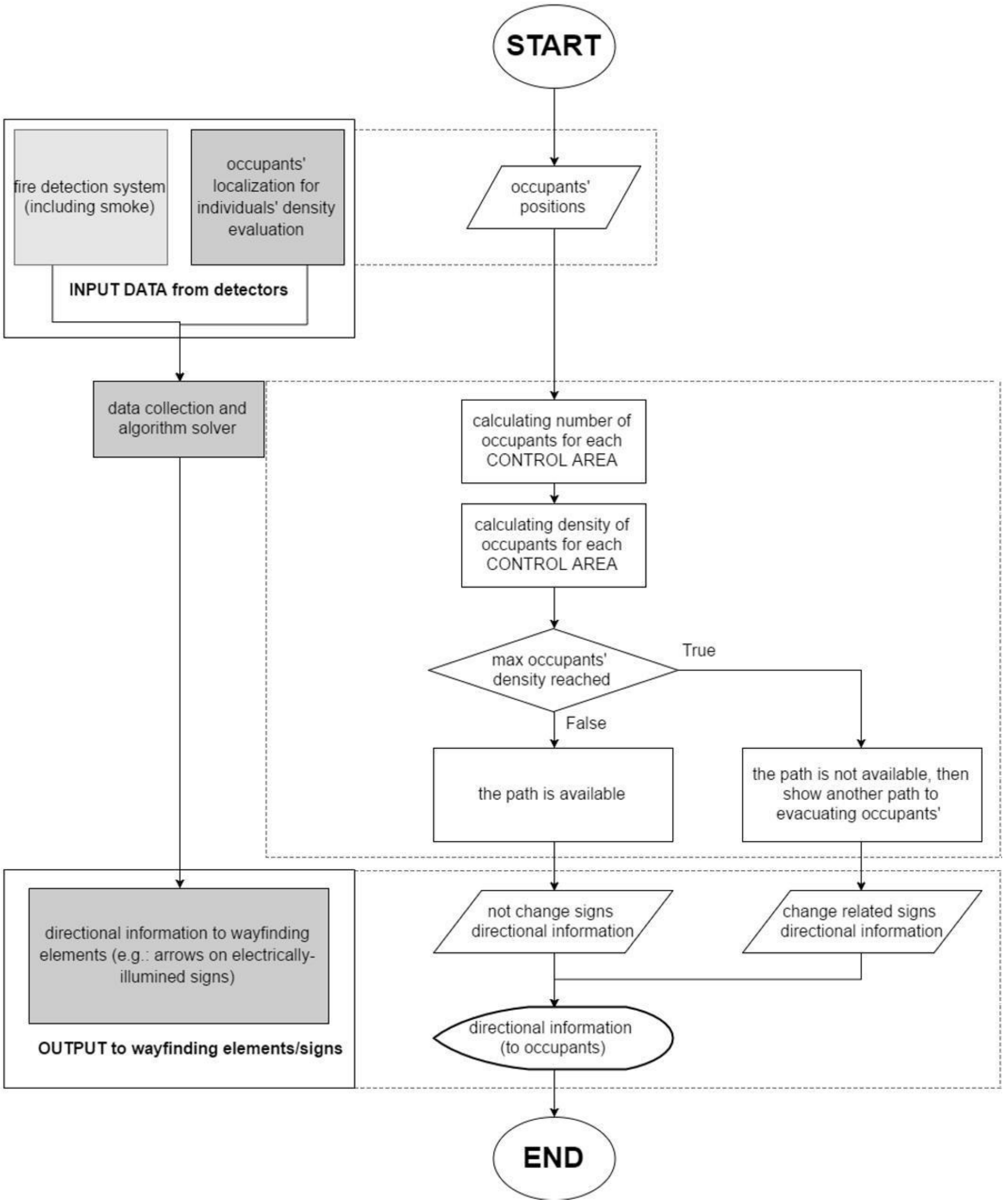

Figure 3. Schematization fo the DensIEGS: system blocks and path choice algorithm (without smoke influence) used for DensIEGS decision about available door/path.

In this study, *DensIEGS* uses "collective" signs (directly placed on the environment), and they are considered applied on doors (e.g.: green for open as available / red for close as unavailable). No smoke and fire conditions are actually included in this work in order to mainly focus on man-*DensIEGS* interactions. The historical scenario given by the case study and the previous experimental drill results about queuing phenomena [1] suggest to address the correct path choices to occupants while they are leaving their seats. Signs could suggest the proper way to evacuate the parterre, the 1st tier and so on in a separate way. Hence, the best path choice will concern with going out from each single level (level are defined in Table 1) by using the less crowded exit. In this sense, the solving algorithm will find the best path within the possible choices "level by level".

Moreover, if all “control areas” referring to the same path or to the same room (e.g.: all the room exits) are evaluated as "unavailable" because of pedestrians' density, the algorithm will suggest as "available" the one with the lowest density. In this way, no loop (or dead branches) could affect the overall solving algorithm.

4.2 DensIEGS implementation for fire evacuation simulation

All the developed files (and an example of simulation outputs for the case study) are available at https://goo.gl/rGboSu. This repository includes the implementation of the proposed path choice algorithm (shown by Figure 3) within the *evac.f90* file.

In order to define "control areas" in the given environment to be simulated, an external input file (*InputArea.txt*) is defined. For each "control area", this file includes: the related identifier of the area (by including the related controlled door); the coordinates of corners; the density limit for closing (DENSITY_CLOSE) or opening (DENSITY_OPEN) the related doors; the area (m^2); the number of agents who is inside at time T=0. It is considered that a "control area" can manage more than one door[12]. An external log of pedestrians' densities in each "control area" is offered by a created external file (*risultati.txt*). Both these files should be placed in the same folder of the *.fds input file for simulation.

In these initial evaluations, it is supposed that all occupants positively respond to *DensIEGS* interaction. To this aim, the "change related signs directional information" block in Figure 3 corresponds to the blockage of the related door by modifying the EVAC_DOORS(I)%TIME_CLOSE and EVAC_DOORS(I)%TIME_OPEN variables, representing the time of door closure/opening. In other words, people use the door only if this is open, and so "available" (in case of low pedestrians' density level along the related path). According to the "data collection and algorithm solver" procedure in Figure 3, performed steps are the following ones:

1. the simulation time is now T;
2. evaluating the pedestrians' density in the control area by counting the number of individuals within the considered area and dividing by the area dimension (by obtaining a person per square meter ratio);
3. if the density is higher than the limit value, the door is considered as closed for the arriving pedestrians, and EVAC_DOORS(I)%TIME_CLOSE =T;
4. return to the first point of these steps, and now the time is T+1;
5. evaluate pedestrians' density again according to step 2;
6. if the current density is lower than the limit one, the path will be available for arriving pedestrians and EVAC_DOORS(I)%TIME_OPEN=(T+1). Obviously, setting EVAC_DOORS(I)%TIME_CLOSE =T when the door is yet close has not effect in door availability; the same happens for opening conditions overlapping.

DENSITY_CLOSE and DENSITY_OPEN can be different so as to allow the clearing out of the "control area" by pedestrians who are immediately arriving here. In this study, we fixed, for each "control area":

- DENSITY_CLOSE equal to 3 persons per square meter that is about the Level-of-Service (LOS) [81,82] E limit condition for waiting pedestrians (we consider that some pedestrians are waiting for their passage across the door; at the same time, while they are waiting, physical contacts among them can exist, according to group motion phenomena and "fast-is-lower" effects [63]);
- DENSITY_OPEN equal to 0.7 persons per square meter that is about LOS D limit conditions for moving pedestrians (we considered that people are moving while clearing out the area by allowing really closer one to each other).

However, in order to avoid the door blockage, DENSITY_CLOSE=100 can be chosen; so as to avoid door opening, DENSITY_OPEN=0.

5 DensIEGS application: effectiveness evaluation results by simulations

Figure 4 schematizes the overall theatre by using the DensIEGS. All the simulated elements are represented: "control areas", placed (just) before a layout bottleneck (e.g.: near a door such as for area 6 in Figure 4-a); at layout variations (such as along the corridor in area 1-2-3-4 Figure 4-a; at the landing such as for area 3A DX in Figure 4-d) or between two consecutive bottlenecks (e.g.: area 5 in Figure 4-c), within the different floor levels; the position of signs; the identification of exits including both main and secondary ones.

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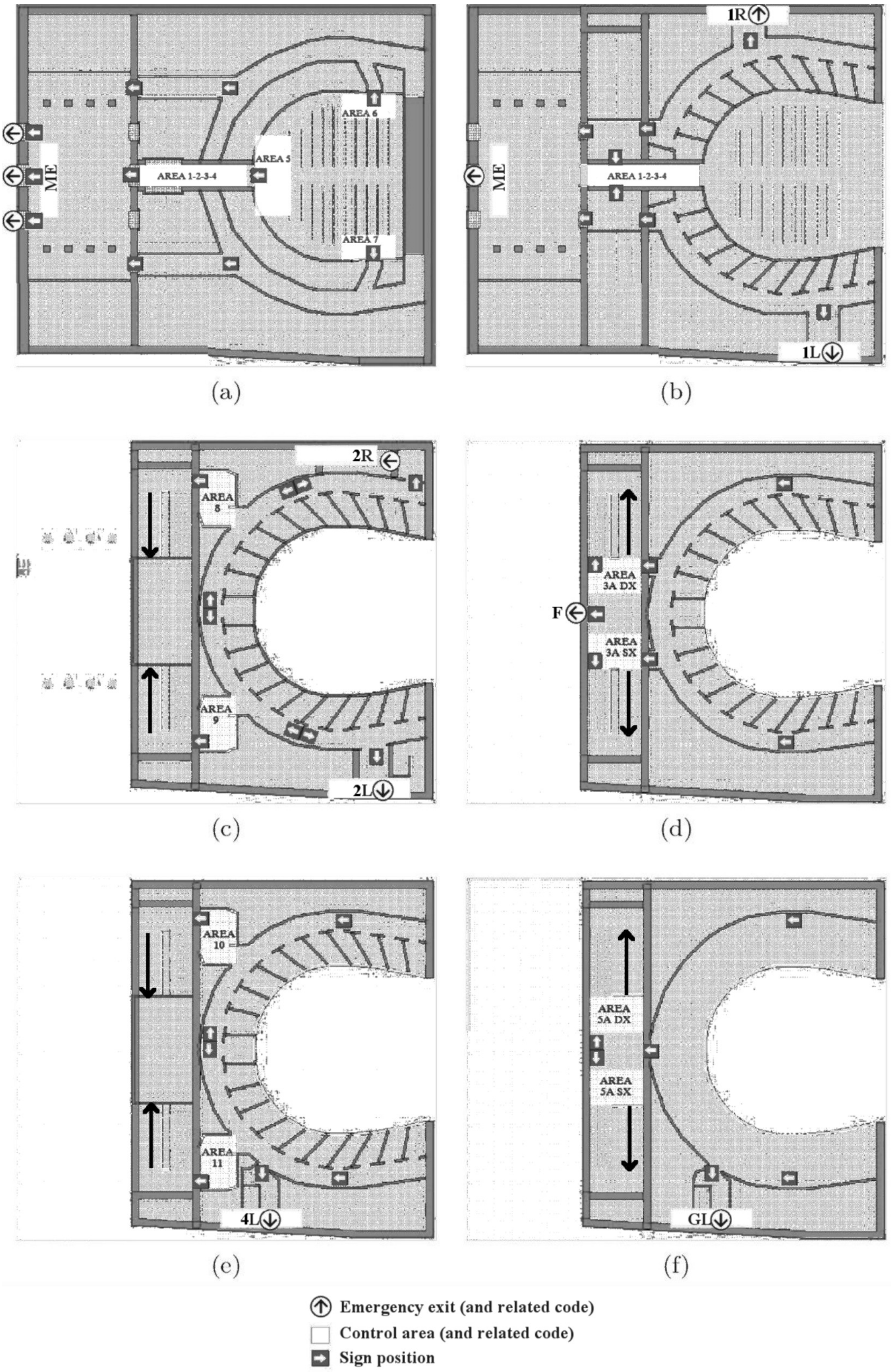
[12] In operative terms, the simulator adopts two control area with the same geometrical and density limit features, but with different door identifiers (one for each door).



(a) (b) (c) (d) (e) (f)

Figure 4. Application scheme of DensIEGS at the different theater levels, including: "control areas" positioning (and related identification code within *InputArea.txt*); signs positioning over the doors and along the paths, managed by the nearby "control area", also according to Section 4.2; exits identifications (including the related code according to Table 1; exit direction along staircases (black long arrows).

Figure 5 resumes the number of exited pedestrians during the time for the "*scenario 0*" (current passive wayfinding

system in the theatre) and the "*scenario IEGS*" (application of the DensIEGS to the theatre according to Figure 4). The "*scenario IEGS*" curve values are average results obtained by performing 8 simulations. Table 3 compares maximum evacuation times connected to the 95% of exited occupants for the whole theatre and each level. The overall percentage reduction of maximum evacuation time is equal to -26% in respect to "*scenario 0*" conditions. Table 4 focuses on the main evacuation variable comparisons for each exit, according to section 3.3.3 specifications. Firstly, percentage differences Δ(%) are evaluated according to Equation 1: when the values are higher than 100%, it means that the related value while using the *DensIEGS* has more than doubled.
Main effects of *DensIEGS* effectiveness are the following ones:

- *a more fair distribution of occupants among the building emergency exits*. *DensIGES* directional suggestions seem to lead occupants to move towards secondary exits. According to Table 4, a reduction in "number of exited pedestrians" is noticed only for the main exit [ME], while flows at secondary exits (especially the ones "on the floor") are preferred;
- *a general speeding up of the overall evacuation process*. Individuals are allowed to choose the less crowded evacuation paths (exits), with a general increase of average motion speeds and exit flows. Exits "on the floor" (e.g.: 2L, 2R, F) denote negative Δ(%) and/or a low increase of maximum evacuation times because of short path length and significant occupants' flows during the time: related percentage differences are >100%. Although speeds and evacuation times for some exits are apparently dissenting, a more adequate distribution of occupants among the different exits is reached at the building scale. Finally, average simulations motion speed for the two tested scenarios are in the values range of previous works involving adults in emergency conditions (with no black-out or smoke) [12,41].
- *a general speeding up for each level*. According to previous considerations, Table 3 and Figure 6 demonstrate how the evacuation timing and the related curve (time against number of exited pedestrians) for each level are positively influenced by these exits choices. Moreover, the evacuation of the 3rd tier shows the lowest Δ(%) value because the two possible exits are really close one to each other. The comparison of Figure 4 and Figure 6 underlines how the same curve shape is shared by similar tiers layout configuration (2nd and 4th tiers).

	Maximum evacuation time (s)		**Δ(%)**
	Scenario 0	**Scenario IEGS**	
Overall theatre	170	125	-26
Level			
Parterre	100	60	-40
1st tier	60	35	-41
2nd tier	150	105	-30
3rd tier	110	85	-22
4th tier	100	45	-55
Gallery	50	35	-30

Table 3. Comparison of maximum evacuation times.

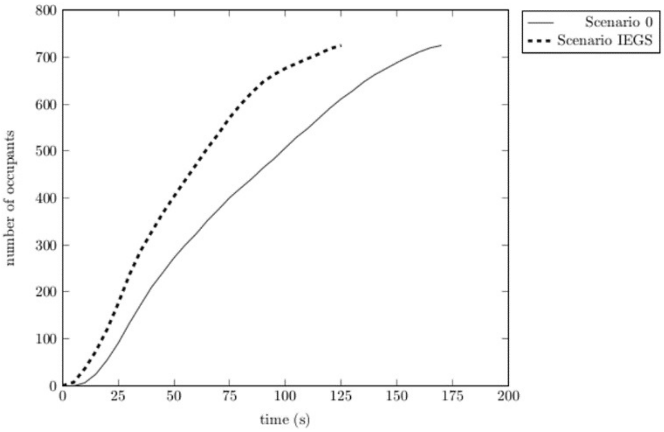


Figure 5. Comparison between "Scenario 0" and "Scenario IEGS" simulations concerning curves about number of exited pedestrians against evacuation time for the whole theater.

The best reductions in evacuation times are retrieved in the parterre, as shown by Figure 6-a and Table 3. The total evacuation time for this level is equal to about 40s (-40% in percentage terms). Figure 7 graphically shows the differences between the evacuation without using the *DensIEGS* (Figure 7-a) and by using it (Figure 7-b), while Table 5 resumes the parterre evacuation quantities for each door. Doors are: main door MD (directly pointing at the main entrance, along area 1-2-3-4 in Figure 4); right RD and left LD doors (secondary exits along the parterre sides). In particular, while moving in "*scenario 0*" conditions of Figure 7-a, most of the people moves towards the main parterre entrance. Hence, overcrowding and queuing phenomena can be noticed and can influence the overall parterre evacuation time. On the contrary, as shown by Figure 7-b, a significant number of people in "*scenario IEGS*" moves towards the lateral parterre exit, thus diminishing the number of people along the queue to the main door. The main door [MD] in the parterre has the same flows for both the scenarios, because the *DensIEGS* evacuation time is sensibly lower. On the contrary, flows at lateral doors increase: then evacuation times decrease for the whole population.

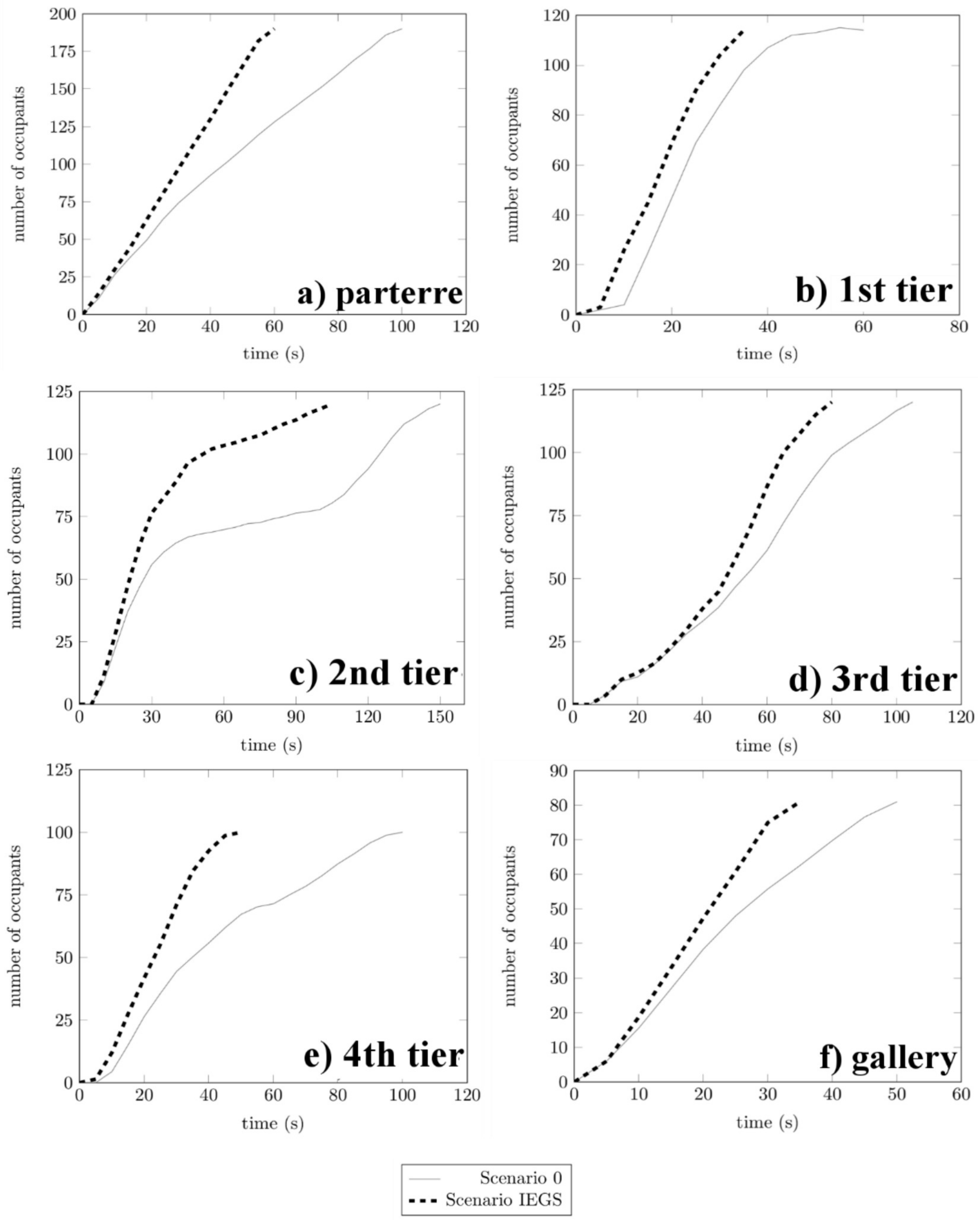


Figure 6. Comparison between "Scenario 0" and "Scenario IEGS" simulations (average results) concerning curves about number of exited pedestrians against evacuation time for the different level one by one.

Finally, some remarks about occupants' exit choice decision have to be pointed out. In the "*scenario 0*" configuration, an average value of about 8% of occupants chooses secondary paths (RD:6%; LD:10%). As we could suppose before the simulations, this percentage principally involves people who sat near the related evacuation exit (near to RD or LD) when the alarm rang (when the evacuation simulation started). These people could represent individuals who surely use secondary exit in evacuation conditions. In the "*scenario IEGS*", the same average value is about 35%. This percentage demonstrates that about the 27% of simulated occupants decides to change his/her evacuation direction because of the *DensIEGS* interaction. In fact, while using the *DensIEGS*, if the control area approaches the critical density, the incoming occupants are then guided to other exits because of signs directional information.

Motion quantity	**Scenario**	**Exit**								
		ME_c	**ME_l**	**1L**	**1R**	**2L**	**2R**	**F**	**4L**	**GL**
flow (pp/s)	IEGS	1.37	0.90	0.57	0.90	0.70	0.30	0.50	1.00	0.90
	0	1.40	0.89	0.60	0.50	0.40	0.20	0.20	0.20	0.30
	Δ(%)	-2	0	-6	80	75	50	150	400	200
number of exited occupants	IEGS	202	264	43	45	29	32	38	41	33
	0	256	333	35	39	12	12	23	7	9
	Δ(%)	-21	-21	22	15	142	161	70	454	249
max evac. time (s)	IEGS	140	130	80	55	45	95	85	40	35
	0	170	175	65	75	30	55	105	40	30
	Δ(%)	-18	-26	23	-27	50	73	-19	0	17
av. speed (m/s)	IEGS	0.69	0.73	0.53	0.51	1.18	0.57	0.41	0.63	0.68
	0	0.60	0.60	0.46	0.44	1.48	0.73	0.52	0.59	0.75
	Δ(%)	16	22	14	15	-20	-22	-21	8	-9

Table 4. Evacuation results for each exit. Exits are identified according to Table 1 (the main entrance is distinguished by central ME_c door and lateral ME_l doors). For each exit, "scenario IEGS" and "scenario 0" values are firstly pointed out. Then, the percentage difference Δ(%) is calculated.

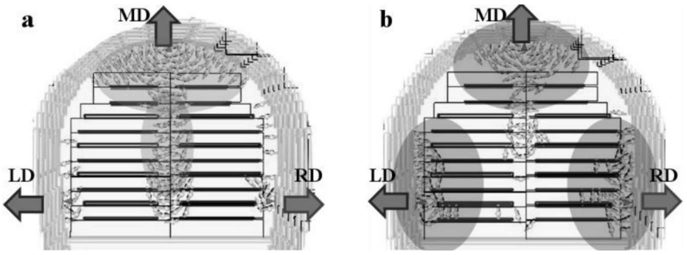


Figure 7. Graphical representation of parterre evacuation differences in "scenario 0" (a) and "scenario IEGS" (b). Gray filled ellipses evidence areas with higher occupants' densities during the evacuation. Exit doors are identified and codified. The background image is taken from a Smokeview simulation frame.

	Main door (MD)			**Right door (RD)**			**Left door (LD)**		
Scenario	**IEGS**	**0**	Δ(%)	**IEGS**	**0**	Δ(%)	**IEGS**	**0**	Δ(%)
max evac. time (s)	60	100	-40	60	55	9	60	35	71
av. evac. time (s)	30	55	-45	35	20	75	35	20	75
flow (pp/s)	1.64	1.64	0	0.72	0.17	321	0.72	0.29	146
exited occupants	101	170	-41	44	10	350	45	10	347

Table 5. Comparison of evacuation quantities for parterre exit door. Door codes are shown according to Figure 7.

6 Conclusions

Italian-style historical theatres represent one of the most significant fire risk-affected scenarios, because of their vulnerability, their complex layout, the presence of high occupants' density, the poor occupants' familiarity with the building layout. In case of fire in similar historic buildings, both heritage and building occupants could suffer from very large damages. Current regulations propose massive interventions on the building configuration, which are often not useful for occupants. This research work proposes a “behavioural design” (BD) approach to increase individuals’ safety based on the following methodology: analysing the needs of evacuating pedestrian and then designing evacuation facilities in order to provide the required answers to these human needs.

Wayfinding activities are essential behavioural issues during emergency, because they allow occupants to rapidly egress the building, and prevent hazardous conditions for themselves (e.g.: exposure to toxic smokes; structural failures; overcrowding phenomena). Hence, this work is aimed at demonstrating how the application of innovative (BD-based) wayfinding systems (that are perceived and used by people in a correct and efficient way) could be able to gain high safety level without any architectural modification to buildings. The paper proposes an Intelligent Evacuation Guidance System (*DensIEGS*), which: detects the environmental conditions and the pedestrians’ flows inside the building by using indoor occupants’ tracking techniques and sensors; elaborates the detected data in order to identifying the best paths; suggests the correct paths to occupants by taking advantages of electrically illumined signs (provided with backup power supply). The pedestrians' density is chosen as referring parameter for the occupants’ evacuation description and solving dynamic algorithm for best paths finding. System elements take advantages of wireless communication so as to avoid massive interventions on the building. *DensIEGS* is applied to a representative case-study. Its effectiveness is compared to the traditional punctual signs by taking advantages of a validated fire evacuation simulator.

DensIEGS seems to be able to guide people along the “correct” paths by taking into account their boundary conditions: in this way, the evacuation time can be drastically reduced and safety levels accordingly increased. Occupants’ number is distributed through the various paths and exits, so as to avoid dangerous overcrowding conditions (that generally affect the egress time by slowing down the evacuees). The estimated evacuation time in *DensIEGS* conditions is up to 26% lower than the one for current wayfinding system conditions (40% for levels with 3 or more different possible paths). In fact, secondary exits are better utilised by people because chosen as the clearest path . The number of people using secondary paths (that are also the less crowded ones) raises to 88% while using *DensIEGS* in respect to the traditional punctual system.

Decreasing the total evacuation time implies increasing the occupants’ safety level, according to the innovative performance-based fire safety engineering design proposed by recent European guidelines. *DensIEGS* can be quickly applied through a reversible intervention: no physical modifications of the building layout are required for their application. Hence, Cultural Heritage features can be effectively preserved, while irreversible alteration to the building can be avoided. Furthermore, many of the required system elements (e.g.: smoke detectors) are often installed in these historical buildings at today.

The effectiveness of the proposed system is 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. Real-world experiments would be needed so as to fully demonstrate the capabilities of similar systems. Furthermore, smokes and fire conditions should be included in effectiveness tests in order to evaluate the technological requirements of the system components when facing to similar environmental conditions. These experiments would also determine the effective requirements for the data to be acquired and for the communication network. Different localization systems could be compared by using different technologies in order to obtain the most efficient system that provides the lowest interference level and the most efficient description of evacuation phenomena. Furthermore, the path choice algorithm should take into account both occupants’ evacuation characterization and fire (smoke) spreading during the evacuation time. Finally, “collective” (the wayfinding signs on the floor, on the wall, on the ceiling; the environmental alarms) and "individual" (based on individual's electronic devices, e.g. a smart-phone, a badge) interactive elements should be tested so as to demonstrate if a stimulus given to all the occupants is better than the one given one by one to them.

Future researches should inquire an optimization of similar systems by considering: the minimization of the number of signs, through investigations on human behaviours and perception of wayfinding elements (including innovative monitoring techniques such as eye-tracking techniques); the architectural integration of signs, by adopting new smart miniaturized components, different power supplies and communication infrastructures, in order to reduce the impact of elements on the building heritage; the possibility to extend evacuation technologies to the normal use of architectural spaces (e.g.: by developing apps for personal devices); the inclusion of guidance elements for people with visual impairments, so as to allow them to autonomously exit the building.

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Manager".

8 References

[1] M. D'Orazio, G. Bernardini, S. Tacconi, V. Arteconi, E. Quagliarini, Fire safety in Italian-style historical theatres: How photoluminescent wayfinding can improve occupants' evacuation with no architecture modifications, Journal of Cultural Heritage. (2016). doi:10.1016/j.culher.2015.12.002.

[2] G. Bernardini, M. D'Orazio, E. Quagliarini, Towards a "behavioural design" approach for seismic risk reduction strategies of buildings and their environment, Safety Science. 86 (2016) 273–294. doi:10.1016/j.ssci.2016.03.010.

[3] M. Kobes, I. Helsloot, B. de Vries, J.G. Post, Building safety and human behaviour in fire: A literature review, Fire Safety Journal. 45 (2010) 1–11. doi:10.1016/j.firesaf.2009.08.005.

[4] Proulx and Guylène, Movement of people: the evacuation timing, SFPE Handbook of Fire Protection Engineering. (2002) pp. 342–366.

[5] G.-Y. Jeon, W.-H. Hong, An experimental study on how phosphorescent guidance equipment influences on evacuation in impaired visibility, Journal of Loss Prevention in the Process Industries. 22 (2009) 934–942. doi:10.1016/j.jlp.2009.08.008.

[6] C. Santos, T.M. Ferreira, R. Vicente, J. a R. Mendes da Silva, Building typologies identification to support risk mitigation at the urban scale - Case study of the old city centre of Seixal, Portugal, Journal of Cultural Heritage. 14 (2013) 449–463. doi:10.1016/j.culher.2012.11.001.

[7] Z. Biao, Z. Xiao-meng, C. Ming-yong, Fire protection of historic buildings: A case study of Group-living Yard in Tianjin, Journal of Cultural Heritage. 13 (2012) 389–396. doi:10.1016/j.culher.2011.12.007.

[8] D.A. Purser, M. Bensilum, Quantification of behaviour for engineering design standards and escape time calculations, Safety Science. 38 (2001) 157–182.

[9] C. Xudong, Z. Heping, X. Qiyuan, Z. Yong, Z. Hongjiang, Z. Chenjie, Study of announced evacuation drill from a retail store, Building and Environment. 44 (2009) 864–870. doi:10.1016/j.buildenv.2008.06.012.

[10] V. Babrauskas, J. Fleming, B.D. Russell, RSET/ASET, a flawed concept for fire safety assessment, Fire and Materials. (2010) 341–355. doi:10.1002/fam.

[11] L. Shi, Q. Xie, X. Cheng, L. Chen, Y. Zhou, R. Zhang, Developing a database for emergency evacuation model, Building and Environment. 44 (2009) 1724–1729. doi:10.1016/j.buildenv.2008.11.008.

[12] R.F. Fahy, G. Proulx, Toward creating a database on delay times to start evacuation and walking speeds for use in evacuation modeling, in: 2nd International Symposium on Human Behaviour in Fire, Boston, MA, USA, 2001: pp. 175–183.

[13] A. Schadschneider, W. Klingsch, H. Klüpfel, T. Kretz, C. Rogsch, A. Seyfried, Evacuation Dynamics: Empirical Results, Modeling and Applications, Encyclopedia of Complexity and Systems Science. (2009) 3142–3176 LA – English. doi:10.1007/978-0-387-30440-3_187.

[14] P. A. Thompson and E. W. Marchant, A computer model for the evacuation of large building populations, Fire Saf. J. vol. 24 (1995) pp. 131–148.

[15] Ministry of Interior (Italy), DM 03/08/2015: Fire safety criteria (Approvazione di norme tecniche di prevenzione incendi, ai sensi dell'articolo 15 del decreto legislativo 8 marzo 2006, n. 139.), 2015.

[16] Italian Government, DM 19/08/1996: Fire safety criteria for entertainment public spaces (Regola tecnica di prevenzione incendi per la progettazione, costruzione ed esercizio dei locali di intrattenimento e di pubblico spettacolo), (1996).

[17] Secretary of State (England and Wales), The Regulatory Reform (Fire Safety) Order, (2005). http://www.legislation.gov.uk/uksi/2005/1541/contents/made.

[18] P. Thompson, D. Nilsson, K. Boyce, D. McGrath, Evacuation models are running out of time, Fire Safety Journal. 78 (2015) 251–261. doi:10.1016/j.firesaf.2015.09.004.

[19] N.C. McConnell, K.E. Boyce, J. Shields, E.R. Galea, R.C. Day, L.M. Hulse, The UK 9/11 evacuation study: Analysis of survivors' recognition and response phase in WTC1, Fire Safety Journal. 45 (2010) 21–34. doi:10.1016/j.firesaf.2009.09.001.

[20] J.D. Averill, D.S. Mileti, R.D. Peacock, E.D. Kuligowski, N. Groner, G. Proulx, et al., World Trade Center Disaster Occupant Behavior , Egress , and Emergency Communications, NIST NCSTAR 1-7, 2005.

[21] N.R. Johnson, W.E. Feinberg, D.M. Johnston, Microstructure and panic: the impact of social bonds on individual action in collective flight from the Beverly Hills Supper Club Fire, in: K. Tierney, R. Dynes (Eds.), Disasters, Collective Behaviour and Social Organization, University of Delaware press, Newark- Delaware, 1994: pp. 168–189.

[22] N. Johnson, Fire in a crowded theater: a descriptive investigation of the emergence of panic, International Journal of Mass Emergencies and and Disasters. 6 (1988) 110–117.

[23] M. Kobes, I. Helsloot, B. de Vries, J.G. Post, N. Oberijé, K. Groenewegen, Way finding during fire evacuation; an analysis of unannounced fire drills in a hotel at night, Building and Environment. 45 (2010) 537–548. doi:10.1016/j.buildenv.2009.07.004.

[24] G. Proulx, Evacuation planning for occupants with disability, in: Fire Risk Management Program Institute for Research in Construction National Research Council Canada, 2002. http://campus.server269.com/wp-content/uploads/downloads/2012/02/proulx-disability-planning.pdf (accessed July 11, 2014).

[25] K. Lena, A. Kristin, B. Staffan, W. Sara, S. Elena, How Do People with Disabilities Consider Fire Safety and Evacuation Possibilities in Historical Buildings?—A Swedish Case Study, Fire Technology. 48 (2010) 27–41. doi:10.1007/s10694-010-0199-0.

[26] M. Tancogne-Dejean, P. Laclémence, Fire risk perception and building evacuation by vulnerable persons: Points of view of laypersons, fire victims and experts, Fire Safety Journal. 80 (2016) 9–19. doi:10.1016/j.firesaf.2015.11.009.

[27] R. Tonikian, G. Proulx, N. Bénichou, I. Reid, Literature review on photoluminescent material used as a safety wayguidance system, National Research Council of Canada, Institute for Research in Construction. (2006). http://www.everglow.us/pdf/nrc-literature-review-of-pl-path-marking-march-2006-rr-214.pdf (accessed December 16, 2013).

[28] M. Kobes, I. Helsloot, B. de Vries, J. Post, Exit choice, (pre-)movement time and (pre-)evacuation behaviour in hotel fire evacuation - Behavioural analysis and validation of the use of serious gaming in experimental research, Procedia Engineering. 3 (2010) 37–51. doi:10.1016/j.proeng.2010.07.006.

[29] Italian Government, DM 10/03/1998: Criteria for fire safety and emergency management at workplace (Criteri generali di sicurezza antincendio e per la gestione dell'emergenza nei luoghi di lavoro), (1998).

[30] Parliament of the United Kingdom, Health and Safety (Safety Signs and Signals) Regulation 1996, (1996).

[31] ISO, ISO 16069, Graphical symbols - Safety signs - S afety way guidance systems (SWGS), (2004).

[32] Italian Organization for Standardization (UNI), UNI 7543:2004 - Safety colours and safety signs, (2004).

[33] International Organization for Standardization, ISO 3864-1:2011 - Annex A, Relationship between dimensions of safety signs and distance of observation, (2011).

[34] British Standards Institution, BS 5499-4:2000 - Safety signs, including fire safety signs. Code of practice for escape route signing, (2000).

[35] H. Ran, L. Sun, X. Gao, Influences of intelligent evacuation guidance system on crowd evacuation in building fire, Automation in Construction. 41 (2014) 78–82. doi:10.1016/j.autcon.2013.10.022.

[36] S.-H. Wang, W.-C. Wang, K.-C. Wang, S.-Y. Shih, Applying building information modeling to support fire safety management, Automation in Construction. 59 (2015) 158–167. doi:10.1016/j.autcon.2015.02.001.

[37] D. Nilsson, H. Frantzich, W.W.F. Klingsch, C. Rogsch, A. Schadschneider, M. Schreckenberg, Design of Voice Alarms.The Benefit of Mentioning Fire and the Use of a Synthetic Voice, Pedestrian and Evacuation Dynamics 2008. (2010) 135–144. doi:10.1007/978-3-642-04504-2.

[38] S. Pu, S. Zlatanova, Evacuation Route Calculation of Inner Buildings, in: Research Book Chapter in Geo-Information for Disaster Management, Springer, 2005: pp. 1143–1161.

[39] L. Chu, A RFID-Based Hybrid Building Fire Evacuation System on Mobile Phone, Sixth International Conference on Intelligent Information Hiding and Multimedia Signal Processing. (2010) 155–158. doi:10.1109/IIHMSP.2010.46.

[40] A.M. Ibrahim, I. Venkat, K.G. Subramanian, A.T. Khader, P. De Wilde, Intelligent Evacuation Management Systems, ACM Transactions on Intelligent Systems and Technology. 7 (2016) 1–27. doi:10.1145/2842630.

[41] M. D’Orazio, S. Longhi, P. Olivetti, G. Bernardini, Design and experimental evaluation of an interactive system for pre-movement time reduction in case of fire, Automation in Construction. 52 (2015) 16–28. doi:10.1016/j.autcon.2015.02.015.

[42] E. Vilar, F. Rebelo, P. Noriega, E. Duarte, C.B. Mayhorn, Effects of competing environmental variables and signage on route-choices in simulated everyday and emergency wayfinding situations, Ergonomics. 57 (2014) 511–524. doi:10.1080/00140139.2014.895054.

[43] C.-H. Tang, W.-T. Wu, C.-Y. Lin, Using virtual reality to determine how emergency signs facilitate way-finding., Applied Ergonomics. 40 (2009) 722–30. doi:10.1016/j.apergo.2008.06.009.

[44] W.H. Van Willigen, R.M. Neef, a. Van Lieburg, M.C. Schut, WILLEM: A Wireless InteLLigent Evacuation Method, Third International Conference on Sensor Technologies and Applications. (2009) 382–387. doi:10.1109/SENSORCOMM.2009.64.

[45] K. Yenumula, C. Kolmer, J. Pan, X. Su, BIM-Controlled Signage System for Building Evacuation, Procedia Engineering. 118 (2015) 284–289. doi:10.1016/j.proeng.2015.08.428.

[46] J. Wang, H. Zhao, S. Winter, Integrating sensing, routing and timing for indoor evacuation, Fire Safety Journal. 78 (2015) 111–121. doi:10.1016/j.firesaf.2015.08.009.

[47] I. Sharp, K. Yu, Sensor-based dead-reckoning for indoor positioning, Physical Communication. 13 (2014) 4–16. doi:10.1016/j.phycom.2013.11.013.

[48] T. Teixeira, G. Dublon, A. Savvides, A survey of human-sensing: Methods for detecting presence, count, location, track, and identity, ACM Computing Surveys. 1 (2010). http://thiagot.com/papers/teixeira_techrep10_survey_of_human_sensing.pdf (accessed November 8, 2014).

[49] K. Yu, I. Oppermann, E. Dutkiewicz, I. Sharp, G. Retscher, Indoor navigation and tracking, Physical Communication. 13 (2014) 1–3. doi:10.1016/j.phycom.2014.02.003.

[50] D. Zhang, F. Xia, Z. Yang, L. Yao, Localization Technologies for Indoor Human Tracking, in: 5th International Conference on Future Information Technology (FutureTech), Busan, Korea, 2010.

[51] B. Castaño, M. Rodriguez-Moreno, A ZigBee and RFID hybrid system for people monitoring and helping inside large buildings, in: 2010 IEEE Symposium on Industrial Electronics and Applications (ISIEA 2010), Penang, Malaysia, 2010: pp. 16–21. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5679504 (accessed November 29, 2013).

[52] H.M. Khoury, V.R. Kamat, Evaluation of position tracking technologies for user localization in indoor construction environments, Automation in Construction. 18 (2009) 444–457. doi:10.1016/j.autcon.2008.10.011.

[53] A. Veichtlbauer, T. Pfeiffenberger, Dynamic Evacuation Guidance as Safety Critical Application in Building Automation, in: S. Bologna et al. (Ed.), CRITIS 2011, Springer-Verlag, 2013: pp. 58–69.

[54] L. Chu, S.-J. Wu, A Real-time Fire Evacuation System with Cloud Computing, Journal of Convergence Information Technology. 7 (2012) 208–215. doi:10.4156/jcit.vol7.issue7.26.

[55] H.W. Hamacher, S.A. Tjandra, Mathematical modelling of evacuation problems: state of the art, in: M. Schreckenberg, S.D. Sharma (Eds.), Pedestrian and Evacuation Dynamics 2002, Springer Verlag, Berlin, 2002: pp. 227–266.

[56] H. Vermuyten, J. Beliën, L. De Boeck, G. Reniers, T. Wauters, A review of optimisation models for pedestrian evacuation and design problems, Safety Science. 87 (2016) 167–178. doi:10.1016/j.ssci.2016.04.001.

[57] Q. Li, T. Plocher, Time-dependent classification and signaling of evacuation route safety, US 7,683,793 B2, 2010. http://www.google.com/patents/US7683793 (accessed June 27, 2014).

[58] C. Richter, A. Sanso, D. Rockett, H. Nersu, SYSTEM AND METHOD FOR DYNAMICALLY AND EFFICENTLY DIRECTING EVACUATION OF A BUILDING DURING AN EMERGENCY CONDITION, US 7,579,945 B1, 2008.

[59] E. Quagliarini, Wooden structures in Italian style theatres between the 18° and 19° century (in Italian), Firenze, Italy, 2008.

[60] A. Seyfried, B. Steffen, T. Lippert, Basics of modelling the pedestrian flow, Physica A: Statistical Mechanics and Its Applications. 368 (2006) 232–238. doi:10.1016/j.physa.2005.11.052.

[61] H. Xie, L. Filippidis, E.R. Galea, D. Blackshields, P.J. Lawrence, Experimental analysis of the effectiveness of emergency signage and its implementation in evacuation simulation, Fire and Materials. (2012) 367–382.

doi:10.1002/fam.

[62] D.R. Parisi, C.O. Dorso, Microscopic dynamics of pedestrian evacuation, Physica A: Statistical Mechanics and Its Applications. 354 (2005) 606–618. doi:10.1016/j.physa.2005.02.040.

[63] D. Helbing, A.F. Johansson, Pedestrian, Crowd and Evacuation Dynamics, in: Encyclopedia of Complexity and Systems Science, Springer, 2010: pp. 6476–6495.

[64] T. Korhonen, S. Hostikka, Fire Dynamics Simulator with Evacuation: FDS + Evac Technical Reference and User ' s Guide, 2010. http://www.vtt.fi/publications/index.jsp.

[65] Z. Zainuddin, M. Shuaib, Modelling the Pedestrian's Perception for the Social Force Model to Reproduce Experimental Data, Applied Sciences. 11 (2010) 865–870.

[66] Italian Government, DLgs 9/4/2008 n.81: Annex XXV - General requirements for emergency signs (allegato XXV, Prescrizioni generali per i cartelli segnaletici), (2008).

[67] DIN, DIN 67510, Photoluminescent pigments and products, (2009).

[68] ISO, ISO 3864-1, Annex A, Relationship between dimensions of safety signs and distance of observation, (2011).

[69] Confederation of Fire Protection Associations Europe, Fire safety engineering concerning evacuation from buildings - Guidelines No 19:2009, 2009. http://www.cfpa-e.eu/wp-content/uploads/files/guidelines/CFPA_E_Guideline_No_19_2009.pdf.

[70] E. Ronchi, D. Nilsson, The Process of Verification and Validation of Building Fire Evacuation Models, NIST Technical Note. 1822 (2013).

[71] S. Heliövaara, T. Korhonen, S. Hostikka, H. Ehtamo, Counterflow model for agent-based simulation of crowd dynamics, Building and Environment. 48 (2012) 89–100. doi:10.1016/j.buildenv.2011.08.020.

[72] T.I. Lakoba, D.J. Kaup, N.M. Finkelstein, Modifications of the Helbing-Molnar-Farkas-Vicsek Social Force Model for Pedestrian Evolution, Simulation. 81 (2005) 339–352. doi:10.1177/0037549705052772.

[73] Ministry of Interior (Italy), D.M. 20-05-1992 n. 569 - Fire safety in historical buildings used as museum and art galleries, 1992.

[74] G.-Y. Jeon, J.-Y. Kim, W.-H. Hong, G. Augenbroe, Evacuation performance of individuals in different visibility conditions, Building and Environment. 46 (2011) 1094–1103. doi:10.1016/j.buildenv.2010.11.010.

[75] B. Yang, J. Luo, Q. Liu, A novel low-cost and small-size human tracking system with pyroelectric infrared sensor mesh network, Infrared Physics & Technology. 63 (2014) 147–156. doi:10.1016/j.infrared.2013.12.020.

[76] Q. Guan, C. Li, X. Guo, G. Wang, Compressive classification of human motion using pyroelectric infrared sensors, Pattern Recognition Letters. 49 (2014) 231–237. doi:10.1016/j.patrec.2014.07.018.

[77] M. Kuipers, A. Tomé, T. Pinheiro, M. Nunes, T. Heitor, Building space–use analysis system — A multi location/multi sensor platform, Automation in Construction. 47 (2014) 10–23. doi:10.1016/j.autcon.2014.07.001.

[78] B. Andò, S. Baglio, C. Lombardo, RESIMA: A Smart Multisensor Approach For Indoor AAL, in: S. Longhi, P. Siciliano, M. Germani, A. Monteriù (Eds.), FORITAAL2013, Springer, Ancona, Italy, 2013. http://www2.diees.unict.it/users/bando/files/resima_2.pdf (accessed April 30, 2014).

[79] J. Wang, D. Chen, H. Chen, J. Yang, On pedestrian detection and tracking in infrared videos, Pattern Recognition Letters. 33 (2012) 775–785. doi:10.1016/j.patrec.2011.12.011.

[80] S.D. Khan, Estimating Speeds and Directions of Pedestrians in Real-Time Videos : A solution to Road- Safety Problem, CEUR Workshop Proceedings. 1122 (2014). http://ceur-ws.org/Vol-1122/paper6.pdf.

[81] L. Yi-fan, C. Jun-min, J. Jie, Z. Ying, S. Jin-hua, Analysis of Crowded Degree of Emergency Evacuation at "Bottleneck" Position in Subway Station Based on Stairway Level of Service, Procedia Engineering. 11 (2011) 242–251. doi:10.1016/j.proeng.2011.04.653.

[82] M. Mori, H. Tsukaguchi, A new method for evaluation of level of service in pedestrian facilities, Transp. Res. 21A(3) (1987) 223–234.