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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-illuminated 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

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

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

7 8 **2 Introduction** 9

10 Researches about individuals' safety in buildings during a fire [1,3–5] demonstrated how the occupants' evacuation is
11 widely influenced by behavioral aspects, architectural spaces features (including their layout) and evacuation
12 wayfinding systems. Many interferences affect the evacuation process especially in historical building [1,6,7], where
13 people move in mostly unfamiliar architectural spaces and high occupants' density are coupled with reduced places
14 [1,8,9].

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

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

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

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

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

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

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

20 Hence, IEGS could be able to “dynamically” interact with occupants in emergency conditions while jointly considering
21 their behaviors and surrounding environment conditions. However, these systems should be designed by avoiding
22 current approaches simplifications and related shortcomings, such as the ones connected to the potential effect of a fire²,
23 and by taking advantages of previous wayfinding studies [1,3–5,28]. The “behavioral design” (BD) approach would
24 help in developing similar systems by founding the building components definition on human behavioral aspects,
25 providing not-invasive solutions while preserving architectural characteristics, and also using innovative design
26 solutions and tools [1,3].

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

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

39 In this study, an innovative IEGS for individuals’ safety in building heritage is defined and evaluated in an historical
40 Italian-style theatre. The proposed occupants’ Density-based IEGS (*DensIEGS*) considers as main input values the
41 occupants’ density along egress paths, doors and exits, so as to evidence slowing down or bottlenecks in evacuation
42 [13,60]. “Collective” signs will address the best evacuation path in terms of pedestrians' density (and so overcrowding
43 probability) to incoming occupants. According to the “behavioral design” approach and previous studies about
44 wayfinding systems evaluation [2,41,45,61], an initial system effectiveness evaluation can be performed by using
45 validated microscopic evacuation simulators [62–64], which are able to reproduce human interactions in emergency
46 evacuation in an accurate way [63]. One of the most powerful approaches is represented by the Social Force Model
47 [63]: experimental-based individuals’ interactions with both other building occupants and environmental elements are
48 represented by assigning evacuation rules (defined in mathematical terms by a series of “invisible” Social Forces) to
49 each person. The overlapping of these interactions evidences the same macroscopic phenomena noticed in real world
50 events [62,63,65]. Analyses on risk-reduction interventions could easily take advantages of this approach also in order
51 to reduce the impact of implementation problems connected to organization of a real-world evacuation drill, creation of
52 the IEGS and application to a case study [2,46].

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58 ¹ E.g.: Siemens® "Total Building Solution": <https://www.youtube.com/watch?v=yep6k5zDtF0> (last access 12/12/2015)

59 ² For example, regulations do not discouraged the application of signs near to (at) the ceiling: nevertheless, during a fire, the ceiling
60 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.

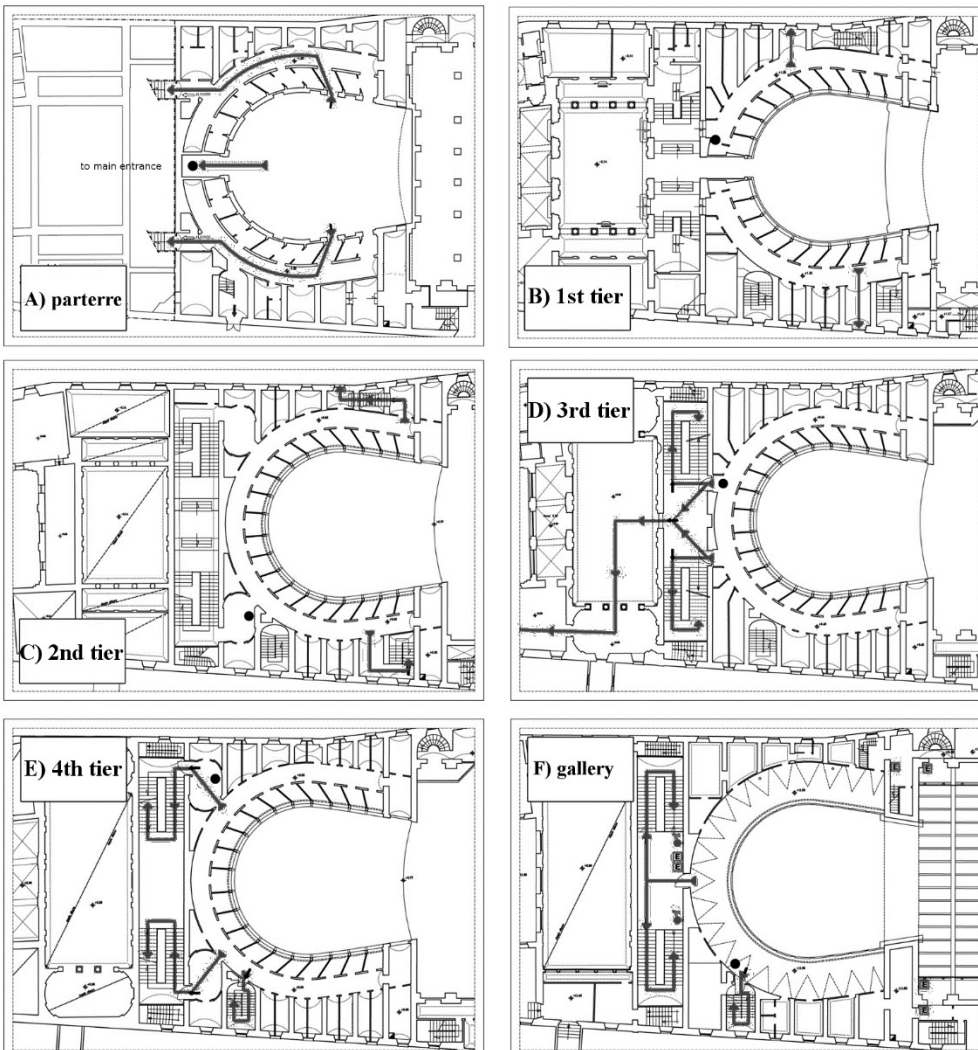


Figure 1. Theater level plans: A-parterre; B- 1st tier and main entrance; C- 2nd tier; D- 3rd tier and foyer; E-4th tier; F-gallery. Evacuation paths (gray arrows) according to the theatre evacuation plan and position of the main evacuation maps hanged on building walls (black dots) are evidenced. The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

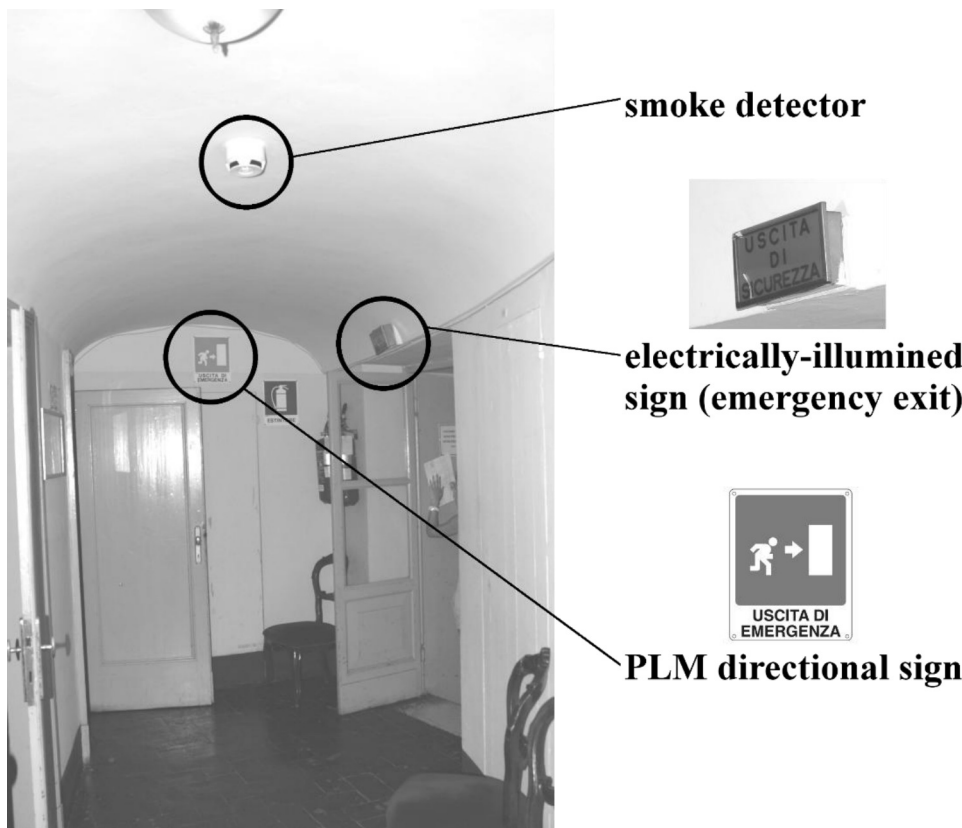


Figure 2. View of the 1st tier corridor (right side), including the current wayfinding sign and other elements within evacuation facilities.

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.

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" index⁶). 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 modifications⁴, 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 v2.5.0⁷. 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 license⁸. 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-in¹⁰ 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

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:

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

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
<i>Scenario 0</i>	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
<i>Scenario IEGS</i>		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

1 The proposed Density-based Intelligent Evacuation Guidance System (*DensIEGS*) uses the pedestrians' density as
2 representative parameter for describing human behaviors and possibility to move along an indoor path.
3

4 **4.1 DensIEGS characterization**

5
6 Figure 3 resumes the overall proposed system by including both the system blocks (on the left) and their related
7 operations within the path choice algorithm (on the right).

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

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

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

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

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

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

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

50 All sensors and signs should be removable, connected by Wi-Fi and supplied by portable batteries¹¹, in order to avoid
51 massive cables and related installation interventions on buildings. Existing electrically-illuminated signs (often placed in
52 building heritage) could be shared with IEGS. Furthermore, another fundamental topic is represented by the fire
53 resistance of elements composing the system (e.g.: electric devices should be hosted by fireproof or fire retardant
54 boxes). At the same time, the electrical equipment should be tested in fire conditions.
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58 ¹¹ With both good durability and low level of maintenance. Communication could be also guaranteed by “power over Ethernet” tech-
59 nologies in no blackout and no fire damages emergency conditions.
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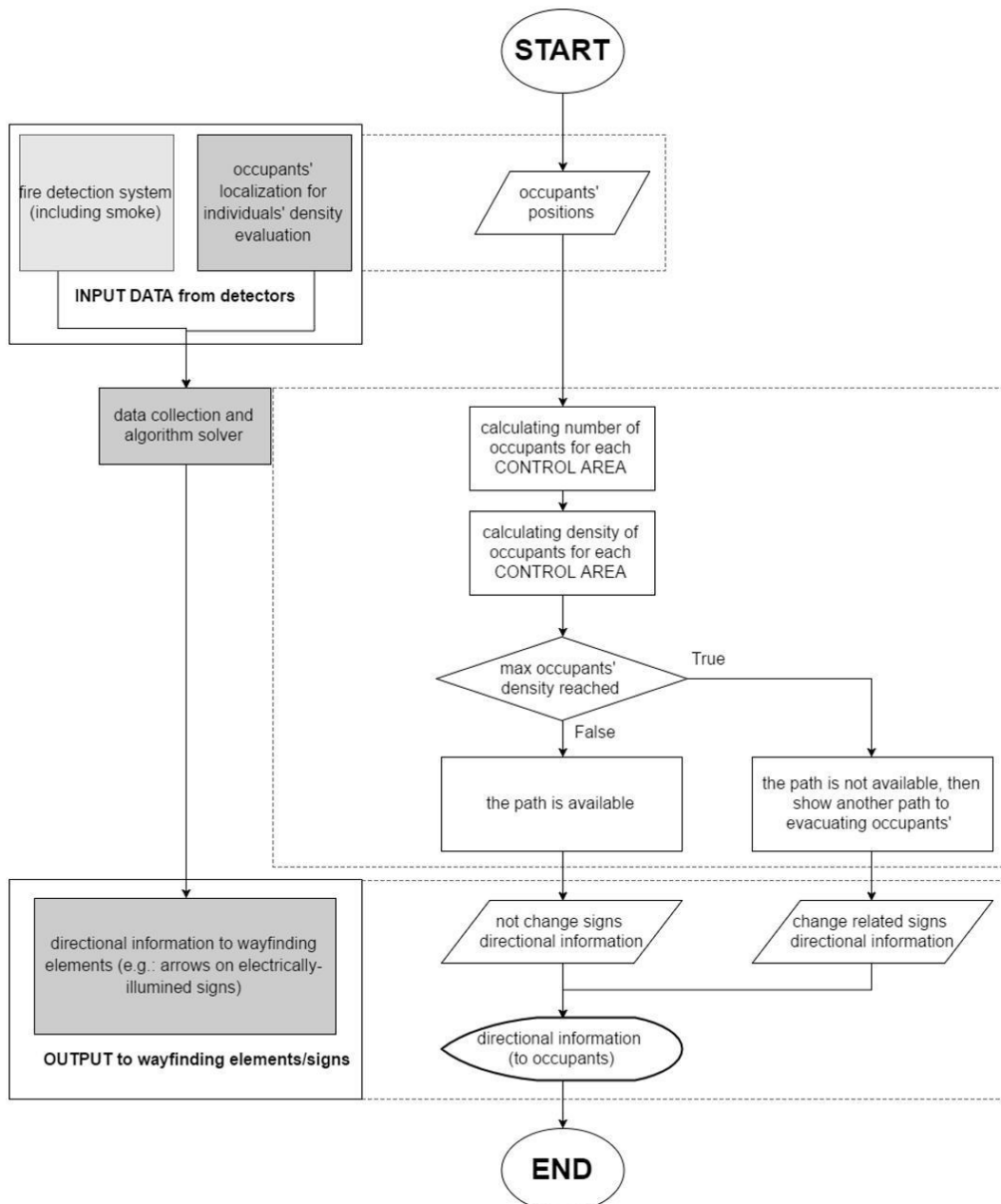


Figure 3. Schematization for the DensIEGS: system blocks and path choice algorithm (without smoke influence) used for DensIEGS decision about available door/path.

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

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

4 In order to define “control areas” in the given environment to be simulated, an external input file (*InputArea.txt*) is
5 defined. For each “control area”, this file includes: the related identifier of the area (by including the related controlled
6 door); the coordinates of corners; the density limit for closing (DENSITY_CLOSE) or opening (DENSITY_OPEN) the
7 related doors; the area (m²); the number of agents who is inside at time T=0. It is considered that a “control area” can
8 manage more than one door¹². An external log of pedestrians' densities in each “control area” is offered by a created
9 external file (*risultati.txt*). Both these files should be placed in the same folder of the *.fds input file for simulation.

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

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

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

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

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

37 38 39 **5 DensIEGS application: effectiveness evaluation results by simulations**

40
41 Figure 4 schematizes the overall theatre by using the DensIEGS. All the simulated elements are represented: “control
42 areas”, placed (just) before a layout bottleneck (e.g.: near a door such as for area 6 in Figure 4-a); at layout variations
43 (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
44 two consecutive bottlenecks (e.g.: area 5 in Figure 4-c), within the different floor levels; the position of signs; the
45 identification of exits including both main and secondary ones.
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59 ¹² In operative terms, the simulator adopts two control area with the same geometrical and density limit features, but with different
60 door identifiers (one for each door).
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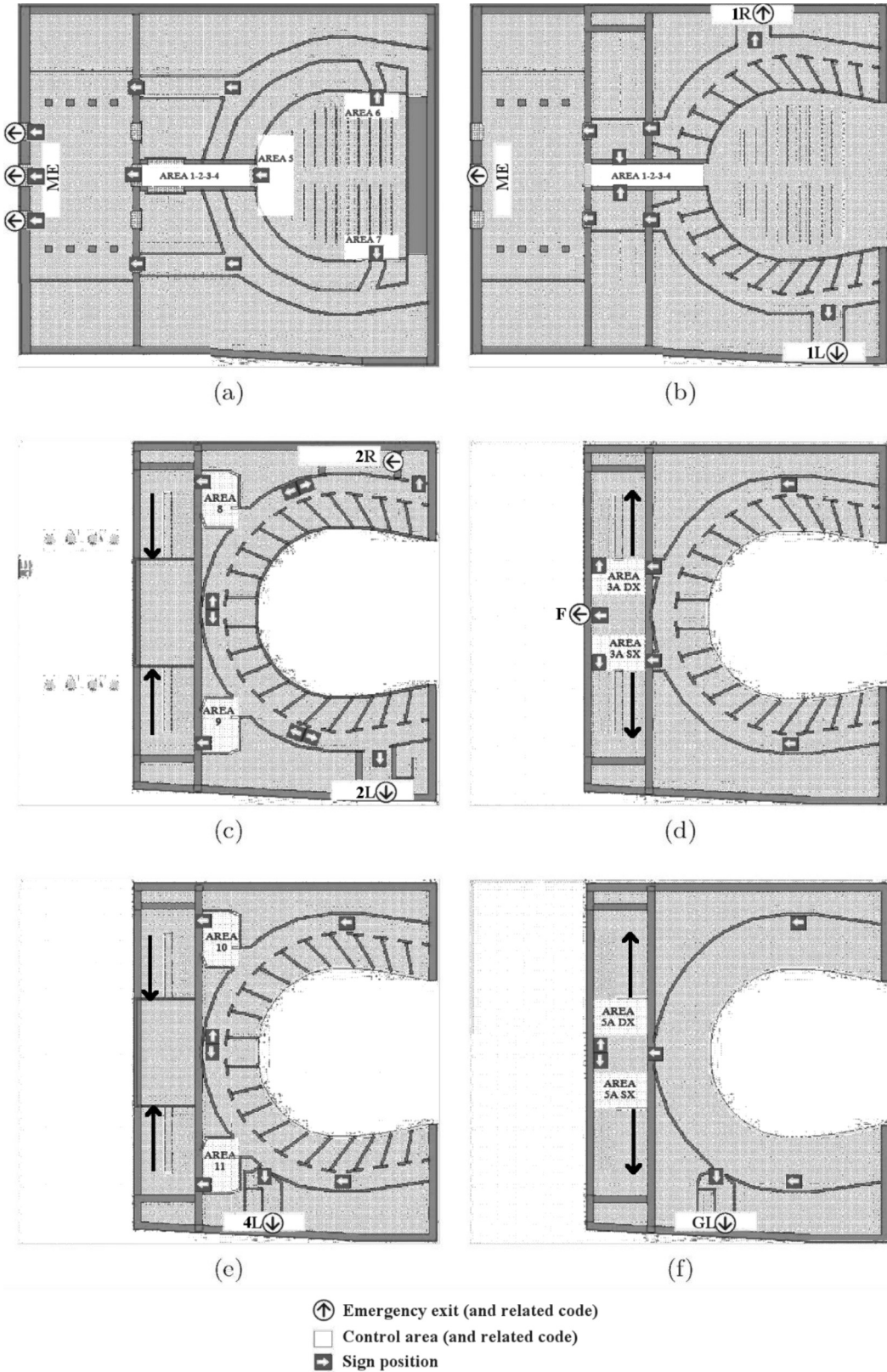


Figure 4. Application scheme of DensIEGS at the different theater levels, including: “control areas” positioning (and related identification code within *InputArea.txt*); signs positioning over the doors and along the paths, managed by the nearby “control area”, also according to Section 4.2; exits identifications (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 $\Delta(\%)$ 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.* *DensIEGS* 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 $\Delta(\%)$ 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 $\Delta(\%)$ 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)		$\Delta(\%)$
	Scenario 0	Scenario IEGS	
Overall theatre	170	125	-26
Level			
Parterre	100	60	-40
1 st tier	60	35	-41
2 nd tier	150	105	-30
3 rd tier	110	85	-22
4 th tier	100	45	-55
Gallery	50	35	-30

Table 3. Comparison of maximum evacuation times.

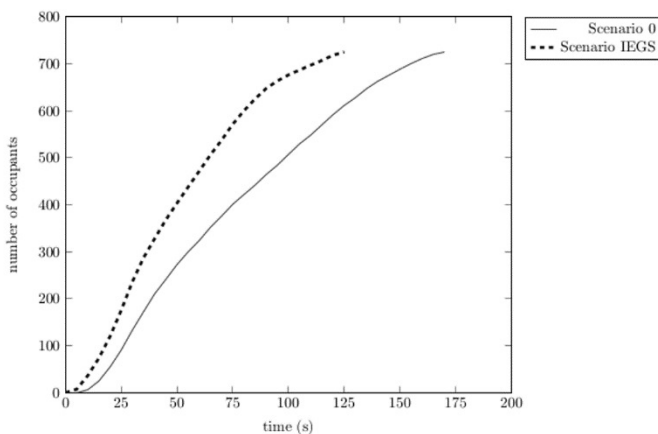
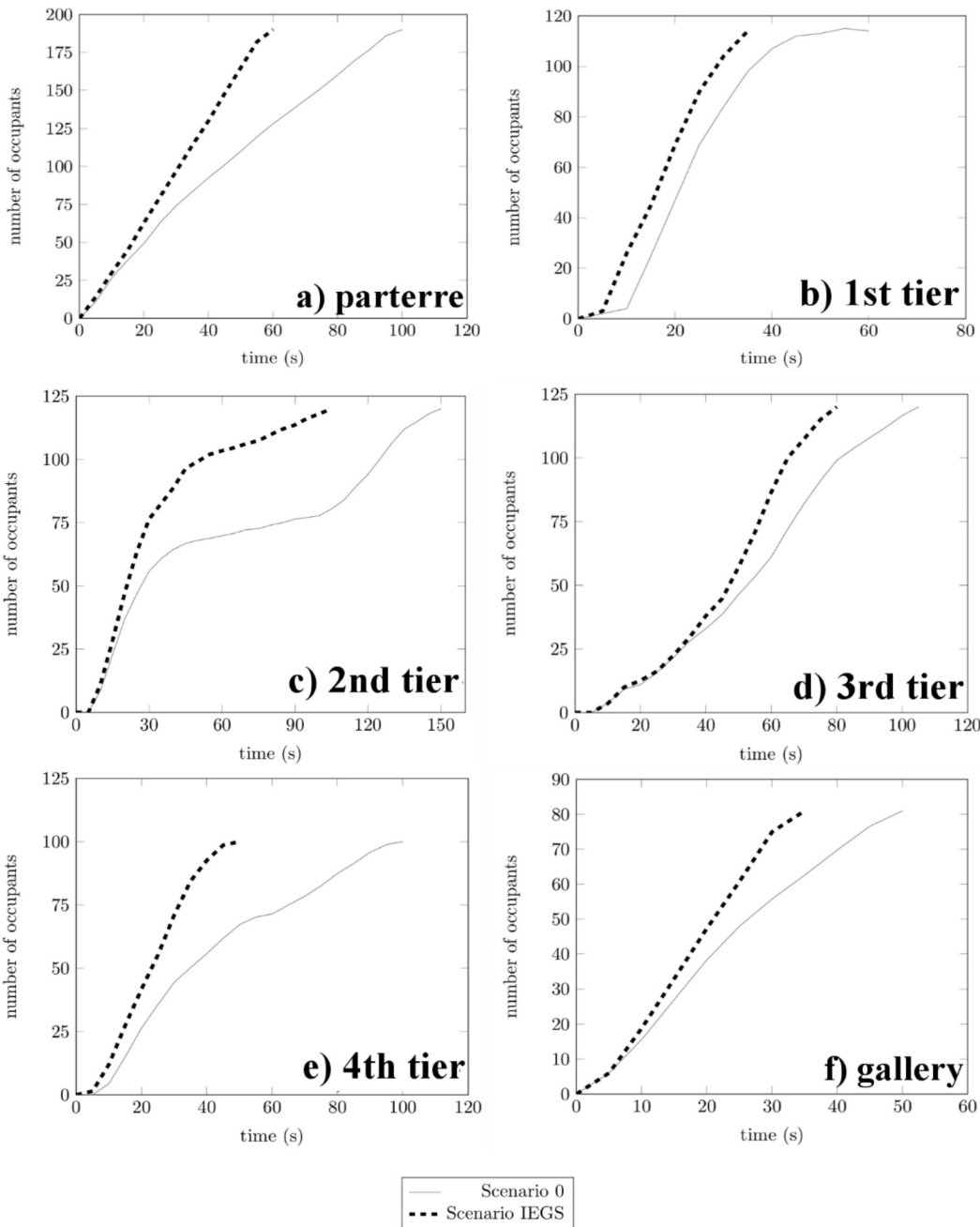


Figure 5. Comparison between “Scenario 0” and “Scenario IEGS” simulations concerning curves about number of exited pedestrians against evacuation time for the whole theater.

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

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



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

57 Finally, some remarks about occupants' exit choice decision have to be pointed out. In the “*scenario 0*” configuration,
 58 an average value of about 8% of occupants chooses secondary paths (RD:6%; LD:10%). As we could suppose before
 59

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
	$\Delta(\%)$	-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
	$\Delta(\%)$	-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
	$\Delta(\%)$	-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
	$\Delta(\%)$	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 $\Delta(\%)$ is calculated.

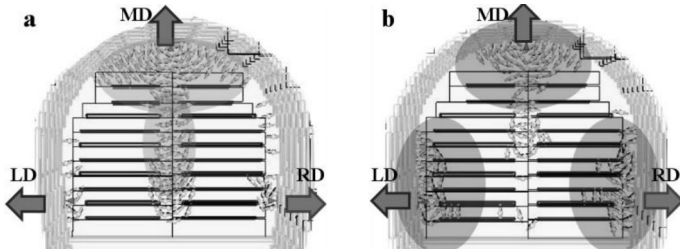


Figure 7. Graphical representation of parterre evacuation differences in “scenario 0” (a) and “scenario IEGS” (b). Gray filled ellipses evidence areas with higher occupants’ densities during the evacuation. Exit doors are identified and codified. The background image is taken from a Smokeview simulation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

Scenario	Main door (MD)			Right door (RD)			Left door (LD)		
	IEGS	0	$\Delta(\%)$	IEGS	0	$\Delta(\%)$	IEGS	0	$\Delta(\%)$
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

1 large damages. Current regulations propose massive interventions on the building configuration, which are often not
2 useful for occupants. This research work proposes a “behavioural design” (BD) approach to increase individuals’ safety
3 based on the following methodology: analysing the needs of evacuating pedestrian and then designing evacuation
4 facilities in order to provide the required answers to these human needs.

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

18 *DensIEGS* seems to be able to guide people along the “correct” paths by taking into account their boundary conditions:
19 in this way, the evacuation time can be drastically reduced and safety levels accordingly increased. Occupants’ number
20 is distributed through the various paths and exits, so as to avoid dangerous overcrowding conditions (that generally
21 affect the egress time by slowing down the evacuees). The estimated evacuation time in *DensIEGS* conditions is up to
22 26% lower than the one for current wayfinding system conditions (40% for levels with 3 or more different possible
23 paths). In fact, secondary exits are better utilised by people because chosen as the clearest path . The number of people
24 using secondary paths (that are also the less crowded ones) raises to 88% while using *DensIEGS* in respect to the
25 traditional punctual system.

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

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

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

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