Chapter 2
Fire Safety and Building Heritage: The Occupants Perspective

Abstract Current regulations and approaches to fire safety seem to be generally characterized by a schematic and deterministic point of view, especially while dealing with Building Heritage. They generally consider how interventions on buildings could be enough for reducing people's risk, because occupants would surely behave in the correct way. Hence, massive modifications to the original building layout can be adopted (limited, e.g., to increasing number and dimensions of egress paths), while effective man-environment and man-man emergency evacuation interactions are underestimated. Starting from this issue, this chapter firstly analyses main limitations of these approaches, by focusing on human behaviors during a fire, especially in case of emergencies in historical buildings. To this end, main aspects of both significant international and national regulations and literature studies on human fire evacuation behaviors are organized and reviewed. Hence, the importance of innovative strategies, such as the ones based on the Fire Safety Engineering approach, is discussed by mainly evidencing the fundamental impact of human behavior modeling as a new tool for designing and evaluating low-impact risk-reduction solutions.

2.1 Safety in (and of) Building Heritage: Main Issues and Concepts

Since providing an "adaptive reuse" of Building Heritage [1, 2] is encouraged by many regulations and guidelines (e.g., [3]), as well as keeping historic buildings operational, the conservation of these architectural spaces should be linked to an adequate response to needs of people who use the spaces itself, in terms of functional requirements. These two issues become really relevant and critical while ensuring safety in Building Heritage and protecting it from natural disasters (fires, earthquakes, floods, hurricanes, storms, and so on) [4].

In fact, when a disaster involves an historic architectural space, the emergency conditions affect and damage not only the building itself (its structural and non-structural elements) and the contained goods and chattels (artworks such as paintings, sculptures, furniture, building decorations), but also the hosted occupants. In general terms, historical scenarios (both single buildings and urban environments)

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are characterized by an important level of risk, in case of different emergencies, because of three main factors [5–7]:

- *Hazard H*: It is related to the possibility that a given disaster with a certain magnitude (or intensity) can happen in a given period of time. This parameter is connected to "intrinsic" features of the considered site in which the building is placed (e.g., seismic zone for earthquake risk [8]; inundation probabilities for natural or climate change-related events [9, 10]), or to activities that are housed in the architectural spaces (e.g., fire sources due to particular activities, manufacturing processes, malfunctioning of plants [6, 11, 12]);
- *Vulnerability V*: It can be related to the possibility that a given element will suffer a certain damage (or losses) level when a given disastrous event will happen. This parameter refers to different characteristics of the architectural space, such built elements and circulation spaces (both single building or urban space), in relation to the inquired emergency kind (e.g., earthquake vulnerability due to building typologies and other building features [8]; building fire vulnerability of structural and non-structural elements, and their related fire response performances [13, 14]). The less a vulnerability index, the higher the built environment resistance index to a given disaster;
- *Exposure E*: It is related to spatial and temporal distribution of "agents" which are exposed to a hazard. In particular, it traditionally deals with the human presences in the considered scenario, by including both human life presence (e.g., number of involved people, occupants'/inhabitants' density), artifacts (with an historical, cultural, and artistic value), and human activities (both from an economic and social point of view) [4, 7, 15]. Furthermore, this factor has to consider: individuals' (building occupants; population at urban scale) behaviors in emergency, risk perception, preparedness levels; emergency management procedures and rescuers' response in the first-aid phase; and maintenance and monitoring systems in order to immediately aid damaged people [7, 11]. Similar elements were previously introduced by works on resilience (and resistance) estimation at territorial scale [5, 16].

From the Building Heritage occupants' perspective, both environmental features and possible damages due to the disaster occurrence can seriously interfere with the individuals, by provoking:

- *direct effects*: due to interferences between people and the event itself and/or direct effects on built environment (e.g., injuries and fatalities due to smoke toxicity in case of fire, during the emergency event itself [17], or building collapse in case of earthquake [7]), or also among individuals during the event (e.g., fatalities due to stampede or mass panic effects in case of evacuation [18, 19]);
- *induced effects*: due to interferences between people and cascade effects or secondary effects (e.g., post-earthquake fires [7]);
- *emergency management effects*: due to evacuation process (including the possibility to autonomously gain assembly points and interferences with environment

during evacuation), medical preparedness, and rescuers' management procedures (including reaching injured people where they are) [7, 20];
- *indirect effects*: mainly connected to effects on human health during the emergency and aftermath diseases including long-term and mental diseases [21];
- effects on the community: connected to economical and social losses (due to e.g., critical infrastructures damages, interruption of business and activities), but also to damages of community symbols and to the necessity of lifestyle changes (e.g., damages to particular human artifacts or monuments; relocation, isolation, and social disruption problems) [22].

The combination of H, V, and E elements affects people's safety levels, in particular when people have to evacuate an historic scenario [7, 20, 23]. The *evacuation* is a *dynamic process* because individuals' choices depend on surrounding environmental conditions evolution during the time: Some specific features about Building Heritage, emergency type, and man-man interactions could hinder (or even prevent) people escaping from the initial dangerous conditions, moving in "safe" conditions and reaching a "safe" area[1] [6–8, 11, 24]. A critical overview of previous literature works [7, 20, 23, 25] demonstrates how the same behavioral issues and schemes can be noticed in different emergencies, scenarios (indoor and outdoor), and environmental scale (single building to urban scale). Hence, from a general conceptual point of view, pedestrians who escape from a building in case of fire or evacuate an urban scenario in case of earthquake can be represented by many similar interactions.

As underlined by Fig. 2.1, surrounding Building Heritage elements and conditions act like stressors on evacuees, whereof presences can vary, during the time, in terms of number and performed activity. These elements influence individuals' behavioral responses (or rather, the "psychonomics" aspects of evacuation) and mainly perceptive aspects, specific motion features, attachment and affiliation, and preparedness to emergency [6–8, 11, 20, 25–29]. Figure 2.1 summarizes how such interactions both affect the *pre-movement* phase (when people spend time performing actions that are not directly connected to leaving the initial unsafe position [20, 23, 30]) and the *evacuation motion* phase (when people effectively move in order to reach a safe place [23, 29, 31]). The psychological impact on people can provoke exceptional destabilizing conditions that lead people to not respond in a correct or "rational" way, that is by adopting the correct evacuation procedures. Hence, evacuees can be directly exposed to additional hazardous elements and also suffer related damages, especially the ones due to direct, induced, and emergency management effects. Two significant examples are offered below. For this reason, particular strategies for architectural space design should be aimed at helping occupants in reaching safer conditions, especially during the motion phase [11, 29, 32].

[1] Such as an assembly point, or another place where people could be not exposed to emergency conditions and be helped by rescuers.

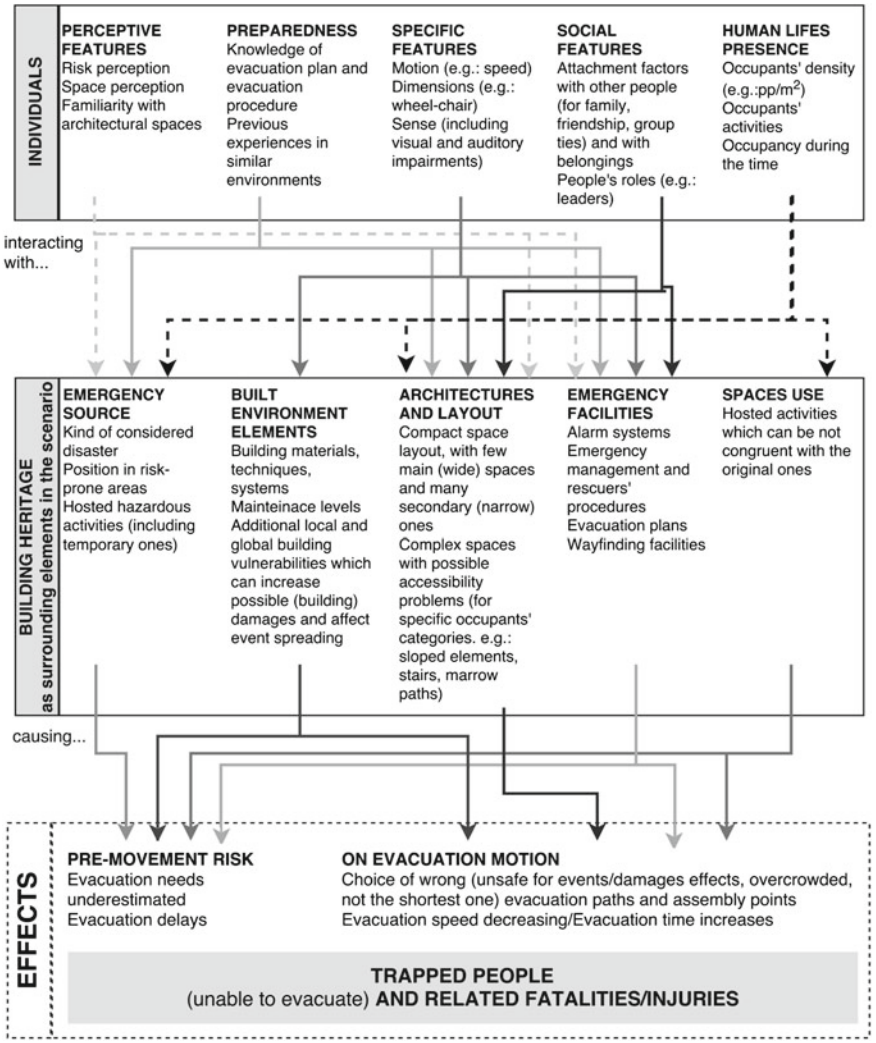


Fig. 2.1 Interferences in the Building Heritage between occupants and environmental elements during an emergency. *Arrows* represents: on the *top*, main interactions between each individuals' features and the environmental factors; on the *bottom*, environmental factors influence on consequences for occupants and hence on damage effects

2.2 Fire Safety in Building Heritage

Fire surely represents one of the most important risks in Building Heritage, because of a particular combinations between the aforementioned risk factors.

H mainly includes the *elements that can increase the possibility of fire occurrence within the building if they are combined* [11, 33]. The first element to be combined is

the "heat" factor, or rather sources of fire. In Building Heritage, the main fire sources are due to old electrical wiring, chimneys and other old heating systems, arson, and open flames in case of particular activities such as building restoration or maintenance interventions.[2] The graphical identification on a building map of these sources could help designers while identified places where the fire could start. The second element to be combined is the "fuel," or rather the presence of combustible materials and their features within the building layout; the main elements to be considered are as follows:

- structural and non-structural elements (e.g., wooden beams, wooden roofs, ancient building finishes, and decorations);
- historical furnitures (including carpets and curtains) and other artworks (e.g., canvas, paintings, solvers, tapestry), and their storages;
- materials for the specific workings and their storages (e.g., building materials, trash, construction equipments during maintenance or restoration interventions).

This "fuel" factor can be represented in the building map, for each floor, by distinguishing areas among their related fire load Q (MJ or kJ) (e.g., compare to NFPA 557[3]). According to current fire safety regulations, this evaluation can be performed by considering the fire load density q (MJ/m^2)[4] or the calorific value of the combustible material (MJ/kg). Table 2.1 resumes some significant common fire loads in Building Heritage. "Fuel" and "heat" factors are combined so as to evaluate the probability that the fire starts, mainly depending on [33–35] the type of fire source and its presence during the time; the type of building (property use) and hosted activity (including temporary ones and maintenance working); the floor area of the considered building; and the characterization of combustible materials. Statistical values and fire records could be retrieved (mainly, from National Fire Corps) and used in order to quickly evaluate the possible ignition frequency in terms of number of possible fires per annum or number of possible fires per m^2 per annum [36].

V concerns *elements that can influence the time during which tenability criteria are not exceeded in the building* (or in a part of a building, when considering each fire zone by itself,[5] and so the Available Safe Egress Time ASET (s) [14, 34, 38], as defined by BS 7974-6:2004. Building Heritage is generally affected by many particular features that can increase the fire growth and the smokes spreading in terms of times (when a fire growth coefficient α (kW/s^2)[6] is significantly high, flashover

[2] A significant example is the Vaccaj's theater fire in July 2008 (Tolentino, MC) that occurred during the building restoration and seriously damaged the theater (http://www.viveremacerata.it/2016/07/29/tolentino-teatro-vaccaj-otto-anni-dallincendio/600363/. In Italian. Accessed 26 Sept 2016).

[3] http://www.nfpa.org/codes-and-standards/document-information-pages?mode=code\&code=557. Accessed 22 Oct 2016.

[4] The kJ per m^2 representation is commonly used for surface materials; in case of furnitures, such as chairs, a kJ per element value could be adopted.

[5] This is the case of delayed evacuation techniques, such as the progressive evacuation strategy: In this case, people move from the damaged fire zone to an adjacent one rather than directly leaving the building. Hence, safety terms are related to each single building part.

[6] Due to the involved combustible materials.

Table 2.1 Common fire loads in building heritage. Fire load densities for different activities, fire load for different elements (furnitures), and calorific value materials are summarized. Values are referred to Italian fire safety codes and handbooks [34, 37], based on UNI EN 1991-1-2, Annex E guidelines. These values are also recommended by the Italian National Fire Corps, in the ClaRaf 3.0 freeware software for fire load calculation and its related database (http://www.vigilfuoco.it/aspx/notizia.aspx?codnews=33487. Accessed 26 Sept 2016)

Fire loads densities	
Activity	Average - 80th percentile (MJ/m^2)
Church	200–525
Museum	300–525
Office	420–511
Public library	1500–1824
School	285–347
Theater (cinema)	300–365
Fire loads	
Element	MJ/element
Armchair	335
Chair (with no padding)	87
Element	MJ/m^2
Book shelf (library, including books)[a]	837
Carpet	47
Curtains[b]	23
Calorific value[c]	
Material	MJ/element
Paper	20.0
Straw	20.0
Textiles	20.0
Wood	17.5

[a]Referred to the shelf floor area.
[b]Mainly, window curtains; referred to the window area.
[c]Values according to [37], p. 716 and ClaRaf database

phenomena could quickly happen in the considered space) and space (fire spreads more quickly in different building parts) [6, 12, 39–41]. Main "intrinsic" building vulnerabilities are as follows:

- combustible materials of structural and non-structural elements, building finishings, furnitures, possible storages;
- scarce fire resistance of some building components (e.g., walls, slabs, and roofing) and/or absence of fire zones, also because of no fire doors;
- building layout:
  - narrow spaces (e.g., passages, exits, corridors, staircases), with additional low ceilings, in which smokes and fire could be channeled, including possible concealed spaces that are generally not used or controlled;

  - vertical openings and direct connections between adjacent levels (in the presence of, e.g., monumental stairways, double height halls); this configuration also influences the fire zone distribution on more building levels; and
  - additional ventilation conditions, which could increase fire effects and its spreading in the building spaces or prevent a correct smoke evacuation.
- possible absence of "active" protection systems, including (automatic) fire detection, fire alarm, (automatic) suppression systems, and smoke control (HVAC[7]) that do not allow to limit the fire spreading.

Other additional vulnerabilities are due to the firefighting teams and to rescuers' operations, with possible delays in interventions due to limited fire safety awareness of the internal rescuers' team or to communications with the local fire brigade (especially in case of no automatic fire detection and alarm systems). The access to the building site by emergency vehicles could be limited in compact urban fabrics, because of street features (e.g., width, slope, stair-streets). Furthermore, in similar environments, fire hydrants could be far from the building. Finally, the building layout could limit rescuers' intervention during the fire, mainly because of the general low familiarity level with the architectural space; a possible scarce support of building facilities for fire suppression (e.g., absence of fire hoses); and the possible necessity to move and use voluminous firefighting equipments in narrow spaces, with no firefighter lifts.

Sometimes, the considered historic building could be affected by external conditions because of additional hazard, such as the presence of possible occurring fires or fire sources, and additional vulnerability, such as the presence of other neighboring fire-vulnerable elements. The building position effectively influences these issues, as for building placed: in hazardous and compact urban fabric (mainly, the old town [42]), which could allow fire propagation between adjacent buildings, near to fire-prone areas (as for the Simonopetra Monastery fire in Mount Athos, Greece in 1990, caused by a forest fire [40]).

Concerning *E*, some differences could be underlined between the different approach: the traditional one that adopts a "prescriptive" approach, and the Fire Safety Engineering one that adopts a "performance-based" approach.

2.3 The Traditional Fire Safety Approach

According to the traditional approach, *E* in Building Heritage fire evacuation seems to be affected only by the *occupants' presence (in terms of number, density, position)*, as shown by the analysis of, e.g., NFPA 101,[8] NFPA 914,[9] [43–48]. From an historical

[7] For example, according to NFPA 90A Standard for the Installation of Air-Conditioning and Ventilating Systems.

[8] http://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards?mode=code\&code=101. Accessed 6 Oct 2016.

[9] http://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards?mode=code\&code=914. Accessed 6 Oct 2016.

point of view, this very quick and simple approach seems to be firstly codified during the eighteenth century.[10] The criterion on which traditional codes are based is easily summarized by [49]:

> Prescriptive approaches rely on the application of a predetermined set of rules that, if employed, limit the risk of the design to an acceptable level.

This concept (and the out coming design criteria) is shared by many current fire safety codes for both new and existing buildings [38]. In this sense, the will of providing a common point of view on fire safety to designers introduces fundamental methodological problems while intervening on the Heritage. This traditional approach is based on two issues.

Firstly, effects on occupants due to fire (in terms of smokes, toxic gases, flames, and so on) and building damages are not generally considered by the traditional approach: building components, structure, and technological systems seem to be enough to avoid the interaction between occupants and these elements. In other words, the historical building elements should be able to reduce fire spreading by, for instance, adopting adequate measures for vulnerability and hazard reduction (compare, e.g., NFPA 941, [43, 44, 46, 48]). Related solutions modify the key factors defined at Sect. 2.2 and could mainly involve the introduction of fire detection and suppression systems, an improvement of fire resistance of building elements, internal walls, and ceilings.[11] Although the effectiveness of similar solutions can surely improve the safety level, they highly contrast the Heritage preservation criterion. In fact, they can introduce massive modifications to building systems (e.g., additional plumbing for fire suppression), implement materials for increasing the fire resistance of structures (e.g., use of fireproof or fire-retardant materials instead of the original ones) or define fire compartments within the same building (e.g., modifying walls and ceiling stratigraphic layout by removing some materials, intumescent products, or adding new finishings and substituting internal doors with fireproof ones) [11, 12, 39, 40, 43].

Secondly, according to the schematic assumption of no significant interferences between evacuees and fire effects, the main occupants' exposure-increasing factors seem to be limited to the geometric ones. Spaces should allow individuals' evacuation in a "reasonable short" time. Hence, the higher the number of occupants, the higher the needed capacity (number and dimensions) of "means of egress" (as defined by, e.g., NFPA 101 and NFPA 914), as if people could be implicitly compared to particles of a liquid in a tank [50]. From this point of view, exposure-increasing factors seem to be mainly limited to:

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[10] For instance, concerning evacuation problems, in the UK, The Fires Prevention (Metropolis) Act 1774 includes the necessity to introduce ladders for multi-story buildings "for assisting persons in houses on fire to escape therefrom"(Read REH (1984) Means of Escape Legislation in Great Britain: A Study in Statutory History. Statute Law Review 5:102112. doi:10.1093/slr/5.3.102, p. 102.).

[11] According to the referring fire-resistance rating standard, as a measure of time, in dependence of building typology, intended use, and/or fire loads (compare to, e.g., Eurocodes, NFPA 914, NFPA 101, other national codes [44, 46].

- *exit layout* in terms of exit number (including place of relative or ultimate safety, smoke-proof enclosures), width (in order to allow "adequate" exit flows (pp/m^2)) [34, 45], positions and reciprocal distance between them (exits should not be so close to each other, so as to avoid the influence of possible obstruction of an exit on the other) [34, 43], direction of door opening ("in the direction of escape" [45]), and solutions for easy door opening (presence of panic handles);
- *paths geometry* in terms of length (mainly, maximum travel distances to an exit, or also to a floor level exit), width dimension, and other slope requirements (especially, for staircases) [43, 45, 46];
- *emergency management strategies* [38, 44, 47] that immediately inform people of the occurring fire, give correct evacuation instructions to occupants (by using, e.g., exit signage; evacuation plan maps visibly posted on building walls; safety training; evacuation drills in order test the effectiveness of evacuation procedures; direct rescuers' help), and keep means of egress available and safe during the whole evacuation process [38, 43, 46]. From this point of view, firefighters and internal rescue team play a fundamental role in controlling the evacuation process [43, 48].

In particular, traditional fire safety codes follow a "prescriptive" approach: They express minimum quantitative requirements of the aforementioned escape layout elements (exits and paths in terms of number, dimension, position) and facilities (wayfinding elements and management strategies)[12] so as to ensure an adequate evacuation process to occupants (compare with, e.g., NFPA 914 and other regulations on Building Heritage [43, 46, 48]). An element which in compliance with these dimensional requirements is a "meas of egress" (compare, e.g., to NFPA 914). Otherwise, they are "means of escape" (compare, e.g., to NFPA 914), meaning that they could not ensure the code evacuation service levels, but they still be used as evacuation paths. In order to avoid the possible project rejection, the fire-safety designers could generally propose two strategies. The first one concerns the design of *architectural interventions* that bring the building into conformity by, for instance, increasing number and width of paths and exits (both modifying the existing ones or open new passages), and reducing traveling distances between two places of safety/exits (e.g., by means of new fire stairs) [34, 45–48]. As for interventions limiting fire spreading and building damages, massive and invasive modifications to the original architectural features are related to the introduction of additional elements (e.g., fire stairs, including stair towers, new doors, and exits so as to increase their number/dimension) that could significantly change the original building layout (and facades), features, and identity, e.g., because of ignoring the minimal intervention criterion [11, 12, 40]. Some typical examples are provided by Fig. 2.2.

[12] As "a special feature of a service or machine, which offers the opportunity to do or benefit from something"; http://www.oxforddictionaries.com/definition/english/facility. Accessed 20 Oct 2016.

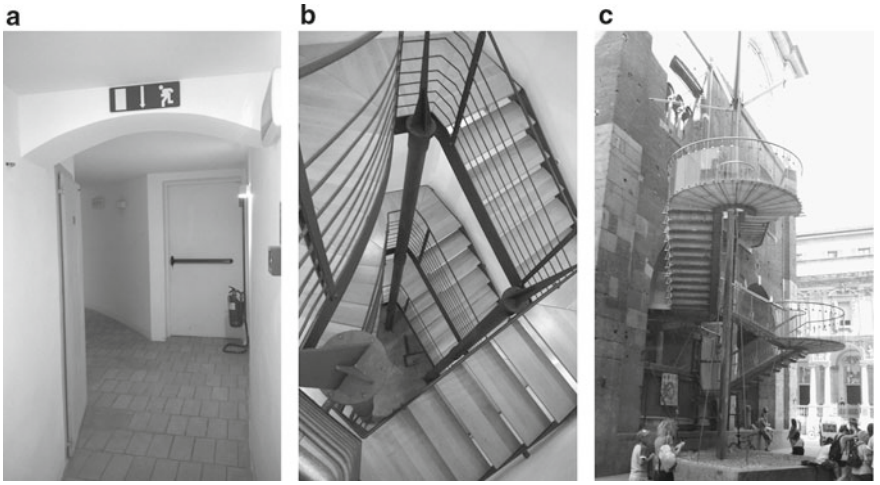


Fig. 2.2 Examples of traditional strategies for increasing occupants' fire safety by considering evacuation issues: introducing fireproof elements, such as doors (a-Mestica Theater, Apiro (MC), Italy) and introducing new evacuation paths, inside (b-Mestica Theater, Apiro (MC), Italy) or outside (c-Palazzo della Ragione, Milan, Italy). Photographs of the author

The second solution is using *compliance alternatives* for fire safety[13] (as shown, e.g., by NFPA 914), or in case of Buildings of special interest (with a very high artistic and cultural value, as for Iconic Buildings), some codes and guidelines propose exceptions to rehabilitation interventions [46] (with a possible joint reduction in maximum occupants' number), or the use of alternative ways of escape [43]. In the first case, no modifications to the original building features are provided. In the second case, alternative solutions can include windows, balcony, and related light or removable evacuation systems (e.g., fixed or freestanding ladders, evacuation chairs). Nevertheless, for the architect, it could be not possible, during the design phase, to probe the real effectiveness of existing escape layout in emergency conditions, while management strategies should be carried out in order to support hazardous evacuation conditions.

In addition to these architectural issues, regulations generally establish the adoption of *wayfinding systems* (safe condition signs and exit signs) so as to help people during the evacuation process by addressing them the correct egress paths [43, 44, 46, 48]. Many regulations define their characterization (of both standard reflective and photoluminescent signs), positioning, and distances between signs (e.g., [51–55]). Nevertheless, suggested application rules seem to conflict with fire spreading effects: in fact, they do not discourage the application of signs near to (at) the ceiling.[14] During a fire, the ceiling level is the first one that suffers smoke

[13] The designer could demonstrate that the existing elements are compliance alternatives themselves.

[14] Obviously not "on" the ceiling that is horizontally on it.

presence: signs could briefly become invisible! Moreover, the application of not photoluminescent signs is widely allowed: in heavy smoke or blackout conditions, these signs are unable to provide a guidance to evacuees.

At matters stand, the traditional approach demonstrates a very simplified approach. For this reason, it is really easy and quick to be used (designers just have to face with a small number of variables, which can be investigated through a building plans analysis, by measuring existing elements and comparing it with regulations requirements), but is strongly influenced by:

- *determinism* [56, 57]: It is considered that people will behave in the correct way (i.e., immediately evacuate the building and follow correct egress paths), thanking to a good evacuation process and plan knowledge, and a correct interaction with exit signage, alarm systems, and rescuers' support. From this point of view, the architectural layout and the introduction of particular building components/technological systems could be enough for positively influencing the human response, for the whole number of occupants;
- *empiricism and experience* [38]: Statistics on previous fires (e.g., deaths, evacuation time), for different building intended uses, can determine the related minimum requirements of safety-increasing interventions. Unfortunately, unlike "common" buildings and not historical scenarios [58, 59], Building Heritage concise databases concerning evacuation quantities (mainly in terms of times) seem to be neglected. In addition, empiric bases for these codes are "out of times": regulations and schematic models are generally based on too old experiments (from the 1950s to the 1980s) [60]. During the time, building occupants' features (e.g., age, motion abilities) have been changed and also their relationships with the architectural spaces and the fire safety system. Hence, similar investigations and related regulations risk to be really obsolete;
- *schematic approach* [12, 38]: Individuals' behaviors and possible interactions with fire effects (mainly, smokes) are not included as "stressors." Hence, escape times and speeds are not included in the fire-safety verifications. For instance, with respect to an hydrodynamic representation of evacuation [50], escape layout dimensions (i.e., width) according to the "prescriptive" approach do not depend on their (specific) flow (expressed in [persons/(m*s)]) but only on the number of persons who can use the considered exit during the evacuation, as for NFPA 914 or other regulations [45, 47, 48]. Furthermore, some regulations try to relate the path length to a probable maximum evacuation time according to different fire risk levels (e.g., [48]): a similar connection seems to be not demonstrated by experimental results and does not consider the effects on escape time due to pre-movement phenomena and occupants' densities along the path.

2.4 Behavioral Issues in a Fire as Exposure-Increasing Factors: Beyond the Performance-Based Approach

Many studies concerning the analysis of real fire accidents, evacuation drills, and occupants' interviews in both modern [61–64] and historic buildings [12, 29, 65] underline how the majority of these "traditional" solutions are not able to effectively increase the occupants' safety level. In fact, the effective human behavioral aspects [20], the potential effect of a fire on occupants [66], the interaction with evacuation facilities [29], and the responses of both not-disable/disable individuals and vulnerable occupants [65, 67] are generally underestimated by these "prescriptive" fire codes [38].

Exposure-increasing factors cannot be limited to geometrical and occupancy aspects, but have to include occupants' behaviors and interactions with architectural spaces, building components, environmental conditions, emergency management procedures (and related facilities), and fire products (mainly: heat, smokes, toxic gases) during the whole emergency evacuation. All these issues can *significantly increase the time needed by occupants for evacuate the building, and so the Required Safe Egress Time RSET* (s) [14, 34, 38], as defined by BS 7974-6:2004. The estimation of RSET and the comparison with ASET in order to understand the effective occupants' fire safety level are basic criterion in performance-based regulations (e.g., NFPA 914, [34, 45]), as shown by previous literature studies [14, 39] and clearly stated by [49]:

> The performance-based methodology requires the quantification of both available safe egress time and required safe egress time [RSET] and an appropriate safety margin to determine the degree of life safety provided.

Hence, as previously evidenced at Sect. 2.1 and Fig. 2.1, related behavioral factors represent one of the most significant elements in determining RSET. In order to properly understand these specific exposure-increasing "stressors"[15] and their consequences on occupants' behaviors, some general remarks on fire evacuation process are discussed, by stressing the attention on fires in Building Heritage. References to current international guidelines on human factors influence assessment (mainly, PD 7974-6:2004) and to both qualitative and quantitative behavioral aspects are included.

2.4.1 Man-Environment Interactions in Building Heritage Evacuation

From a general point of view, different emergency typologies (i.e., fire, earthquake, flood, terrorist attack) which can affect different scenarios (including the Building Heritage one) are generally characterized by the same emergency actions and

[15] Or rather, "drivers" or "triggers."

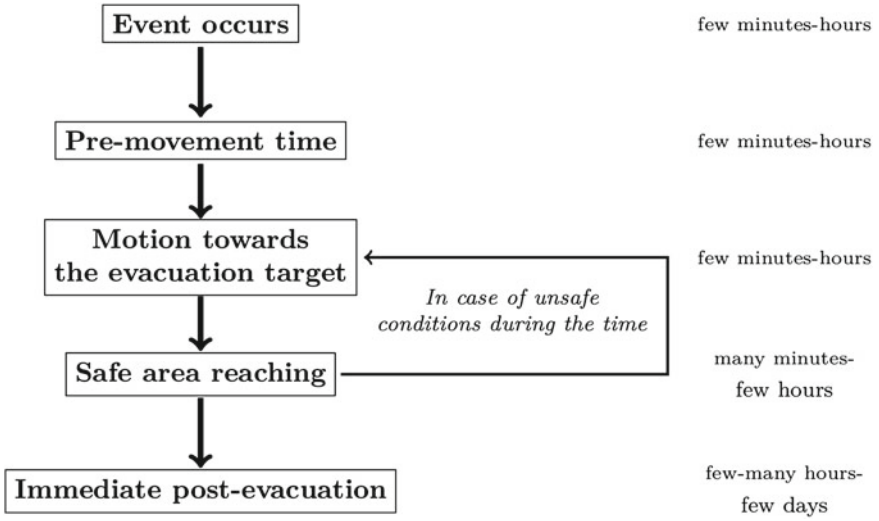


Fig. 2.3 Evacuation phases as sequence of human response to a disastrous event

response scheme [12, 20, 23, 25–27, 31, 58, 59, 68]. Despite of specific differences due to disaster effects and damages in the architectural scenario (e.g., smoke in a fire; debris in an earthquake), this common behavioral scheme can be chronologically organized in typical evacuation phases, as shown by the emergency flowchart in Fig. 2.3. This evacuation flowchart has been recently adopted by international and national codes and guidelines for fire safety (e.g., BS 7974-6:2004, [34, 38, 69]). At the same time, similar evacuation quantitative and qualitative aspects could express these behavioral factors: Table 2.2 resumes these elements according to previous works about databases concerning "human" factor in emergency and by focusing on fire [23, 58, 59]. Nevertheless, the same approach is confirmed by other works concerning different emergencies [7] and by studies on behavioral differences (due to individual's perception, characteristics, disabilities [65, 70] and social, geographical, and cultural background [31, 71]).

Fire Effects on Building Heritage Occupants

First of all, "traditional" fire safety codes seem to not consider how consequences of a fire in terms of both products of combustion (smoke, toxic gases, flames, heat) and environmental modifications (e.g., failure of structural and non-structural elements) can really condition human responses during the emergency. Table 2.3 resumes the general fire interferences with architectural spaces and human behaviors, according to previous work classification [17, 20, 70, 81, 83]. The fire and its consequences provoke negative effects on occupants from physical, physiological, and psychological point of views, and in this way, it implies variations in egress times (including influence of evacuation choices about, e.g., paths), and number of deaths and injured

Table 2.2 Elements to be considered for characterizing the evacuation process from the "occupants' perspective," by including type (qualitative; quantitative with principal unit of measure), a short description and references

Elements	Type [unit of measure]	Short description and References
Risk perception	BQ and MQ (e.g., participation to building evacuation [%])	How people perceive the event and building (e.g., possibility of event occurrence, safety level, perception of buildings and safe areas, familiarity with building layout, preparedness, interactions with alarm systems), and their results (mainly: decision to evacuate) [65, 70]
Pre-movement	BQ	Perception of event or/and their effects (e.g., alarm perception, visible smokes, or flames); man-man interactions for information exchange, social attachment, and attachment to belongings [68, 72–74]
	MQ [s]	Time of reaction to the event; pre-movement time characterization [23, 38, 59]
Evacuation motion (speed)	MQ [m/s]	Average values of speed and characterization in different conditions of crowdedness (including level of service definition); horizontal and vertical paths (and geometry); environmental conditions (lighting levels, smoke layer height, smoke density, gases toxicity, and irritant smokes); evacuation facilities (wayfinding facilities, rescuers' help) [12, 17, 29, 75–77]
Group behaviors	BQ	Actions between group members (e.g., attractive and repulsive phenomena; panic conditions) [18, 26, 72, 74]
	MQ [m], [s], [m/s]	Distances between individuals, delays in motion along paths (an individual waiting for other people), and groups member's speed (in case of cohesion phenomena, proxemic behaviors, and panic conditions) [78–80]

(continued)

Table 2.2 (continued)

Elements	Type [unit of measure]	Short description and References
Occupants' characteristics	BQ	Differences in actions and reactions [65, 70, 72]
	MQ (e.g., speed [m/s], dimension [m], and reaction times [s])	Specific parameters depending on individuals' features and possible impairments, especially while moving [23, 59, 73, 81]
Evacuation behaviors	BQ	Series of actions during evacuations [26, 32, 69]
Evacuation path obstruction and bottlenecks	BQ and MQ (mainly: speed [m^2], density [people/m^2])	Influence of environmental conditions (including smokes and irritant gases) on queue delays or block egress on travel speeds [17, 77, 81, 82]
Exit and path choice decisions	BQ and MQ (e.g., flow [people/(m*s)])	Influence between environmental conditions (including smokes or flames presence), emergency facilities (wayfinding systems, rescuers' help), other people positions (e.g., fast-is-lower effects; queue; social attachment, panic conditions), familiarity with building layout on egress paths and travel times on paths choices [12, 18, 23, 26, 72, 73]

BQ - pure Behavioral Qualitative data and decisional aspects; MQ - Motion Quantities and occupancy characterization

[17, 66, 77, 81]. Factors in Table 2.3 highly affect the occupants' egress time during the whole process, as shown in Fig. 2.3. Hence, finding the faster way to escape from a building is fundamental during an emergency situation, especially because of Building Heritage vulnerabilities described in Sect. 2.2, such as not protected spaces and not fireproof building materials.

Pre-movement

When a fire strikes the historic building, people spend a significant time in different actions before leaving the initial unsafe position [23, 30, 68, 72], so as to understand if the evacuation is really needed and to be sure that no important elements are abandoned in the initial position (e.g., belongings). Main behaviors are linked to interpreting any information announced about dangers; interacting with other neighboring individuals and exchanging information with them; waiting for other people (because of attachment to people phenomenon); identifying the evacuation

Table 2.3 Effects of fire on environment and occupants

Elements	Effects on environment	Effects on occupants
Smoke, flames, toxic gases, heat	*General effects*: some evacuation paths cannot be used; damages (or even failures) of structural and non-structural elements	*Direct effects*: anoxia (for O_2 reduction); smoke and gases toxicity effects; heating-related phenomena including possible burns (as well as because of flames)
	Smoke effects: visibility reduction; wayfinding elements can be not visible (especially the ones applied at the ceiling level)[a]	*Psychophysic effects*: increasing of heart rate; outflow of blood from organs of digestion; increase of adrenaline level; increase of the organic capacity to absorb toxins
		Psychological and behavioral effects: (increasing) agitation, anxiety, and fear; panic phenomena (including "herding behaviors"), competitive and individualistic behaviors, stampede and counterflow[a]; disorientation and confusion about the building layout and the evacuation directions; searching familiar places and familiar people

[a]Compare with Sect. 2.4.1 motion behaviors

direction; trying to collect belongings (attachment to things phenomenon); and performing individual safety procedures (e.g., drop-cover-hold during earthquake; fire extinction). According to studies on real-world fires and drills [12, 58, 59, 72, 84], effects due to evacuation starting delays depend on the type of building and activities in which people are engaged.[16] Possible automatic detection and alarm systems (e.g., smoke detectors for building fire and collective [85] or individuals' alarm systems [72]) could effectively communicate to people the emergency starting and so reduce the pre-movement time because of clear information about possible hazards. Otherwise, if alarm systems are not present, individuals' pre-movement could start in case of evident damages and fire effect. In this case, a lack of time for evacuation decisions could be perceived by occupants and lead people to adopt a fatalistic and individualistic approach to evacuation [70].

[16]As such, different proposals of time probability distributions have been provided [30, 72]; from a general point of view, the Weibull distribution seems to be the most befitting one, but a lack of experimental activities in Building Heritage exists. Hence, designers could reasonably use data from similar building use in new structures for their RSET analysis.

National and international codes and standards include tables for evaluating these elements depending on the performed activity or building use, as in PD 7974-6:2004 or [34, 38], and so as to describe which solutions could be adopted to reduce this pre-movement time. In particular, according to the PD 7974-6:2004, people in Building Heritage as museums, theaters, and their premises could be associated to occupants' category B (awake and unfamiliar) [38]: in other words, "occupants are unlikely to evacuate unless encouraged by staff or instructed by a voice alarm system, and even this can be ignored in some cases,"[17] because they need to have complete information about what is happening. A similar problem is also confirmed by a recent study on fire drills in an historical theater [12]: over 70% of occupants attended the voice alarm and then decided to evacuate, while about 50% of participants spent more time in pre-movement phase because they started moving after collecting belongings or waiting for other people and talking with them.

Although the presence of alarm systems[18] for interaction with people is included in fire safety codes, their application in Building Heritage can be influenced by a limitation in spaces (because of typical installation problems, e.g., interferences between wiring or plumbings and building structural and non-structural elements) or to not/partially efficiency (in case of, e.g., old systems or scarce maintenance levels; wrong positioning of detection devices in order to have an easy application of them) [11]. In other terms, it can be considered, as a precaution, a level A3 alarm system for Building Heritage as in PD 7974-6:2004, Annex A. As an alternative to technological systems, management strategies could improve the pre-movement phase, but similar solutions imply a wide presence of internal safety team members and an appropriate level of preparedness [11, 40, 43]. According to the literature reviews, Building Heritage surely denotes an ineffective awareness and education of hosted occupants, who are not trained to correctly face the evacuation, and could be characterized by a limited internal rescuers' team: according to PD 7974-6:2004, a management level M2 could be considered so as to include these limitations, also according to some remarks of current fire safety codes about minimum management strategies to be ensured (e.g., for Italian theaters [48]).

Motion Toward the Evacuation Target

The pre-movement phase finishes when the individual decides to effectively leave the initial unsafe position and move toward a safer area [20, 26, 31, 80, 81], by taking advantage of wayfinding tasks [62, 86]. In this sense, evacuation targets can be represented by the places of relative or ultimate safety (final assembly points at building exits). Occupants' spontaneous and immediate participation to this phase essentially

[17] Compare with PD 7974-6:2004, p. 26.

[18] The word "systems" suggests that more than one device and/or building components should compose these evacuation facilities. The same comment refers to wayfinding systems.

depends on the event intensity/magnitude (the question is: "is it necessary[19] and possible[20] to evacuate the space?") [81].

The motion phase generally lasts for few minutes and is influenced by man-environment and man-man interactions [20, 38]: people generally would like to prevent collisions (with obstacles and other moving individuals [26]), walk with their preferred speed (such as in free motion conditions [78]), and maintain a certain distance with the other individuals in the group (because of social attachment phenomena [72, 74]). These attractive and repulsive interactions are activated by evacuees depending on a maximum distance value, which changes in relation to mechanisms between people and between people and environmental obstacles [31, 38, 78]. In fact, elements (both people and obstacles) are taken into account for pedestrians' evaluations only if they are placed closer than the activation distance from the pedestrian. This distance is generally considered equal to 3 m for interactions among individuals [31, 78] and up to 20 cm for obstacles because of boundary layer conditions [38, 82].[21] Hence, the use and occupancy of evacuation layout space could decrease when these obstacles interfere with evacuees.

Figure 2.4 resumes main man-environment interactions in Building Heritage and evidences their effects on human motion quantities (according to Table 2.2), by distinguishing their complexity level. 1st level interactions directly affect the evacuation time and are also included in traditional fire-safety codes. 2nd level interactions are able to directly modify the effective individuals' speed because of geometric (path dimensions and slopes) and visibility (smokes) boundary conditions [38, 59]. From this point of view, individuals' evacuation can be slowed down or also stopped in case of adverse environmental conditions such as dense fire smokes [12, 20, 61, 66, 81]: narrows spaces (also with low ceilings) can increase the hazardous conditions according to Sect. 2.2 discussion.

3rd (or higher) level interactions are mainly related to building layout complexity (compare with PD 7974-6:2004, Sect. 5.2.3) and to the presence of evacuation management strategies and facilities (mainly, exit signage) because these aspects are firstly able to condition occupants' wayfinding activities in Building Heritage [12, 28, 87]. This problem is really evident in many historical buildings (e.g., medieval buildings and complexes) with an high level of spatial complexity, such as "large building complexes with integration of a number of existing buildings on the same site" (Building level B3 according to PD 7974-6:2004, Sect. 5.2.3). In such a way, also apparently less complex scenarios (e.g., historical theaters, as shown in Sect. 4.1) can be considered in this category, even if they have one focal point in spaces and enclosure layout [38]). In fact, as previous evidenced by Sect. 2.2, they generally have a small number of main entrances, commonly used by occupants in normal conditions, and many secondary exits and paths which are

[19] In this sense, the issue is really influenced by pre-movement behaviors, with respect to the adopted emergency management actions and other similar events experienced by people.

[20] Here, the problem is related to trapped people and deaths.

[21] Nevertheless, people generally allow physical contact with some small obstacles, such as chairs or other small furnitures.

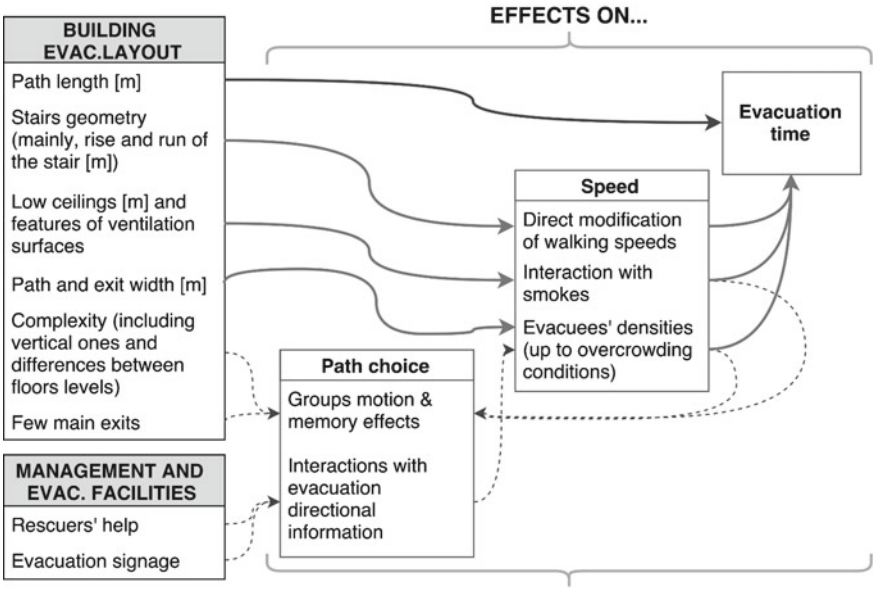


Fig. 2.4 Human behavioral interactions (expressed by arrows) with building evacuation layout, management and facilities, and their effects. Arrows stiles express the level dependencies in relation to the evacuation time: continuous and black for 1st level direct on time; continuous and gray for 2nd level direct on speed; dashed for 3rd level or more direct on path choice and recursive

ignored [11, 12, 29, 40]. Besides these architectural issues, wayfinding-influencing individuals' behaviors mainly refer to the occupant's level of knowledge in relation to the environment, since occupants are generally unfamiliar with the building layout, and so to the so-called memory effect [78], similarly to what happens in normal motion conditions [86, 88]. Experimental works demonstrate that in case of inefficient or partially efficient wayfinding systems (including conditions of their scarce visibility [12, 77]), people hesitate and then preferably choose well-known paths, especially in unfamiliar spaces [12, 28, 89] (e.g., move toward the previously used entrance). Moreover, social attachment and group phenomena such as "herding behavior" [26, 78] lead people to adopt similar wayfinding procedures and use the same paths in these conditions [12]. On the contrary, effective management strategies (rescuers' instructions) and accurately arranged wayfinding facilities (in terms of position and visibility) encourage people to move toward correct egress paths with an higher speed and a lower decision time, since evacuees exactly know where to go [32, 76, 77, 89, 90]. Concerning management strategies, a direct help to occupants given by internal safety team members allows to increase the evacuation procedure effectiveness because of the so-called leader effect [91]. In other cases, leadership entities could emerge "from within the crowd and offering practical guidance that other crowd members could follow" ([18], p. 31). Although the positive influence of such solutions is also confirmed by works on evacuation modeling and training

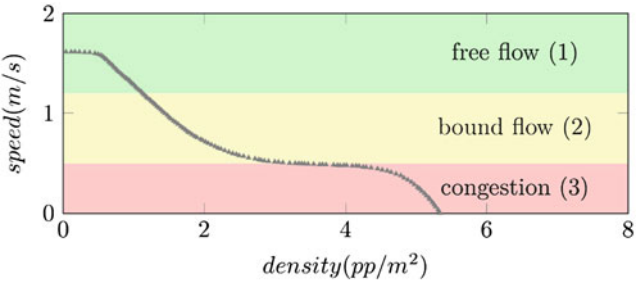


Fig. 2.5 Fundamental diagram example (density-speed relation according to [93]): The three phases of motion transitions are evidenced

activities [92], the effectiveness of these phenomena depends on the management level (compare with PD 7974-6:2004), and in many cases, it could be very laborious for rescuers since they could be involved also in firefighting (as an alternative, internal safety team should include two groups with different operational rules [43, 48]).

As a consequence of wayfinding choices, groups phenomena and path crowding conditions along motion paths [19, 32, 50, 80] can change evacuees' speeds, also in a recursive way, during the egress process. In addition, the historical building layout is able to increase local overcrowding situations because of physical bottlenecks along paths (e.g., small doors or other gaps).

Groups motion conditions widely affect individuals' velocity in terms of direction versus modulus: a convergence of pedestrians' behaviors and choices when they are in group conditions is noticed and can also lead to disastrous overcrowding effects. Hence, motion and exit flows vary, especially in typical Building Heritage narrow spaces (e.g., small corridors and staircases, spaces with a significant obstacles presence). Beside the qualitative description of human behaviors, physical quantities that can represent these group phenomena, according to Table 2.2 and a "pedestrian dynamics" point of view [80], are pedestrians' flow rate, people density, and motion speeds [19, 25, 75]. Relations between these variables are included in the so-called fundamental diagrams of pedestrians' dynamics. Figure 2.5 shows an example of density-speed diagram [93] in order to evidence the three different transition phases in motion (item numbers are related to the figure labels):

1. for low densities, people move with their preferred speed [80], in free flow conditions;
2. for medium range densities, a bound flow is evidenced, and people have to slow down their speed for man-man and man-environment (bounds and different obstacles [82]) interactions;
3. for high-density conditions, congestion phenomena are noticed: people significantly slow down their speed and can be blocked during their motion in case

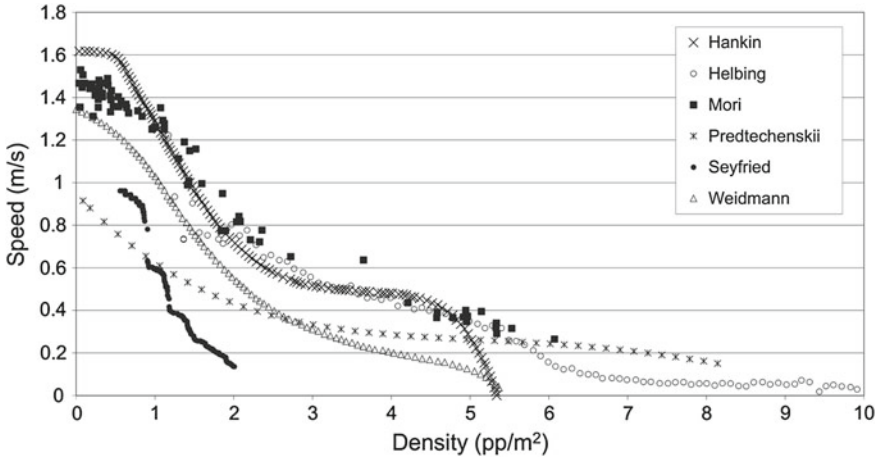


Fig. 2.6 Comparison between density-speed fundamental diagrams in different experiments and authors

of critical conditions (in general terms, there are too many people per m^2, for example more than $\frac{5 \text{ person}}{m^2}$ [78, 93][22] up to $\frac{10 \text{ person}}{m^2}$ [19]).

Figure 2.6 shows a comparison between two experimentally based density-speed diagrams.[23] Experiments' results depend on many factor such as (but not limited to):

- space bounds (e.g., corridor) directional flows (mono-directional, bidirectional, at T-shaped junctions, crossroads) [75];
- experimental conditions in terms of building/space intended use (e.g., mono-directional flows of students at school, English travelers at railway station [93], along a corridor in experimental proof);
- normal conditions in real-world, laboratory experiments, real-disaster conditions, evacuation drills, and approaches used in quantities measurement [19] and;
- social and cultural background [71].

[22] Generally, the pedestrian's dimension can be described with a circle of radius 0.6 m [78].

[23] Data of diagrams are retrieved at https://goo.gl/bMMrr9 (Accessed 11 Oct 2016) and based on the Online Database of ped-net.org (2014). It includes Hankin [93]; Helbing D, Johansson A, Al-Abideen HZ (2007) The dynamics of crowd disasters: An empirical study. Physical Review E 75:46109; Mori M, Tsukaguchi H (1987) A new method for evaluation of level of service in pedestrian facilities. Transp Res 21A(3):223234; Seyfried A, Steffen B, Lippert T (2006) Basics of modeling the pedestrian flow. Physica A: Statistical Mechanics and its Applications 368:232238. doi:10.1016/j.physa.2005.11.052; Weidmann U (1993) Transporttechnik der Funger. IVT - ETH, available at http://e-collection.library.ethz.ch/eserv/eth:5929/eth-5929-01.pdf.

Safe Area Reaching

Finally, people reach safe areas and generally stop the evacuation process. According to experimental works, including the ones performed in different historical scenarios [20, 31, 74], the concept of "safe area" should not be limited to the current "place/area of refuge" definition (compare, e.g., NFPA 101, NFPA 914, [45, 48]). In fact, it is generally connected to better surrounding conditions such as not visible (or limited) presence of hazard (including the one due to effects provoked by the event source, i.e., smokes) and possibility to reunite the group (because of social attachment phenomena). In this sense, some additional (intermediate) safe areas could be not limited to spaces protected from the effects of fire. Behaviors while people are moving toward a safe area and when they reach a safe area are strictly connected: people's actions and decisions are aimed at maintaining safe conditions in evacuations. Hence, individuals allow to restart their motion if they believe the reached position as unsafe during the time or because of rescuers' instructions.

Immediate Post-evacuation

When the safe areas are reached, the first part of the emergency (the effective evacuation phase) ends and the emergency response is activated by organized rescuers (e.g., firefighters), in order to set emergency management procedures off [11, 43, 55, 88]. However, similar rescuers' emergency activities can be acted also during the motion phase in order to help people while reaching the evacuation site, especially in case of first aid to particular individuals' categories (e.g., person with motion disabilities, elderly [43, 65]). Right after the evacuation, significant attachment behaviors can be still evident, especially in terms of attachment to belongings (and to private ownership, including households and vehicles), the related desire to come back home or to return where they are placed (e.g., in the initial position) [27].

2.4.2 Representing and Simulating Human Behaviors: The Performance-Based Approach

Since the prescriptive fire safety codes approach ignores interactions between evacuees and Building Heritage, which could lead to the unsafe conditions for occupants described in Sect. 2.4.1, "traditional" architectural solutions could be not sufficient to guarantee substantial fire risk-reduction and evacuation improvement. Hence, according to performance-based regulations (e.g., NFPA 914, [34, 44, 45]) and previous literature studies [14, 39], the evaluation of risk levels and then of safety solutions has to be based on a realistic quantification of the emergency process from the points of view of fire spreading, Building Heritage damage and occupants' response to the event. The Fire Safety Engineering (FSE) shares this methodology [38].

From this point of view, this approach is founded on the definition of emergency scenarios, in terms of building and occupants' characterization, as shown by key

Table 2.4 Fundamental design concepts and solutions in performance-based fire safety and FSE, including references

Concepts	Key factors
Fire scenarios definition (main and critical ones)	Fire sources; fire propagation stages; fire reaction of building components; fire loads; effects of firefighting solutions [14, 34, 81]
Evaluation of human behaviors in emergency and related scenarios	Consolidated literature on human behaviors [20, 23, 59]; international guidelines on evacuation behaviors and building occupancy characterization (e.g., PD 7974-6:2004); guidelines for "in situ" evacuation drills (e.g., PD 7974-6:2004, [33, 43, 44, 46]) for both behavioral investigations and occupants' and rescuers' preparedness tests
Statistical and probabilistic approaches	Scenario-based simulation techniques by using trustfully (verified) fire evacuation simulators [81, 94, 95]

concepts and factors in Table 2.4. In particular, in Building Heritage, some significant scenarios should be related to the individuals' escaping features (e.g., speeds), occupants' densities,[24] and level of familiarity with architectural spaces (and related wayfinding activities, according to Sect. 2.4.1 issues).

Firstly, this implies the definition of two performance criteria, as stated in NFPA 914:

- Historic Preservation: "Historically significant rooms, space, or contents shall not be exposed to instantaneous or cumulative fire effects that cause irreversible damages";
- Life Safety: "Any occupant who is not intimate with ignition shall not be exposed to instantaneous or cumulative untenable conditions."

Historic preservation is assigned to firefighting strategies and to actions for the "salvage of items of historic value"[25] [43]. Obviously, it includes aspects connected to the ASET estimation and so on the impact of vulnerability and hazard factors expressed in Sect. 2.2, especially when the historic goods to be preserved is the building itself.

[24] From this point of view, the RSET estimation considers at least two scenarios: maximum design population and sparse population (1/3 of maximum occupants number).

[25] When it is not possible to limit fire and damages spreading, a sort of evacuation for furnitures, paintings, and other goods and chattels, performed by firefighters and/or members of the internal safety team. In this case, "solutions to prevent crowding of routes and congestion of the personnel and rescue teams if evacuation of people and items of historic value is going on at the same time" [43].

Concerning Life Safety, as clearly reported by [49]:

> The performance-based methodology requires the quantification of both available safe egress time and required safe egress time [RSET] and an appropriate safety margin to determine the degree of life safety provided.

Human behaviors and modifications of the environment during the emergency evacuation time are dynamic phenomena that can be jointly represented through simulation model [96]. The analysis of evacuating individuals' behaviors, and their organization, allows to trace relationships between Building Heritage and individual's performances in terms of decision criteria (e.g., "where I go while evacuating? which are my evacuation targets?") and motion quantities (e.g., "which is my speed? which are my delay times? which my distances from other interfering elements?") [31, 32, 94, 97].

In particular, in the number of possible fire simulator [38], advanced methods for ASET estimations, such as the one that use computational fluid-dynamics simulators for fire spreading representation [81], could be able to evaluate fire effects in terms of dangerous combustion products for occupants' safety (radiant heat, production of irritant or toxic gases, smokes that limit visibility conditions), also according, e.g., ISO 13751:2012. At today, many interesting studies applied a similar tool, although they were focused on the building components performance rather than on the interactions with evacuees [39, 98].

Concerning human behaviors, different modeling approaches are proposed for providing:

1. simulation tools for evacuation assessment in different scenarios [25, 95, 99]: These tools are useful for architects and safety designers so as to define RSET and so trace reliable bases for developing risk-reduction strategies and evaluate the impact of proposed ones;
2. serious game simulation tools so as to improve preparedness of members of the firefighting and emergency management service team [100] (according to management strategies defined by PD 7974-6:2004 and other regulations [43, 55]) or to test the individuals' behaviors [101]; and
3. real-time systems for emergency management [32, 76, 102]: they can be operative used during the emergency, in order to enhance the management and the alarm systems levels, as remarked by PD 7974-6:2004 and other regulations [43, 55].

Table 2.5 characterizes three significant pedestrians' evacuation simulation modeling approaches (according to previous classification [7, 25, 78, 95, 96, 103]), by stressing on the main elements in Building Heritage scenarios defined in Sect. 2.4.1. Table 2.6 summarizes application pros and cons and evidences some significant model examples.

From a general point of view, simulation models should be based on:

- *individual's characterization*: the parameters describing each person [78, 80], such as dimension, mass, preferred speed, distances of interactions with other elements, and perception of the surrounding environment. These parameters can be fixed

Table 2.5 Characterization of main modeling approaches for simulating pedestrians' motion in evacuations according to behavioral and environmental factors in Building Heritage

Factors	Macroscopic approach	Microscopic approaches	
	Hydrodynamic (flow-based)	Cellular automata	ABM and SFM
Motion environment	Coarse network system, which divided space in rooms, corridors, staircases, and so on; each of them is similar to a "pipe" (length and section width)	Fine network system, in which plane grid cells—2D (discrete representation with obstacles and paths)—can have different selectable geometries and dimensions; no direct representation of vertical differences between floor level[a]	Generally, continuous space (2D or 3D); it can be directly described as an agent in ABM, so as to assign particular modification features during the time[b]
Evacuation time	Continuous	Discrete	Discrete or continuous
Individual's representation	As a liquid that moves along pipes	As elements interacting with the surrounding conditions; generally, simulated individuals are homogeneous, but heterogeneous description (different kinds of evacuees) are allowed	As elements interacting with the surrounding conditions, by means of interactions between mass-points, since each individual is a moving object in the space; in ABM, individuals can have specific evacuation desires and behavioral responses, and they can interact; different individuals' types can be engaged
Fire	Possible to consider fire effects for each room (e.g., smoke layer height)	Allowed according to the discrete space representation (e.g., CFD simulators): Each grid cells has a fire effect value[a]	By using a discrete space representation (also in 3D; thanks to, e.g., CF simulators); ABM could introduce additional behavioral features in fire evacuation simultaneous simulations

(continued)

Table 2.5 (continued)

Factors	Macroscopic approach	Microscopic approaches	
	Hydrodynamic (flow-based)	Cellular automata	ABM and SFM
Motion rules including evacuation target and path choice	Speed-density or flow-density relations are used, in a sort of "channeled" motion; since people are homogeneously described, all occupants of the same room generally move toward a certain fixed target	Local choices and motion behaviors can be assigned to moving evacuees by means of cells rules, by also considering local fire effects and queuing models, by, e.g., means of "throw of a weighted die"[a]	Motion rules and path choice criteria can be given to each individual or each individuals' type; ABM and SFM approach can be combined in order to describe psychological evacuation rules and desires in motion
Delays in motion	Limited to room preset values	Possible for each grid cell or groups of cells	Possible for evacuee's type (also based on his/her position) and for each individual
Group effects	Generally not allowed because of homogeneous crowd	Possible to take into account especially in case of heterogeneous individuals' description	Social attachment, "herding behaviors" and also counterflow are easily allowed thanks to possible psychological included features
Familiarity with layout	Generally not allowed because of homogeneous crowd, but people in each room could have a navigation input scheme (preferred evacuation target)	Possible to take into account especially in case of heterogeneous individuals' description, thanks to the "weighted die" approach (e.g., for route finding)	Each evacuee could have a preferred evacuation target based on his/her knowledge level of spaces and evacuation procedures, or could move by following other people's decisions
Interaction with wayfinding solutions	Generally not allowed because of homogeneous crowd	Possible by including some grid cells weights to this end, as for familiarity effects	Included in terms of both desires in case of ABM (by also modeling these solutions as specific agents), so as to modify the egress route, or by modifying evacuees speed and trajectory

[a] "The value of the variable at one cell determined by the values of variables at the neighboring cells" [95].

[b] This possibility is particularly useful when defining Building Heritage damages in terms of e.g., structural and non-structural elements failures (actually developed for earthquake scenarios [7]), damages to some technological systems.

[c] "Keep it simple, stupid" (compare to http://people.apache.org/~fhanik/kiss.html. Accessed 22 Oct 2016.)

Table 2.6 Main pros and cons for application of modeling approaches for simulating pedestrians' motion in Building Heritage evacuations. Additional notes and examples are provided

	Macroscopic approach	Microscopic approaches	
	Hydrodynamic (flow-based)	Cellular Automata	ABM and SFM
Main pros	Real-time applications; quick computation process (good for large-scale application and long-lasting evacuation time); results in terms of LOS and queuing levels in the building areas	Probabilistic motion attitudes allowed; combination with other microscopic approaches; not excessively heavy application for high number of simulated individuals or long-lasting evacuation time	Individuals' interactions can be directly included in the motion law, with an accurate description in space and time thanks to the continuous representation approach; probabilistic interactions features with (possibly unlimited) different pedestrians' types characterization; for ABM, different motion law can be chosen
Main cons	Limited ability for complex geometrical spaces (due to coarse representation), heterogeneous population and behaviors; analyses for each coarse network elements and not for subregions; flow-based solutions could be affected by experimental limitations (no specific studies on fundamental diagrams for Building Heritage evacuation)	Discrete space and time representation can imply not accurate (mainly spatial) results for local analyses especially in case of large grid cells; psychological factors in human behaviors are difficult to be described	Time-consuming techniques; KISS^c principle in software modeling (especially for ABM-based models) versus too high complexity level for evacuees' features and emerging motion behaviors representation

(continued)

Table 2.6 (continued)

	Macroscopic approach	Microscopic approaches	
	Hydrodynamic (flow-based)	Cellular Automata	ABM and SFM
Notes and significant examples	Included in RSET evaluations guidelines [38]; for LOS definition, please compare to [104]	PeDGo[a]: multi-purpose evacuation simulator, in which motion is function of individuals' specific (walking speed, visual perception, reaction times, and patience in queuing) and stochastic variations	buildingEXODUS[b]: ABM model based on fine network system can include interactions with fire (including toxicity), building elements and exits (usable or most familiar exit); FDS+EVAC[c]: freeware simulator which jointly simulate fire spreading (CFD-based) and evacuation (SFM-based) [81], and can include smoke visibility and wayfinding elements [108] effects on evacuees

[a] http://www.traffgo-ht.com/de/pedestrians/products/pedgo/. Accessed 22 Oct 2016.
[b] http://fseg.gre.ac.uk/exodus/. Accessed 22 Oct 2016.
[c] https://pages.nist.gov/fds-smv/. Accessed 22 Oct 2016

values, depend on surrounding conditions, or connected to statistical distributions or random functions [78, 81];

- *motion equation (or motion law)*: the equation (or the set of equations) that effectively describe how people move in the scenario, and so which is the evacuees' flow (in macroscopic and global models) or the individual's velocity (in microscopic approaches) during the time. This issue mainly depends on the adopted simulation approach, as shown in Table 2.5, as well as the representation of specific evacuation phenomena;
- *evacuation path/target choice*: rules describing which is the path chosen by each individual during is motion [81, 103]. Rules can be externally fixed (a sort of "a priori" imposition by the software user, as also for familiarity conditions representation) or assigned to each pedestrians depending on the surrounding conditions (about environment, its modifications during the time, relations with other pedestrians, or wayfinding elements influence.

The simplest and quickest approach is the macroscopic one, which is associated with a hydrodynamic (or flow-based) models. Since people's safety in fires mainly depends on the possibility to evacuate the building in the shortest time [14, 23], this approach compares the whole group of evacuees (divided per rooms)

to a compressed fluid or gas, moving on a pipe [25, 50, 96, 104, 105]: hence, the evacuation speed (or flow) essentially depends on the fluid density, with possible gas-kinetic model attributes so as to evidence additional crowd excitement features. Performance-based guidelines consider these aspects by including tables and graphs for calculating motion parameters values in simplified conditions, for both corridors and stairs [38, 82]. The level of service (LOS) [104] can be useful in this model so as to simply quantify (and classify) density conditions and motion characterization, so as to also be useful for real-time applications [32]. Unfortunately, this simple and quick consideration seems to be correct only for medium and high pedestrians' densities and is widely affected by issues described in Sect. 2.4.1 and shown in Fig. 2.6.

Concerning microscopic approaches, one of the first general purpose attempts in behavioral simulations and representation could be represented by Kurt Lewin's "Field Theory,"[26] developed in the 1940s and 1950s. In this model, Lewin inquired the possibility to forecast human behaviors by jointly adopting social sciences and statistics techniques: in particular way, his theory examines patterns of interaction between the individuals and surrounding environment and traces possible human responses as consequences of these interactions. Lewin's theory was shared, few decades later, by Dirk Helbing, who, in the latest 1990s, adopted a similar point of view in order to develop his social force model—SFM [26, 80]. This breakthrough in evacuation simulation was also allowed by both the development of the chaos theory[27] and to computer-aided calculations potentialities. SFM represents a significant example of continuous-space (2D or 3D) description of the environment for pedestrians' motion: individuals can move continuously in space (and time). Evacuees are guided by motion equations following different motion equations [80, 81]. SFM founds its motion law on the analysis of real evacuations [26, 31]. As stated by [106]:

> the model considers that each pedestrian is driven in his movement by forces of interaction (attractive and repulsive forces) with the environment and with other nearest pedestrians.

Proposals for introducing panic conditions [78], integrations between the social force model and agent-based model—ABM,[28] [97, 106] and integrations with discrete models [95] where proposed. In particular, SFM and ABM can be easily combined because of the Lagrangian methodology shared by these microscopic approaches, as remarked by [106]:

> the interactions between agents produce phenomena and quantitative values that are comparable with the experimental ones for the whole system.

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[26] See "Lewin, K., 1951. Field theory in social science; selected theoretical papers. Harper & Row, New York, NY, USA."

[27] Which considers the high effective level of complexity connected to phenomena inside a given population.

[28] In general terms, ABM identify agents involved in an environment, and the interactions between them are described. Interactions can be also described in terms of rules. A greater discussion of ABM is offered from a general point of view by [107] and the pedestrians' evacuation simulation [80].

2.4.3 How to Help Occupants: Problems to Be Solved

Performance-based fire safety codes and the FSE approach can quantitatively estimate the impact of risk-reduction solutions in terms of effects on Building Heritage (ASET, fire spreading effects, damages to hosted elements) and possible evacuation improvement (RSET). Design alternatives can be tested through advanced simulation techniques and could also refer to noninvasive and management strategies [6, 11, 32, 40], by taking advantage of traditional building engineering techniques and probabilistic methods for scenario creations. In this sense, the scenarios will can combine: users'-occupants' "standard" profiles; occupants' densities and occupancy schedules with possible daily/monthly/yearly/particular event occupancy distribution; types of occupants classified by motion abilities and familiarity levels; possible variations of the scenario inputs depending on materials uncertainties, time, and different building activities, so as to estimate on fire resistance of building components, fire loads, and fire sources.

In the number of strategies for defining the best solution [40], the minimal intervention criterion should be considered as an essential one, together with economical and RSET improvement aspects. At the same time, the historic building should be considers as "alive" since it hosts and will host individuals and their activities: Hence, the impact of architectural interventions should be aimed at ensuring a correct service level for occupants also in different conceivable use conditions [57]. To this end, according to previous sections outlines, complex Building Heritage fire safety issues should be inquired through an effective evaluation of safety level for individuals and of strategies for its increase, in agreement with the following pillars:

1. crowd phenomena and interactions between people, especially in case of high-density spaces, and related representation through the pedestrians' dynamics tools (simple ones like LOS or fundamental diagrams, and detailed ones like motion simulators);
2. current Building Heritage layout and probable environmental modifications due to the disaster, in relation to individuals' behaviors;
3. interventions strategies in Building Heritage that could improve the evacuation process by duly informing people of emergency conditions and suggesting correct evacuation choices to them, especially for unfamiliar or unprepared occupants.

Performance-based and FSE methods allow to perform the needed investigations so as to simulate emergency development and human reaction. Some additional steps are needed, in particular about specific low-impact solutions aimed at obtaining adequate evacuation behaviors from occupants.

A larger number of experiments should involve not only drills in new (or rather contemporary) buildings, but also in Building Heritage (e.g., divided by building

intended use), so as to widely confirm behavioral studies and retrieve specific evacuation quantities (i.e., try to define a sort of "quick" evacuation time assessment databases as for new buildings and general purposes [58, 59]) in significant environment, and in relation to current (existing) building components, evacuation facilities, and layout elements. Hence, this point mainly concerns aforementioned pillars 1 and 2 tasks. Therefore, experimental data would allow to increase the process of model validation [25, 94, 106], by means of case studies in order to prove their applicability to building heritage.

As shown in Sect. 2.4.1 and in particular in Sect. 2.4.1 emergency activities, wayfinding strategies can ensure an adequate level of safety during the evacuation. Evacuation times and path choices are mutually conditions, especially during the decision-making phase [73]: when a wayfinding system is not efficient, the majority of people can choose the same (e.g., most familiar) path and suffering from bottlenecks and overcrowding effects. Hence, their accurate design of evacuation facilities layout cannot exclude investigations on their perception and use by the pedestrians. Their effective support can be often influenced by the pedestrians' perceptive aspects in relation to [32, 62, 73, 76, 77, 109]:

- signs position: floor/at the ceiling; perpendicular/parallel to the evacuation flow direction;
- distances: between man and sign/between two consecutive signs;
- environmental conditions: mainly, smoke presence, blackout, and lighting;
- dimensions of the composing elements;
- lighting: standard reflective signs, PLM materials, and electrically illumined signs; and
- possibility to interact with people: through static ("passive": independent from the surrounding conditions) or dynamic ("active": dependent on surrounding conditions by means of a escape route identification algorithm) information.

The use of wayfinding signage, especially in Building Heritage, can easily decrease the necessity of burdensome management level strategies for the internal safety team members, who are so allowed to perform actions aimed at firefighting and salvage of the historic value items [43, 44, 46]. Furthermore, wayfinding facilities do not require architectural layout modifications and generally limit interventions on structural and non-structural elements [11, 12, 32, 65].

Despite their importance, wayfinding signage systems seem to be not defined so as to effectively interact with evacuating occupants. Some fire safety codes and current practices implicitly generally include low-efficiency solutions. Suggested signs positions (at the ceiling) is provided so as to make them visible by many evacuees with limited visual obstructions; nevertheless, during a fire, rising smokes could briefly prevent their identification, especially in case of reflective signs and in case of low ceilings. Furthermore, many regulations allow the application of reflective (non-PLM) exit signage in combination with emergency lighting. In case of smoke and lights on, they can be difficultly seen by evacuees [77, 109]. The application of adequate emergency lighting systems could be difficult in particular valuable historic scenarios because of, for instance, wiring applications. In case of blackout, older

systems could be affected by some failures (e.g., capacity deterioration of battery systems, scarce maintenance)[11]. The design of similar facilities seems to avoid an effective investigation on human needs in evacuation and so to limit the performance-based approach only for the verification phase. Notwithstanding the raising number of experiments about wayfinding systems influence on human path choices, perceptive and cognitive aspects are still missing, or some related behavioral issues are not still included by regulations and simulators [108, 109]. On the contrary, FSE methods should be combined with the "reasoning through the evacuation behaviors" so as to give the best help to evacuees in each reasonable condition [7]. This remark also implies the need to implement wayfinding systems-related behaviors in simulators and the development and test of flexible, "intelligent," "active," and fully interactive[29] wayfinding systems.

In hazardous emergency conditions, knowing and defining human behaviors are then basic aspects since building design and architecture are supposed to be centered on man.[30] The combined FSE-behaviors approach would allow to reach this goal by analyzing which minimal interventions on the Building Heritage could effectively increase occupants' safety in emergency motion.

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[29] "Involving communication between people or reactions between things that work together" according to the Cambridge Dictionary, http://dictionary.cambridge.org/dictionary/english/interactive. Accessed 24 Oct 2016.

[30] Compare to the Vitruvian man's concept, or to the Le Corbusier's *"Le Modulor"* (1948) and *"Vers une architecture"* (I ed., Paris, Cres, 1923).

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