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Towards a “behavioural design” approach for seismic risk reduction strategies of buildings and their environment

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Abstract. Earthquake safety paradigms in urban scenarios can be represented by: buildings response to ground shaking; possibility to evacuate urban areas; rescuers’ assistance to evacuating pedestrians after reaching assembly points in the urban fabric. The first element is widely investigated and involves studies on buildings vulnerability and site hazard. Last two issues are strongly influenced by urban scenarios modifications due to the earthquake and human behaviours during both event and evacuation. Consequently, understanding how people behave in similar conditions becomes an essential issue in order to properly evaluate the urban risk assessment, efficiently organize evacuation procedures and plan interventions (on critical buildings, infrastructures). Hence, this paper firstly offers an overview of current literature on human behaviour in earthquake so far as urban scenario safety is concerned. Critical factors that determine individuals’ response performances focus on human behaviours and environmental modifications due to the earthquake. The study underlines how some of the assumptions about the existing paradigms seem to be not consistent with the knowledge set out in the literature: individuals' behaviours are generally neglected while proposing risk-reduction strategies (management, interventions on buildings), and these strategies are supposed to directly induce correct emergency behaviours on people. On the contrary, a successful approach should combine traditional evaluations with innovative analyses on human behaviours and man-environment interactions in earthquake conditions: hence, this paper finally suggests a “behavioural design” approach. Following fire safety engineering criteria, simulation models would be used for evaluating the exposure parameter and check operative strategies for interferences reduction in emergency conditions.

Keyword. earthquake evacuation; human behaviours in earthquake; earthquake risk assessment; buildings and urban scenarios safety; conceptual framework; behavioural design for architecture and building constructions

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1 Introduction

Knowing and defining human behaviours in emergency conditions are basic problems in the safety assessment process. The analysis of the “human” factor in relation to critical scenarios (D’Orazio et al., 2014b; Kobes et al., 2010) represents one of the bases for proposals about interventions on buildings and emergency management strategies. The "human" factor effect becomes the fundamental issue when the built environment suffers modifications due to the occurring disastrous event and people have to strictly interact with the scenario in order to reach safe conditions (such as in case of evacuation). Hence, a joint man-environment investigation approach is needed, for example, in fire (Kobes et al., 2010; Proulx, 2002) and earthquake (Akason et al., 2006; Alexander, 1990; D'Orazio et al., 2014b; Kosaka, 1996; Prati et al., 2013) emergencies. An interesting similarity can be performed between fire and earthquake evacuation and the related approaches to the design of risk-reduction strategies.

Fire evacuation is mainly performed during the event, or rather while the fire is spreading inside the building. Human behaviours are influenced by fire propagation stages and environmental modifications (e.g.: reaction-to-fire of building materials, smoke productions) (Kobes et al., 2010; Proulx, 2008). In general terms, the environment where people move is "dynamic" because of the propagation of the event and its effects. The possibility to escape from a building during a fire is a consequence of decisions carried out by occupants in relation to the surrounding environment (Kobes et al., 2010): in general terms, building planning and design actions should be oriented to a minimization of the total evacuation time. Studies focused on human behaviours in a fire and also provided a quantification of motion and wayfinding activities (Kobes et al., 2010; Proulx, 2002; Shi et al., 2009). The fire safety engineering (Borg and Njå, 2013; Kobes et al., 2010; Korhonen and Hostikka, 2010) approach considers these behavioural issues as fundamental for the correct building design. Recent national and international regulations positively adopted researchers' works outlines (BSI, 2004; Confederation of Fire Protection Associations Europe, 2009; Ministry of Interior (Italy), 2015). At the same time, design tools have been recently developed in order to consider these phenomena and then to properly help the architects during the design phase (Borg and Njå, 2013; Korhonen and Hostikka, 2010; Ronchi and Nilsson, 2013; Zheng et al., 2009).

Similarly, earthquake safety paradigms are strictly influenced by man-environmental interactions, especially in urban scenarios. Earthquake evacuation is generally performed after the main shake itself (and so during the immediate aftermath). Although the environment where people move can be considered less dynamic than the one of a fire (because of the kind of emergency), the surrounding damaged scenario highly influences evacuating individuals while they are gaining a safe condition (Alexander, 1990; D'Orazio et al., 2014b; Yang et al., 2011). Thus, "behavioural aspects" in earthquake should be considered while dealing with individuals' safety level and related risk-reduction strategies.

According to previous works and to the synthetic representation of Equation 1, the earthquake risk R at urban scale (Ambraseys, 1983; Villagràn De León, 2006) can be determined by the site hazard H (Klügel, 2008), the buildings vulnerability V (Calvi et al., 2006)and the exposed elements E (Mouroux and Brun, 2006; Villagràn De León, 2006):

$$R = R(H, V, E) \qquad (1)$$

This definition links the three essential issues which have to be inquired (D'Orazio et al., 2014b). The site introduces the possible earthquake characteristics through its related hazard (Klügel, 2008). The urban layout is composed by built areas, public spaces (streets and squares) and infrastructures that can suffer from a certain damage level in function of the earthquake magnitude (Federal Emergency Management Agency, 2009a; Grünthal, 1998; Mouroux and Brun, 2006). The "human presences" in the scenario must be considered in terms of both inhabitants' number and inhabitants' response to the event (Alexander, 2012; D'Orazio et al., 2014b). At the same time, people choices are influenced by the earthquake magnitude itself and to environment modifications due to the earthquake (e.g.: ruins and debris formation) (Bernardini et al., 2016; Grünthal, 1998; Prati et al., 2012; Quagliarini et al., 2016; Rao et al., 2011). In fact, on one side, they could be trapped or injured for buildings damages and collapses. On the other side, their possibility to reach safe places and meeting points could be compromised, and rescuers actions could not be really efficient. These statements clearly show how the earthquake safety paradigms can be influenced by three linked main key factors:

- the buildings response to ground shaking, as function of buildings vulnerability and earthquake magnitude (or ground acceleration) (Grünthal, 1998; Hill and Rossetto, 2008; Lagomarsino and Giovinazzi, 2006);
- possibility to evacuate urban areas, as function of buildings and infrastructures damage and pedestrians flows along the evacuation paths (Amini Hosseini et al., 2014; Mishima et al., 2014; Quagliarini et al., 2016; Truong et al., 2013);
- rescuers' assistance to evacuating pedestrians after reaching assembly areas in the urban fabric, as function of emergency management procedures, real pedestrians' evacuation process, and the scenario damages (Amini Hosseini et al., 2014; D'Orazio et al., 2014a; Italian technical commission for seismic micro-zoning, 2014).

Contrary to what is observed in the fire safety field, a limited number of studies deals with human behaviours in earthquake conditions (Alexander, 1990; Bernardini et al., 2016; D'Orazio et al., 2014b; Kosaka, 1996; Prati et al., 2013, 2012), and only few of them success in providing tools or rules that could be effectively useful for management actions and planning interventions on buildings and urban scenarios (such as behavioural schemes (Alexander, 1990; D'Orazio et al., 2014b; Murakami and Durkin, 1988), motion quantities (Bernardini et al., 2016; D'Orazio et al., 2014b; Hori, 2011) and simulation models (D'Orazio et al., 2014a; Hori, 2011; Okaya and Takahashi, 2013; Osaragi et al., 2014; Shimura and Yamamoto, 2014; Truong et al., 2013)).

Current regulations and best practices about earthquake risk assessment, interventions on buildings at urban scale and emergency management planning generally overlook the "human" factor significance. In this way, they seem to follow a deterministic and schematic point of view. It is supposed that building layout and wayfinding systems can directly induce individuals' behavioural uses. Hence, interventions on buildings and emergency management strategies could be enough for reducing people risk, because occupants would surely behave in "the correct way" (e.g.: using right emergency procedures and paths). For instance, while building construction solutions focus on the vulnerability of the built element as itself, current guidelines mainly limit the definition of evacuation layout elements (mainly, routes, assembly points and evacuation sites) to: rough geometric aspects (e.g.: ratio between outdoor spaces dimensions and facing buildings heights (Italian technical commission for seismic micro-zoning, 2014); distance of refuge places from buildings and between adjacent assembly points (Sapountzaki, 2002)); avoiding (or limiting) secondary hazards and cascade effects (Bureau of Urban Development - Tokyo Metropolitan Government, 2010; Federal Emergency Management Agency, 1996; Italian technical commission for seismic micro-zoning, 2014) (including earthquake-induced fire spread at urban scale); estimating post-earthquake debris quantities (Federal Emergency Management Agency and National Institute of Buildings Science, 2003). These approaches ignore (or, at least, widely underestimate) people's response to earthquake and evacuation choices, as well as excessively simplify criteria for path (total or partial) blockage (e.g.: by using simple geometrical criteria).

Nevertheless, earthquake risk-reduction strategies would really take advantages of behavioural aspects, as for the fire safety case. Understanding how individuals act in these emergency conditions would allow to develop integrated "risk maps" combing traditional and innovative evaluations: evaluations related to traditional parameters and results of behavioural analyses should be easily combined in order to offer suggestions about operative strategies for planning risk reduction strategies, and evaluating community resilience aspects (Ainuddin and Routray, 2012; Alexander, 2012; Amini Hosseini et al., 2014; Cutter et al., 2008; D'Orazio et al., 2014b). A similar approach is urgently needed in urban historical city centres and high population density areas, where the man-environment interactions are particularly strong, the related general high-risk level and focused interventions could be planned in order to concentrate capitals on strategic elements in the urban factory.

Starting from this point of view, this paper tries to outline a new methodology for assessing risk at urban scale and designing risk-reduction strategies. The method considers human behaviours and response in case of earthquake, and man-environment interactions during the emergency phase as fundamental elements for developing effective risk-reduction strategies. For this reason, the proposed approach is called "behavioural design".

The "human" factor analysis is offered involving both quantitative and qualitative aspects of human behaviours in earthquake. For this reason, methods about how to investigate and organize human behaviours are firstly provided. Secondly, human behaviours are summarized by evidencing the main gaps for the development of a full "behavioural" approach". Then, the environment is approached through a discussion about possible modifications that can influence people choices. Finally, suggestions about a "behavioural design" approach (i.e.: try to design architectural spaces and risk-reduction strategies starting from human behaviours) for the earthquake safety assessment and planning are suggested, by ideally following the fire safety "psychonomics" (Kobes et al., 2010). In the research context, simulation models (both theoretical models and software tools) are stressed as useful tools for scenarios definition and emergency phenomena investigations. Current methodologies could be combined with simulation results analysis on individuals' response while evaluating possible risk-reduction strategies effectiveness in all respects.

2 Overview of considerable researches into human behaviours in earthquake emergency

This section outlines the bases of the proposed approach by dealing with the fundamental issues in human behaviours investigation. For this reason, the three main aspects involves: defining the exposure parameter; tracing methods and rules for behavioural analysis; summarizing the current knowledge about human behaviours by evidencing the most important challenge in behavioural analyses; focusing on man-environment interactions, with a particular attention to earthquake magnitude, environmental modification and cascade effects; offering an overview of current human behaviour modelling.

2.1 Exposure parameter definition

While H and V are strictly connected to the physical environment, the exposure parameter E (Ambraseys, 1983; Mouroux and Brun, 2006; Villagràn De León, 2006) would be aimed at considering the effects of the earthquake occurrence on the population. Current methodologies are mainly based on:

- population densities in a given location, in relation to possible buildings damages and earthquake magnitude (mainly, by macroseismic scales), so as to quantify possible fatalities, injuries, and displaced population (Federal Emergency Management Agency and National Institute of Buildings Science, 2003; Rahman et al., 2015; Shapira et al., 2015; Spence et al., 2011);
- presence of buildings and monuments with an historical-artistic-cultural value for the society (Mouroux and Brun, 2006) for estimating the possibility of total or partial losses of exposed elements;
- critical infrastructures and strategic buildings characterization (Alexander, 2012), also for aspects concerning business continuity and post-disaster management;
- quantification of economic activities on the territory (Federal Emergency Management Agency, 2009a; Wood et al., 2014), including economical losses for the population, Repair Cost Rates – Loss Ratios (Federal Emergency Management Agency, 2009a), and insurances (Autoritè des Marchès Financiers, 2012; Werland and Pitts, 2012).

Data could be quickly organized through inventories (taking advantages of GIS tools) (Pollino and Fattoruso, 2011; Rahman et al., 2015) about population census, demographical aspects, occupancy and value of elements, use of lands, buildings features according to typological classes, and also in combination with databases about other disaster risks (e.g.: fire risk for the urban scale) (Rahman et al., 2015). Although defining similar aspects is obviously important, the present risk assessment offers a sort of static overview about population fatalities and physical losses, while it completely ignores individuals' response during the emergency: for this reason, an underestimation of effective problems connected to human behaviours seems to be introduced (Alexander, 2012; Bernardini et al., 2016; D'Orazio et al., 2014b; Prati et al., 2013). Nevertheless, Civil Protection statistics evidence how a significant percentage of fatalities is not due to structural failure of buildings and related collapses: up to 25% of human losses are due to the possibility of safely evacuating buildings and urban parts, gaining safe areas and being helped by rescuers[1] (Alexander and Magni, 2013; Shapira et al., 2015). Human behaviours, evacuation procedures and post-disaster emergency management strategies directly affect this data and also determine the resilience level for the considered population (Alexander, 2012; Cutter et al., 2008; D'Orazio et al., 2014a). For this reason, *E* should directly include also these aspects; otherwise, a behavioural index has to be defined and combined in risk assessment evaluations at Equation 1. A similar approach would be take advantages of current exposure estimation methodologies, including scenarios creation in different part of the day/week/month/year, including holidays periods (Ferreira and Oliveira, 2009)(with an high relevance in case of tourist destinations (Mäntyniemi, 2012; Sullivan and Häkkinen, 2010)).

2.2 How to define human behaviours: analysis methods

In order to develop methods and tools for evaluating risk-reduction strategies by including their effects on human behaviours, deep investigations about individuals' actions, criteria of choice and motion features during an earthquake emergency have to be performed. The most important aspects are connected to perception of earthquake risk (in anticipation of the event) and procedures during the earthquake, including the evacuation characterization (Akason et al., 2006; Alexander, 1990; D'Orazio et al., 2014b; Murakami and Durkin, 1988; Prati et al., 2013). Unfortunately, a scarcity of data can be actually noticed in earthquake human behaviours analysis, in respect to other emergencies (mainly, fire risk), as also evidenced by Section 1 .

Hence, behavioural inquiries are essential. They can be performed by carrying out these main methods (limitations of each method are stressed):

- a *direct observation during the earthquake itself*, with the physical presence of the researchers where and when the event occurred (Alexander, 1990; Boileau et al., 1978; Seneca, 1972). This method was the first performed data collection method, especially during "wide" scale events, but can highly suffer from subjective and incomplete evaluations;
- *questionnaires or interviews on resident population* about: risk perception (Ainuddin et al., 2013; Santos-reyes et al., 2014), choice of evacuation routes (Mishima et al., 2014; Miyamoto et al., 2011; Tai et al., 2010) and behaviours during the event ((Akason et al., 2006; Kosaka, 1996; Prati et al., 2013, 2012). Their

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[1] www.protezionecivile.gov.it/jcms/it/descrizione_sismico.wp;jsessionid=F5D27C1681510C9963A14E7E05737C10?pagtab=3#pag-content (in Italian; last access: 01/08/2015)

main limits is connected to possible biases due to "lack of professional training of the public and the media" (Yang and Wu, 2012, p. 1779) or to the "conscious" and "unconscious" individuals' meditations in answers. Moreover, interviews on population can be strictly related to the analysed case;

- *analysis of videotapes concerning real world events*, mainly so as to define behaviours (quantitative and qualitative aspects) in emergency (including evacuation) conditions (Bernardini et al., 2016; D'Orazio et al., 2014b; Hori, 2011; Yang and Wu, 2012; Yang et al., 2011). However, codified methodologies should be used while inquiring similar elements, in order to avoid the influence of analyser's interpretation and scenario quantities parametrization[2]. A deep sharing of initial sources for the researchers (e.g.: main studies included links for videotapes download) can be also easily allowed;
- *evacuation drills analyses*. They should be generally avoided because of main differences with the real world events (Yang et al., 2011), mainly due to the interactions between man, earthquake and modifications of the built environment;
- *use of virtual reality (VR) simulations*, including for training purpose (Takimoto et al., 2004)[3]. This is a really promising research method also used for investigations about other kinds of emergency especially for wayfinding issues (e.g.: fire (Cosma et al., 2016; Vilar and Rebelo, 2008)). "Immersive" VR environment allow the configuration of many different scenarios. However, results could be affected by some behavioural biases, also according to drills evaluation (Yang et al., 2011);
- *innovative social media channels methods* in order to inquire e.g. the earthquake perception and aftermath phase, by using ICT and social media technologies (Cheng et al., 2015; Mora et al., 2015). Similar methods could support traditional questionnaires.

Analyses would be aimed at defining qualitative and quantitative aspects of human behaviours. Similarly to previous works about databases about "human" factor in emergency conditions applied in other disasters (e.g.: fire) (Helbing and Johansson, 2010; Schadschneider et al., 2009; Shi et al., 2009), Table 1 resumes the main data that should be analysed so as to contribute to earthquake emergency investigation from the behavioural point of view (Bernardini et al., 2016).

Analysed Data	**Type [main unit of measure]**	**Short description**	**Main references**
earthquake risk perception	qualitative	how people perceive the earthquakes and their results (e.g.: possibility of event occurrence, safety level, perception of buildings and safe areas)	(Ainuddin et al., 2013; Santos-reyes et al., 2014)
	quantitative [%]		
pre-movement phase	qualitative	perception of the earthquake (e.g.: ground perception)	(Akason et al., 2006; D'Orazio et al., 2014b)
	quantitative [s]	time of reaction to the event; pre-movement time characterization	
evacuation speed	quantitative [m/s]	average values of speed and characterization in different conditions of crowdedness/paths	(Bernardini et al., 2016; D'Orazio et al., 2014b; Hori, 2011; Li et al., 2015; Yang et al., 2011)
group behaviours	qualitative	actions between the group members (e.g.: attractive and repulsive phenomena)	(Alexander, 1990; Bernardini et al., 2016; D'Orazio et al., 2014b)
	quantitative [m]	distances between individuals	
occupant characteristics	qualitative	differences in actions and reactions	(D'Orazio et al., 2014b; Li et al., 2015)
	quantitative (e.g.: [m/s], [m], [s])	specific parameters (e.g.: speed, body dimensions,	

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[2] Videotapes analyses allow to determine motion quantities and behavioral patterns but do not succeed in determining the effective instant of individuals' choice and the related cognitive aspects.

[3] http://www.hitlabnz.org/index.php/research/interaction-design?view=project&task=show&id=21 (last access: 11/09/2015)

		reaction delays,)	
evacuation behaviours	qualitative	series of actions during evacuations	(Alexander, 1990; Bernardini et al., 2016; D'Orazio et al., 2014b; Murakami and Durkin, 1988; Prati et al., 2013)
evacuation path obstruction	quantitative (e.g.: speed $[m^2]$, density $[people/m^2]$)	influence of environmental conditions (including generated ruins) on queue delays or block egress on travel speeds	(Bernardini et al., 2016; Quagliarini et al., 2016; Truong et al., 2013)
	qualitative		
exit and path choice decisions	quantitative (e.g.: flow [people/(m s)])	influence of environmental conditions (including generated ruins) and other people positions on travel paths and travel times on paths choices	(Bernardini et al., 2016; Mishima et al., 2014; Truong et al., 2013)
	qualitative		

Table 1. Data that contribute to an evacuation characterization by completing recent works outlines (Bernardini et al., 2016): these aspects should be considered by evacuation databases. For each analysed data, type (quantitative: physical quantities; qualitative: pure behavioural and decisional aspects) and short description are provided.

A statistical approach in data organization is needed because of the behavioural differences due to both individual's perception and characteristics (including presence of individual's disabilities) (Ainuddin and Routray, 2012; D'Orazio et al., 2014b; Santos-reyes et al., 2014; Solberg et al., 2008), and also to general local factors (social, geographical and cultural background) (D'Orazio et al., 2014b). Large databases concerning real events are able to increase the statistical significance of results (Bernardini et al., 2016; Yang and Wu, 2012); at the same time, they should contain cases from all over the World. In fact, studies on massive earthquake (Alexander and Magni, 2013; Shapira et al., 2015; Spence et al., 2011)[4] are able to fully describe an event and its consequences, but remain strictly connected with a precise geographical area and a single event . However, a comparison between related reports can largely underline differences in human behaviours and in built environment modifications. Moreover, a significant example can be represented by investigations on earthquakes in the same geographical area during a significant number of years (such as, Italian Earthquakes analysis along the last 60 years: Friuli-Venezia-Giulia (1976) (Boileau et al., 1978); Irpinia (23 November 1980, Mw 6.89 ±0.04 - X degree MCS[5]) (Alexander, 1990; Gizzi et al., 2012); Umbria-Marche (1997) (Prati et al., 2012); L'Aquila (2009) (Alexander and Magni, 2013; D'Ayala and Paganoni, 2010); Emilia-Romagna (2012) (Moretti and et al., 2013; Prati et al., 2013)). A comparison between related data mainly allow to trace the "evolution" of human behaviours during the time, and so to compare the effectiveness of behavioural models. An analogous meditation has been offered by recent works on fire evacuation models (Thompson et al., 2015).

The *qualitative analysis* allows to define actions and attitudes that pedestrians carry out during the emergency procedure in relation to both the environment and other people. The qualitative analysis takes advantages of applying a social-science based point of view (Solberg et al., 2008), according to investigations about other kind of disasters (Kobes et al., 2010; Riad et al., 1999; Shiwakoti et al., 2008a). Methods are summarized in previous works (Bernardini et al., 2016; D'Orazio et al., 2014b; Murakami and Durkin, 1988; Yang and Wu, 2012; Yang et al., 2011). Distinguishing behaviours between the ones "common to other kinds of evacuation" and the ones "specific of this case" (Bernardini et al., 2016; D'Orazio et al., 2014b) is useful so as to evidence which interactions are characteristics of the earthquake evacuation, and what should be deepened. A significant issue is represented by defining when a behaviour can be defined "recurrent" (D'Orazio et al., 2014b). One of the most comprehensive approaches (D'Orazio et al., 2014b) fixes rules for the acceptance of recurrent behaviours (present at least in the 30% of cases) by associating each behaviours to the specific emergency conditions.

Quantitative analyses involve the quantification of physical quantities in motion (including walking speeds and density-speeds diagrams (Schadschneider et al., 2009)) and delays (e.g.: in evacuation starting). They are mainly obtained by

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[4] case studies in order to mainly describe human behaviors, retrieve epidemiological data, define relations between the earthquake magnitude and the number of fatalities and analyze the aftermath response

[5] http://emidius.mi.ingv.it/DBMI04/query_eq/external_call.htm?eq_id=3132&eq_group= (in Italian; last access: 25/8/2015)

analysing videotapes of real words events, by using different motion tracing techniques (Bernardini et al., 2016; D'Orazio et al., 2014b; Hori, 2011; Yang et al., 2011). However, a "standardization" in pedestrians' tracking techniques could be defined. In videotapes, the position of each detected pedestrian is pointed out (at the hip level (Bernardini et al., 2016) or on the head (Yang et al., 2011)) at regulars time intervals (suggested time intervals: 0.25s to 0.625s (Burghardt et al., 2013)), during the whole pedestrian's evacuation process. Previous works underline how manual tracking systems flow could be used in each circumstance (including when there are some problems in chosen videotapes characteristics, e.g. not such as the not uniform backgrounds to human motion or the images resolution (Bernardini et al., 2016)). Then, positions data can be mainly managed so as to evaluate motion speeds, distances between individuals, pedestrians' trajectories and density-speed diagrams. The traditional four measurement methods for defining fundamental diagrams of pedestrians' dynamics (Zhang et al., 2011) can be used with the aim at delineating density-speed or density-flow diagrams. About related time range, literature works about pedestrians' dynamics (Bernardini et al., 2016; Burghardt et al., 2013) point out the necessity to choose the related value by analysing the environmental conditions and the regularity of pedestrians' flow: in general terms, the maximum limit of about 5s in normal conditions should be smaller because of higher speeds, such the ones noticed in real evacuation conditions. Retrieved behaviours and related motion quantities can be organized in behavioural patterns so as to offer emergency and evacuation flowchart that summarize the process evolution during the time (Alexander, 1990; D'Orazio et al., 2014b; Mishima et al., 2014; Murakami and Durkin, 1988). Simulations models or emergency time lines for planners and rescuers can be also defined according to different operative rules (e.g.: motion law equations) (D'Orazio et al., 2014a; Hori, 2011; Li et al., 2015; Shimura and Yamamoto, 2014; Tai et al., 2010; Truong et al., 2013).

2.3 Human behaviours in earthquakes

The organization of qualitative and quantitative data leads to evidence how human behaviours are the results of interactions phenomena in emergency conditions. A good organization of human behaviours can take advantages of: defining the referring elements for human behaviours; outlining the evacuation phases and the related main behaviours. Human behaviours can denote individual or collective features, and mainly depend on relationships and interferences with other persons, the surrounding environment (especially the built environment) and the earthquake characteristics (e.g.: the perceived magnitude or ground acceleration) (Akason et al., 2006; Alexander, 1990; D'Orazio et al., 2014b; Murakami and Durkin, 1988; Solberg et al., 2008). In order to sum up these interactions, studies propose schemes for describing factors explaining the various aspects of individuals' behaviours of occupants (Murakami and Durkin, 1988) or organizing models according to agent-based architectures (D'Orazio et al., 2014b). Hence, dependencies in earthquake evacuation involve the *individuals* (or pedestrians while speaking about the evacuation phase) and the surrounding *environment* (built elements, earthquake features and modifications in the scenario).

Different emergency phases can be distinguished, also according to other kinds of disaster (D'Orazio et al., 2014b; Kobes et al., 2010; Riad et al., 1999): each of them denotes particular activated human behaviours depending on the surrounding scenario and on the series of previous and successive actions.

Hence, following previous works (Bernardini et al., 2016; D'Orazio et al., 2014b), Table 2 summarizes the main retrieved behaviours by: classifying them in the related emergency phase; providing a short description; defining the surrounding conditions and interaction elements, and the main related literature references. Moreover, behaviours that are common to other evacuation kinds are highlighted by *.

Earthquake emergencies display four main phases (Alexander, 1990; Bernardini et al., 2016). In general terms, differences in activities or reactions due to sex are not relevant (Kosaka, 1996), while differences due to social, cultural and geographical background are confirmed as introduced at paragraph 2.2 .

Evacuation stage	**Behaviour: short description**	**Type of evacuation considered**	**Relationship in activation of behaviour**	**Main references**
Pre-movement phase	*Social attachment and information exchange*:* people exchange information and evaluate together the level of danger	indoor + outdoor	pedestrian	(Alexander, 1990; D'Orazio et al., 2014b; Rao et al., 2011)
	Attachment to things:* people prefer to collect their belongings and then start the evacuation	indoor	environment	(Bernardini et al., 2016; Rao et al., 2011; Riad et al., 1999)
	Response to sensible events: the evacuation is generally needed for sensible events (magnitude higher than a 5th degree in the Richter Seismic Scale - IV degree in EMS-98 scale); some safety	indoor + outdoor	environment	(Akason et al., 2006; Grünthal, 1998; Okaya and Takahashi, 2013; Prati et al., 2013; Solberg et al., 2008)

	issues (“drop-cover-hold on” procedures) can be performed during the shake, with relation to the ground shaking; disaster denial could provoke delays in evacuation starting			
Motion toward the evacuation target	*Attraction towards safe areas*:* people would like to exit/move far from the buildings, and reaching “safer conditions” in the “safe” areas as described below	indoor + outdoor	environment	(Alexander, 1990; D’Orazio et al., 2014b; Murakami and Durkin, 1988)
	Preferred path definitions: people gain the evacuation targets through the widest and clearest of dust and rubble paths, especially in a close urban fabric	outdoor	environment + pedestrian	(Alexander, 1990; Quagliarini et al., 2016; Truong et al., 2013)
	Fear of buildings: people run out of buildings, maintaining a “safety distance” from them, and avoiding path with debris and ruins	outdoor	environment	(Alexander, 1990; Bernardini et al., 2016; Mora et al., 2015)
	Not keeping a “safety distance” from “low obstacles”: people allow moving towards trees, shelters and street furniture, in order to find a temporary “safe” point.	outdoor with “low obstacles”	environment	(Bernardini et al., 2016; D’Orazio et al., 2014b)
	Repulsive mechanisms to avoid physical contact:* people modify their trajectories in order to avoid the collision with environmental objects and other pedestrians	indoor + outdoor	environment + pedestrian	(D’Orazio et al., 2014b; Helbing and Johansson, 2010; Truong et al., 2013)
	Attraction for group bonds:* pedestrians (especially when sharing a cohesion bond) prefer to remain close each other during the evacuation, gather during the evacuation and prefer to organize evacuation groups	indoor + outdoor	pedestrian	(Alexander, 1990; Bernardini et al., 2016; D’Orazio et al., 2014a; Solberg et al., 2008)
	“Herd Behaviour” and influence of “collective” velocity:* pedestrians’ behaviours and choices are shared in group conditions, because decisions are shaped by social dynamics	indoor + outdoor	pedestrian	(D’Orazio et al., 2014b; Helbing and Johansson, 2010; Lakoba et al., 2005; Solberg et al., 2008)
	Increased guide effect for presence of rescuers/evacuation plans/high social support/evacuation leader: an improvement of emergency phases (including appropriate behaviours and motion speeds) is noticed when at least one of these factors occurs	presence of rescuers / evacuation procedure / leader	environment	(Bernardini et al., 2016; Hou et al., 2014; Li et al., 2015; Yang et al., 2011)
	Panic conditions: traditional “panic conditions” seem to be uncommon, mainly because of pro-social behaviours activations; they can be represented by an increase of individual’s choices depending on group phenomena	indoor + outdoor	environment + pedestrian	(D’Orazio et al., 2014b; Lakoba et al., 2005; Mawson, 2007; Solberg et al., 2008)
	Interruption of outdoor evacuation for high ground shaking: in outdoors, people slow down or stop the evacuation when the ground highly shakes; at the same time, some activities become difficult to be performed.	outdoor	environment	(Akason et al., 2006; Alexander, 1990; Bernardini et al., 2016; Grünthal, 1998; Murakami and Durkin, 1988; Solberg et al., 2008)
Safe area reaching	*Safe areas definition:* evacuation targets are considered “safe” areas because of their geometry, level of damage and social factors; evacuation timing criteria could be used by people in order to choose the target	outdoor	environment + pedestrian	(Alexander, 1990; D’Orazio et al., 2014b; Mishima et al., 2014; Murakami and Durkin, 1988; Quagliarini et al., 2016)
	Influence of not immediate danger feelings or panic conditions: people interrupt the evacuation, or end the evacuation, or remain	outdoor	environment + pedestrian	(Alexander, 1990; D’Orazio et al., 2014b; Kosaka, 1996; Rao et al., 2011)

	near the same place when local conditions of danger are not evident (not immediate danger feelings) or people are influenced by a sort of "helplessness level" (panic conditions) that also drives people to follow other pedestrians' choices	
Immediate post-evacuation	*Social attachment:* pro-social behaviours and reciprocal help seem to appear also in the aftermath, also in direct relation with the physical damages (especially in residential areas)	(Drury et al., 2015; Rao et al., 2011; Solberg et al., 2008)
	Attachment to things, belongings and home: people prefer return home, also in order to collect belongings after the earthquake	(Alexander, 1990; Murakami and Durkin, 1988; Osaragi, 2012; Prati et al., 2012; Rao et al., 2011)

Table 2. Human behaviours in earthquake conditions. Elements of reference are evidenced: *Environment* (buildings and other obstacles, safe areas, evacuation paths, earthquake characteristics, ruins, presence of rescuers/evacuation plans) and *Pedestrian* (social relationships between individuals). Behaviours marked by * are common to other kinds of disasters: in this case, references can involve also studies about other disasters.

2.3.1 Pre-movement phase

The *pre-movement phase* (during the shake and in the next few seconds) is characterized by actions that are not directly connected with the evacuation process, such as collecting belongings, exchanging information and attempting safety procedures (Akason et al., 2006; Alexander, 1990; Grünthal, 1998; Rao et al., 2011; Riad et al., 1999; Solberg et al., 2008). As also described at paragraph 2.4 , contrarily to the other disasters, a significant relationship between the performed behaviours and the earthquake magnitude (or the ground acceleration) seems to be noticed, especially in the choice to evacuate (Akason et al., 2006; Grünthal, 1998): in fact, when the earthquake reaches a certain magnitude, people usually decide to evacuate, if related actions are possible. Some time-wasting and dangerous behaviours, that could not be associated to safety procedures, could be present in most parts of the emergency procedure: in particular, the "attachment to things effect" is retrieved in both the pre-movement phase (Alexander, 1990; Bernardini et al., 2016; Riad et al., 1999).

Concerning quantitative analyses results, the quantification of pre-movement motion delays is rarely performed (D'Orazio et al., 2014b; Kuwata and Takada, 2002). Hence, deeper investigations are actually needed in order to quantify when people decides to leave their initial positions: this factor could affect the moment people pour into the streets and the outdoor effective evacuation starts. Moreover, according to other emergencies (e.g.: fire (Shi et al., 2009)), different delay times could be associated to different building intended uses or different activities (including individual's safety procedures, attachment phenomena, information exchange with the surrounding individuals (Bernardini et al., 2016; D'Orazio et al., 2014b)).

Relations between percentages of people that activate evacuation procedures and earthquake magnitude are widely addressed and codified in international documents (Grünthal, 1998) through the analysis of experimental data, as also shown at paragraph 2.4 .

2.3.2 Evacuation phases: motion and safe area reaching

The *evacuation phases* last for minutes and involve the abandon of the initial positions in order to reach a safer area. Behaviours in the two main parts (*motion towards the target*; *safe area reaching*) are strictly connected: Table 2 underlines how people's actions and decisions are aimed at maintaining "safe" conditions in evacuations (such as, staying far from ruins, preferring larger paths, avoid areas with high buildings) (Alexander, 1990; Bernardini et al., 2016; D'Orazio et al., 2014b; Quagliarini et al., 2016). The end of the immediate evacuation procedure occurs in outdoor areas: these "safe" areas (Bernardini et al., 2016; D'Orazio et al., 2014a) are evacuation assembly points in which people gather after the first immediate phases. They can be chosen by individuals in a spontaneous way or by following the guide effect given by rescuers, evacuation plans or evacuation leaders (Alexander, 1990; Bernardini et al., 2016; Santos-reyes et al., 2014; Yang et al., 2011). When a free choice is possible, these safe areas are wide spaces in urban fabric (e.g.: large crossroads or squares, the middle of wide avenues), with convenient geometry, level of damage and social requirements (Alexander, 1990; Bernardini et al., 2016; Mawson, 2007). Nearest safe areas are generally preferred, also according to the attachment to things effects: people seem to prefer to go not far from their houses and belongings (Bernardini et al., 2016; Prati et al., 2012; Riad et al., 1999).

A more detailed description of man-built environment interactions is provided at paragraph 2.5 .

Empirical studies, previous behavioural review and works about model definition (Alexander, 1990; D'Orazio et al., 2014b; Prati et al., 2013; Solberg et al., 2008) evidence how traditional panic theories (Quarantelli, 2002) are generally falsified, also according to research on other disasters (Auf Der Heide, 2004; Mawson, 2007). Panic conditions seem to be avoided thanking to the pro-social attitudes of the damaged population (Rao et al., 2011; Solberg et al., 2008). Otherwise, authors underline how panic conditions can be sometimes described as a sort of "helplessness" or "astonishment" at the earthquake (D'Orazio et al., 2014b; Murakami and Durkin, 1988): people seem to prefer gathering near the same place and following other pedestrians' choices and to adequate their velocity to the others' one (D'Orazio et al., 2014a; Lakoba et al., 2005). This point of view accents the wide presence of collective behaviours (Bernardini et al., 2016; Lakoba et al., 2005; Rao et al., 2011), as shown by Table 2. However, a general panic level can be admitted in scenarios with low social support (Rao et al., 2011; Solberg et al., 2008), in case of high earthquake magnitude (e.g.: ≥IX degree in EMS98 scale) (Grünthal, 1998) or in some emergency phases (e.g.: immediately running out from building during the shake without safety procedures) when particular cultural and geographical conditions are present (Alexander, 1990; D'Orazio et al., 2014b). Deeper investigations about panic-related phenomena should be performed also in order to obtain rules for behavioural models and related motion equations.

Attachments to belongings and to other people are noticed also in individuals' behaviour concerning the use of an own vehicle during the evacuation (Lamb et al., 2011): the over reliance on cars, the preference of walking motion for short paths (<6.25km) and the influence of neighbours while deciding for the abandonment of the vehicle are observed.

Concerning quantitative analysis, previous works mainly focused on defining motion average values or analysing case-studies in order to validate simulations models and/or calibrate the related parameters (Bernardini et al., 2016; D'Orazio et al., 2014b; Hori, 2011; Li et al., 2015). Evacuation motion speeds denote higher values in comparison to other kind of evacuation, such as in a fire (Shi et al., 2009): this result is retrieved in works analysing different cases studies in various geographical locations (Bernardini et al., 2016; D'Orazio et al., 2014b; Hori, 2011), and is also confirmed by investigations about density-speed diagrams (Bernardini et al., 2016). Previous works mainly focused on average instantaneous speeds (Bernardini et al., 2016; D'Orazio et al., 2014b; Hori, 2011; Li et al., 2015). In indoor conditions (Bernardini et al., 2016), the average instantaneous speed is about 2.5m/s, while the speeds distribution for numerous pedestrians' groups (log-normal curve with mode at about 2.0m/s) underlines the influence of densities-related phenomena. Outdoor average speeds are generally higher in respect to indoor ones, especially while people are near a building or exiting from a building (D'Orazio et al., 2014b), as immediate consequence of the *fear of buildings* behaviour (Alexander, 1990). In case of very small group (composed by less than 10 individuals), the motion speed is 4.1m/s while people are moving in outdoor conditions(Hori, 2011). In addition, a recent work (Bernardini et al., 2016) has been provided fundamental diagrams for pedestrians' dynamics in earthquake conditions and the related density-speed Kladek's formula by analysing two real-world cases: although a critical density value (density value corresponding to null speeds) was not yet retrieved, correlations trends are similar to the ones of other disasters. Distances between individuals in the same evacuation group were investigated so as to quantify grouping phenomena (mainly, group attractions and repulsion between individuals): an average distance between two individuals' centres of mass is equal to about 1.8m (Bernardini et al., 2016; D'Orazio et al., 2014b). Experiments about man-environmental obstacles in outdoor conditions were also performed, but results could be affected by a low statistical significance (Bernardini et al., 2016). However, although quantitative analyses are connected to real-world cases, resulting data are still based on samples generally characterized by:

- small number of investigated individuals (an exception is represented by (Bernardini et al., 2016));
- few different event locations (Yang and Wu, 2012);
- often limited to groups with low pedestrians' density (generally <0.4persons/m^2) (Bernardini et al., 2016; D'Orazio et al., 2014b);
- no consideration of age classes;
- no data about disabled people.

Finally, studies concerning tourists areas have been addressed (Mäntyniemi, 2012), but behavioural aspects should be deepened. In particular, evacuation path choices criteria and motion speeds could be influenced by the familiarity to the environment, as also suggested by previous models about other kind of evacuation (e.g.: influence of memory effect in buildings evacuation choices (Lakoba et al., 2005)).

2.3.3 Immediate post-evacuation

When the safe areas are reached, the first part of the emergency (the evacuation) ends and the emergency response (Alexander, 1990; Murakami and Durkin, 1988) is activated by Civil Protection and/or other organized rescuers, in order to set emergency management procedures off (Italian technical commission for seismic micro-zoning, 2014). However, right after the shaking, significant attachment behaviours are still evident (Alexander, 1990; D'Orazio et al., 2014b; Murakami and Durkin, 1988; Solberg et al., 2008) and can also persist for many times in the aftermath (Prati et al., 2012; Rao et al., 2011), such as the attachment to belongings and the related desire to come back home. At the same time, lasting pro-social behaviours seem to be able to increase the resilience of the population (Ainuddin and Routray, 2012; Alexander, 2012; Drury et al., 2015; Rao et al., 2011).

2.4 Relation between earthquake magnitude and human behaviours

As shown by Table 2, behavioural analyses prove how earthquake magnitude directly affects *pedestrians'* behaviours during both the shake and the evacuation phase. Earthquake features (in terms of event magnitude, ground motion intensity, presence of local shakes amplifications and so on) obviously represent the trigger for the emergency, by directly provoking ground shaking and possible displacements (Federal Emergency Management Agency, 2009a; Wyss, 2014). Earthquake magnitude is usually expressed according to macroseismic scales, such as EMS98 (Grünthal, 1998) or MMI (Akason et al., 2006; Mochizuki et al., 1988).

The same tendencies are noticed for both the individuals and groups (Alexander, 1990; Bernardini et al., 2016; D'Orazio et al., 2014b; Prati et al., 2012).

Firstly, human perception of the event in terms of reaction and response to the event (Alexander, 1990; D'Orazio et al., 2014b; Murakami and Durkin, 1988) are highly influenced (*Response to sensible event* in Table 2): in particular, percentages of people noticing the event and participating to the evacuation procedure is directly connected to the earthquake magnitude (Grünthal, 1998), and related estimation equations have been provided (Quagliarini et al., 2016). Unlike other evacuation kinds, limit conditions are introduced: the evacuation procedure is activated when it is possible to percept the earthquake (≥IV degree of EMS98 scale) (D'Orazio et al., 2014b; Grünthal, 1998); a limit for general panic conditions is proposed (≥IX degree in EMS 98) (Alexander, 1995; Grünthal, 1998; Kosaka, 1996). The response of people to earthquake magnitude also depends on geographical features, such as the common magnitude of recurring earthquakes in a precise area, as well as cultural aspects on behaviours (Alexander, 1990; Boileau et al., 1978; D'Orazio et al., 2014b). In fact, when earthquake intensity is particular strong, people could also directly run out from buildings without attempting safety procedures (e.g.: drop-cover-hold on procedures) (Alexander, 1990; D'Orazio et al., 2014b; Mochizuki et al., 1988; Yang and Wu, 2012).

Secondly, the earthquake magnitude affects the difficulty in performing particular actions or in taking decisions in a conscious way (Kosaka, 1996). In particular, the ground acceleration interferes with the possibility to move: if ground highly shakes while people are moving, the evacuation can be slowed down or interrupted (Bernardini et al., 2016; Grünthal, 1998; Yang et al., 2011).

Further activities aimed at providing specific considerations about the earthquake scales (including both MW, ML and MS Richter scales and EMS98 scale; taking into account possible scales correlations (Musson et al., 2009)) and human behaviours (especially from a quantitative point of view) should be included. Adopting the earthquake magnitude (as well as ground acceleration) as reference element for human behaviours would be useful for behavioural comparisons between different scenarios. This physical parameter directly characterizes the event itself, the occurrence on a particular area (and so both local amplification phenomena and effects related to the distance from the earthquake epicentre). From this point of view, the earthquake characterization for behavioural inquires could take advantages of both the ground acceleration and the perceived duration of the shake. For instance, the earthquake duration could be related to the pre-movement time (as well as for the ground acceleration or displacement, also according to previous works (D'Orazio et al., 2014b)). Behavioural inquires could be directly joined to earthquake hazard H studies, with integrated models definition for H evaluation and combinations with earthquake losses simulators (Tang and Wen, 2009; Vetter and Taflanidis, 2014).

2.5 Interactions between individuals and post-earthquake built environment

During the emergency and, in particular, the evacuation phase, people choices and motion actions are strongly influenced by the modification of the scenario due to the earthquake, as also shown by Table 2. The definition of probable post-earthquake scenarios that pedestrians (and the rescuers) would face during the evacuation phase is essential in order to introduce planning and design strategies (at both building and urban scale) aimed at reducing the resulting interferences between the built environment and the "human" evacuation process. These interferences are fundamental especially in outdoor conditions (Alexander, 1990; D'Orazio et al., 2014b; Ferlito and Pizza, 2011; Italian technical commission for seismic micro-zoning, 2014; Quagliarini et al., 2016). Two main aspects affect human response and behaviour in this evacuation:

- *presence of casualty* due to the direct collapse of buildings, and to indirect earthquake consequences (Shapira et al., 2015; Spence et al., 2011);
- *built environment-related human behaviours*, when individuals have to modify their behaviours and emergency actions in relation to surrounding post-earthquake environment, so as to maintaining their own safety conditions (Alexander, 1990; Caiado et al., 2012; D'Orazio et al., 2014a; Truong et al., 2013).

Both of these problems are connected to building construction issues. The estimation of vulnerability parameter V (Cagnan et al., 2010; Calvi et al., 2006; Federal Emergency Management Agency, 2009a; Grünthal, 1998; Mouroux and Brun, 2006) for the different elements (such as: single buildings and aggregates; historical heritage; infrastructures; city parts) within the urban fabric are combined to seismological parameters in order to estimate the possible damages (Federal Emergency Management Agency, 2009a; Grünthal, 1998; Lagomarsino and Giovinazzi, 2006; Zuccaro and Cacace, 2015).

Two main methods can be used with this purpose. Empirical Methods (EM) mainly estimates building vulnerability and possible damages on building typologies and macroseismic intensity (D'Orazio et al., 2014a; Gizzi et al., 2012; Grünthal, 1998; Lagomarsino and Giovinazzi, 2006; Musson et al., 2009). Hence, they are easy to be applied and can be supported by a statistical point of view. Analytical Methods (AM) combine seismological parameters to the simulation of the mechanical building response (Cagnan et al., 2010; Calvi et al., 2006; Clementi et al., 2015; Lagomarsino and Giovinazzi, 2006) and so they need accurate investigations on each built environment element.

Methods for vulnerability evaluation and damages estimations could be characterized by:

- *scales of applications*. E.g.: damages at "macro" (that is urban) scale can be quickly evaluated through empirical (macroseismic) methods based on building typologies and on large databases of previous disasters.
- *levels of confidence and accuracy*. E.g.: analytical methods could be also used to forecast possible failure and collapse mechanisms of each building because of the deeper knowledge of the building itself (Arcidiacono et al., 2015; Preciado, 2015; Wen et al., 2002).

2.5.1 Loss estimations techniques for determining human casualties and possibility to evacuate

Many studies involve earthquake epidemiology and mortality in order to define correlations between the number of casualties, the buildings damages and the earthquake features (mainly, the intensity) (Alexander and Magni, 2013; Alexander, 2012; Federal Emergency Management Agency and National Institute of Buildings Science, 2003; Shapira et al., 2015). The *Estimation of social losses* (Federal Emergency Management Agency and National Institute of Buildings Science, 2003) *and casualty rate* (in terms of injured and death people) (Alexander, 2012; Holzer and Savage, 2013; Shapira et al., 2015) also depends on scenario configuration in terms of population density, presence of tourists, building and outdoor spaces occupancy and "population dynamics" during the day and during the year (Federal Emergency Management Agency and National Institute of Buildings Science, 2003; Ferreira and Oliveira, 2009). Many works involve the analysis of specific case studies (Alexander and Magni, 2013; Cousins, 2013). Complete reviews and global databases (Shapira et al., 2015), estimation models (including related software simulators for urban or territorial scales applications) (Huang et al., 2009; Spence et al., 2011), discussions about the frontiers of this research have been recently offered (Alexander, 2012; Holzer and Savage, 2013; Shapira et al., 2015; Spence et al., 2011). Main causalities causes are divided into:

- direct physical damages: buildings and infrastructures collapse, including ruins generation (implosion; failure mechanisms activation; collapse towards outdoor spaces, such as along the roads or the squares), and roads damages;
- induced physical damages: including cascade effects (e.g.: landslides, fires, tsunami);
- indirect effects of the earthquake on human health: including effects during the earthquake itself (e.g.: heart attacks, shocks) and aftermath diseases;
- medical preparedness and rescuers' management procedures: including the possibility to reach assembly points and injured people where they are.

Direct physical damages are one of the most important aspects, because of the possibility to provide prediction about post-earthquake scenarios based on real world event databases (Gizzi et al., 2012; Grünthal, 1998; Solberg et al., 2010). Levels of people risk propose an increasing level of individuals' injury and of probability of serious casualties depending on the buildings damages (Alexander, 2011; Federal Emergency Management Agency and National Institute of Buildings Science, 2003). Hence, the human losses estimation can be expressed in function of buildings vulnerability, earthquake intensity and human occupancy of buildings (Alexander, 2012; Grünthal, 1998). On the other side, the building collapse directly influences the opportunity to evacuate for the occupants (D'Orazio et al., 2014a; Quagliarini et al., 2016), and so both the *presence of trapped people* under debris and the *possibility to participate in the evacuation phase* (Alexander, 2012; Federal Emergency Management Agency and National Institute of Buildings Science, 2003; Georgescu, 1988; Spence et al., 2011). From an operative point of view, a critical value connected to the percentage of collapsed building or to the activation of damage mechanism could be proposed on statistical bases, by distinguishing the different structure typologies and their vulnerability. Future studies should improve knowledge about the impact of similar elements mainly on number of evacuating pedestrians, critical point for rescuers concerning trapped people, and relation with human behaviours (e.g.: attachment to trapped familiars and other injured people (Mawson, 2007; Rao et al., 2011), belongings and home (Prati et al., 2012; Riad et al., 1999); panic conditions (D'Orazio et al., 2014b)).

2.5.2 Built environment-related human behaviours

According to Table 2 definitions, direct interferences on human behaviours due to the built environment modifications are:

- buildings shaking: in indoor, the occupants' perception of the earthquake is influenced by the building response during the earthquake, with a significant impact on whole pre-movement phase in terms of event reaction (*Response to sensible events*) (Akason et al., 2006; D'Orazio et al., 2014b; Mochizuki et al., 1988; Yang et al., 2011);
- ruins and "high buildings" influence: people prefer to activate repulsion phenomena both during motion and path choice (*Fear of buildings*; *Repulsive mechanisms to avoid physical contact*; *Preferred path definitions*; *Safe areas definition*), because they are psychologically perceived as dangerous obstacles (Alexander, 1990; Bernardini et al., 2016; D'Orazio et al., 2014b; Mora et al., 2015);
- presence of visible significant buildings damage, including debris and ruins (more than a grade 3 – substantial to heavy damage in the EMS98 scale (Grünthal, 1998; Musson et al., 2009)): significant ruins along the streets, buildings collapse, and consequent loss of belongings, provoke the activation of particular individuals' choices (*Fear of buildings*; *Panic conditions*; *Preferred path definitions*; *Safe areas definition*), attachment behaviours or pro-social attitudes (*Social attachment*; *Attachment to things, belongings and home*) like in other disasters (Bernardini et al., 2016; D'Orazio et al., 2015; Mawson, 2007; Rao et al., 2011; Riad et al., 1999).

Post-earthquake collapses and ruins also geometrically influence the evacuation procedures and the access to the damaged areas by rescuers during the emergency management procedures because:

- when a building (or a part of a building) implodes, the possibility to evacuate the building itself is decreased, and occupants can be trapped or (Alexander, 2012; Quagliarini et al., 2016; Shapira et al., 2015);
- significant ruins along roads (or damages to the roads network itself) can reduce the evacuation path width or the safe areas dimension, slow down pedestrians' speeds, or even deny the use of the path or of the safe area (Alexander, 1990; Bernardini et al., 2016; D'Orazio et al., 2014a; Federal Emergency Management Agency and National Institute of Buildings Science, 2003; Ferlito and Pizza, 2011; Goretti and Sarli, 2006; Italian technical commission for seismic micro-zoning, 2014; Truong et al., 2013).

Starting from the last damage and geometrical aspects, Table 3 resumes how the post-earthquake scenario evaluation (by introducing the Vulnerability and Damage Assessment Methods (VDAM) for the built environment elements) can be useful for the evaluation of interferences with the human evacuation process and the emergency management. Forecasting damage conditions along streets and defining paths choice criteria in outdoor conditions are two of the most relevant issue in respect to human behaviours.

Analysed element	VDAM	Output	Benefits	Involvement in human behaviours analysis	Application scale
Single building (including critical buildings)	*EM*	damage level (qualitative description)	quick methods, based on typological inquiries and few variables; large scale applications; estimation about partial/total collapsed and "unfit for use" buildings (Grünthal, 1998; Lagomarsino	*Estimation of social losses and casualty rates*; *Presence of trapped people*; *Possibility to participate* (Federal Emergency Management Agency and National Institute of Buildings Science, 2003)	Urban/territorial

			and Giovinazzi, 2006)		
	AM	identification of the possible failure mechanisms (order of activation), description of main variables affecting the damage level (e.g.: floor displacement for RC framed buildings)	more reliable damages estimation versus time-consuming modelling and deep buildings analysis; application to complex elements that are to be classified; identification of possible damages mechanisms and of the building parts unavailable during the evacuation and after the earthquake (Arcidiacono et al., 2015; Preciado, 2015)	*Response to sensible event:* prediction of perceived ground motion inside buildings; *Estimation of social losses and casualty rates*; *Presence of trapped people*; *Possibility to participate in the evacuation phase*: based on possible failure mechanisms; *Preferred path definitions*: possibility to use certain evacuation paths in indoor conditions based on possible failure mechanisms and structural performance of the building (including environment modifications due to secondary risky phenomena such as fire) (Georgescu, 1988)	Single building; buildings complex
Transportation infrastructures (including bridges)	*EM*	damage level (qualitative description) (Federal Emergency Management Agency, 2009a; Grünthal, 1998; Musson et al., 2009)	quick methods, based on typological inquiries and few variables; large scale applications (Federal Emergency Management Agency and National Institute of Buildings Science, 2003)	*Preferred path definitions; Safe areas definition*: possibility to use the infrastructure is damaged in case of large scale evacuations, for: population evacuation (Kunwar et al., 2014; Osaragi et al., 2014; Ye et al., 2011), return to home procedures (Osaragi, 2012)	Urban/territorial
	AM	identification of the possible failure mechanisms (order of activation), damage level, description of main variables affecting the damage level (Jara et al., 2013)	application to complex elements that are hard to be classified or that include different structural and functional features; identification of possible damages mechanisms and damage level (Jara et al., 2013)		Single complex element
Roads network (including infrastructural elements such as bridges, tunnels)	*EM*	level of damages (qualitative description) for each element (whole/part of an evacuation paths/safe areas) by considering the vulnerability of all the facing (and/or interfering) buildings and infrastructures (Caiado et al., 2012; Ferlito and Pizza, 2011)	large scale applications; estimation of rough debris and ruins areas along the evacuation paths (D'Orazio et al., 2014a; Federal Emergency Management Agency and National Institute of Buildings Science, 2003; Quagliarini et al., 2016)	*Repulsive mechanisms to avoid physical contact*; *Fear of buildings*: *Influence of not immediate danger feelings or panic conditions*; *Preferred path definitions*; *Safe areas definition*: determining the level of damages for each network element in order to forecast unavailable/partially available roads for evacuating pedestrians (Caiado et al., 2012; D'Orazio et al., 2014a; Truong et al., 2013) and rescuers' operations (Hashemi and Alesheikh, 2013; Italian technical commission for seismic micro-zoning, 2014)	Urban/territorial scale; single road or square
	AM	Failure mechanism of particular complex elements along the evacuation paths/on the safe areas	application to complex elements that are hard to be classified or placed in critical locations		Single building or element placed in a critical location (e.g.: crossroads, safe areas, assembly points)

Table 3. Vulnerability and Damage Assessment Methods (VDAM) for buildings, roads, and infrastructures: main characteristics

in terms of output evaluations for empirical methods (EM) and analytical methods (AM); retrieved benefits when applying the method; use of VDAM results as input value for human behaviours analysis according to Table 2 (including references) and paragraph 2.3 .

About ruins prevision, qualitative methods are able to provide description of buildings damages in terms of external ruins (Federal Emergency Management Agency, 2009a; Grünthal, 1998; Musson et al., 2009). According to post-earthquake scenarios generation techniques in terms of buildings losses (partial or total collapse, "unfit for use" buildings), these methods have been combined to GIS based software or simulation models (Campos Costa et al., 2009; D'Orazio et al., 2014a; Federal Emergency Management Agency, 2009a; Hashemi and Alesheikh, 2013, 2011; Hori, 2011; Tang and Wen, 2009; Vicente et al., 2010) in order to have a large scale applications. Moreover, the analysis of zenithal and satellite images (V. Baiocchi et al., 2012; Valerio Baiocchi et al., 2012; Quagliarini et al., 2016) confirms that, earthquake intensity being equal, the generated ruins area increases with increasing building vulnerability. Current methodologies allow to estimate the amount of debris in relation to the building typology, the construction materials and the damage level (for both structural and non-structural elements) (Federal Emergency Management Agency and National Institute of Buildings Science, 2003). The application of these experimental-based techniques is strictly limited by USA databases employment. Quick methods should be able to characterize the dimension of ruins and debris areas along the streets: similar results would be essential for both analysing the evacuation phase (D'Orazio et al., 2014a; Hashemi and Alesheikh, 2013) and the emergency procedures management (Italian technical commission for seismic micro-zoning, 2014) in a more efficient and objective way. In this sense, some initial researches have been developed on experimental bases for some buildings typologies (Quagliarini et al., 2016) in order to forecast the ruins depth in function of earthquake magnitude and building vulnerability. Although this allows to move towards a quantitative representation of earthquake features instead of a macroseismic characterization (Grünthal, 1998) also according to paragraph 2.4 , further activities are urgently needed.

Recent studies about evacuation simulation proposed methods for reproducing choices effects (in terms of path and safe areas selections), mainly by considering weights for the streets (usable and blocked) that include several experimental-noticed geometrical and damage criteria (Caiado et al., 2012; D'Orazio et al., 2014a; Hashemi and Alesheikh, 2013; Truong et al., 2013). For example, pedestrians can evaluate a probability of path choices based on visual elements (presence of obstruction and significant visible building damages, width of the path, highness of facing buildings, distance between actual position and safe area, presence of other pedestrians, presence of rescuers along the path) (Quagliarini et al., 2016). These criteria can be also combined with common evacuation behavioural effects, such as the memory effect (Lakoba et al., 2005). In this way, traditional building construction evaluations will be merged to the "behavioural" point of view.

2.6 Cascade effects influence: natural cascading phenomena

Earthquake-induced events are relevant in some scenarios. In fact, human safety during the evacuation phase can be also putted at risk by cascade effects, or rather by other disastrous and dangerous events provoked by the earthquake occurrence (Federal Emergency Management Agency and National Institute of Buildings Science, 2003; Pescaroli and Alexander, 2015). These phenomena can directly damage citizens or threaten their possibility to evacuate or gain safe areas. At territorial scale, main natural cascading phenomena are represented by landslides (Chousianitis et al., 2014), inundation (Federal Emergency Management Agency and National Institute of Buildings Science, 2003) and tsunami (Ishida and Ando, 2014; Ishiguro and Yano, 2015; Lindell et al., 2015; Mäntyniemi, 2012). In particular, a tsunami (as well as an inundation) strongly affects the evacuation possibility for citizens in terms of mortality rate (Ishiguro and Yano, 2015), usable paths, motion speeds (both pedestrians and vehicles) (González-Riancho et al., 2013; Lämmel et al., 2010a) and particular individuals' behaviours (Ishida and Ando, 2014; Lindell et al., 2015), because of man-water and environment-water interactions (e.g.: reduction of evacuation speeds and possibility to survive depending on the water flows (Matsuo et al., 2011)[6]). Additionally, indoor earthquake-induced fires can deny occupants to exit from the building (Georgescu, 1988); urban post-earthquake fires represent an increasing of surrounding risk conditions, and can block some evacuation paths in the urban fabric (Nishino et al., 2012; Osaragi, 2012; Osaragi et al., 2014).

2.7 Organization of behavioural models

In order to sum up human behaviours in earthquake emergency and evacuation, studies proposed models and schemes based on empirical analyses.

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[6] http://www.arr.org.au/wp-content/uploads/2013/Projects/ARR_Project_10_Stage1_report_Final.pdf (last access: 02/02/2016)

A first organizational approach is related to the chronological organization of the disaster phases: this approach allows to describe which are the actions performed by people during the time and so the needed relations with the emergency management procedures (Alexander, 1990; Murakami and Durkin, 1988); then, behavioural flowcharts (Alexander, 1990; D'Orazio et al., 2014b) or 2D graphs (e.g.: time versus space dimension) can be organized (Murakami and Durkin, 1988). These schemes go from seconds (while ground is shaking) to days or months (during the recovery phase).

The second approach is oriented to define theories (and related models) that are able to represent the emergency process (often referring to "*ideal or preferred conditions*") by evidencing "*theoretical links between different variables or relationships in or among groups*" (McEntire, 2004, p. 3). Links between the various factors can be resumed by the theories of social behaviours (Solberg et al., 2008), or by few innovative research works and their implementation on simulation software (D'Orazio et al., 2014a; Osaragi et al., 2014; Shimura and Yamamoto, 2014; Truong et al., 2013). Recently, studies introduced a social modelling approach (Yu, 2009), that allows to trace relations between individuals and surrounding elements (built environment, earthquake features and other pedestrians) (D'Orazio et al., 2014a, 2014b; Quagliarini et al., 2016), for example by using the same agent-based model approach proposed for other disasters representation (Helbing and Bialetti, 2012).

3 Towards a "behavioural design" approach for risk reduction strategies

The Section 2 literature overview on critical factors about human behaviours and related man-environment influences demonstrates that individuals' behaviours interact with the conditions of the surrounding built environment in case of earthquake emergency conditions in urban scenarios.

As also previously evidenced in Section 1 , in the last years, an equivalent approach, based on human behaviours analysis, has been developed for the fire safety field (Borg and Njå, 2013; Kobes et al., 2010). The Fire Safety Engineering (FSE) methodologies and the "psychonomics" approach (Kobes et al., 2010) are based on considering "human" behaviours as fundamental elements for developing risk-reduction strategies. Results of this issue produced: researches on how human behaviours can afflict the safety level, especially during the emergency evacuation (Proulx, 2002); studies about architectural strategies or building components for reducing risk and interferences, and for improving the evacuation phases (D'Orazio et al., 2015; Ran et al., 2014; Tonikian et al., 2006); combined tools for jointly analysing the human behaviours, the fire spreading and the environmental modifications, such as evacuation simulators (Korhonen and Hostikka, 2010; Tang and Ren, 2008; Zheng et al., 2009); international guidelines that explain how to consider the "human" factors while designing risk-reductions interventions on new and existing buildings (BSI, 2004; Confederation of Fire Protection Associations Europe, 2009); national regulations that institute the possibility to use the FSE approach beside the traditional methodologies (Ministry of Interior (Italy), 2015).

Although the importance of "human" factor in earthquake safety was remarked by studies and guidelines dealing with exposure parameter (Villagràn De León, 2006), community resilience (and resistance) (Ainuddin and Routray, 2012; Alexander, 2011; Cutter et al., 2008; Lucini, 2014; Villagràn De León, 2006), comprehensive dissertations and lists of resilience studies including the social science point of view (Lucini, 2014), earthquake safety design methodologies in urban scenarios seem to not effectively include behavioural aspects and human emergency choices as key factors in determining emergency scenarios, possible risk-reduction strategies and emergency management actions (Drabek, 1990; Federal Emergency Management Agency, 2009a, 2009b; Hoetmer and Drabek, 1991; Italian technical commission for seismic micro-zoning, 2014).

3.1 Earthquake safety and man-environment interactions in urban scenarios

To bring earthquake safety policy into line with individuals' behaviour during an earthquake emergency, it is firstly necessary to outline the links between post-earthquake scenarios creations, loss assessment methodologies and definition of risk-reduction strategies. Starting from Equation 1 parameters, Figure 1 offers a critical summary of these aspects, evidences the three main factors that should be considered for improving citizens' safety levels and traces their interplays based on behavioural and disaster analysis according to previous paragraphs:

- the *environment* with modifications due to the earthquake, in terms of built element damages, ruins formation and possibility that certain roads can be obstructed by debris (Anastasiadis and Argyroudis, 2007; Federal Emergency Management Agency and National Institute of Buildings Science, 2003; Foo and Davenport, 2003; Goretti and Sarli, 2006; Quagliarini et al., 2016);

- the *individuals* (that is the damaged population) by including both traditional statistical aspects (fatalities and casualties) (Shapira et al., 2015; Spence et al., 2011) and behaviours while interacting with post-earthquake environment and moving towards safe areas (Alexander, 1990, 1995; Bernardini et al., 2016; D'Orazio et al., 2014b; Yang et al., 2011);
- the *rescuers*' management in disaster conditions, in order to access the urban fabric, to provide help the damaged population, and to have the possibility to reach safe areas effectively used by people (Chen et al., 2012; Italian technical commission for seismic micro-zoning, 2014; Wu et al., 2013).

Man-environment interactions refer to behavioural analysis at paragraphs 2.3 and 2.5 , and also affect human decisions about evacuation paths and safe areas that are chosen by *individuals*. In fact, the use of assembly points and evacuation sites identified by the emergency evacuation plan can be influenced by these behaviours because (Alexander, 1990; Bernardini et al., 2016; D'Orazio et al., 2014b; Tai et al., 2010; Yang et al., 2011): some areas could be not reached by the citizens; they could suffer overcrowding (or under crowding) conditions; some spontaneous safe areas could be shown at the end of motion phases. Hence, *rescuers*' operations should be aimed at providing first aid where people are effectively assembled (Tang and Wen, 2009). Finally, the post-earthquake *environment* and its modifications (e.g.: debris, ruins) impact the possibility to access some urban fabric parts and to use some evacuation routes for the *rescuers* (Goretti and Sarli, 2006).

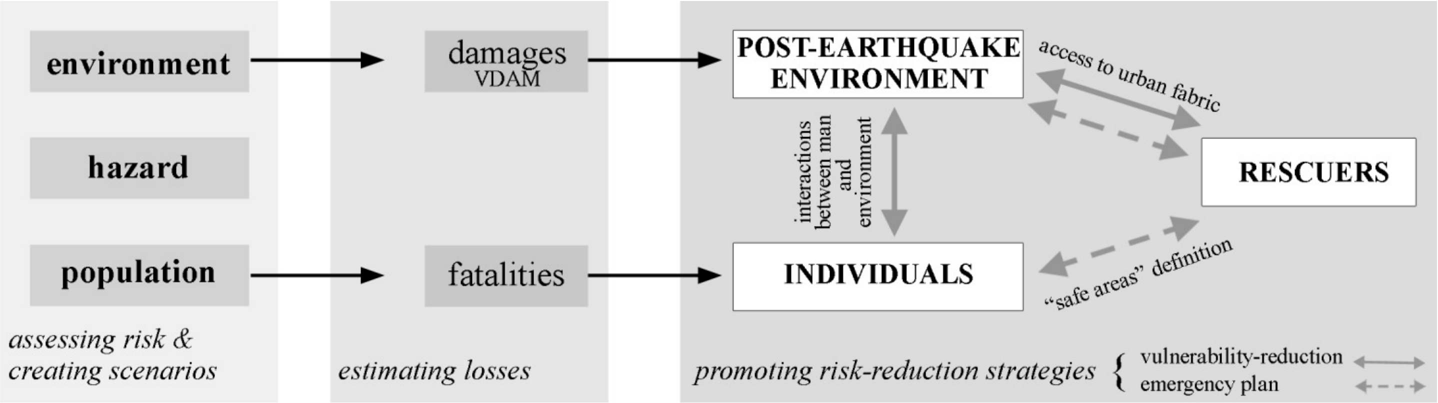

Figure 1. From risk-assessment and scenarios creation techniques to strategies for risk reductions: main factors, intentional aspects and kinds of risk-reduction strategies should be jointly considered while facing earthquakes.

According to the Equation 1 parameter definition (Villagràn De León, 2006), Figure 1 also organizes the main risk-reduction strategies in two main groups. *Vulnerability-reduction strategies* consider physical interventions on existing buildings (e.g.: retrofitting and seismic upgrade (Campos Costa et al., 2009; Roy et al., 2013)) and infrastructures (Zanini et al., 2012)or performance-based design approaches for the new elements (Ghobarah, 2001; Saadat et al., 2014; Wen, 2001) in order to improve the seismic response of the built environment when the earthquake occurs (Foo and Davenport, 2003). This policy could gain the best results because of the direct approach on vulnerable elements and the obtainable reduction of induced damages, physical losses and so casualties, replacement and repairing costs (Campos Costa et al., 2009; Hays et al., 1998). Nevertheless, a wide planned application scale, an organized widespread implementation to buildings and infrastructures are needed so as to reach considerable and effective results and this policy should be sustained by an active public administrations participation (in terms of e.g.: public-private partnerships, tax relief) (Bureau of Urban Development - Tokyo Metropolitan Government, 2010; Hays et al., 1998). *Emergency plan strategies* include the set of operating procedures so as to face the disaster occurrence (Federal Emergency Management Agency, 1996; Hosseini et al., 2009; Tai et al., 2010; Ye et al., 2011)[7]; they are mainly intended for rescuers and local authorities but should actively include citizens' commitment. Emergency procedures and plans at urban scale are part of community safety indicators (Ainuddin and Routray, 2012; Amini Hosseini et al., 2014; Cutter et al., 2008; Hosseini et al., 2009) because they allow citizens to gain safe areas and rescuers to organize the first aid actions. Improving the evacuation phase could mean increasing the level of safety by considering an higher community resistance (Villagràn De León, 2006). For these reasons, an emergency plan has both to address roles, responsibilities, actions and collaborations in the rescuers' team (single organization/more organizations), to identify the emergency and evacuation layout elements (e.g.: routes, evacuation sites, safe areas, recovery areas, emergency

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[7] http://www.protezionecivile.gov.it/jcms/en/piano_emergenza.wp;jsessionid=98D5D9B88684CB013B47087021C46154.worker1?request_locale=en (last access: 10/14/2015)

shelters) and to mark them on a site maps (Ainuddin and Routray, 2012; Federal Emergency Management Agency, 2009b, 1996; Hosseini et al., 2009; Italian technical commission for seismic micro-zoning, 2014; Wright, 2010). Emergency plans are actually limited to considerations about post-earthquake environment, for defining which layout elements can be used in emergency conditions (Hosseini et al., 2009; Wright, 2010). Interferences between built environment elements and evacuation layout (mainly, routes, assembly points and evacuation sites) pointed out by current guidelines can be resumed in terms of: rough geometric aspects (e.g.: ratio between outdoor spaces dimensions and facing buildings heights (Italian technical commission for seismic micro-zoning, 2014); distance of refuge places from buildings (Sapountzaki, 2002)); avoiding (or limiting) secondary hazards and cascade effects (Federal Emergency Management Agency, 1996; Italian technical commission for seismic micro-zoning, 2014) (including earthquake-induced fire spread at urban scale (Bureau of Urban Development - Tokyo Metropolitan Government, 2010)); estimating post-earthquake debris quantities (Federal Emergency Management Agency and National Institute of Buildings Science, 2003); recommended distances between adjacent assembly points (Sapountzaki, 2002). The emergency plan definition denotes many problems while facing with historical city centres (Gavarini, 2001; Mishima et al., 2014; Miyamoto et al., 2011), high population density and wide urban areas (Bureau of Urban Development - Tokyo Metropolitan Government, 2010; Shimura and Yamamoto, 2014; Tai et al., 2010), because of public spaces configurations, complexity conditions in relation to the inhabitants' number, and the impossibility to modify the urban fabric. Nevertheless, the emergency plans effectiveness could be limited because they do not contemplate behavioural aspects in an earthquake, as also underlined by Figure 1. In fact, individuals could adopt particular decisions during the pre-movement and the motion phase (evacuation path, target and selected safe area) that could lead them in dangerous conditions (e.g.: running away from buildings without performing drop-cover-hold procedures in case of panic conditions (Alexander, 1990, 1995; D'Orazio et al., 2014b); choosing vulnerable or damaged paths and then arriving in blocked streets (Goretti and Sarli, 2006; Hashemi and Alesheikh, 2013; Quagliarini et al., 2016; Truong et al., 2013); choosing overcrowded paths and risking bottlenecks effects for both pedestrians and vehicles (Bernardini et al., 2016; Petruccelli, 2003)) or drive them away from prepared first aid areas in the urban fabric (the ones addressed by the plan).

3.2 Models for earthquake evacuation simulations

Simulation models for earthquake evacuation can be able to evaluate probable man-environment interactions and human choices in emergency conditions. Resulting analyses allow tracing reliable bases for developing earthquake risk-reduction strategies. Two main simulations models can be considered according to the scenario creation factors in Figure 1.

Models for losses estimations are able to estimate built environment damages (VDAM) and human casualties. These models are respectively based on studies discussed at paragraph 2.5 and are characterized by:

- adopting a statistical approach about buildings suffering a certain damage level and number of fatalities (e.g.: by offering percentage values for the analysed sample);
- possible applications at both urban or territorial scales;
- related results reliability generally depends on the knowledge level about hazard and vulnerability in the different parts of the analysed territory.

Models and evaluation procedures have been combined with GIS-based software and databases in order to obtain easy-to-use tools (Campos Costa et al., 2009; Hashemi and Alesheikh, 2010; Hori, 2011; Huang et al., 2009; Tang and Wen, 2009; Vicente et al., 2010).

Models for simulating human behaviours and motion in both normal and evacuation conditions was provided by literature works (D'Orazio et al., 2014a; Helbing and Johansson, 2010; Lakoba et al., 2005; Ronchi and Nilsson, 2013; Shiwakoti et al., 2008b; Zheng et al., 2009). Table 4 resumes characterizing factors about main pedestrians' evacuation simulation modelling approaches (according to previous (Kuligowski and Peacock, 2005; Schadschneider et al., 2009; Shiwakoti et al., 2008b)): relevant issues concerning man-environment interactions and application pros and cons are stressed.

	Macroscopic approaches	**Microscopic approaches**		
	Hydrodynamics approach	**Cellular automata**	**Social force model**	**Agent based model (ABM)**
Individual's representation	As a liquid that moves along pipes	As elements interacting with the surrounding conditions; different individuals' types can be engaged (D'Orazio et al., 2014a; Helbing and Bialetti, 2012; Helbing and Johansson, 2010; Korhonen and Hostikka, 2010)		
Environment representation	As a pipe (length; section width)	Grid cells (spatial 2D discrete representation with obstacles and paths) with different	Continuous space (2D or 3D) and time representations (Helbing and Johansson, 2010;	Environment can be directly described as an agent (D'Orazio et al., 2014a; Quagliarini et al.,

		selectable geometries and dimensions	Lakoba et al., 2005); combined models can adopt discrete 2D representation (D'Orazio et al., 2014a)	2016); different spatial description are allowed
Ruins, debris, other post-earthquake interfering elements or conditions	Changes in pipe section width or in motion speed for the whole group of individuals	Discrete ruins representation through occupied grid cells; changes in local speeds value by modifying the motion algorithms connected to some cells	Possible geometrical continuous descriptions of earthquake-induced obstacle (D'Orazio et al., 2014a); changes in local speed values for the single pedestrian (during the time; based on his/her position)	Modification rules can be assigned to different built environment elements (or related types); interactions between agents are able to represent behavioural evacuation rules (D'Orazio et al., 2014b)
Motion rules including evacuation target and path choice including	Mainly channelled motion towards a certain fixed target; use of speed-density or flow-density relations (Seyfried et al., 2005)	Local choices and motion behaviours can be assigned by cells rules; possible simplified motion law according to modified queuing models (Lämmel et al., 2008)	Motion rules and path choice criteria (D'Orazio et al., 2014a; Lakoba et al., 2005) can be given to each individuals or each individuals' type	The motion law is directly assigned to each single agent or individuals' type; different microscopic approaches can be combined in order to describe evacuation rules (Helbing and Bialetti, 2012)
Main pros	Possible real-time applications (Pu and Zlatanova, 2005); quick approach; large scale application (Kunwar et al., 2014; Lämmel et al., 2010a); direct correlation with level of service (LOS) (Fruin, 1971)	Behavioural aspects included and individuals' choices allowed; combination with other microscopic approaches (Zheng et al., 2009); application also urban scales, high number of simulated individuals, long-lasting evacuation time	Continuous spatial (and, ideally, time) description allows accurate analysis; many pedestrians' types can be characterized; direct inclusion of other man-environment interactions (e.g.: man-wayfinding elements (Nassar and Al-Kaisy, 2008)) in the motion law (Helbing and Johansson, 2010)	Interactions and individuals' choices included; complex behavioural rules can be combined to a simple motion law; different motion law can be combined to the same ABM architecture (Di Mauro et al., 2013; Lämmel et al., 2010a)
Main cons	Limited ability in case of heterogeneous population, counterflow, complex behaviours (Lämmel et al., 2010b)	Discrete representation of motion in space and time can imply not accurate results (especially in local evaluations); psychological factors in human behaviours and related behavioural phenomena are difficult to be described (Pelechano and Malkawi, 2008); only quantitative analyses are allowed (Hori, 2011)	Time-consuming techniques; KISS principle in software modelling ("KISS - The Kiss (Keep it simple stupid) principle," 2003) (especially if combined with ABM) versus too high complexity level for human behaviour representation	KISS principle in software modelling ("KISS - The Kiss (Keep it simple stupid) principle," 2003) versus too high complexity level for human behaviour representation

Table 4. Main modelling approaches for simulating pedestrians' motion in evacuations by considering main human behavioural aspects and environment characterization.

Previous works analysed modelling approaches and related software that can be also used for earthquake evacuation simulation, especially in indoor conditions, but they are mostly developed in order to analyse fire event or indistinct evacuation without environmental modifications (Gwynne et al., 1999; Kuligowski and Peacock, 2005; Pelechano and Malkawi, 2008; Zheng et al., 2009). While many fire evacuation simulators are available, only few works about earthquake evacuation simulations have been developed during the last years. Table 5 compares the main available pedestrians' evacuation simulation models (with related software implementation) by distinguishing each of them according to Table 4 classification and main simulator characteristics. Table 5 consists of pedestrians' evacuation simulators because moving on foot represents the first way to face an earthquake emergency and to gain the nearest evacuation places (Alexander, 1990; Bernardini et al., 2016; Quagliarini et al., 2016), especially in case of compact urban fabric (Gavarini, 2001), high population density areas, considerable damage levels along roads (impossibility to use vehicles), according to Section 2 behavioural analyses results. Moreover, Table 5 also includes recent software tools for evacuation planning at urban scale.

The majority of simulators denotes applications to case studies in order to demonstrate their capabilities and comparing different evacuation strategies and urban scenarios by varying human behaviours (mainly, evacuation choices) and rescuers' organizations (mainly, identification of safe areas) (Beck et al., 2014; Di Mauro et al., 2013; Kunwar et al., 2014; Lämmel et al., 2010a; Tai et al., 2010; Ye et al., 2011). The application of the same model (by including different interaction conditions) to a large number of cities allowed to compare urban fabrics safety levels (Kunwar et al., 2014). In addition, some models offer guidelines for scenarios definitions in terms of population, urban fabric and evacuation sites characterization by elaborating local administration and Civil Defence information and by taking advantages of GIS integration (Di Mauro et al., 2013; Shimura and Yamamoto, 2014).

ABM-based models are able to simulate different evacuation agents, individuals' choice and interaction rules.

Firstly, by considering earthquakes from a territorial point of view, large scale evacuation transportation models assume a fundamental rule (Hu et al., 2014; Murray-Tuite and Wolshon, 2013). A similar concept has been applied at urban scale (Petruccelli, 2003; Tang et al., 2012); in this case, some simulators incorporate private vehicles (Di Mauro et al., 2013; Lämmel et al., 2010a)and public transport (Osaragi et al., 2014) effects on pedestrians' evacuation (e.g.: traffic flow congestion; enhancement in gaining farther evacuation places).

Secondly, a limited number of works includes buildings damages influences in the scenarios (Beck et al., 2014; D'Orazio et al., 2014a; Osaragi et al., 2014; Shimura and Yamamoto, 2014; Truong et al., 2013)by focusing the attention on: damages previsions; ruins formation in the scenario; man-environment interactions in terms of motion rules (e.g.: repulsion from obstacles) and evacuation path choice. On the contrary, many simulators accept no damage levels in case of low intensity earthquakes (Ye et al., 2011) in order to reduce the scenario complexity. The ruins depth estimation is rarely performed (D'Orazio et al., 2014a; Quagliarini et al., 2016; Shimura and Yamamoto, 2014), although debris dimensions strongly influence human evacuations according to paragraphs 2.5 . Debris and blocked streets can be introduced as a reference element for rescuers' actions (e.g.: street-openers that remove debris) (Hashemi and Alesheikh, 2013). Besides, secondary hazard previsions (Osaragi, 2012; Osaragi et al., 2014; Shimura and Yamamoto, 2014) allows to have quantitative evaluations for evacuation plan strategies (Bureau of Urban Development - Tokyo Metropolitan Government, 2010; Federal Emergency Management Agency, 1996; Italian technical commission for seismic micro-zoning, 2014; Nishino et al., 2012; Wright, 2010). Both these two aspects should be taken into account while dealing with: risk interferences, number of autonomous evacuating pedestrians, rescuers' actions strategies for aiding trapped or injured people, spreading of risk and exposure during the time (e.g.: some safe areas could be temporarily affected by other hazards).

Thirdly, some relevant issues about interactions during the evacuation phases organization have been considered. Models introduced rescuers as independent agents that are able to move in the scenario, provide guidance to evacuating pedestrians (Okaya and Takahashi, 2015, 2013, 2011) or interact with environmental elements (e.g.: street-openers)(Hashemi and Alesheikh, 2013). About evacuation rules, single-stage (people directly move towards the final evacuation place) and two-stage processes (people firstly move towards a temporary gathering place and then towards to large area evacuation sites) (Shimura and Yamamoto, 2014) can be simulated. In this sense, two-stage procedures can represent the prevalent rescuers' approach in evacuation site planning with distinction between assembly points, areas in which first aid can be effectively provided, and shelters areas (Bureau of Urban Development - Tokyo Metropolitan Government, 2010; Federal Emergency Management Agency, 1996; Hosseini et al., 2009; Italian technical commission for seismic micro-zoning, 2014). Furthermore, some other significant behavioural phenomena in *safe area reaching* phase are simulated: people can spontaneously gather around significant urban fabric areas (Tai et al., 2010) and also stop their evacuation without gaining an evacuation places (D'Orazio et al., 2014a; Truong et al., 2013)because of environmental surrounding conditions (e.g.: blocked streets; moving around the same zone) or social attachment phenomena (Alexander, 1990; D'Orazio et al., 2014b; Mawson, 2007). Evacuation path choices (where to go, which are preferred roads) can be also described through a statistical approach based on real world questionnaires response, so as to obtain simplified results for plan analysis tools (Mishima et al., 2014; Okaya and Takahashi, 2013; Tai et al., 2010).

Simulation models and emergency evacuation plan analysis tools take into account Citizens' return home travels (Osaragi, 2012; Osaragi et al., 2014), consider effects due to attachment to belongings and home phenomena, according to experimental behavioural results (Prati et al., 2012).

About pedestrians' motion law, the majority of models adopts a speed-density (or flow-density) approach. ABM allows to modify the individuals' speed with particular decisional rules in connection to near obstacles or pedestrians' desires (e.g.: passing with or without changing direction and speed; stopping) (Hori, 2011). The speed-density relationship representation is generally simplified by adopting common bi-linear (Kunwar et al., 2014) (or tri-linear (Osaragi, 2012)) diagrams or queue models (Lämmel et al., 2010a), with maximum pedestrians density limitations. In particular, speed trends and values are generally the same of normal motion conditions. Recent works about earthquake evacuation fundamental diagram (Bernardini et al., 2016) and average motion speed values (Bernardini et al., 2016; D'Orazio et al., 2014b; Hori, 2011) reject this choice: these simulators could overestimate the process duration especially during the first phases, when people leave buildings and experimental speeds seem to be 1.5 (Bernardini et al., 2016; D'Orazio et al., 2014b) to 3 times (Hori, 2011) higher than the normal motion ones. Finally, although some models use experimental motion quantities as input for pedestrians' parameters (D'Orazio et al., 2014a; Hori, 2011; Li et al., 2015), validation tests have been performed for very few simulators (D'Orazio et al., 2014a; Li et al., 2015). However, existing validation guidelines for pedestrians' evacuation simulators (Ronchi and Nilsson, 2013; Shiwakoti et al., 2008b)would be applied in order to assess software results correctness (e.g.: application of standard scenarios for comparing different simulators output). Otherwise, approaches based on the "Microscopic dynamics of pedestrian evacuation" (Parisi and Dorso, 2005; Zheng et al., 2009)could adopt a rough validation by considering their implicit "Lagrangian" methodology (Parisi and Dorso, 2005; Rabiaa and Foudil, 2010; Ronchi and Nilsson, 2013): "*interactions between agents produce phenomena and quantitative values that are comparable with the experimental ones for the whole system*" (D'Orazio et al., 2014a, p. 155). Because of differences between real life scenarios and evacuation trials (Yang et al., 2011), data about real world events would be preferred for software validations. For this reason, although recent studies provided significant databases of real world earthquake evacuations (Bernardini et al., 2016), current experimental analyses results should be soon additionally enriched.

Model	**Space representation**	**Scale**	**Buildings damages and secondary hazards**	**Software integration**	**Path choice and evacuation criteria**	**Use of experimental data for input set-up, validation, comparative analyses**
ABM (combined with speed-density or flow-density relations)						
(Kunwar et al., 2014)	Road network (nodes+lines)	Urban	No	Open Street Maps (OSM)	Simulations with different choice criteria	-
(Lämmel et al., 2010a)	Road network (nodes+lines)	Urban	Tsunami inundation	GIS	Simulations with different choice criteria (Nash; shortest path)	-
(Hori, 2011)	Road network + 2D	Urban, single building (indoor)	No	GIS; CAD	Moving along the walls (no safe area/exits information; people can go back in case of dead end corridors)	Individual's speed values distribution (average, standard deviation) from real earthquake case study analysis
(Osaragi, 2012; Osaragi et al., 2014)	Road network (nodes+lines)	Urban	Only street blockage (based on earthquake intensity and buildings height); fire risk	-	Shortest path algorithm (to final safe area or next roads intersection) and additional safety costs for street blockage and paths with fire risk; two-stages evacuation and return home travel allowed	-
(Beck et al., 2014; Truong et al., 2013)	Road network (nodes+lines)	Urban	Only street blockage (based on earthquake intensity); obstacles (blocking a street) modelled as an agent	GIS	Blocked street avoidance after agent encounters the obstacle; leader effect in path choice; agent could not reach a safe area	Evacuation behaviours defined by questionnaires results
(Shimura and Yamamoto, 2014)	Road network (nodes+lines)	Urban	Ruins depth (building floor number and average height); fire risk	GIS	Pareto ranking methods (path cost based on: total evacuation distance, fire risk level, probability to reach a safe area, total evacuation time); single-stage or two-stage evacuation organization	-
(Di Mauro et al., 2013)	Road network (nodes+lines)	Urban	Tsunami inundation	OSM + GIS	Shortest path algorithm with different usable infrastructural elements(e.g.: bridges)	Comparisons with previous results of (Lämmel et al., 2010a)
Social force model						
(Li et al., 2015)	2D (continuous)	Single building (indoor)	No	-	Exit door choice (one or two doors; route capacity and route distance)	Calibration of social force model parameters for the indoor earthquake evacuation
Social force model + ABM						
(D'Orazio et al., 2014a)	2D (discrete)	Urban	Ruins depth (earthquake intensity, building height and vulnerability)	-	Path choice probability (ruins area, geometry, presence of other evacuating pedestrians, distance to safe area); agent	Individuals' speed values from literature works and experimental results (D'Orazio et al., 2014b);

					could not reach a safe area	qualitative and quantitative validation by comparing simulator and experimental results
(Okaya and Takahashi, 2015, 2013, 2011)	2D	Urban, single building (indoor)	Study conditions clearly exclude damages	3D CAD (building); RoboCup platform[8]	Path choice according to questionnaires results (indoor); evacuation guidance (leader effect) by rescuers (outdoor)	-
Evacuation planning and behavioural analyses						
(Ye et al., 2011)	Road network (nodes+lines)	Urban	Study conditions clearly exclude damages	GIS	Known safe areas and shortest path algorithm	-
(Hashemi and Alesheikh, 2013)	Road network (nodes+lines)	Urban	Street blockage (removable debris)	GIS	Random choice (within a distance of 5m) by avoiding blocked streets; optional memory effect in order to avoid previously experienced roads	-
(Tai et al., 2010)	Road network (nodes+lines)	Urban	No	GIS	Statistical choice of the final shelter; spontaneous significant clustering areas in the urban fabric	-

Table 5. Comparison between the main available earthquake pedestrians' evacuation simulators.

3.3 Merging existing paradigms and the "behavioural design" approach

Existing paradigms of earthquake safety in urban scenarios mainly focus on building construction and rescuers' management.

Actual building design approaches (including vulnerability-reduction interventions) are generally characterized by a sort of architectural determinism (Marmot, 2002): it is supposed that the architectural space configuration and the adopted design strategies are able to directly induce individuals' behavioural uses. According to this point of view, interventions on buildings (e.g.: enhancing the seismic response; positioning evacuation signs along paths) could be enough for reducing people risk. At the same time, it can be generally considered how: the majority of citizens would know the emergency plan procedures; each individual would apply them in emergency conditions; individuals would gain the organized evacuation sites by plan roads; rescuers would be able to effectively manage pedestrians' motion and behaviours. The same concept is generally adopted by existing paradigms of fire safety (Kobes et al., 2010) when introducing dimensional requirements (width, length and number) for evacuation paths and exits.

While this approach seems to exclude behavioural aspects or at least underestimate them, experimental studies demonstrate how the interplays shown by Figure 1 play a leading role in emergency conditions. For this reason, a "behavioural design" approach should be spread. The proposed approach can be easily characterized by adapting the architectural space depending on human behaviours. In particular, interventions on the building heritage will be proposed where they are effectively needed and by considering their effects on users (in this case, citizens in emergency conditions). This issue is considerably significant while dealing with historical heritage and individuals' safety, because of preservation criteria for historic buildings, urban scenarios features and surrounding built environment safety conditions. The application of "behavioural design" methodologies will take advantages of both traditional evaluations (vulnerability and hazard analysis, scenario creations) and innovative tools such as evacuation simulators. Simulators results are able to describe possible pedestrians' behaviours and choices in emergency conditions and so to evidence crucial phenomena for inhabitants' safety in the urban fabric, according to the interplays shown by Figure 1. For this reason, they could be used in order to propose vulnerability-reduction interventions on "hot-spots" in the urban fabric (e.g.: buildings or infrastructures along paths with high pedestrians' or vehicles flows; buildings facing safe areas used by citizens), and to develop emergency plan strategies. Table 6 resumes traditional "behavioural design"-oriented paradigms and methodologies and tries to provide their possible combination: the final proposed merged strategies

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[8] http://www.robocuprescue.org/agentsim.html (last access: 22/10/2015)

should be able to jointly consider building constructions, rescuers' management and human behaviours. An helpful example for defining these results would be given by the recent development of fire safety engineering methodologies (Borg and Njå, 2013; Kobes et al., 2010; Korhonen and Hostikka, 2010).

Figure 2 adopts the traditional PDCA (plan–do–check–act) cycle[9] approach for earthquake risk (Kubo et al., 2011; Tang et al., 2012; Yoko and Norio, 2006)and includes “behavioural design” elements and evaluations in risk-reduction strategies definition.

The scenario is described by input concerning built environment, human presences during time and possible human behaviours: a statistical point of view, such as the one offered by Monte Carlo simulation (Goretti and Sarli, 2006; Hori, 2011; Nishino et al., 2012), should be preferred. Generated scenarios are analysed according to both traditional VDAM and innovative human evacuation simulators. A significant series of simulations (Korhonen and Hostikka, 2010) could be carried out in order to understand how people behave in relation to the possible environmental damage scenarios. Also according aforementioned fire safety researches, output variables could be analysed in order to evaluate the impact of evacuation interactions, such as evacuation time, chosen paths, pedestrians’ flow rate at the safe areas or along certain paths.

Quantitative and qualitative results could be evaluated at both overall urban fabric and single “hot-spot” scales: localizing emerging issues (e.g.: critical phenomena in evacuation) would be able to propose risk-disaster strategies within the city map and the emergency plan layout. “Risk maps” would combine evaluations related to traditional parameters and results of human behaviours simulators, such as by overlapping maps about building vulnerability and about inhabitants' density and positions. Non-pedestrians evacuation (rescuers vehicles, private cars and other means of transportation) should be considered (Lämmel et al., 2010a; Osaragi et al., 2014). According to Table 6 outlines, proposed interventions would be based on improving post-environment conditions in urban fabric “hot-spots” through direct building construction methods or avoiding wrong evacuation choices (e.g.: hesitating in dangerous areas, spending time in time-wasting behaviours) for pedestrians (especially the most vulnerable ones) through guidance systems (rescuers, evacuation leaders, wayfinding sign) (D’Orazio et al., 2014a). Fire evacuation criteria are based on the minimization of evacuation time (Proulx, 2002): people have to gain safe assembly points in the shortest time because of the fire spreading risks during the time. Earthquake evacuation criteria should generally include a minimum-risk principle because of the features of this “instantaneous event”: after the earthquake, people mainly interact with a quite static modified environment and have to firstly avoid secondary hazards. Obviously, in case of earthquake-induced phenomena such as fire (Nishino et al., 2012; Osaragi et al., 2014) or tsunami (Di Mauro et al., 2013; Ishida and Ando, 2014; Lämmel et al., 2010a; Lindell et al., 2015; Mas et al., 2013), the time minimization criterion is a relevant issue.

Finally, proposed strategies should be tested again by using simulation tools in order to evaluate their possible effectiveness and compare different strategies outcomes: the scenarios analysis outputs would be used for comparisons. Inputs, outputs and final risk-reduction aims have to be shared between public local administrations, Civil Defence organizations, town planning managers, architectural and safety designers and population.

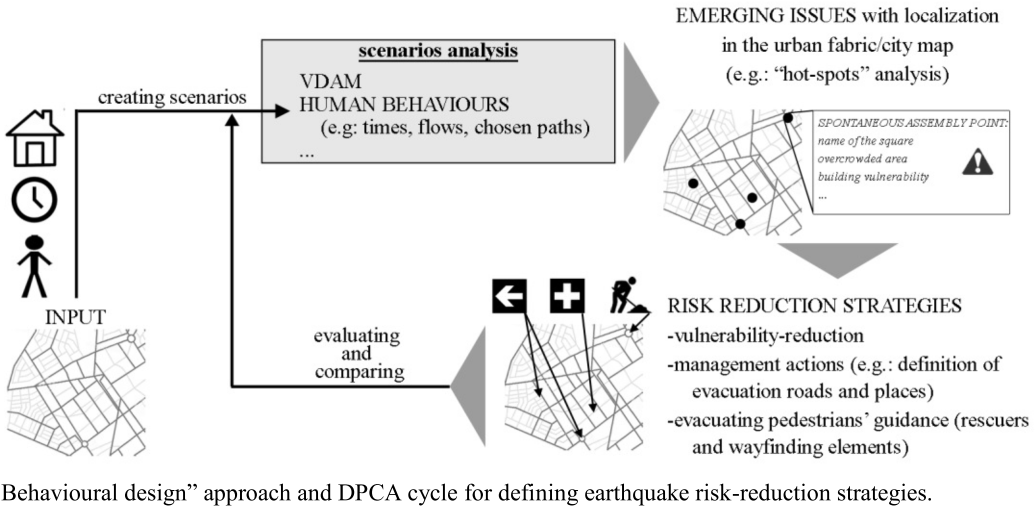

Figure 2. “Behavioural design” approach and DPCA cycle for defining earthquake risk-reduction strategies.

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[9] Or rather, the so called Deming’s cycle (https://www.deming.org/theman/theories/pdsacycle ; last access: 02/02/2016)

	Paradigms		**Merged strategies**
Main urban fabric elements	**Traditional**	**“Behavioural design”-oriented**	
Buildings and critical infrastructures	Hazard estimations Building use in case of critical buildings and infrastructures (e.g.: hospitals) Human fatalities (exposure) Economical losses VDAM Earthquake-induced fire risk	Estimation of occupants that can exit the building Pedestrians' flows near the buildings during the time “Hot-spots” due to building-man interferences (e.g.: high damaged buildings near overcrowded paths or areas)	Vulnerability-reduction in order to: reduce human losses; allow people to exit the building; allow business continuity (especially for critical buildings and infrastructures); avoid significant damages in overcrowded parts of the urban fabric
Transportation infrastructures (including bridges)	Hazard estimations VDAM	Sorted pedestrians' flows Pedestrians' and/or vehicles flows during the time “Hot-spots” due to overcrowded elements	Vulnerability-reduction for business continuity Territorial scale evacuation management and return home procedures
Road networks as evacuation paths	Hazard estimations VDAM of facing built elements Possible blocked paths and debris estimation for rescuers and street-openers Roads with secondary hazards interferences	Pedestrians' and/or vehicles flows during the time “Hot-spots” due to evacuation process: bottlenecks due to critical evacuating pedestrians' flows; pedestrians-vehicles interferences; flows at paths intersections (same directions of counterflow); probable choice of roads affected by secondary hazards	Evaluation of main emergency plan evacuation roads and places based on: probable use by pedestrians (people should be aided where they mainly move and arrive), probable damage level (buildings and infrastructural elements), secondary hazard interferences; adopting the minimum-vulnerability principle in case of more than one similar choice Vulnerability-reduction of built elements along the main evacuation roads Management procedures (plans and emergency actions) for avoiding pedestrians' flow overcrowding especially in vulnerable areas; adopting emergency plan communication strategies or evacuation guidance facilities (e.g.: evacuation signs) Identification of possible main points for rescuers' localization in order to: guide the evacuating pedestrians towards evacuation roads and places; provide first aid to the population if possible where they spontaneously gather or provide a two-stage evacuation guided by rescuers
Evacuation places (assembly points, evacuation sites, shelters)	Hazard estimations VDAM for shelters and other built evacuation sites Geometrical areas of places and maximum allowed pedestrians' density Debris estimation for forecasting probable usable (clean of ruins) areas Places with secondary hazards interferences	Estimation of pedestrians' gaining the evacuation place and final related pedestrians' density Probable spontaneous assembly points “Hot-spots” due to evacuation process: overcrowded areas; spontaneous assembly points affected by secondary hazards	

Table 6. Combining traditional and “behavioural design” oriented paradigms and analysis would produce more effective strategies for facing the earthquake risk at urban scale.

4 Conclusions

Current methodologies for earthquake risk assessment and definition of risk-reductions strategies widely overlook the presence of individuals in the scenario and their response in case of emergency. For this reason, understanding human behaviours in an earthquake emergency and during the following evacuation is essential in order to provide appropriate policy measures for disaster risk-reduction, especially in complex urban scenarios. This work attempts to organize human behavioural aspects by focusing the attention on interplays between the individuals and built environment elements. Finally, the use of simulation model for representing human behaviours in emergency are analysed and a new combined methodology for earthquake safety at urban scale is offered.

Although the number of behavioural studies is growing, current knowledge about human behaviours in earthquake should be deepened through the analysis of real earthquake evacuation phenomena, including the effective influences of geographical and cultural background on emergency behaviours. However, current works offer a significant overview and allow defining bases for behavioural models simulations. Future simulation tools should widely take advantages of these studies for their development and validations.

Finally, a new “behavioural design” approach to earthquake safety is proposed. The approach is founded on the combination between the existing tools and methods and the application of behavioural studies and simulators. Starting from current results and gaps in earthquake individuals’ safety design, this work is one of the first attempts to introduce human behaviours within earthquake safety while dealing with risk reduction strategies, by adopting a comprehensive and systematic method. Hence, this paper focuses on the theoretical bases of this new “behavioural” approach. Some examples of implicit “behavioural design” in earthquake evacuation and risk analyses involves are provided by the application of some simulators for earthquake scenarios description and human evacuation behaviours representation. Nevertheless, they could be improved by taking into account of this paper outcomes, with the purpose to develop operative design tools and methodologies. The following required steps are surely represented by real world applications in order to demonstrate the full effectiveness of a similar methods.

The final aim of “behavioural design” approach tools and methods will be the reduction of interferences between the built environment and the “human” process. Tools previsions would be used during the earthquake safety planning in order to evaluate operative strategies concerning both operational aspects (e.g.: the definition of more suitable evacuation plans, first aid management), building construction (e.g.: interventions concerning urban planning and building vulnerabilities) and building components (e.g.: urban wayfinding systems). The “behavioural design” methodology could be used in case of interventions on the existing town and the project of new city parts.

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