UNIVERSITÀ POLITECNICA DELLE MARCHE
Scuola di Dottorato di Ricerca in Scienze dell'Ingegneria
Curriculum in Ingegneria Civile Ambientale Edile Architettura

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A behavioural approach to the earthquake safety planning of historical centres

Development of innovative methodologies and tools for planners and evacuees

Ph.D. Dissertation of:
Silvia Santarelli

Advisor:
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XVII edition – new series

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Civitanova Marche, May 2019

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Abstract

When an earthquake occurs, the survivors start to evacuate. Especially in historical centres, their safety during the evacuation is strictly connected to the surrounding damaged built environment. In fact, several factors as the high vulnerability of the built heritage, the compact urban fabric and the complex urban paths network, can increase the evacuees' difficulty to locate safe zones and moving toward them. Furthermore, the people's scarce familiarity with the place, with the emergency plan and with the evacuation paths to follow, drastically raise the probability they can be involved into fatalities while trying to get themselves safe.

In the last decades, studies and regulations about the risk evaluation, the emergency planning and the evacuation management had a large development, also producing engineering methods and advanced models, but they have been focused especially on fire emergency and the indoor environments. Only recently, specific studies and guidelines for the assessing, planning and management of the earthquake emergency in urban scenarios have been produced. However, such tools are quite simplified approaches, mainly aimed to prepare and coordinate the emergency rescuers' operations, without effectively supporting survivors during their evacuation immediately after the shake. In a such context, the capacity to autonomously move into the post-earthquake build scenario and gain safe place, also called 'self-help', is the main resource evacuees' can carry out.

Although the regulation guidelines and the self-help can be valuable resources for the emergency evacuation in the most of urban centres, in historical centres they often cannot be adopted because of the spread criticalities characterizing their application in those scenarios. In fact, as demonstrates by the latest Italian earthquakes of 2016, many people for several and different reasons decide to stop their evacuation in temporary occasional shelters, waiting there the rescuers' aids.

The current work starts from the analyses of the consolidated methods and tools for risk reduction in both indoor and outdoor environments. Then, new methodologies for the urban emergency planning and the post-earthquake evacuation management in the historical centres are proposed. A performance-based approach is adopted to evaluate the criticalities deriving from the men-environment interaction in post-earthquake historical scenarios and to offer possible solution to such aspects. To this aim, several fields of study are individuated (i.e.: buildings and paths vulnerability, the preventive evaluation of post-earthquake damage scenarios and the related effects on the evacuation process; the evacuees' emergency wayfinding) and novel methodologies and tools are offered where necessaries. The

proposed methodologies are applied to a real case study and tested using an internationally validated behavioural simulation software specialized for the earthquake urban emergency. Key Performance Indicators (KPIs) are adopted to quantify the evacuation performances and evaluate the effectiveness of the proposed planning and guidance methodologies.

The adoption of the proposed studies in combination with traditional methodologies and tools could be useful to help emergency planners during the analyses and designing phases. Furthermore, this could represent a considerable practice for the optimization of the emergency measures, in case of limited resources/possibilities, or in case of scenarios with relevant constrains as the historical ones.

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Chapter I

1 Introduction

1.1 Earthquake risk and the historical centres

The safety conditions for survivors during the earthquake evacuation, as the presence of fatalities on the path, the possibility to gain safe area or to be reached by rescuers, need to be estimated either for indoor and outdoor built scenarios. The evacuees' safety during the evacuation and the relative path choice are strongly influenced by the earthquake effects because of dynamic man-environment relationships in emergencies (Bernardini, D'Orazio, and Quagliarini 2016). Particularly, historical urban centres denote a high interference level between the old building heritage, the urban fabric and the present population (including tourists who can be unfamiliar with the environment). In fact, many problems occur during the evacuation phases mainly because of interactions between human process and environmental factors (hazard, building heritage vulnerability and following damages) (Gavarini 2001; Indirli et al. 2013).

Italian Civil Protection statistics highlight that up to the 25% of fatalities affecting evacuees are due to the possibility of safely evacuate, to move along the safe paths and to gain assembly points[1]. These because in urban environment, changes to the built heritage caused by the earthquake (such as damage to buildings and the relative debris produced) seriously interfere with the safety of people, triggering potentially fatal interactions. People who have died or become trapped in buildings are direct consequences of the collapses generated (Shapira et al. 2015). However, even during the urban evacuation following the quake, critical interferences can be generated between people and the post-earthquake environment, such as to reduce the chances for survivors to reach a safe area and be rescued (D'Orazio et al. 2014). Dangerous interactions can be emphasized by the presence of factors such as unfamiliarity with the place and emergency procedures, as well as by the effects on the building induced by the earthquake (eg: rubbles, fires, landslides). This is more true for historical centres, because of their criticalities as the compact and complex conformation of the urban fabric

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

and the high vulnerability of historical buildings (Gavarini 2001). The relevance of the produced interferences, due to these elements, during the evacuation phase immediately after an earthquake has been highlighted by the series of seismic events of January 2017. For this reason, to understand these interactions and to assess possible interferences are indispensable processes, on which the safety assessment should be based, especially in the emergency planning phase.

In fact, the planning phase plays a central role for risk mitigation since it is the simplest and largely adopted way to improve of the resilience of the urban system as ensemble of physical elements, functions and human activities) (Hart et al. 2019; Sharifi 2019). Current planning tools for the earthquake emergency in urban scenarios do not take these interactions into account, and suggest simplified models to adopt for the mitigation of seismic risk (Italian technical commission for seismic microzonation 2014). On the contrary, steps forward to consider human behaviour have been made in fire engineering (Fire Safety Engineering - FSE) (Ministero dell'Interno 2015), also in the field of historical buildings. The FSE has recently introduced methods for the joint human-environment analysis of safety levels, and therefore for the evaluation of effective interventions to reduce risk. According to other studies for risk reduction produced by the DICEA research group (Bernardini, Quagliarini, and D'Orazio 2019; Bernardini 2016), the techniques of Behavioural Design BD (Bernardini, D'Orazio, and Quagliarini 2016) are used to propose a technology transfer from the FSE from the fire indoor scenario to urban scale for the earthquake.

1.2 Aims of the work

The current work adopts a Behavioural Design point of view and tries to suggest novel methodologies and tools for the earthquake risk reduction in historical centre, basing on the analyses of men-environment interactions. Learning from the consolidated field of the indoor fire emergency, the relevance of the emergency planning and of the evacuation management strategies have been confirmed as key activities for the risk reduction also for the outdoor environment. The present thesis aims to propose a combined traditional-innovative methodology for the earthquake emergency planning in urban scenarios, specialized for the peculiarities of the historical centres. Furthermore, a novel intelligent guidance system, able to understand the environmental and the behavioural conditions produced by earthquake, is proposed too. This last tool could be particularly significant for the evacuees' wayfinding in the most critical areas of old centres.

The lines of investigation necessary to the aims concern: the assessment of the vulnerability for the build heritage and for the paths network of the historical centre; the quantification and evaluation of damage (mainly in terms of debris production) and the related effects on urban layout and exodus ways; the behaviour of people in the emergency and its representation; the emergency wayfinding and guidance systems. For each one of these lines the literature studies have been analysed and, when necessary, innovative BD-based or experimental based methodologies were proposed and singularly validated. The proposed planning and guidance methods are applied to a real case study and their effectiveness is tested with the help of a behavioural simulation software specialized for the earthquake emergency in outdoor scenarios.

Chapter II

2 State of the art

2.1 Current methods and tools for earthquake risk analyses and mitigation in historical urban centres

During the first emergency phases, the historical centre and particularly the urban paths network should solve to several requirements connected to users' necessities and earthquake-induced modifications, especially because of physical interferences between population, rescuers' mobility and earthquake effects (Shimura and Yamamoto 2014; Bono and Gutiérrez 2011; Mishima et al. 2014). According to a general risk assessment approach (D'Andrea, Cafiso, and Condorelli 2005), the evacuation paths risk depends on the combination between: hazard *H*, vulnerability *V* and exposure *E*.

In existing urban scenarios, *H* (Klügel 2008) is particularly relevant because of both local soil amplification phenomena and specific earthquake-induced effects on soil (e.g. landslide, liquefaction) (Teves-Costa and Veludo 2013; Italian technical commission for seismic microzonation 2014). Cascade effects, such as earthquake-induced fires, are also considered in emergency road network models, especially in case of compact urban fabric (Nishino, Tanaka, and Hokugo 2012; Shimura and Yamamoto 2014). Despite its relevance, risk reduction policies basing on the hazard factor minimization can be introduced only during the urban and building designing phases. Hence, it cannot be a plausible solution for the historical centres.

Traditional risk reduction strategies mainly base on the *V* factor minimization through intervention on buildings (Marques et al. 2018; Lamego et al. 2017). However, the vulnerability assessment for the historical centres should consider a combination of further several elements as the urban fabric and the urban paths network features (Cherubini 2002). Vulnerability based solution for risk reduction are deeply enquired by following Section 2.1.1.

Finally, *E* analysis should include the human presence into the scenario during both the earthquake and the following evacuation, in terms of behaviour, motion and possible fatalities (D'Orazio et al. 2014; Mishima et al. 2014). Surrounding environmental conditions, as visible damages, street geometric aspects and presence of rescuers, seriously influence pedestrians' choices about evacuation paths (Alexander 1990). For this reason, the definition of possible post-earthquake scenario and the analyses of men-environment interactions during the evacuation play an important role for earthquake risk assessment and reduction.

Risk reduction strategies basing on the men-environment interaction analyses are recently spreading. However, such solutions mainly relate to the Fire Safety Engineering (FSE) field and they are still poorly enquired for the application to earthquake emergency in outdoor environment.

From this point of view, the proposal of a holistic method for the earthquake risk evaluation concerning evacuation paths network elements could help safety planners to analyse the whole scenario and assess the mutual influences of risk factors in terms of evacuees' safety and effectiveness of rescuers' operations.

The preventive emergency planning and first emergence management are key activities for the safety of citizens and the effectiveness of evacuation. In fact, the emergency plan can be described as the "key" tool that describes and defines the series of activities, both preparatory and planning and operational, aimed at reducing risk and describing the actions and emergency measures to be implemented in the event of an earthquake. Is evident as the emergency planning process influence all the following process as the intervention on built heritage, the organization of rescue operations and the least but not the last the evacuation process. However, several reasons make the historical centres problematic scenarios for the emergency planners, where the application of traditional methodologies and tools often do not guarantee acceptable results in terms of safety.

In the following Sections, a not exhaustive overview on literature studies and regulations concerning the problematic and the significative issues in mitigating the earthquake risk of the historical centres are presented.

2.1.1 The seismic vulnerability of paths networks and of buildings

During post-earthquake evacuation, people's safety and rescue operations are strictly correlated to the vulnerability and damage of surrounding environment. Particularly, in historical centres, evacuation paths and related facing buildings need a punctual assessment since they are the elements principally influencing safety in post-earthquake damaged scenario (Argyroudis et al. 2015; Bernardini et al. 2017a).

Several studies evaluate the paths network vulnerability in exceptional events such as earthquake, flooding, volcanic phenomena and sabotage (Argyroudis et al. 2015; Khademi et al. 2015; Koetse and Rietveld 2009; Bell et al. 2008). Paths vulnerability influencing factors jointly involve the network configuration and the possibility of suffering from physical damages along the streets (Federal Emergency Management Agency 2003; A. Goretti and Sarli 2006; Ertugay, Argyroudis, and Düzgün 2016; Jenelius and Mattsson 2012).

The first aspect involves the open spaces layout within the urban fabric. For a certain time, safe areas should be achievable for pedestrians by using reliable and "safe" paths with possible alternative routes. This means that the emergency paths network configuration has to respect redundancy, reliability and safe destination criteria (Anhorn and Khazai 2015; Khademi et al. 2015).

The second aspect mainly involves the seismic damage of built heritage. Hence, vulnerability reducing interventions seem to be really significant in risk-reduction policies for historical architectural heritage (Modena et al. 2011; Indirli et al. 2013).

Studies about the paths network vulnerability, distinguish between intrinsic and extrinsic vulnerability (Tesoriere, Marinella, and Russello 2001). The first concerns the elements constituent the path itself (as for example the quality and typology of street surface, foundation, embankments, bridges), with the aim to classify and compare urban paths and related specialized elements (Pitilakis, Crowley, and Kaynia 2014; Ferlito and Pizza 2011; Adafer and Bensaibi 2015; Federal Emergency Management Agency 2003; Tesoriere, Marinella, and Russello 2001). The second considers the other elements (not of the path itself) that can make the path out of order after an earthquake. The buildings directly facing paths are the principal extrinsic elements to consider for the paths network analyses in the historical centre (Caiado, Macario, and Carlos S 2011; Argyroudis et al. 2015).

Several studies (Anbazhagan, Srinivas, and Chandran 2012; Zanini et al. 2016), demonstrates that the damage of street itself (e.g.: cracks, landslides, subsidence or explosion of underground lifelines) does not exclude the emergency pedestrian evacuation. Some authors (Anbazhagan, Srinivas, and Chandran 2012) propose a damage scale dedicated to road networks and experimentally produced by assessing the intrinsic vulnerability values and other seismic parameters (i.e.: moment magnitude, epicentre distance, hypocentre distance). However, the experimental dataset focused on extra-urban roads and does not provide any information about the intrinsic assessment for historical urban centres. Hence, in the historical centres the paths safety and practicability can be substantially due to the performance extrinsic elements: the surrounding buildings.

The seismic vulnerability of buildings is deeply enquired by literature studies. Two are the main developed approaches for of the buildings seismic vulnerability assessment (Calvi et al. 2006; Lagomarsino and Giovinazzi 2006; Mochi, Predari, and Vinci 2016): the analytical methods (mechanical) and the empirical methods (macroseismic). Although the analytical methods are characterized by high reliability, they need high knowledge of manufactures and high time and costs. For those reasons analytical methods are generally employed for the study of single strategical structures or constructions with a particular historical and artistical value (Lagomarsino 2006; Lagomarsino and Giovinazzi 2006). Contrarily, the empirical (macroseismic) are quick methods, generally based on a typological approach (that can influence their reliability). They could be integrated with others buildings' details, representing further variables defined in function of the adopted method (Calvi et al. 2006; Lagomarsino and Giovinazzi 2006; Mochi, Predari, and Vinci 2016). Empirical methods are employed both for single buildings and aggregates, representing at today the largely adopted tools for the vulnerability study at urban and territorial scales. The most common empirical methods are the fragility curves and the vulnerability curves. The fragility curves (Barbat et al. 2010; Pitilakis, Crowley, and Kaynia 2014) offer the probability to have, for a given buildings stet, a given effect (e.g.: damage degree, economical loss, human loss) as function of the macroseismic intensity. Although fragility curves are a powerful and versatile tool for the comprehension of the seismic response, they cannot avoid the vulnerability index assessment and the consequent definition of vulnerability classes. Instead, vulnerability curves (Lagomarsino and Giovinazzi 2006; Giovinazzi and Lagomarsino 2004) correlate hazard, in term of macroseismic intensity I, with the mean damageμ_D, measured in EMS-98 scale and obtained according Eq. 1 (Grunthal 1998).

$$\mu_D = 2.5\left[1 + tanh\left(\frac{I + 6.25 \cdot V_I - 13.1}{Q}\right)\right] \qquad 1$$

Their shape only depend by the buildings vulnerability index V_I (Lagomarsino and Giovinazzi 2006; Giovinazzi and Lagomarsino 2004), which concerns the typological, structural and constructive features of each enquired unit. Thus, it is evident as damage and vulnerability are linked to the probability P_k (see Eq. 2) that a unit presents the level of damage k given a certain I (Lagomarsino and Giovinazzi 2006). V_I is an absolute scale index, which allows to compare elements from different scenario. Furthermore, as that V_I is correlated to the expected mean damage, it can represent a simplified approach to the probable damage scenario definition as function of the expected earthquake severity (Caiado, Macario, and Carlos S 2011; Pitilakis, Crowley, and Kaynia 2014; Lagomarsino and Giovinazzi 2006).

$$\boldsymbol{P_k = \frac{5!}{k!(5-k)!}(0.2\mu_D)^k(1-0.2\mu_D)^{5-k}} \qquad 2$$

As previously remarked, to the aim of assessing the seismic vulnerability of emergency paths in historical centre and the related post-earthquake conditions, the buildings should be related to respective urban fabric context. According to a such perspective, Ferlito et al. (Ferlito and Pizza 2011) proposes a quick method for the analyses of urban emergency streets network vulnerability and practicability. In this method a normalized vulnerability index of building is adopted. Then, several adjustments are introduced in order to assess punctual correction due to local urban fabric geometrical features (i.e. the 25% reduction of street sections width for paths with either built sides, unfavourable relation between building height and street width *h/W*) and local geomorphologic features (i.e. lithological factors and ground parameters). The study (Ferlito and Pizza 2011) also enquiry the impact of street intrinsic elements (e.g.: bridges, walls, embankments, galleries) and proposes a quantification of their influence in term of whole vulnerability index. The presence of these intrinsic factors influencing the whole vulnerability index highlight the methodology could be most finely calibrated for modern urban centres instead of historical ones. Moreover, the work presents others limits: the obtained vulnerability indices can be used only within the analysed urban centres since they are relative normalized indices; the study does not provide any correlation between the assessed vulnerability and the produced damage. Hence, the method (Ferlito and Pizza 2011) seems to be incomplete while describing possible building and paths interferences with pedestrian during the post-earthquake evacuation in historical centres.

2.1.2 Probabilistic damage scenarios assessment methods

The definition of probabilistic damage scenarios (related to different earthquake severities) is fundamental in order to (Salgado-Gálvez et al. 2016; Quagliarini et al. 2016): produce an effective earthquake emergency plan; organize rescue operations; optimize the resource allocation on the urban context. In fact, the estimation of probable buildings debris depths and the consequent (partial or total) paths blockages are needed to design emergency management strategies, by including the definition of access paths and position of safe zones, safe paths for evacuees, available paths for emergency vehicles (Moretti and Azzara 2013; Ertugay, Argyroudis, and Düzgün 2016; Rojo, Beck, and Lutoff 2017).

Classic approaches to the preventive definition of such damage scenarios mainly concern with: the building heritage vulnerability characterization (Calvi et al. 2006; Cagnan et al. 2010), the analyses of geometrical interferences between buildings and streets (Italian technical commission for seismic microzonation 2014) and the assessment of probable debris volume (Federal Emergency Management Agency 2009).

As remarked by the previous Section 2.1.1, the vulnerability based approach takes advantage of correlations between macroseismic building vulnerability (Giovinazzi and Lagomarsino 2004; Tiago Miguel Ferreira, Maio, and Vicente 2016), earthquake intensity scale and experimental-based building damage scale, this last (mainly, based on EMS-98-related intensity and damage scales and shown in Figure 2-1) (Grunthal 1998).

Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction (very heavy structural damage)** Total or near total collapse.

Figure 2-1. Classification scale, proposed by (Grunthal 1998)*, for the grades of damage 'k' suffered by masonry buildings. A brief qualitative description and occurring frequency of building suffered damages for each level of the scale is also offered by the work.*

Similar models are offered by the fragility curves (Pitilakis, Crowley, and Kaynia 2014; Argyroudis et al. 2015) that, for a given building typology, correlate the earthquake severity (measured in terms of, e.g., Peak Ground Acceleration-PGA, macroseismic intensity or spectral displacement) to the probability of occurrence for all the level of damage (measured in EMS-98) or related loss of performance. Further recent approaches tried to elaborate rapid seismic damage prediction of buildings (according to building damage classes) by combining different seismic ground motion parameters (e.g.: PGA, Housner Intensity, Peak Ground Velocity, Peak Ground Displacement) and also including local effects estimation (Morfidis and Kostinakis 2018). Some studies focused on specific case-study in terms of built environment and earthquake (i.e.: described according to the seismic Moment Magnitude M_w) scenario characterization so as to outline post-earthquake assessment of buildings damage concerning both structural and non-structural elements (Allali, Abed, and Mebarki 2018; Agostino Goretti, Molina Hutt, and Hedelund 2017). Up to now, despite the suitability of such methods for quick analyses of large urban areas, these methods do not generally consider debris generation and paths networks occupancy.

The geometrical approach (Italian technical commission for seismic microzonation 2014) is a very quick method for the building-street interference assessment. It is based on simple geometrical measures (i.e. the building mean height h [m] and the width of the facing street W [m]) and it estimates the interference occurrence when the ratio $h/W \geq 1$. However, this approach does not consider factors as the building seismic vulnerability and the earthquake severity. At the same time, the method is not able to estimate the produced debris depth since it only takes into account the occurrence of blocked conditions when the h/W ratio is higher than a threshold. For this reason, the occurrence of such kind of interference does not imply street section blockages and vice versa. Furthermore, this method does not seem to be adequate for the historical centres. In fact, the imposed geometrical condition for path safety $h < W$ (Italian technical commission for seismic microzonation 2014) is not generally verified in such places because of the inadequate proportions between path widths and facing buildings heights

Finally, the debris volume assessment (Federal Emergency Management Agency 2009) is based on a macroseismic earthquake representation to evaluate the amount of structural and non-structural debris depending on the building vulnerability. However, this is a high-complex and time-consuming approach, and it refers to standardized volume-weight ratios that are not representative of particular scenarios as the historical ones. Furthermore, the method does not consider the geometrical relation between buildings and streets and does not provide any consideration about the produced debris depth on streets.

Other methods focuses on the post-earthquake sensing of debris by adopting satellite images (Baiocchi et al. 2012). These high reliability methods do not provide any correlation between damage and vulnerability, and so they cannot be adopted for the preventive assessment of probabilistic damage scenarios. Nevertheless, recent works (Quagliarini et al. 2016) propose sensing methods could be employed to assess experimental correlations for the esteem of debris width. This approach uses a normalized building vulnerability index (Ferlito and Pizza 2011), by combining it with the earthquake magnitude in order to introduce the event description in a modified vulnerability index V^* [-]. Finally, a correlation between V^* and the external debris percentage QX [%] is proposed and validated by means of experimental datasets of earthquakes that affected historical urban areas. Figure 2-2 shows the experimental correlation for the debris prediction proposed by (Quagliarini et al. 2016).

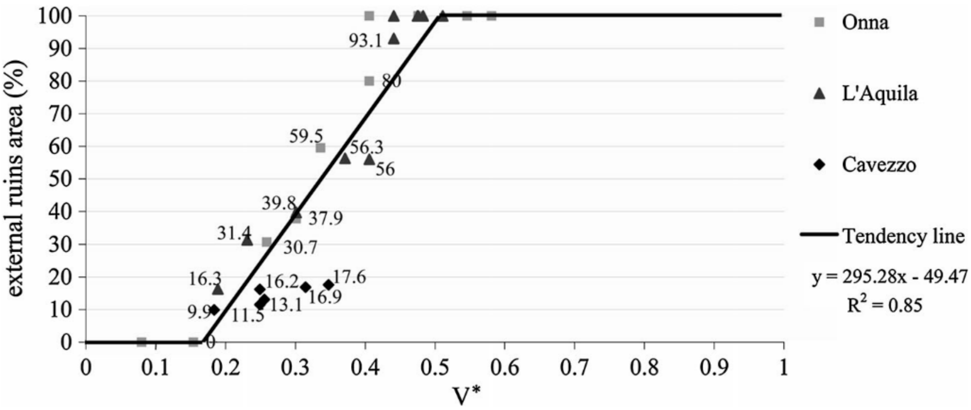


Figure 2-2. Experimental correlation, proposed by(Quagliarini et al. 2016)*, for the preventive debris depths assessment basing on aerial images and sensing methods.*

According to this obtained correlation, it is possible to estimate the probable debris depth production on streets. Intensity-based correlation on building damages are founded on the severity description in terms of the earthquake effects because of the seismic intensity scale definition (Grunthal 1998). Differently, the magnitude is a rapid-to-evaluate seismic parameter (D.-Y. Chen, Wu, and Chin 2017) and a main seismic severity descriptor in earthquake modelling (e.g. in finite-fault modelling) approaches (Villar-Vega and Silva 2017), especially in case of areas placed near to the earthquakes epicentre. Similar features can be referred to other seismic parameter (e.g.: ground shaking related as PGA).

Defining and locating interferences between evacuees and post-earthquake damaged environment at a urban scale (Vicente, Ferreira, and Maio 2014) should take advantage of quick assessment methods such as the ones based on building vulnerability, in order to extend the evaluation process to the whole investigated area in a short time. The assessment of debris dimensions on the streets could be very useful to evidence possible critical issues for urban emergency mobility during the evacuation phases, i.e., the identification of unavailable evacuation paths for evacuees' flow and emergency vehicles transit within the historical centre (Rojo, Beck, and Lutoff 2017).

2.1.3 Human behaviours in emergency evacuation: performance-based analyses and tools

The individuals' choices (and related safety) during the emergency evacuation strictly depend by the evolution of environmental and behavioural conditions. This consideration is true regardless of the type of considered emergency or the environment in which the evacuation takes place (Solberg, Joffe, and Rossetto 2008; Schadschneider et al. 2009; Kobes et al. 2010; D'Orazio et al. 2014). The representation of people's behaviours during emergency and the related consequences in terms of motion, as function of environmental, cultural and social factors, have been largely enquired by literature (Shiwakoti, Sarvi, and Rose 2008; Haghani and Sarvi 2018; Zheng, Zhong, and Liu 2008). Several studies have been produced to this aim, although they could be classified into two principal approaches:

the macroscopic and the microscopic approaches. Macroscopic models (Kormanová 2014) work in analogy with the fluid-dynamic theories, offering a quick and qualitative representation of behavioural dynamics especially for large crowds. Contrarily, the microscopic approaches (Santo and Aguirre 2004; An 2012) are high time and cost consuming however they offer a most advanced and accurate definition of man-man and man-environment interactions. In the last decades, the availability of high-performance calculators strongly contributes to the spreading and consolidation of microscopic models that have been adopted in several applications.

Implementing these models have been possible to have simulation tools, considering both environmental and behavioural factors for normal and (different) emergency conditions both for indoor and outdoor scenarios (D Helbing et al. 2002; Korhonen and Hostikka 2010; D′Orazio et al. 2014; Lämmel, Grether, and Nagel 2010). Some studies propose simulation tools to enquiry the impact on evacuation performances of specific factors as for example the evacuation in complex environments (Zhong-an, Mei-ling, and Xiao-hua 2011; Li, Zhang, and Jiang 2019; Guo, Huang, and Wong 2012; Yuan et al. 2009; Pelechano and Malkawi 2008), the presence of social and behavioural phenomena (Tsai et al. 2011; D Helbing, Farkas, and Vicsek 2000; Hashemi 2018; Chu et al. 2006; Hou et al. 2014; Rabiaa and Foudil 2010; Shapira et al. 2018), the impact of environmental modifications due to the emergency (Hirokawa and Osaragi 2016; Bross and Geography, n.d.; Lämmel, Grether, and Nagel 2010; Liu et al. 2014) or the effectiveness of emergency evacuation facilities and systems (Xie et al. 2012; Nassar 2011; Chu et al. 2006). At today, emergency simulators represent a useful tool for risk assessment and emergency management basing on advanced analyses. In fact, their adoption is also suggested by regulations since they are performance-based oriented analyses of risk reduction strategies. Table 2-1 summarizes and briefly presents the most employed models for crowd dynamics in emergency evacuation.

	Object and Factor	*Cellular Automata Model (CAM)*	*Social Force Model (SFM)*	*Agent Based Model (ABM)*
People	Representation	Punctual elements placed in cells respecting the imposed crowding rules (e.g.: maximum number of hosted elements also depending on their sizes)	Punctual elements generated in the scene whose motion and behave is dynamically defined by interactions rules (in terms of interchanges of forces)	Virtual agents (individual and behavioural) governed by interaction rules among agents, producing most complex behavioural phenomena
	Characterization	Individuals interacting between themselves and with the environment. Different features can be modelled (e.g.: gender, age, familiarity with the scene)	Individuals interacting between themselves and with the environment. Different features can be modelled (e.g.: gender, age, familiarity with the scene, panic, clogging)	Individuals interacting between themselves and with the environment. Different features can be modelled (e.g.: gender, age, familiarity with the scene, panic, clogging, leader effect, social attachments, competitive/collaborative behaviour)
	Behavioural dynamics	Psychological and social factors can be reproduced with some difficulties. Hybrid CAM are produced to optimize such aspect.	Combination of attraction and repulsion forces defines the individual's behavioural profile in physical, psychological and social terms	Dynamics between singles homogeneous / heterogeneous agents are regulated by interaction rules. The overlap of rules can easily reproduce complex behavioural dynamics
	Motion dynamics	Discrete representation of motion in space and time	Continuous representation of motion in space and time. Individuals move into a force field exercised by the combination for each instant of environmental elements, surrounding people and personal goals/dynamics	Continuous representation of motion in space and time. Computationally most expensive than the other models but especially suitable to represent pedestrians with unique behaviours dynamics (heterogeneous humans)

Environment	Representation of the scene	Discrete 2D system consisting of a regular grid of cells. The state of each cell dynamically evolves at each discrete time step depending on its and neighbour cell variables	Continuous 2D or 3D space containing individuals, borders, obstacles and goals (destinations)	Continuous 2D or 3D space containing agents (of each type they are defined)
	Interfering objects in the scene	Discrete representation of the presence of debris/smoke through occupied cells	Modelled as physical occupation of space who exercise a previously defined attraction or repulsion force	Different environmental agents can be modelled, each one with the related interaction rules with individuals (human agents)
	Spatial rules for path choice	Exit dynamics concerning exit choice in different conditions, also considering the presence of obstacles and behavioural factors	Once the final goal is setted, the path choice is produced considering behavioural and environmental interactions in each evacuation instant	Evacuation dynamics concerning moving, path choice in different conditions, also considering complex dynamics concerning behavioural and environmental factors

Table 2-1. Mains microscopical approaches for the representation of human dynamics specialised for emergency

The current work takes advantage of the simulation software “EPES” (Earthquake Pedestrians’ Evacuation Simulator) (D′Orazio et al. 2014; D’Orazio et al. 2014; Bernardini, Quagliarini, and D’Orazio 2016). This tool has been developed, experimentally validated and internationally published during the past years by a research group, headed by the professors M. D’Orazio and E. Quagliarini, of the Department of Construction, Civil Engineering and Architecture of the Polytechnic University of Marche. EPES is an experimental based simulator specialized for the reproduction of behavioural and environmental dynamics related to earthquake emergency evacuation in urban outdoor environment. The software employs a social force and agent based combined model for the representation of environmental and human dynamics of the emergency. The implemented intentional model, presented in Figure 2-3, briefly summarizes the interactions and dependencies between human and environmental agents modelled in the software.

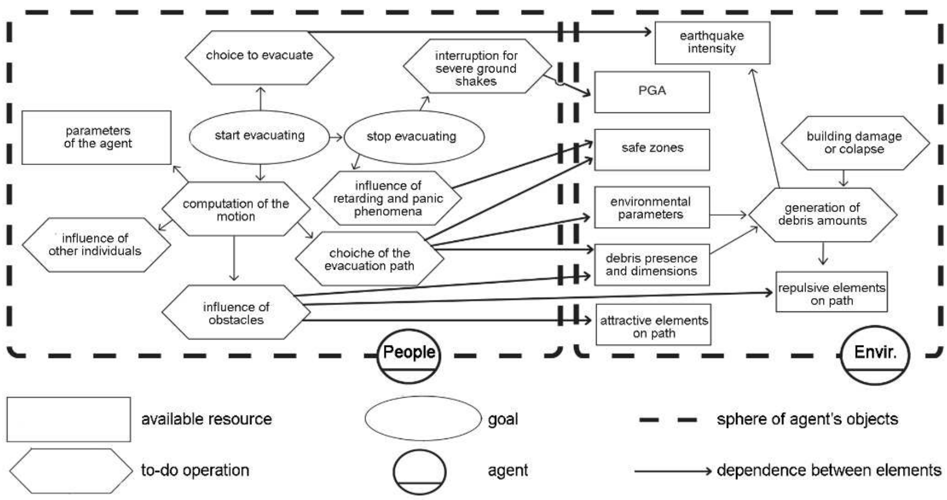


Figure 2-3. Intentional model of elements, interactions and dependencies between the considered agents implemented in the simulation software EPES (D′Orazio et al. 2014).

Among the advantages offered by EPES there is the possibility to knowing, for each time step, several aspects about the evacuees’ performances and the post-earthquake scenario. Considering a significative number of simulations, so as to confer a statistical value to results, the offered outputs allow to assess the evacuees and the environment dynamics for individual and collective performances. These information could be also classified in function of each planned safe area so as to know their probabilistic employ in the emergency evacuation, the performance of here arrived people and the features of their followed paths. Finally, the outputs offered by the software could be combined among them or also refined into most complex Key Performance Indicators (KPIs). This operation can be very useful to obtain aggregate and more significative information, useful in assisting safety planners to produce advanced analyses and performance-based assessment for the urban earthquake emergency.

Object	Output	Unit of measure
Individual performance	Instantaneous velocity	m/s
	Position for each time step	x, y
	Required safe evacuation time	s
	Tortuosity of the followed path	-
Whole evacuation performance	Population in each planned SA	pp
	Percentage population in each planned SA	%
	Population out of the SA	pp
Post-earthquake environment	Building produced debris depth	m
	Produced debris areas	m^2
	Crowding in each paths of the network	pp/m^2
	Percentage of use for each edge of paths network	%

Table 2-2. Output information offered by the software EPES - Earthquake Pedestrians' Evacuation Simulator (D'Orazio et al. 2014; D'Orazio et al. 2014, 2017) *for the quantification and analyses of simulated evacuation performances.*

2.1.4 Crowding assessment: the pedestrian flow theory

If the focus is shifted a little from behavioural models to the theories of flow for pedestrians it can be observed that, despite the second does not consider the emergency condition, the two may have common interests and be complementary in some respects. The pedestrian flow theory was born as a development of the original one for the vehicular traffic flow. The application of flow theory to the pedestrian case is the translation to the pavement of what happens on the road lane. The pedestrian flow theory evaluate, with varying conditions of the route, the possibility for the single pedestrian to maintain his / her desired speed, to walk against the current, to overcome others pedestrians, to cross a pedestrian flow, to freely vary the movement without interference and speed changes.

A milestone of pedestrian flow theory, particularly interesting for the present work, are the studies of Fruin (J J Fruin 1971; John J Fruin 1971) about the definition of Level Of Service (LOS) for routes. This studies, also adopted by the Highway Capacity Manual (HCM) (Transportation Research Board (TRB) 2000), evaluate with varying conditions of the route the possibility for the single pedestrian to maintain his / her desired speed, to walk against the current, to overcome others pedestrians, to cross a pedestrian flow, to freely vary the movement without interference and speed changes. A very significant part is the introduction of synthetic indicators for path employ which aim to define the flow that a given route can take: the level of services. As shown in Figure 2-4, these indicators summarize in a capital letter (from A to F) the increasing presence, and so flow conditions, of a pedestrian current from free flow (LOS A) to overflow in capacity (LOS F). The LOS indicators are usually based on a maximum capacity expressed in people per minute per meter. They offer a description and a quantification of mains variables both for the wlkin areas, stairs and squares.

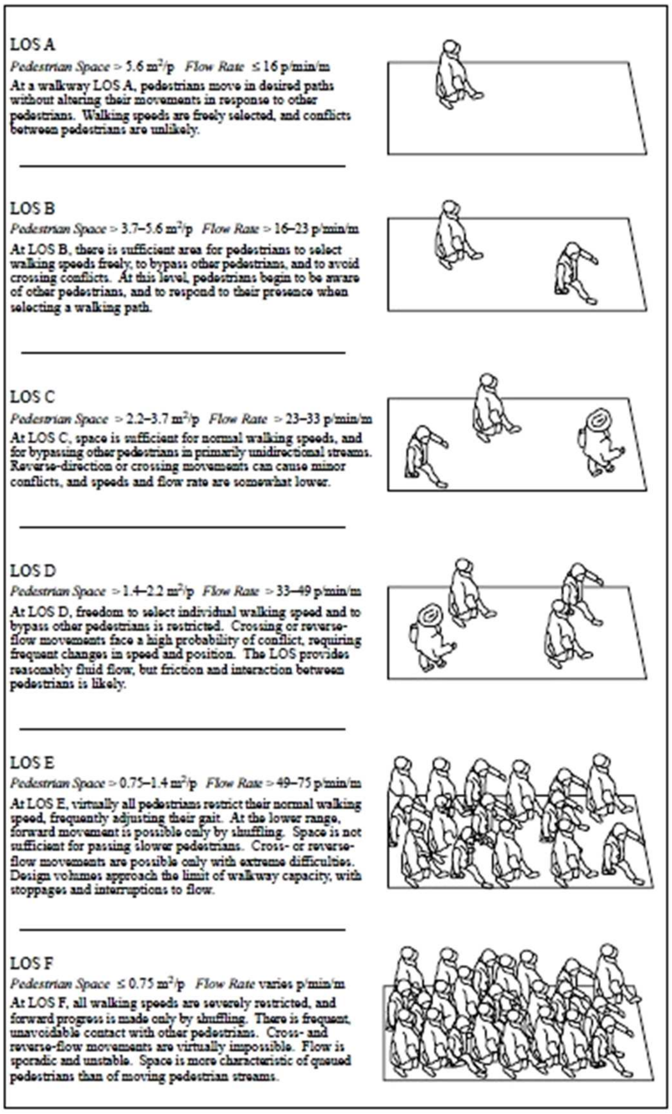


Figure 2-4. Description of the Level of Service (LOS) for the pedestrian flow assessment proposed by Fruin (J J Fruin 1971).

For each LOS level a range of average pedestrian speeds is provided in m / s and a range of the actual crowding condition in square meters / person, as well as data indicating the possible interval of the pedestrian flow value. Despite these values are not obtained for emergency applications, the proposed methodology for assessing crowding and related use of paths could be a solid tool useful to consider the human density in paths and safe areas during and after the emergency.

2.2 The earthquake emergency planning

Evacuation plans and rescuers' emergency activities' definition are aimed at reducing the exposure factor *E* through management strategies (X. Chen et al. 2012). Evacuation plans' definition strictly depends on national and local regulations, which, over the decades, adopt this strategy as an important risk reduction tool (Italian technical commission for seismic microzonation 2014; Federal Emergency Management Agency 1996). Nevertheless, analyses of evacuation performances and adopted behaviours highlight that, especially in historical city centres, evacuees often do not follow (or do not know, as for tourists) the evacuation plan (Quagliarini et al. 2016). An effective implementation of similar strategies could be difficult because it should need a widespread communication of the emergency procedure to the population and/or a large number of rescuers during the disaster response phase (Ainuddin and Routray 2012).

Only recently, the Italian regulations seem to do some steps on this direction with the introduction of guidelines for the safety and the security of public events (Directive n. 11001/1/110/(10) of the 07/18/2018 and previous ones). Even if this effort is not focused on the earthquake emergency field, it demonstrates an increasing attention toward a performance-based approach for the emergency planning and designing of risk mitigation solutions. Furthermore, these guidelines represent one of the few codified methodologies suggested for the emergency management and planning in outdoor urban environment. In fact, the most of current regulations and guidelines for emergency concerns the case of fire in indoor environment. This trend is also confirmed in the international landscape and by the scientific national and international literature (Bernardini, Quagliarini, and D'Orazio 2018).

2.2.1 Italian regulations for the earthquake emergency planning

Although they do not consider any performance-based approach, the Italian guidelines for earthquake emergency represent one of the most advanced regulations for seismic risk mitigation in the European panorama (Cara et al. 2018). The principal responsible to producing tools and guidelines for emergency is the Civil Protection Department (CPD)[2]. It defines the general criteria for emergency planning and addresses them to the Regions, which give guidelines for preparing provincial and local plans. In order to deliver an efficient response to calamities, local boards need to plan an event management, to detect risk scenarios on the territory, strategies and intervention models, as well as responsibilities and how to exchange information between the central system and its branches. The main tools offered to this aim by the CPD are the Guidelines for Seismic Microzonation (SM) (Civil Protection Department and Conference of autonomous regions and provinces 2008) and the Handbook for analyses of Limit Condition for Emergency (LCE) (Italian technical commission for seismic microzonation 2014).

[2] http://www.protezionecivile.gov.it/national-servic/activities/emergency (last access 10/07/2019)

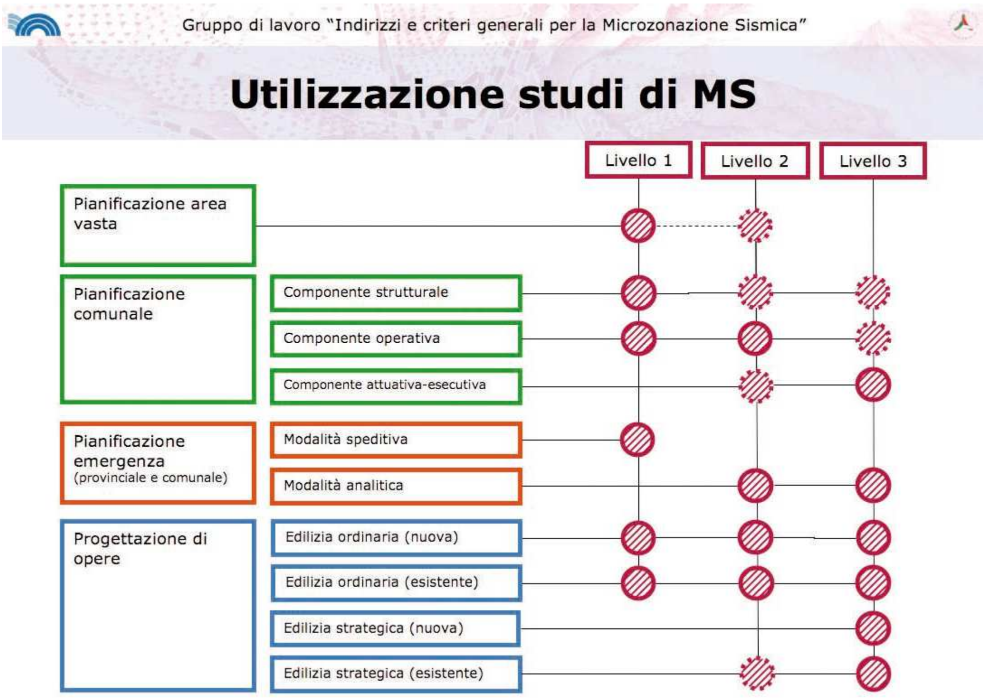


Figure 2-5. Conceptual map of the suggested utilization of the Seismic Microzonation study offered by the related official document (Civil Protection Department and Conference of autonomous regions and provinces 2008)

While the SM analyse is aimed to know and quantify the presence of possible local amplification phenomena, due to seismic response of soil, the LCE analyse directly focuses on the emergency planning and managing issues (Cara et al. 2018; Dolce et al. 2018). The SM suggested employ, shown in Figure 2-5, highlight their relevance for the planning processes. However, for the emergency planning of municipality the SM offers punctual analyses of the territory seismic hazard, useful to employ into a more holistic emergency planning method as the LCE analyses. As Figure 2-6 shows, the limit condition for emergency is defined as the condition whose overcome interrupts the most of urban functions (e.g.: residential, commercial, strategical) except the emergency management functions that remain operative.

These functions mainly concern the organization of rescuers' operations as for example the setting of medium and long terms safe areas collecting survivors and first emergency resources (respectively called gathering areas and recovery areas), or the preservation of road infrastructure for the connection and access within and out of the urban centre. All the elements that, following the geometrical criteria evidenced in Figure 2-7, result interfering with the selected emergency structures, paths and safe areas are also indicated in the analyse(Italian technical commission for seismic microzonation 2014).

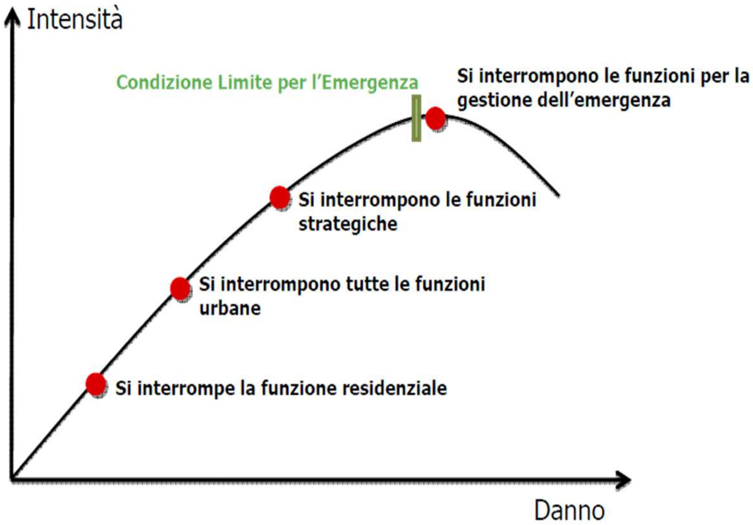


Figure 2-6. Schematization of the dynamics of urban functions for the emergency as function of the accused seismic damage. The Limit Condition for Emergency aims to preserve only the emergency management functions while all others broke down.

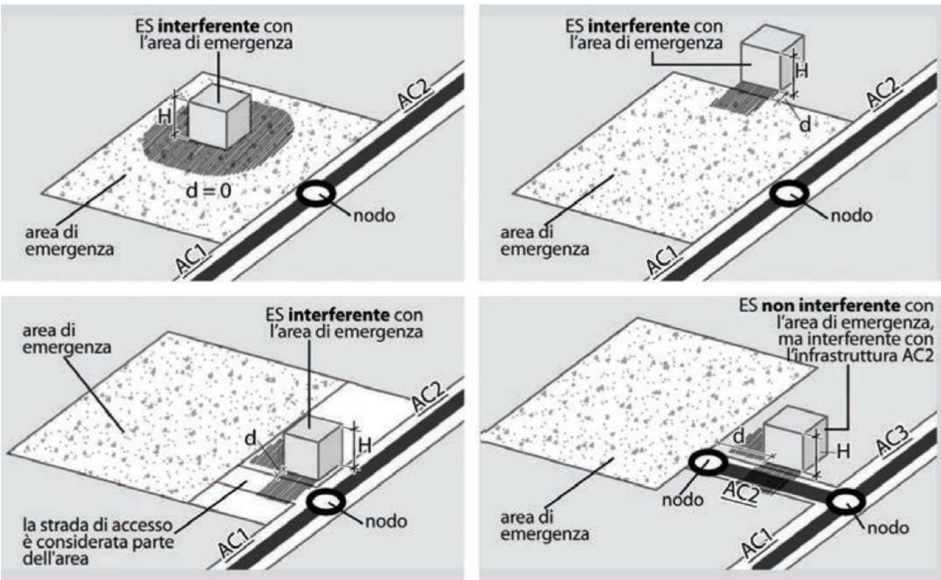


Figure 2-7. Interfering criteria based on the geometrical parameters of height of buildings, width of streets, building distance from safe areas. Extract from the LCE handbook (Italian technical commission for seismic microzonation 2014).

Figure 2-8 proposes an example of the results obtained by the limit condition analyse, extrapolated from the LCE handbook. Taking advantage of the data in the Municipal Emergency Plan, the strategic structures and the emergency areas are connected through a robust and redundant emergency road infrastructure system. This last is responsible of the external accessibility of the centre and of the internal connection of the highlighted emergency structures during the emergency. Despite the LCE analyse is strictly correlated to the emergency plan and the seismic hazard characterization of the place, their exclusive management nature is confirmed by the absence, in the offered analyse, of the waiting safe areas.

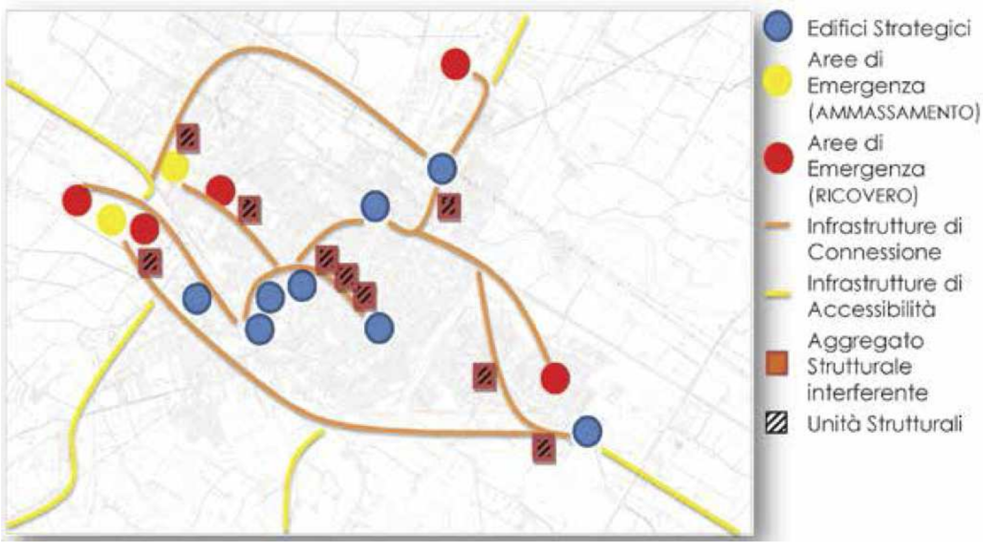


Figure 2-8. Example of limit condition analyse for emergency taken from the LCE handbook (Italian technical commission for seismic microzonation 2014)*. The emergency structures (assumed by the municipal emergency plan) and the connection infrastructures are highlighted on the map together to the elements interfering with this emergency management system.*

As introduced by the operational guidelines concerning the "Determination of general criteria for the identification of the Coordination and Emergency Area Operational Centers" (Presidenza del Consiglio dei Ministri - Dipartimento della Protezione Civile 2008), the waiting areas are the first destinations for evacuees before or immediately after a shake. These areas should be capillary spread into the urban fabric and, in these points, the arrived individuals can be reached by rescuers and have the first aids. Contrarily to the analyse of Limit Condition for Emergency, although several directives introduce elements about the emergency plan and the emergency operations, a single, clear and dedicated guideline for the redaction of the Municipal Emergency Plan is still missing. At today the main indications about the requirements and the redaction of this document are offered by the Law n.81/2008 (Ministero del Lavoro e delle Politiche Sociali 2008). However, these indications are dedicated to the safety of work places and it offers little inspiration for its application to the earthquake emergency in urban environment.

2.3 The self-help practice and the evacuees' emergency wayfinding

Wayfinding represents the process through which people orientate in the environment with the aim to move from an initial point to a different destination point. This process involves human sensorial mechanisms in relation to individuals' features (e.g. familiarity with the spaces and the surrounding environment conditions) (Car, Taylor, and Brunsdon 2001). The support offered by guidance systems during the evacuees' emergency wayfinding can modify the evacuees' behaviours, improving the evacuation performances and leading population to the planned emergency areas in a more efficient way. This issue is commonly applied to architecture and evacuation facilities (Carattin et al. 2016) (including exit signs, evacuation instructions and maps (Carattin et al. 2016)).

To date, emergency guidance solutions are largely studied for fire emergency in indoor scenarios (Filippoupolitis and Gelenbe 2012; Ran, Sun, and Gao 2014; Vilar et al. 2013). The related effectiveness during emergencies are investigated, especially in indoor conditions such as in complex and historical buildings (Ran, Sun, and Gao 2014). However, the benefits of its application could be extended to further different catastrophes and outdoor scenarios, especially by considering the smart cities perspective (Asimakopoulou and Bessis 2011). In fact, the adoption of guidance systems during the post-earthquake urban evacuation, basing on behavioural design criteria, could improve the effectiveness of the 'self-help' practice (allowing people to autonomously move towards 'safe' paths and gain assembly areas) and look towards a performance-based approach (as for the fire safety case (Bernardini, Quagliarini, and D'Orazio 2016; Kobes et al. 2010)). During the initial emergence phases, the 'self-help' could have valuable benefits, especially because the public safety personnel may be not present in the scenario or may face some difficulty in reaching the damaged zones (Hashemi and Alesheikh 2011; Moretti and Azzara 2013).

Guidance systems are generally used to help people during fire emergencies. Although fire and earthquake produce different scenarios and have different time spread during the emergency, the involved evacuees' wayfinding processes can be represented in a very similar way (Gelenbe and Wu 2012; Onorati et al. 2014), especially from an ontological point of view (Taccari et al. 2014).

Therefore, guidance systems supporting the emergency wayfinding should be encouraged also for outdoor earthquake evacuation (Sato, Izumi, and Nakatani 2014; Taccari et al. 2014). Because emergency wayfinding in outdoor scenario is a quite recent field and it is still being developed, only few studies involve this issue. Major studies apply wayfinding concepts to crisis management with the aim to design emergency plan (Bernardini, D'Orazio, and Quagliarini 2016) and rescue operations (EL-Gamily, Selim, and Hermas 2010) by adopting the 'traditional' perspective. Evaluation techniques mainly take advantage of evacuation simulators (Mishima et al. 2014; Kinugasa and Nakatani 2011), but real experiments are also performed (Ishikawa et al. 2008). Finally, a limited number of studies offer methods for pedestrians' safe evacuation at urban scale (Shahabi and Wilson 2014; Shimura and Yamamoto 2014) by also involving post-earthquake evacuation (Kinugasa and Nakatani 2011) and defining the system from an ontological point of view (Taccari et al. 2014). Examples of validations of these tools by means of simulators has been also offered (Sato, Izumi, and Nakatani 2014).

While dealing with earthquake evacuation in an urban environment, emergency guidance systems should consider the main factors influencing evacuees' safety and performances (in terms of delay and effectiveness). In fact, these variable factors (e.g. overcrowding on the escaping path (Kinugasa and Nakatani 2011), cascade and secondary effects (Pescaroli and Alexander 2015), and paths blockage (Ferlito and Pizza 2011; Quagliarini et al. 2016) due to vulnerable elements (Tesoriere, Marinella, and Russello 2001; A. Goretti and Sarli 2006) and bad visibility conditions (Mishima et al. 2014)) could substantially modify the performances effectiveness. Each one of these variables, influencing the emergency wayfinding for outdoor post-earthquake evacuation, is well evidenced by literature studies but the lack of works adopting a jointly approach can be noted. In fact, studies concerning their combined impact on emergency wayfinding performances and their implementation on emergency guidance systems could be adopted in order to assess people's safety during the emergency evacuation.

2.3.1 Overview on the Emergency Guidance Systems supporting the evacuation in indoor and outdoor environments

Table 2-3 summarizes the main existing typologies of systems used for indoor and outdoor emergency guidance and the related assistance to evacuees, referring to the relevant literature. Currently, the most widespread technologies for monitoring the environment and assisting people during evacuation are passive systems, also known as traditional ones (e.g.: video surveillance, motion detectors, smoke or fire detectors, signage, alarm). However, the use of these systems has revealed several limitations. For example, provided information are predetermined and statics, the systems often do not cooperate with each other and the indicated escape routes do not consider the real environmental conditions. These limitations could generate situations in which indications, offered through traditional system, are conflicting or even incorrect, operating to the detriment of the safety of the evacuators. This demonstrates how traditional solutions may be insufficient during emergencies, especially in highly crowded environments, and how more performing tools (deriving from advanced and innovative approaches) are needed.

Recent studies employ active and intelligent systems, able to monitor both the environment and the present people, operating an interactive emergency management based on real data collected. Active systems represent a significant advance in terms of emergency planning and performance management, dynamically guiding evacuees through advanced databases and algorithms. Active systems are based only on environmental information (Yenumula et al. 2015), or on occupant movement (Wang, Zhao, and Winter 2015). Contrarily, intelligent guidance systems are able to combine environmental and behavioural parameters, becoming true Intelligent Evacuation Guidance System (IEGS) (Ran, Sun, and Gao 2014; Sato, Izumi, and Nakatani 2014; Ibrahim et al. 2016) optimizing information through forecasting scenarios of disaster scenarios. In fact, during the evacuation, people adopt different wayfinding strategies to save themselves in relation to the boundary conditions. However, actuating not-informed wayfinding strategies can often be fatal since evacuees are not aware of the real and overall status of the surrounding space (e.g.: risk level along paths linked to the built heritage vulnerability, position of the best and shortest escape routes) (Dirk Helbing and Johansson 2010; Bernardini, D'Orazio, and Quagliarini 2016).

Emergency Guidance System	*Main features*	*References*
Passive (traditional) (i.e.: standard, reflective, photoluminescent, and electrically illumined signs, acoustic alarms)	• Simplicity and rapidity of activation; • Low cost / impact on architectural spaces; • Static and predefined information; • Monitoring of environments with limited cooperation between systems (e.g.: alarm only).	(Proulx, Kyle, and Creak 2000; Filippidis 2006; Xie et al. 2012)
Active (interactive) (i.e.: interactive signage, applications for smartphones, smart building components, smart street furniture)	• Monitoring of environments or people; • Interoperability between systems; • Adaptation of the indications offered to the evolution of the emergency; • Complexity / cost / implementation impact; • Compatibility with personal driving devices.	(Wang, Zhao, and Winter 2015; Yenumula et al. 2015; Isikdag, Zlatanova, and Underwood 2013; Yasufuku et al. 2017)
Intelligent (innovative) (i.e.: smart building components contextualized in smart systems for indoor and outdoor)	• Combined monitoring of environments and people; • Automatic interpretation of high-level data (natural language, movement); • Definition of emergency forecast scenarios; • Optimization of resources including management; • Integration with "smart" building components; • Complexity / cost / implementation impact.	(Naser and Kodur 2018; Groner 2016; Kollmann et al. 2016; Ran, Sun, and Gao 2014)

Table 2-3. Classification of the principal emergency guidance systems developed at today, proposed in (Santarelli et al. 2018)*. A brief characterization of the systems and some literature references are offered in the table.*

Table 2-4 proposes a quick description of the most relevant studies on guidance systems and their application. This scheme allows to produce a direct comparison between the main features and the related experimental tested effectiveness of the different guidance systems analysed in these studies.

Scene	*Typology*	*Description*	*Effectiveness or Perception*	*Reference*
outdoor, tsunami emergency evacuation	electrically illumined signs	experimental test of signages of several dimension characterized by white pictogram on green background and combined to flash light positioned at decisional points at a height of 4,5 meters	varies depending on the signage dimension, brightness and typology of the test (in situ or virtual reality)	(Yasufuku et al. 2017)

outdoor, touristic	standard signs	incentive to active transportation systems for pedestrians and bicyclists through touristic road signs with white text on green background positioned at decisional points	the 53.1% of the sample saw signs	(Keliikoa et al. 2018)
indoor, emergency	led applied to standard signs in combination to alarm messages	experimental test of improved standard signs, positioned at decisional points and exits, offering negative and positive information in combination to appropriate and not appropriate alarm messages	almost the 66% of the sample followed the system, a little variation is due to the influence of alarm messages	(Galea et al. 2017)
indoor, emergency	coloured flashing lights remarking exit	experimental test done with different colours and intensities of flashing lights	red and orange flashing lights favourite the individuation of exits	(Nilsson, Frantzich, and Saunders 2005)
indoor, emergency	dissuasive elements to active signs and dissuasive signs	test in virtual environment of different ways to offer dissuasive information in emergency signs, also combining flashing lights	38% with standard signs and 77% with active signs	(Olander et al. 2017)

Table 2-4. Summarization of the main studies assessing the effectiveness of outdoor guidance systems and comparison to the effectiveness of other studies for indoor guidance systems.

To suggest the appropriate evacuation path to users, guidance systems generally take advantage of routing algorithms typical of graph theories (Car, Taylor, and Brunsdon 2001). Literature mainly distinguishes among different functioning algorithms (e.g. breadth-first search, depth-first search, depth-limited search, shortest path search, iterative deepening search, bidirectional search, Dijkstra) (Zhan 1997). Routing algorithms for emergency guidance systems (Shimura and Yamamoto 2014) should consider the emergence environmental and behavioural influencing factors to process the safest way to escape (which is not necessarily the shortest way). In fact, suggested paths could be not acceptable for emergency navigation within the damaged scenario: parts of the paths network (graph) could be impracticable or significantly hazardous (e.g. debris, fires, gas leaks).

Finally, always for the indoor emergency field, could be highlighted the presence of recent studies enquiring the effectiveness of guidance systems specially defined to interact with people suffering perceptive disabilities (Saade, Salhab, and Nakad 2018; Jeon and Hong 2009).

Starting from the offered state of the knowledges, the development of intelligent guidance systems specially designed for the outdoor environment and the earthquake emergency applications is a desirable advance. In fact, as for the indoor evacuation, also the outdoor emergency wayfinding processes could take advantage of such systems and improve the evacuees' safety especially in high risk scenarios as the historical centre ones.

Chapter III

3 Innovative methods and tools focused on Behavioural Design

The proposed work of thesis is organized following the present phases and the related methods:

i. Dataset definition and pre-event analyses. In this initial phase, all the needed data about built heritage, paths network, soil characterization and population assessment are collected and organized in several dataset in order to the assessment method they refer to. Then, the pre-event analyses related to the several enquired aspects are produced for a preliminary evaluation;
ii. Definition of a safety guidance methodology for Intelligent Evacuation Guidance System (IEGS). After the ontological frame of the system operation and the related limits a guidance method, specialized for the earthquake emergency evacuation in historical centre, is proposed.
iii. Research of the best-performing emergency layout. Basing on the pre-event analyses, several emergency layouts are designed. Hence, the performance of each emergency layout is assessed with the help of a simulation tools. Once the best-performing layout is obtained, on the base of the pre-event analyses, the proposed guidance system is introduced in the defined scenario. The effectiveness of the guidance system and its impact on the evacuation performances are than tested by adopting the EPES simulation software and Key Performance Indicators (KPIs). In this last phase, two different post-earthquake damage scenarios are also compared in order to consider different levels of safety;
iv. Application of the proposed methodology to a pilot study for a real historical centre. All the proposed methodologies, previously validated in individual studies, are jointly applied to the case study. Hence, the feasibility and the effectiveness of the proposed risk reduction solution by the adoption of traditional-innovative methodologies for the earthquake emergency planning and evacuation management in historical centres are evaluated.

3.1 Dataset definition and pre-event analyses

According to the presented state of the art, and to the methodologies proposed in the following, both environmental and population features should be collected for the related characterization and the appropriate analyses. Table 3-1 summarizes the main features, respectively related to each element to evaluate, adopted by the employed methodologies and useful to the proposed ones.

Elements	*Aspects*	*Features to assess*
Built heritage	geometrical aspects	• mean height of facades • length of the path-facing façades • planar and elevation shapes • number of floors
	macroseismic vulnerability	• typological and constructive aspects
	presence of specialistic elements	• e.g.: towers, churches, monumental buildings, palaces
Paths network	geometrical aspects	• mean width of the path section • length of the street edge • presence of either built sides
	vulnerability aspects	• presence of underground natural or anthropic cavities • presence of underground pipelines • typology
	presence of specialistic elements	• e.g.: bridges, embankments, tunnels
	usage profile	• average flux • typology
Hazard	forecasting factors	• maximum expected severity • most probable expected severity
	seismic soil characterization	• presence of local amplification factors • lithological and sitological parameters
Population	resident people	• number and distribution on the territory
	people regularly hosted	• e.g.: foreign students and workers, afflux to permanent markets and to facility • number, typology and distribution on the territory
	people occasionally hosted (e.g.: tourists, users of facilities)	• e.g.: tourists, afflux to weekly market, afflux to spectacles or entertainments • number, typology and distribution on the territory

Table 3-1. List of the collected features, for each element considered in the proposed work, employed or adopted in the proposed work.

According to the related methodologies, the features collecting methods could be different basing on the available resources. However, the obtained parameters should respect the characteristic of use and the unit of measure according to the following sections.

The resident population analyses can be offered by the ISTAT periodical census. To determine the regularly and occasionally hosted population, the study refers to the limit crowding imposed by regulations in relation to the capability or to the surface of each considered structure. In particular it is considered that:

- *Historic civil architectural heritage*: on-site investigation to find information on the number of staff in service. The number of possible visitors/customers is added considering the surface of the spaces open to the public and a crowding index based on 0.4 people/sqm;
- *Specialist religious structures*: count of the number of seats available for each structure. Addition of a franc to consider the situation of people standing, counted considering 0.7 people/sqm, as per D.M. 08/19/1996, in relation to the surface area available for this purpose;
- *Assistance institutions*: on-site investigation to find information concerning the number of available beds. The data of the staff in service and the fluctuating number of visitors is added, calculated by averaging the data relating to three days of typical turnout;
- *School buildings*: survey to determine the number of classrooms available. Evaluation of the number of students per classroom by setting the parameter of 25 students/classroom, as per M.D. 26/08/1992, and of the number of professors and staff in service at the same time;
- *Cultural and entertainment buildings*: count of the number of seats available for each structure. Addition of a franc to consider the situation of people standing, counted considering 0.7 people/sqm, as per D.M. 08/19/1996, in relation to the surface area available for this purpose;
- *Commercial buildings*: the crowding index is obtained by imposing 0.4 people/sqm on the plan surface, net of the wall thickness, as per D.M. 07/27/2010;
- *Accommodation facilities*: on-site survey to find the maximum accommodation capacity in terms of beds and staff on duty;
- *Restoration exercises*: crowding is obtained by imposing an index of 0.7 people/sqm on the surface of the plant net of the wall thickness, as per D.M. 08/19/1996;
- *Bar and coffee*: from an on-site survey it is estimated the number of consumers who, on average, crowd the exercise in 60 minutes.

3.1.1 The combined building-path vulnerability and the in-paths obstructions assessments

Remarking the relevance to enquiry the combined effect of built heritage and paths network for the pre-event analyses of the scenario, the current section proposes an new quick methodology for paths network vulnerability assessment in existing city centres (especially in case of historical scenarios) by means of three ad-hoc indices (Santarelli et al. 2017; Santarelli 2018). The indices are obtained taking advantage of macroseismic buildings vulnerability methods (Lagomarsino and Giovinazzi 2006; Giovinazzi and Lagomarsino 2004) and geometric parameters (Ferlito and Pizza 2011; Italian technical commission for seismic microzonation 2014) (see Section 2.1.1).

The Link Vulnerability Index V_{link} considers the vulnerability of buildings facing each path, by also including their effective geometrical incidence on the path length. V_{link} expresses an absolute numerical vulnerability value for each edge of the paths network. A possible scenario relative analyses is also offered through the Normalized Link Vulnerability Index V_{link}^{N}. At last, the Link Blockage Index B_{link}, is offered to consider single building vulnerabilities, earthquake macroseismic intensity (then possible building damage) and street geometric parameters, so as to define if paths could be available in the post-earthquake scenario. In the proposed work (Santarelli et al. 2017), the complete path section blockage is considered, without inquiring the debris depth on the street, since this work is focused on pedestrian evacuation possibility. This way, the work also offers a first approach that tries to overcome the relevant problems in considering earthquake intensity included into quick methods for streets-building interference estimation, that it is still lack.

The proposed methodology (Santarelli et al. 2017) requests that in the interested zone the geometrical and vulnerability values are collected for paths and buildings basing on respective indicated methods, then, the Link Vulnerability Index V_{link} is obtained for each n^{th} edge of paths network following Eq.3 (Santarelli et al. 2017).

$$\boldsymbol{V_{link,n} = \sum_j V_{I,j} \cdot \frac{l_{build,j}}{L_{link,n}}} \qquad \mathit{3}$$

The Link Vulnerability Index V_{link} assesses the expectation of unsafe conditions for pedestrians' evacuation, due to "extrinsic" vulnerable elements along the link. V_{link} influencing factors are: buildings geometrical incidence on the edge dimension in term of lengths of the elements (respectively indicated as $l_{build,j}$ and $L_{link,n}$) and the vulnerability of the j link-facing buildings $V_{I,j}$, as defined in Figure 3-1.

Within the same scenario, the link vulnerabilities can be normalized by dividing single link vulnerability values by the maximum link vulnerability value obtained for the studied edges set. The advantage to work with the so obtained Normalized Link Vulnerability Index V_{link}^{N} is that it is a relative index with finite limits [0, 1], useful to classify paths in descriptive macro-classes (i.e.: 0.00-0.25 low, 0.25-0.40 medium-low, 0.40-0.70 medium-high, 0.70-1.00 high). Furthermore, to have a relative vulnerability system could be useful for planners to design the emergency paths network and to define a priority ranking of interventions on building heritage.

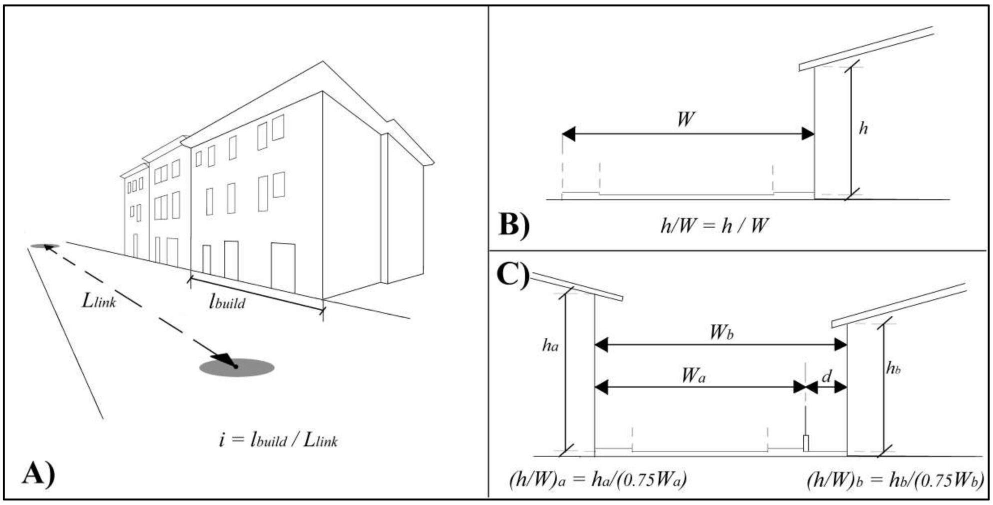


Figure 3-1. Geometrical parameters of buildings and paths adopted by the Link Vulnerability Index with the related measurement technique. Extract from (Santarelli et al. 2017).

V_{link} and V_{link}^{N} can be useful in order to identify the most vulnerable edges of urban streets network but they do not supply any information about the possibility that a given path could be practicable (not presenting entire section blockages) during the evacuation. In fact, vulnerability indices do not depend on earthquake intensity *I*. Therefore, the proposed study (Santarelli et al. 2017) offers the plausibility of link blockages by considering the B_{link} index. This last index does not enquiry about the effective or probable building collapse mechanism, but only the possibility to have a potential strong interference between the built element and the facing paths.

B_{link} bases on the expected damage level of buildings *k95* (conservatively assessed as the 95th percentile of its cumulative distribution function obtained by Eq. 2) and on the building-path geometrical ratio *h/W*. As shown in Eq. 4, when those parameters simultaneously exceed their respective critical limits it could be supposed that both damage and context conditions are present so as the related path section is completely blocked by building debris on street side (Santarelli et al. 2017; Caiado, Macario, and Carlos S 2011; Shimura and Yamamoto 2014):

- About the damage condition, when *k95* is pair to the 4th grade of the EMS-98 scale (Grunthal 1998) are expected heavy structural damages (for masonry structures serious failure of walls, partial structural failure of roofs and floors), implying critical conditions in term of path operability (Caiado, Macario, and Carlos S 2011).
- For the context condition, the method (Santarelli et al. 2017) proposes the limit of *h/W=1*, according to geometrical approaches (Ferlito and Pizza 2011; Italian technical commission for seismic microzonation 2014)]. Such limit condition relates the projection of the entire building façade on the facing path section, considered as the most invasive damage mechanism for the path. Moreover, to consider the unfavourable condition given by facing buildings producing debris on the same street

section, when either path sides are built the path width W is reduced of the 25% (Ferlito and Pizza 2011).

$$B_{link} = \begin{cases} \boldsymbol{Blockage} & \exists\ \boldsymbol{building} \in \boldsymbol{link} \mid \boldsymbol{h/W} \geq \boldsymbol{1} \wedge \boldsymbol{k95} \geq \boldsymbol{4^\circ\ EMS98} \\ \boldsymbol{Practicable} & \boldsymbol{elsewhere} \end{cases} \quad 4$$

Differently from the vulnerability indices, the Link Blockage Index B_{link} can produce alternative path blockage scenarios, different in function of the supposed macroseismic intensity I (considered in $k95$). In this way, it is possible to define a set of different post-earthquake scenarios based on increasing earthquake severity, on which calibrate possible risk reduction and emergency management strategies.

The test of the proposed methodology (Santarelli et al. 2017), evidenced its capability to comprehend and represent the influence of built heritage and respective urban fabric layout, on the safety of historical centre paths network. Produced results offer a map ranking the vulnerable links and exposing the in-paths network points subject to probable blockages depending by the analysed seismic severity. The proposed indices represent a useful tool, combining with classic methods, for the emergency planning of safe paths for evacuees and rescue vehicles and for the designing of strategies for the earthquake emergency mitigation and management.

3.1.2 The damage scenarios prediction

During earthquake emergencies, the paths network permits inhabitants to reach safe areas, and rescuers to access damaged zones and help population. However, after a seism, the buildings along the paths can generate debris amounts on them, whose directly influence the evacuees' safety and the possibility to tread the paths selves both for pedestrians and vehicles. Historical centres paths network especially suffer from that phenomena since their geometrical and context characterization (e.g.: scarce streets widths, high planar complexity, unfavourable relationship between paths and related facing buildings in elevation).

As noticed in Section 2.1.2, the preventive assessment of debris production on urban paths network can be possible by combining vulnerability analyses and debris amount analysis by using aerial images, into experimentally-based correlations (Quagliarini et al. 2016). According to this work, the here proposed method (Santarelli, Bernardini, and Quagliarini 2018) wants to demonstrate the robustness of the experimental approach for debris production prediction and to propose supplementary debris formation criteria by adopting other empirical building vulnerability methods (Tiago M. Ferreira, Vicentea, and Varum 2014; Giovinazzi and Lagomarsino 2004). The adoption of quick empirical vulnerability methods has been confirmed in order to favour a full-scale application for historical centres. Furthermore, the proposed method modifies the original approach in order to introduce the influence of urban context (as geometrical constrains for debris spread) directly from the experimental data extraction. The changes and improvements made by the proposed method (Santarelli, Bernardini, and Quagliarini 2018) are mainly summarized in Table 3-2. In the proposed method, the earthquake building debris amount along the streets mainly depends on: building vulnerability (propensity to suffer a certain damage level); earthquake severity (normalized moment magnitude); street width in respect to the building height (in order to define the possibility of complete path blockage due to ruins).

Factor	*Original approach* (Quagliarini et al. 2016)	*Proposed work* (Santarelli, Bernardini, and Quagliarini 2018)
Earthquake severity	considered as normalized moment magnitude	considered as normalized moment magnitude
Building Vulnerability methods	only one macroseismic method considered (Ferlito and Pizza 2011)	tree macroseismic methods considered (Ferlito and Pizza 2011; Tiago M. Ferreira, Vicentea, and Varum 2014; Giovinazzi and Lagomarsino 2004)
Geometrical context index	not considered	considered (h/W ratio for each building along the path)
V* (independent variable of the prediction laws)	only function of the earthquake severity and of the building vulnerability	function of the earthquake severity, the building vulnerability and the geometrical context
path width covered by debris (dependent variable of the prediction laws)	trilinear law expressing only the average debris depth predicted	conservative bilinear laws expressing the maximum and the average predicted percentage of path width covered by building debris
reliability of the law	considered by R^2	considered by R^2 and statistic error analyses
debris prediction confidence level for planner	not considered	different exceedance probability (EP) levels of depth overestimation
building typology application	masonry buildings	masonry buildings

Table 3-2. Main changes made by the proposed method (Santarelli, Bernardini, and Quagliarini 2018) *to the original one* (Quagliarini et al. 2016).

Adopting a such modified approach, new and more reliable experimental correlation for the debris depth prediction have been obtained. Figure 3-2 shows the obtained bilinear correlations, and related equations, for the maximum and the average trends.

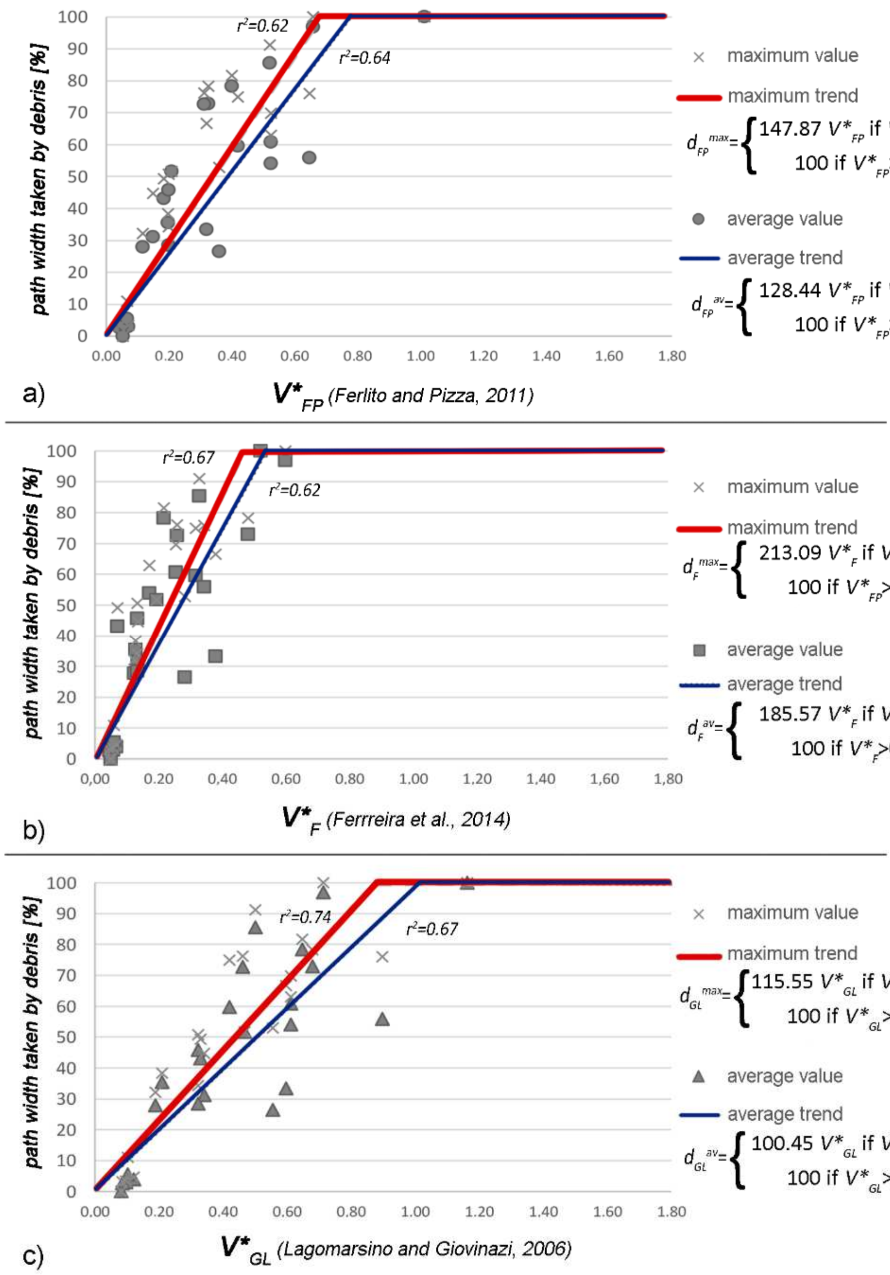


Figure 3-2. New prediction laws offered by (Santarelli, Bernardini, and Quagliarini 2018) *for the three enquired building vulnerability method* (Ferlito and Pizza 2011; Tiago M. Ferreira, Vicentea, and Varum 2014; Lagomarsino and Giovinazzi 2006). *Red lines and blue lines*

respectively highlight, for each method, the expected maximum and average percentages of street section covered by building debris.

The methodology (Santarelli, Bernardini, and Quagliarini 2018) has been tested on post-earthquake aerial images related to a part of Corso Umberto I in Amatrice, (IT). The employed images only refer to the damages related to the 2016 August 24 shake. Obtained results seem to confirm the capability of the propose methodology in describing such emergency scenarios issues (for both representing "average" and maximum debris production conditions). Furthermore, they evidence that, independently from the adopted vulnerability method, a good bilinear correlation between earthquake debris generation and modified vulnerability index V^* exists.

The choice of which vulnerability method could be used can vary depending on the owned detail and the level of building data within the scenario, the skill of the compiler, as well as the desired level of confidence about predictions uncertainties. Especially in historical centres, the expected damage scenarios could be forecast so as to evidence the conditions of the post-earthquake urban environment during the evacuation phases and the possible presence (and related location) of street blockages which could hinder the evacuation processes and first responders operation (both on foot and by vehicle).

The method, offering punctual results for each side of the analysed buildings, can be used for the preventive analysis of damage scenarios. However, given the computational burden deriving from its application on entire urban scenarios, its use can be optimized by implementing it in dedicated software tools or integrating it with already existing tools.

3.1.3 The path risk assessment

As underlined in Section 2.1, current methodologies for the earthquake risk assessment of paths network in historical centres, (representing a strategic element for both evacuees' and rescuers), seem to be affected by different lacks. For example, they seem to overlook aspects related to the presence of underground cavities (influencing the seismic wave and the built response), possible local soil phenomena (i.e.: liquefaction) and other risk deriving from the presence of underground pipelines (Lancioni et al. 2014; Menoni et al. 2002). Although some studies (Adafer and Bensaibi 2015; Cherubini 2002; Ferlito and Pizza 2011) offer reliable bases to this end, no one seems to involve the analysis of historical centre scenarios by including the combination of effects related to the previous factors.

In this section, a new holistic methodology considering the evidenced path risk-affecting factors for historical centres are proposed (Quagliarini et al. 2018). Elements composing the paths network, divided in streets (links) and nodes (differenced as points between links or squares), are individually assessed through the related form respectively shown in Figure 3-3 and Figure 3-4. Each form reports a list, for both links and squares, of the main noticed risk affecting factors and the related influencing parameters with possible considered alternatives (each one associated to a numeric value for the definition of the final Risk Index I_R).

ID	Factors	ID	Parameters	Alternatives
A	Path analysis	A.1	Link code	–
			1° Node code	–
			2° Node code	–
		A.2	State	Clear
				Partially obstructed
				Obstructed
B	Exposure	B.1	Street type	Interconnection
				Access
		B.2	Direction of travel	Single
				Double
		B.3	Carriageway	Separated
				Unique
		B.4	Path type	Urban
				Suburban
		B.5	Average Flow	Low
				Medium
				High
C	Geometric features	C.1	Length (m)	$0 < L \leq 0.33\ L_{max}$
				$0.33\ L_{max} < L \leq 0.67\ L_{max}$
				$0.67\ \mathrm{L_{max}} < L \leq L_{max}$
		C.2	Width (m)	$0.67\ W_{max} < W \leq W_{max}$
				$0.33\ W_{max} < W \leq 0.67\ W_{max}$
				$0 < W \leq 0.33\ W_{max}$
D	Physical-structural features	D.1	Finishing surface	Asphalted
				Paved
				Rough
		D.2	Potential landslides	No landslide, retaining walls in both sides
				Landslide, retaining walls in one side
				Landslide, no retaining walls
		D.3	Underground elements	Low-risk pipes
				High-risk pipes
				Caves, cisterns or cavities
		D.4	Conservation state	High
				Medium
				Low
		D.5	Street Typology	Level link
				Hillside link, with retaining walls
				Hillside link, without retaining walls
				Tunnel
				Bridge and viaduct
E	Extrinsic vulnerability	E.1	V_{Nlink}	$0 < V_{Nlink} \leq 25\%$
				$25\% < V_{Nlink} \leq 50\%$
				$50\% < V_{Nlink} \leq 75\%$
				$75\% < V_{Nlink} \leq 100\%$
F	Seismic hazard	F.1	Design ground acceleration (a_g)	$a_g \leq 0.05\ g$
				$0.05\ g < a_g \leq 0.15\ g$
				$0.15\ g < a_g \leq 0.25\ g$
				$a_g > 0.25\ g$
		F.2	Ground type	A
				B
				C
				D
				E
		F.3	Topographic amplification factor	T1
				T2
				T3
				T4

Figure 3-3. Links assessment form The figure is taken from the original methodology paper (Quagliarini et al. 2018).

ID	Factors	ID	Parameters	Alternatives
B	Exposure	B.1	Usage	Wide crossroad
				Pedestrians' zone
				Parking area
		B.2	Presence of obstacles	Absence
				Presence
		B.3	Square type	Urban
				Suburban
		B.4	Average Flow	Low
				Medium
				High
C	Geometric features	C.1		$0.67\ A_{max} < \mathrm{A} \leq A_{max}$
				$0.33\ A_{max} < \mathrm{A} \leq 0.67\ A_{max}$
				$0 < \mathrm{A} \leq 0.33\ A_{max}$
D	Physical-structural features	D.2	Potential landslides	No landslide, retaining walls in more than one sides
				Landslide, retaining walls in one side
				Landslide, no retaining walls
		D.5	Square Typology	Level Square
				Hillside Square with retaining walls
				Hillside Square without retaining walls

Figure 3-4. Squares assessment form The figure is taken from the original methodology paper (Quagliarini et al. 2018).

Three different calculation approaches are proposed to combine the risk-influencing factors (Quagliarini et al. 2018) and then to obtain the I_R index:

- the Modified Cherubini's approach. This approach bases on the original work of Cherubini (Cherubini 2002) for the earthquake vulnerability and risk analysis of urban systems. Mains modifications are done in order to introduce aspects concerning the possible presence of underground elements, the relevance of extrinsic elements for the vulnerability assessment and the consideration of seismic hazard factors due to soil and seismic local characterization;
- the Expert judgement approach is assessed basing on the experience of the research team and on other literature studies. In this approach too, as for each one of the three considered approach, aspects about the underground elements, the extrinsic vulnerability and the hazard factors are introduced by related factors (and so parameters);
- the Analytical Hierarchic Process approach (AHP) (Opricovic and Tzeng 2004; Triantaphyllou 2000) is produced in order to consider a mathematical consolidated procedure ensuring the holistic perspective of the work. As the others produced approaches, aspects about the underground elements, the extrinsic vulnerability and the hazard factors are assessed by the approach.

Figure 3-5 shows the so obtained sets of values (weights), respectively associated to factors Wc_K, to parameters Wi_K and related alternatives Sp_{iK}, for each one of the three calculation approach proposed by the study (Quagliarini et al. 2018).

		Modified Cherubini's approach		Expert judgement		Analytical hierarchy process (AHP)		
Factor ID	Parameter ID	Wc_K	Sp_{iK}	Wc_K	Sp_{iK}	Wc_K	Wi_K	Sp_{iK}
B	B.1	0.2	0.4	0.333	0.4	0.045	0.272	0.5
			0.6		0.6			1
	B.2		0.6		0.6		0.272	0.5
			0.1		0.1			1
	B.3		0.2		0.2		0.036	1
			0.1		0.1			0.5
	B.4		0.6		0.6		0.272	1
			0.3		0.3			0.5
	B.5		0.1		0.1		0.147	0.33
			0.3		0.3			0.67
			0.5		0.5			1
C	C.1	0.40	0.1	0.667	0.1	0.067	0.667	0.33
			0.5		0.5			0.67
			1		1			1
	C.2		0.2		0.2		0.333	0.33
			0.4		0.4			0.67
			0.6		0.6			1
D	D.1	0.80	0.3	1.000	0	0.381	0.143	0.33
			0.55		0.3			0.67
			0.8		0.5			1
	D.2		0.1		0		0.429	0.33
			0.8		0.8			0.67
			1		1			1
	D.3		0.1		0.33		0.143	0.33
			0.6		0.67			0.67
			0.8		1			1
	D.4		0.3		0		0.143	0.33
			0.55		0.3			0.67
			0.8		0.5			1
	D.5		0.1		0		0.143	0
			0.4		0.4			0.25
			0.5		0.5			0.5
			0.6		0.6			0.75
			0.8		0.8			1
E	E.1	0.60	0.25	1.000	0.25	0.126	0.126	0.25
			0.5		0.5			0.5
			0.75		0.75			0.75
			1		1			1
F	F.1	1.00	0.25	1.000	0.25	0.381	0.400	0.25
			0.5		0.5			0.5
			0.75		0.75			0.75
			1		1			1
	F.2		0		0		0.400	0
			0.25		0.25			0.25
			0.625		0.625			0.5
			1		1			1
			0.75		0.75			0.75
	F.3		0		0		0.200	0
			0.25		0.25			0.5
			0.25		0.25			0.5
			0.5		0.5			1

Figure 3-5. List of weights for each one of the three approach proposed by the study (Quagliarini et al. 2018).

Hence, the characterization of paths network elements (done by the related forms) and the three considered calculation approaches are combined, as shown in Table 3-3, to produce the mathematical formulation of path Risk Index I_R related to each approach. The Normalized Risk Index I_R^N for each approach is also offered by the method (Quagliarini et al. 2018) in order to work with a scenario relative scale for risk values (with limits from 0 to 100%). In order to obtain simplified graphical risk maps of the analysed centres, I_R^N values could be organized into four set: low risk (0-25%); medium-low risk (25-50%); medium-high risk (50-75%); high risk (75-100%).

	Modified Cherubini's approach	*Expert judgement*	*Analytical hierarchy process*
description	Weighted sum is normalized by the maximum obtainable from factors and then by the related weight of each factor	Sum of alternatives values, each one weighted for the respective value of factor	The first weighted sum between parameters and alternatives is further weighted by factors' values and finally summarized
I_R	$\sum_{K=1}^{5}\left[\frac{(\sum_i Sp_{iK})}{(\sum_i Sp_{iK}^{max})}\cdot Wc_K\right]$	$\sum_{K=1}^{5}\left(\sum_i Sp_{iK}\cdot Wc_K\right)$	$\sum_{K=1}^{5}\left[\left(\sum_i Sp_{iK}\cdot Wi_K\right)\cdot Wc_K\right]$
I_R^N	$\frac{I_R}{\sum_{K=1}^{5} Wc_K}$	$\frac{I_R}{\sum_{K=1}^{5}(\sum_i Sp_{iK}^{max}\cdot Wc_K)}$	I_R already producing normalized values

Table 3-3. Schematization of the three calculation approaches for the path Risk Index offered by the proposed method (Quagliarini et al. 2018).

A preliminary methodology validation was performed by applying it to a real-world sample (limited to significant Italian case studies), then, the best-performing approach is applied to the historical centre of Offida (AN, Italy) (Quagliarini et al. 2018).

According to obtained results, this novel holistic methodology can be applied to have under control the overall risk situation of paths in historical centres and so to provide evaluation tools for scenario assessment and emergency planning. During the evaluation of evacuation management strategies, results from its application could suggest which links should be excluded from selected paths because of their high-risk level, and which could be considered safer (according to a relative scenario sample-based scale).

3.2 Definition of a safety guidance methodology for Intelligent Evacuation Guidance System (IEGS)

3.2.1 Ontology for IEGS, related problems and limits

Adopting the paradigms of distributed intelligence - Internet-of-Thing (IoT) (Guinard, Trifa, and Wilde 2010; Naser and Kodur 2018), behavioural modelling (Simeone 2015; D'Orazio, Quagliarini, and Bernardini 2017) and Supporting digital technologies for information and building modelling (Antwi-Afari et al. 2018), intelligent emergency guidance systems produced for urban environments must be designed to network intelligent and interactive building components , able to:

1. "understand" in a timely manner what are the environmental conditions and the actions of the users through a network of sensors incorporated in technological systems and traditional or innovative components;
2. "evaluate" (and "predict") the impact of boundary conditions on the level of performance for the occupants (e.g.: comfort, safety, use) through models of human-environment and forecasting interaction;

3. "interact" with the occupants (with environmental or individual devices) and adapt automatically (mainly by changing the status of its "active" elements, such as those with integrated electrical components) to the users' functional requests. This section proposes an ontological definition of intelligent emergency guidance systems according to an initial unifying scheme (regardless of the type of emergency), both in architectural spaces indoors and outdoors (Santarelli et al. 2018).

A guidance system is intelligent when it is able to question itself, heuristically process the information collected and operate accordingly to its state. Therefore, its components must guarantee the interoperability of the system itself. To this end, they exploit the IoT (Internet of Things) technologies (Guinard, Trifa, and Wilde 2010), especially if spread over the territory, thus configuring themselves as an interconnected network in which the individual devices are able to communicate, exchange data (between them, with the outside, with the processing centre) and maintain a limited degree of elaborative autonomy. Without the interconnection between the parts, the system lacks the possibility of knowing its status and, despite the presence of heuristic processes, it loses the potential of intelligence. From the analysis of the operative characters (in a many-one-many scheme), three main functional elements are identified:

- the *sensorial nodes*, responsible for monitoring the basic variables related to the environment and the occupants. As shown in Table 3-4-A, the detectable quantities are aimed at knowing and measuring flows of people and the presence of missing/trapped people, danger and usability of the space;
- the *processing core* contains control algorithms and is able to combine and refine the data collected by the sensorial nucleus to extrapolate more complex information (e.g.: neural networks due to evolution and expansion of the emergency over time, impractical paths, movement and behaviour of people), presence of emotional alterations, state of health / need for help). On these bases, it produces the safe route maps and processes the evacuation routes for the evacuating, dynamically variable with the emergence of the emergency and the forecast scenarios carried out;
- the *implementation nodes* direct evacuators according to the evacuation plan and along the processed escape routes. As shown in Table 3-4-C, the devices that can be used for this purpose are many and their use, sizing and application varies according to the architectural space considered (i.e.: driving through collective building components or individual devices such as smartphones).

These three functional nuclei are sequentially connected and cyclically iterated according to a predefined time interval (linked to the characters of the emergency or to the utilities of the system). The cycle starts when the system detects (automatically or manually) the emergency and ends only when it returns. The same element can perform multiple local functions (e.g.: local flow controls) to respond when the interconnection fails, accelerating the calculation process from an IoT perspective.

Methods/Devices	Main scope	Employ	Measures
A- Monitoraggio:			
temperatura	rivelamento incendi	indoor	°C, °F, °K
umidità	rivelamento incendi	indoor	%, var%
	segnalazione percorsi inagibili	ind./outd.	varie

fumi, polveri, agenti tossici	segnalazione percorsi inagibili	ind./outd.	booleana
presenza di ostruzioni	calcolo capacità di deflusso	outdoor	m
ampiezza libera del percorso	calcolo capacità di deflusso	ind./outd.	pers/m2
affollamento	profilazione, indirizzamento soccorsi	ind./outd.	x, y, z
posizione persone	profilazione, indirizzamento soccorsi	ind./outd.	varie
registrazioni audio/video			
B- Elaborazione:			
algoritmi d'instradamento	valutazione delle vie di esodo	ind./outd.	percorso
algoritmi di controllo	verifica delle condizioni presupposte	ind./outd.	varie
modelli simulazione diffusione incendio (CFD, FDS)	sviluppo probabilistico emergenza	indoor	varie
modelli simulazione generazione macerie sismiche	sviluppo probabilistico emergenza	outdoor	varie
tecniche di data mining	sviluppo probabilistico dell'emergenza	ind./outd.	varie
C- Guida d'emergenza:			
allarmi	allertamento collettivo evacuanti	ind./outd.	dB, lux
diffusori sonori	informazione collettiva evacuanti	ind./outd.	dB
cartelli segnaletici attivi	instradamento collettivo evacuanti	ind./outd.	lux, m
portali led colorati	segnalazione percorso inagibile	ind./outd.	lux, m
laser	instradamento in bassa visibilità	outdoor	nm, mW
applicazioni smartphone	istradamento singolo evacuante	ind./outd.	-

Table 3-4. Not exhaustive list of main methods/devices related to each functional core, taken from (Santarelli et al. 2018).

3.2.2 A novel IEGS method for the earthquake emergency in historical and urban centres

Basing on the state of the art offered in Section 2.3, this part of the work aimed at defining a new guidance method for a safer evacuation in case of earthquake evacuation in urban systems (Bernardini et al. 2017b). According to the presented ontology for IEGS, the overall system architecture of the proposed dynamic guidance system (*Seismic Pedestrians' Evacuation Dynamic Guidance Expert System* - *SpeedGuides*) is developed on three main pillars. A simplified scheme of its configuration, together with the main functional elements, are shown in Figure 3-6.

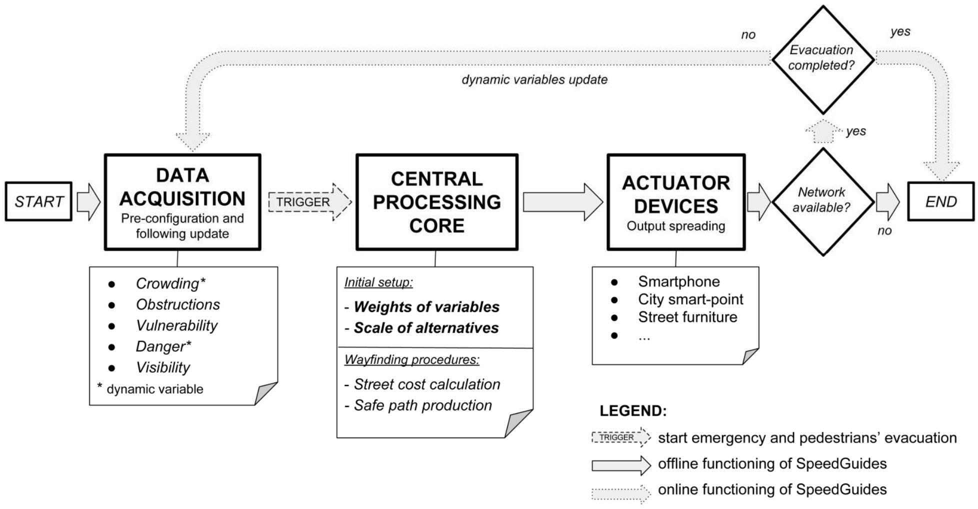


Figure 3-6. SpeeddGuides overall architecture and main competences of each involved module, taken from (Bernardini et al. 2017b). *Different arrows in the scheme show the on-line and the off-line functioning of the system.*

SpeedGuides (Bernardini et al. 2017b) can lead evacuees along the safest paths to a safe destination (extracted from emergency plan) by considering the main variables influencing their motion performance. As previously stated, the evacuees' safety is influenced by the variable *Crowding, Obstructions, Vulnerability, Danger* and *Visibility*. A distinction between optimal, limits and unacceptable conditions in term of safety is offered adopting the ad-hoc scale $a_j = [0,1] \cup \{K\}$. 0 corresponds to the optimal condition, 1 to the limit condition and the isolated value K to the unacceptable condition. Values between the limits 0 and 1 correspond to intermediate conditions. For each variable, the assessment methods are considered as follows:

- *Crowding* relates to the influence of human densities on respective escaping velocities within each paths of the network. This factor is directly related to behavioural aspects, mainly the path choices. In our method, this variable is measured by using the Level Of Service *(LOS)* for pedestrians (see Section 2.1.4), as reported in Figure 3-7. While *LOS A* and *B* are assumed from the study as optimal density conditions for evacuation, *LOS E* is the limit acceptable condition where the group dynamics take over the individual preferences in term of speed and direction (*LOS* C and *D* are intermediate conditions between these two condition). *LOS F* is assumed by the study as an unacceptable condition for evacuation since the pedestrians' speed is almost null, physical contacts involve evacuees and escape is not possible;
- *Obstructions* relate to the possible presence of debris (from damaged buildings) along the paths. In this study we focus on streets blockade by debris, which cannot be used to escape form pedestrians. The paths blockages states (assessed through the Boolean values 'Blockage' and 'Practicable') is assessed by damage previsions (or real-time data) (Kwan and Ransberger 2010; Dong and Shan 2013). According to the

methodology for the in-path obstruction assessment, proposed in Section 3.1.1, we assume that a street section is reasonably closed when the following two conditions are contemporarily verified for almost one structural unit along the path: the damage of structural unit is equal or higher than the 4th grade of EMS-98 (Grunthal 1998) and the ratio between the height of the structural unit and the width of the facing street section is higher or equal to one (see Eq.4). (Italian technical commission for seismic microzonation 2014; Ferlito and Pizza 2011). Following this statement, the presence of the 'Blockage' condition along the path corresponds to the unacceptable condition, otherwise the path is 'Practicable' (optimal condition);

- *Vulnerability* assesses the tendency of built elements of the escape path (e.g. buildings, monuments, towers, bridges and embankment) to suffer earthquake-induced damages. The present work adopts quick macroseismic method for buildings vulnerability (Lagomarsino and Giovinazzi 2006) and single vulnerability value for each path of the studied zone according to the method proposed in Section 3.1.1 (Santarelli et al. 2017). Vulnerabilities are normalised within the case study and organized in four vulnerability classes. This variable cannot produce unacceptable conditions for evacuation since its independency from earthquake severity parameters;
- *Danger* relates to the possibility for evacuees to be involved in fatalities along the path (effects due to, e.g. fires, toxic smoke or dust, explosions, earthquake-induced floods) (Bernardini, D'Orazio, and Quagliarini 2016). The intensity of each threat cause depends on the different effects on exposed people's health. Minor intensities can produce delays in evacuation without interrupting it, while mortal threats must be avoided (or rather, they imply the unavailability of the related street). As shown in Figure 3-7, the proposed three levels for this variable are based on the possible effects on evacuees' health.
- *Visibility* affects the individuals' perception of the surrounding environment. 'Bad visibility' conditions (e.g. presence of thick dusts, smoke, darkness, black-out conditions) along a path can provoke deceleration of pedestrian's escaping motion (D'Orazio et al. 2014). Hence, paths with 'good visibility' should be preferred. Values are here defined by adopting a qualitative point of view.

The defined variables do not have the same importance in evaluating the evacuees' safety levels (Socharoentum and Karimi 2016; Bernardini, D'Orazio, and Quagliarini 2016). Hence, the relevance of each influencing variable on the safety cost of path is associated to a weight w_j. According to other works on earthquake risk assessment, the Analytic Hierarchy Process (AHP) method (Saaty 1980; Triantaphyllou 2000) is adopted to propose a 'severity' ranking of the affecting factors. The Weight Sum Model *(WSM)* (Triantaphyllou 2000) is adopted for evaluating the safety cost of the i-th path $C_{P,i}$ by merging all the variables in a single index, as shown in Eq. 5. The higher is the street cost, the lower is its estimated safety.

$$\boldsymbol{C_{P,i} = \sum a_j \cdot w_j} \qquad \qquad \boldsymbol{5}$$

For $j = Danger, Obstruction, Crowding, Vulnerability, Visibility.$

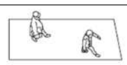
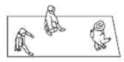
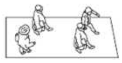
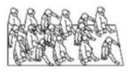
Variable	*Reference of variable*	*Level*	*Description*	a_j
Crowding	(Fruin, 1971)	 *LOS B*	• Pedestrian Space > 3.7 m²/p; • Walking speed freely selected. Sufficient area to bypass other pedestrians and avoid crossing conflicts.	*0*
		 *LOS C*	• Pedestrian Space 3.7÷2.2 m²/p; • Space sufficient for normal walking speeds and for bypassing other pedestrians. Crossing can cause minor conflicts.	*0.33*
		 *LOS D*	• Pedestrian Space 2.2÷1.4 m²/p; • Freedom to select individual walking speed and to bypass pedestrians is restricted. Crossing or reverse flow with conflicts.	*0.66*
		 *LOS E*	• Pedestrian Space 1.4÷ 0.75 m²/p; • Pedestrians restrict their normal walking speed, space is not sufficient for passing slower ones. Limit of walkway capacity.	*1*
		 *LOS F*	• Pedestrian Space < 0.75 m²/p; • Walking speeds are severely restricted.	*k*
Obstruction	(Santarelli, Bernardini, Quagliarini, & D'Orazio, 2017)	PRACTICABLE	Street without blocked sections.	*0*
		BLOCKAGE	Street with almost one blocked section	*k*
Vulnerability	(Santarelli et al., 2017)	$0.00 \leq V_{link}^{N} < 0.25$	Low (L)	*0*
		$0.25 \leq V_{link}^{N} < 0.40$	Medium-Low (ML)	*0.33*
		$0.40 \leq V_{link}^{N} < 0.70$	Medium-High (MH)	*0.66*
		$0.70 \leq V_{link}^{N} \leq 1.00$	High (H)	*1*
Danger	(Bernardini, D'Orazio, & Quagliarini, 2016)	OPTIMAL	No threat along the street.	*0*
		LIMIT	Minor threat (e.g.: slight dust, no toxic smoke, small localized fires).	*1*
		UNACCEPTABLE	Mortal threat (e.g.: thick dust, toxic smoke, widespread fires, explosion, toxic substances leaks, floods).	*k*
Visibility	(D'Orazio, Spalazzi, Quagliarini, & Bernardini, 2014)	GOOD	Absence of visibility interferences.	*0*
		BAD	Presence of smoke, thick dust, darkness.	*1*

Figure 3-7. Schematization of the influencing variable, with related assessment methods and discretization scale, adopted by the proposed method SpeedGuides (Bernardini et al. 2017b).

The safest path connects the initial individuals' position node to a destination node (a safe area or other strategical structures) and it is calculated by applying the Dijkstra's best path algorithm (Zhan 1997). This algorithm finds the minimum cost path in both oriented and non-oriented graphs. As $C_{P,i}$ expresses the edge (path) safety level, the minimum cost path (the one minimising the sum of each edge $C_{P,i}$) is the safest way to escape from the starting point to the destination.

When a network is available, the variables are regularly updated coherently with the nature of the emergency and to the employed technologies. This allows the proposed guidance system (Bernardini et al. 2017b) to comprehend the real scenario (related to both environmental and behavioural elements) and to opportunely change the offered information optimizing the safety of suggested ways to emergency areas. The proposed IEGS (Bernardini et al. 2017b) is tested on the case study of Civitanova Marche (MC, Italy) with the help of behavioural simulator specialized for earthquake emergency (D'Orazio et al. 2014; D'Orazio et al. 2014).

By implementing the proposed guidance system in personal or collective devices, evacuees could take advantage of expert judgement and navigation algorithm during the evacuation process by only employing an ad hoc database (defined also in near real-time with the emergency course). Adopting robust emergency guidance systems during evacuation in historical centre could improve the effectiveness of the self-help practice, improve the people's safety during the evacuation and reduce the risk of the historical centre adopting not-invasive solutions based on the exposition factor management.

3.3 Research of the best-performing emergency layout with and without the safety guidance facility

3.3.1 Assessment of the alternative emergency layouts

Basing on the previous proposed methodologies, a pre-event analyses can be offered. The enquired aspects will represent the bases to produce a first proposal for the designing of several alternative emergency layouts. In fact, the jointly consideration of vulnerability, probabilistic post-earthquake scenarios and risk, could lead the emergency planner to research and evaluate further solutions than the ones proposed by traditional planning methods. Employing the proposed indices, is also possible (and recommended) in this phase to produce an analyse, and following emergency layouts, based on the expected earthquake severities. In this sense, the designed alternative layouts will intrinsically consider the seismic characterization specifically for the place they are applied.

The performance of each alternative emergency layout is assessed with the help of the simulation software EPES (D'Orazio et al. 2014; D'Orazio et al. 2014) (Section 2.1.3), specialized for the urban earthquake emergency. The employ of simple simulation outputs and KPIs (see following Section 3.3.3) could represents a simple but valid evaluation technique. Through this procedure is possible to operate the iteration process toward the definition of the "best-performing" emergency layout. The so obtained "best-performing" layout represents the solution to the optimization problem for the designing of emergency plan without the introduction of further evacuation facilities or the interventions on historical heritage. That proposed planning methodology, combining traditional and innovative methods, is calibrated on the peculiarities of the historical centre and on the real evacuation dynamics between people and post-earthquake environment.

Three alternative emergency layouts are tested:

- *Layout A* - municipal emergency plan. The only safe areas present in the municipal emergency plan are considered;
- *Layout B* – maximization of the safe areas. Starting from the layout A, new further safe areas are introduced wherever the urban fabric allows this possibility;

- *Layout C* – optimization of the safe areas. Starting from the layout B, the less populated safe areas are deleted to favourite the reaching of others nearby waiting areas.

Only the best alternative, deriving from the simulation results, is considered in the following phases of the work.

3.3.2 Introduction of the proposed guidance system

Once founded the best alternative, the performance of this emergency layout is tested with and without the introduction of the safety guidance system proposed in Section 3.2.2. In this phase of the work, the maximum expected earthquake intensity is considered and the two methodology for the post-earthquake damage scenarios assessment, respectively proposed in Sections 3.1.1 and 3.1.2 (Santarelli, Bernardini, and Quagliarini 2018; Santarelli et al. 2017), are implemented in the simulator.

Similarly to the tests produced for the evaluation of the best alternative, the influence of the proposed guidance system (see Section 3.2.2) and its capability to modify the evacuees' behaviour, in term of motion and interactions during the evacuation, is assessed taking advantage of EPES simulation tool (D'Orazio et al. 2014; D'Orazio et al. 2014). Operatively, minimizing the safety cost associated to each edge of the paths network, several preferential evacuation routes can be defined for the analysed centre. Such routes connect each node of the paths network to the planned safe areas so as in every decisional point of the path network the evacuees can have a suggested way to follow. Despite the suggestions concerning safe ways, the presence of the implemented behavioural model allow the evacuees to interact with each other and with the surrounding environment so that, even if assisted, the evacuation process respects real behavioural dynamics.

The comparison between spontaneous (without the safety guidance facility) and guided evacuation performances is analysed. According to the KPIs definition, in order to assess the effectiveness of the introduced guidance system, the several scenarios have been compared. In this work, the maximum expected seismic severity is adopted in simulations. The related post-earthquake damage scenarios, considered by the simulator, are assessed through the implementation of the previously presented methods for debris depth prediction (Santarelli, Bernardini, and Quagliarini 2018) and for the in-paths obstructions assessment (Santarelli et al. 2017). The choice to implement and test both these methods for the post-earthquake scenario assessment, is due to the fact that all two own a good statistical approximation of real data but, their different methodology and their slightly different aims offer a differently conservative analyse. Recent studies (Quagliarini, Bernardini, and Lucesoli 2019) demonstrate that, despite the in-paths obstructions method (Santarelli et al. 2017) produces a less conservative analyse, it offers a best approximated analyses of damage scenarios if considered in whole terms. However, only the debris depth prediction low is considered for the simulations concerning the choice between the alternative emergency layouts while, both methods are considered for the assessment of "best-performance" layout with and without the safety guidance facility.

Table 3-5 summarizes the simulations plan followed in this study for the choice of the best-alternative layout and the evaluation of the introduction of the safety guidance system also depending on the adopted methodology for the post-earthquake damage scenario.

Stage	Earthquake Intensity	Population [people]	Post-earthquake damage scenario	Emergency layout	Path choice mode
best-alternative	6°	1400	debris depth prediction	A – municipal emergency plan	spontaneous
	6°	1400	debris depth prediction	B – safe areas maximization	spontaneous
	6°	1400	debris depth prediction	C – safe areas optimization	spontaneous
best-performing	6°	1400	debris depth prediction	I – best-alternative	spontaneous
	6°	1400	debris depth prediction	II – best-alternative with guidance system	guided
	6°	1400	in-path obstructions	III – best-alternative	spontaneous
	6°	1400	in-path obstructions	IV – best-alternative with guidance system	guided

Table 3-5. Summary of the produced simulations evidencing the scenarios tested for the research of the best-alternative layout and of the best-performing solution

3.3.3 Key performance indicators (KPIs) for the results evaluation

To assess the effectiveness of an emergency layout and the effects it can have on evacuation processes the Key Performance Indicators (KPIs) have been adopted in this work. These indicators return a quantitative indication of the individual evacuation progresses and of the overall exodus process. Basic indices, offered in output by the adopted simulator EPES (D'Orazio et al. 2014), can be combined in higher abstraction KPIs, whose allow to evaluate significant and not immediate aspects related to the tested solution. Hence, the use of KPIs makes it possible to evaluate the effectiveness of the tested solution and its influence in terms of safety for people. Table 3-6 presents a brief description and the mathematical formulation of the KPIs used in the present study. All symbology notations are shown in the notation table of Appendix A.

KPIs	Description	Equation	Measure
$\overline{t_{evac,sa}}$	Average time taken by evacuees to reach the interested waiting area	$\overline{t_{evac,sa}} = \sum_{Np,sa} t_f - t_i / N_{p,sa}$	[s]
$t_{evac,sa}^{max}$	Maximum time taken by evacuees to reach the interested waiting area	$t_{evac,sa}^{max} = max(t_f - t_i)_{sa}$	[s]
$\%_{p,na}$	Percentage of population that stops in temporary opportunistic shelters (overall data)	$\%_{p,na} = N_{p,na} / N_{ptot} \cdot 100$	[%]
$\%_{p,sa}$	Percentage of population that reaches the interested waiting area over the time D_{evac}	$\%_{p,sa} = N_{p,sa} / N_{ptot} \cdot 100$	[%]
$\overline{t_{evac}}$	Average time taken by evacuees to reach the waiting areas (overall data)	$\overline{t_{evac}} = \sum_{Npzs} t_f - t_i / N_{pzs}$	[s]

t_{evac}^{max}	Maximum time taken by evacuees to reach the waiting areas (overall data)	$t_{evac}^{max} = max(t_f - t_i)$	[s]
D_{evac}	Duration of evacuation, computable for the entire process or for a partial component (e.g.: a section of the evacuation route)	$D_{evac} = t_{f,max} - t_{i,min}$	[s]
$\%_{psa,tot}$	Percentage of population that reaches the waiting areas over the time D_{evac} (overall data)	$\%_{psa,tot} = \sum_j \%_{p,saj}$	[%]

Table 3-6. List of the Key Performance Indicators (KPIs) used by the proposed thesis for the evaluation of the methodology related to the emergency planning and the guidance system.

Further than the numerical KPIs, a graphical elaboration of obtained results can be offered by the evacuation flow curves. That representation shows the number of individuals arrived in the safe areas (waiting areas) as function of the lasted simulation time. In a such kind of analyses the performance related to several solutions could be directly compared either for singles safe areas that for the overall scenario.

3.4 Application to a real case study

The proposed methods, and the related analyses, are applied to a case study in order to show their capabilities, the offered results and the contribute they could take in the emergency designing process for the earthquake emergency in urban and historical centres. An historical village, representative of the most of Italian historical centres, has been chosen for the application. The necessary data, resumed in Table 3-1, together with the cartographic supports, the municipal emergency plan and the LCE analyse of the centre, have been collected with the contribute of the municipal offices. Two seismic severities are considered for the offered results: the most frequent and the maximum expected earthquake macroseismic intensities (Grunthal 1998), defined for the case study through historical data. In this work, a perimeter within the case study have been selected in order to limit the quantity of proposed results and focuses on the application and potentialities of the proposed methodologies. Following Section 4.1, punctually presents all the previous defined elements, data and parameters for the selected zone of the case study. All the innovative methods and tools, proposed in this work of thesis, have been assessed for the case study and presented and discussed in Section 4.2. It is important to highlight that, although the case study is representative of a wider reality, the obtained results are calibrated specifically on the features of the considered historic centre (e.g.: population, urban fabric, vulnerability, geometries, paths network). For this reason, a "higher" level of abstraction is recommended in reading these results, suitable for understanding how the application of the proposed methods can contribute to seismic emergency planning in historical centres.

Chapter IV

4 Application of the innovative methods

4.1 The Offida case study

The proposed methodology has been applied to the old centre of Offida (AP, Italy), that is a touristic historical village located about 16 Km inland from San Benedetto. As demonstrated by Figure 4-1, this old village has medieval origins and at today it preserves its structures almost unchanged both in terms of the urban fabric and the built heritage. The medieval build heritage is mainly characterized by two or three floors masonry and stone buildings that, during the time, have been partially restored. The urban fabric presents the original paths network. It is characterized by narrow and irregular edges, and by a generally widespread building-path geometrical ratio (relation between the building height and the facing street width) higher than the unit.

Concerning earthquake risk, Offida is characterized by a medium-high level of seismic hazard (seismic zone 2) [3] with an expected PGA between 0.175 – 0.200g associated to a return period of 475 years (source: http://esse1-gis.mi.ingv.it/, last access 10/05/2019). The data provided by the Regional Department of Historical Seismology of the National Institute of Geophysics and Volcanology (INGV) testify to the occurrence, between 1882 and 2006, of 43 seismic events, 10 of which with an intensity between the V and the VIII degree of the MCS scale (extracted from the Italian macroseismic database 2015, source: https://emidius.mi.ingv.it/CPTI15-DBMI15/query_place/, last access 05/05/2019). Figure 4-2 shows the temporal distribution of the most significant earthquakes that have involved the territory of Offida and the related macroseismic intensity estimated basing on the damages and the effects perceived in the territory in question. Recently, Offida has been affected by intense seismic activity over times, including the ones connected to the Central Italy seismic sequence in 2016–2017 (in this case, without reporting considerable damages).

The maximum and the most frequent expected earthquake severities (measured in moment magnitude scale) are respectively equal to 6.0 and 4.0 Mw. According to a conservative approach, the application of the proposed methodologies and the related validation process is exclusively offered for the maximum expected severity (Mw equal to 6.0). However, a real emergency planning process can take advantage of assessing and testing several earthquake severities in order to obtain wider analyses.

[3] OPCM 3274/2003, Annex A - seismic classification of Italian Municipalities

Figure 4-1. Comparison between the actual aerial image and the Gregorian cadastre (1935) for the historical centre of Offida. The original paths and buildings systems are almost completely preserved at today.

Concerning the seismic soil response, local amplification phenomena are investigated by the earthquake microzonation. Regarding the Municipality of Offida, this study is reported in the Municipal Civil Protection Plan published in September 2012. Offida was assigned classes A, B, B +. Calculated the Housner's intensities, for all the available velocimetric recordings, we proceeded to renormalize Housner's ratios and converted them into amplification coefficients, according to the following table: A = 1.0; B = 1.1; B + = 1.2, shown in Figure 4-3 extracted from the municipal civil protection plan.

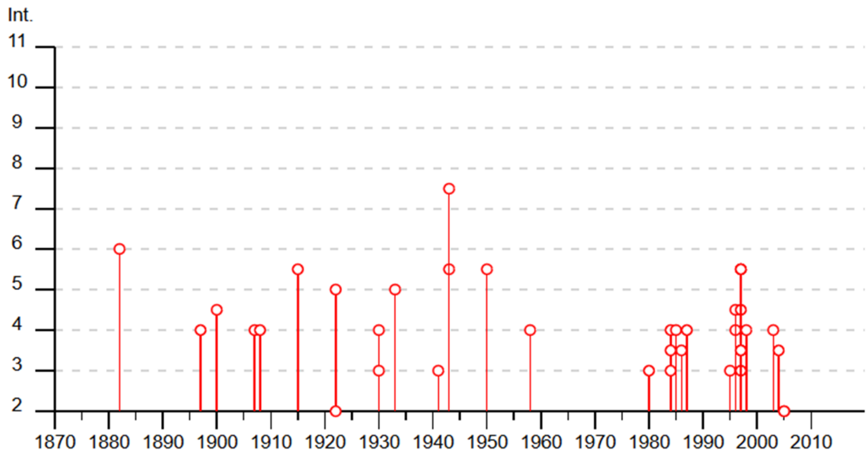


Figure 4-2. Representation of the historical seismicity for the territory of Offida offered by the INGV (Italian National Institute of Geophysics and Vulcanology) updated to the 2015 census. (https://emidius.mi.ingv.it/CPTI15-DBMI15/query_place/, last access 05/05/2019)

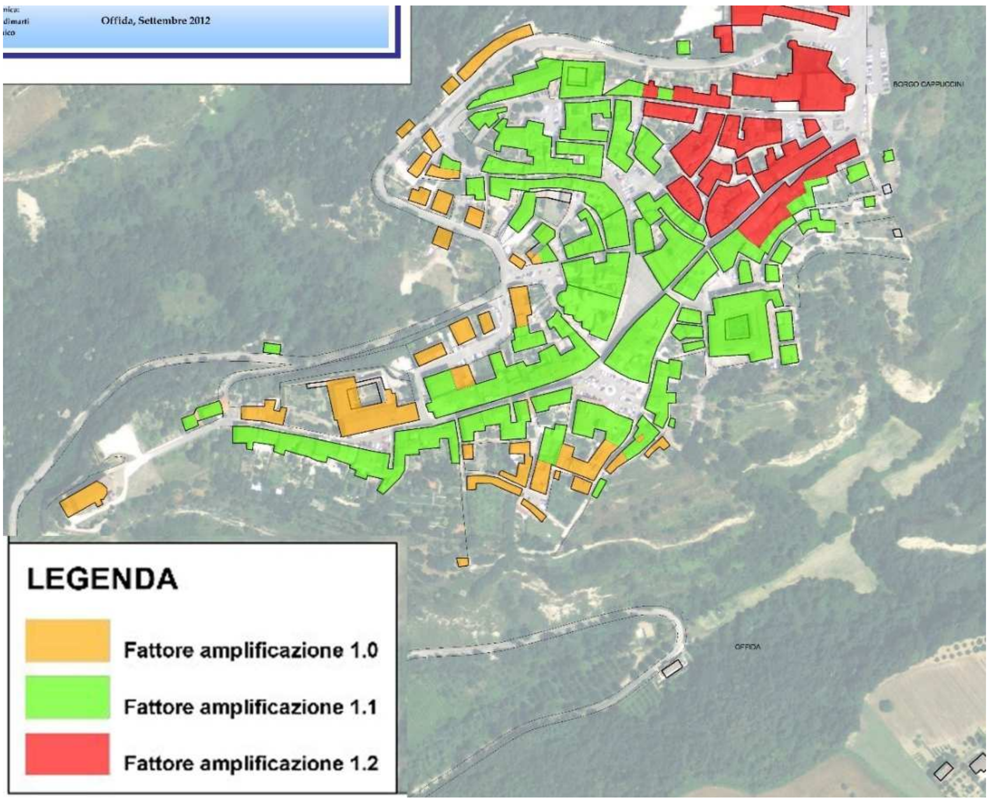


Figure 4-3. Map of local soil amplification phenomena produced by the microzonation study for Offida and offered by the Municipal Plan of Civil Protection.

From the human exposition point of view, the historical village of Offida is characterized by both residential and touristic population. Its significative artistic and cultural value (presence of religious sites, theatre hosting exhibitions during the whole year, museums, cultural events in both winter and summer seasons) is confirmed by the population analyses offered in following Section 4.2.1.

In the end, the historical centre of Offida (its buildings and urban fabric features, its level of seismic hazard and its population) can be considered as representative of the majority of Italian medieval centres.

4.1.1 Current regulations: the emergency plan and the CLE

Figure 4-4 shows an extract from the municipal emergency plan of Offida in which, in green, the Waiting Areas are highlighted. According to the Section 2.2.1, Waiting Areas are "places of first reception for the population; squares, squares, parking lots, public or private spaces that are not at risk (landslides, floods, collapse of adjacent structures, etc.) can be used, reachable through a safe route. The number of areas to choose is a function of the accommodation capacity of the available spaces and the number of inhabitants. In these areas the population receives the first information on the event and the first kinds of comfort. The Population Waiting Areas will be used for a period of time ranging from a few hours to a few days" [4]. Hence, these zones are especially relevant for the survivors in the first post-earthquake evacuation phase. A careful analyse of the Waiting Areas, indicated by the emergency planner for the interested zone, reveals the planning strategies: all the squares and outdoor spaces with a minimum considerable capability are indicated, even if they are not directly reachable by the strategic emergency paths indicated by the CLE. In fact, the analyse of Limit Conditions for Emergency (CLE), shown in Figure 4-5, highlights that planned Shelter Areas and Gathering Areas are located out of the historical centre and are reachable only by vehicles. Then, the predisposed connection infrastructures (red lines in Figure 4-5) link the Waiting Areas, reached by people during the immediate post-earthquake evacuation, to the other areas for longer stay. Therefore, although the redundancy of safe areas is a safety-oriented choice, not all areas indicated by the plan have the same relevance (as possibility to be timely rescued).

[4] Definition by the Civil Protection Glossary

(http://www.protezionecivile.gov.it/jcms/it/glossario.wp?contentId=GLO13370 last access: 30/05/2017)

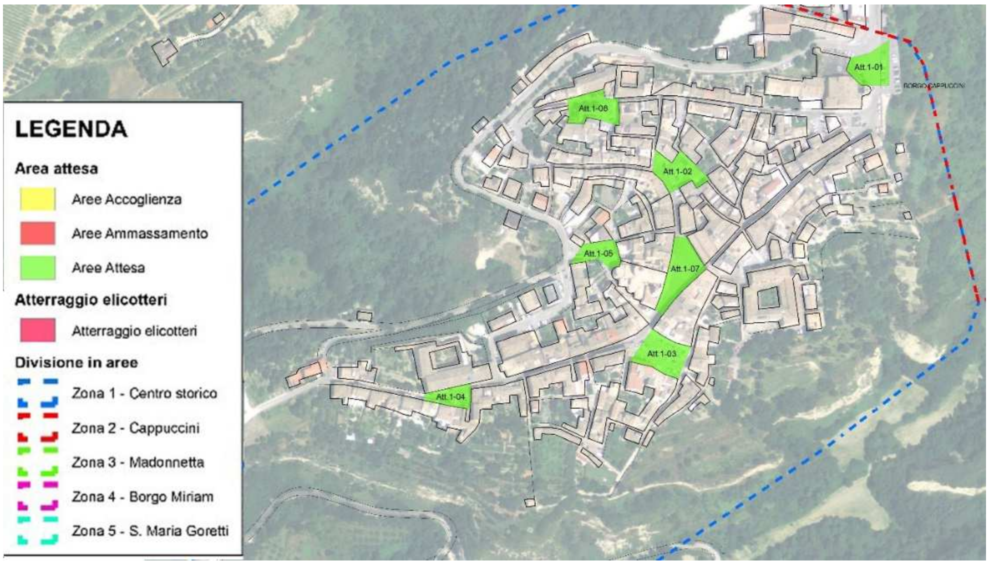


Figure 4-4. Extract from the municipal emergency plan of Offida. The strategic elements of the plan (e.g.: waiting areas, gathering areas, reception area) concerning the historical centres are evidenced in the figure.

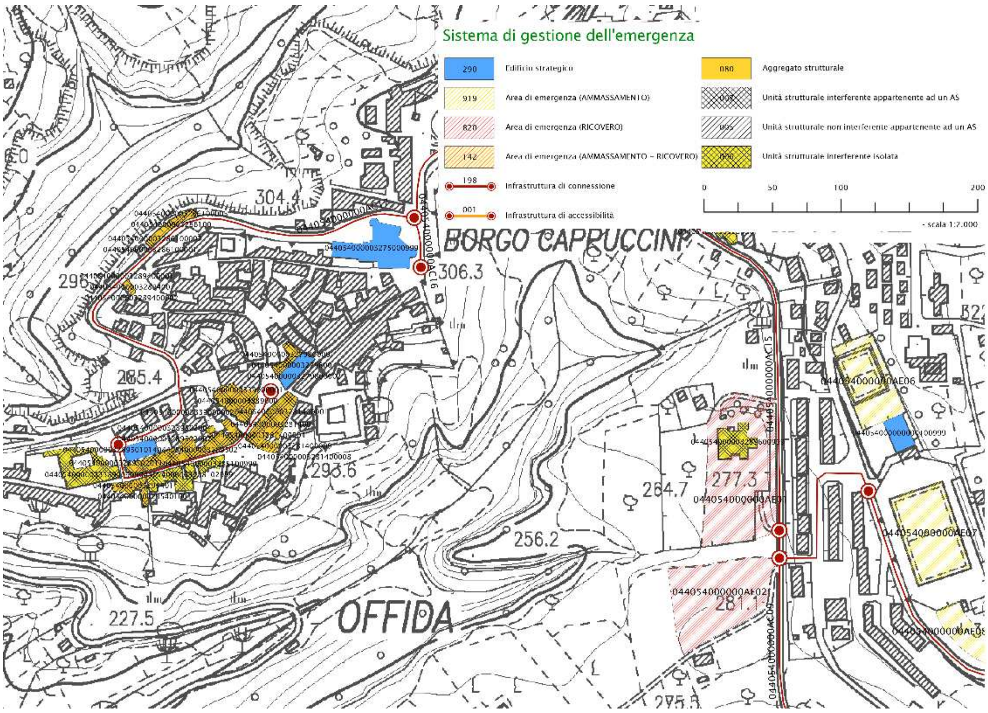


Figure 4-5. Extract from the Emergency Limit Condition (CLE) analyses concerning the historical centre of Offida (updated to October 2018). The planned systems of emergency paths, strategic structures and interferent buildings, according the municipal emergency plan of Figure 4-4, are shown in the figure.

4.2 Results of the application of the novel methodologies

4.2.1 Pre-event scenario analyses

According to Section 3.1, the population analysis is done for the case study. Figure 4-6 shows an overall population capacity map, relating to both resident and hosted people, where the population is localized to the related building structures. Then, the maximum loading condition crowding is enquired between several possibilities. The highest is resulted to be the one related to the Saturday evening crowding scenarios, whose quantification is summarized in Figure 4-7.

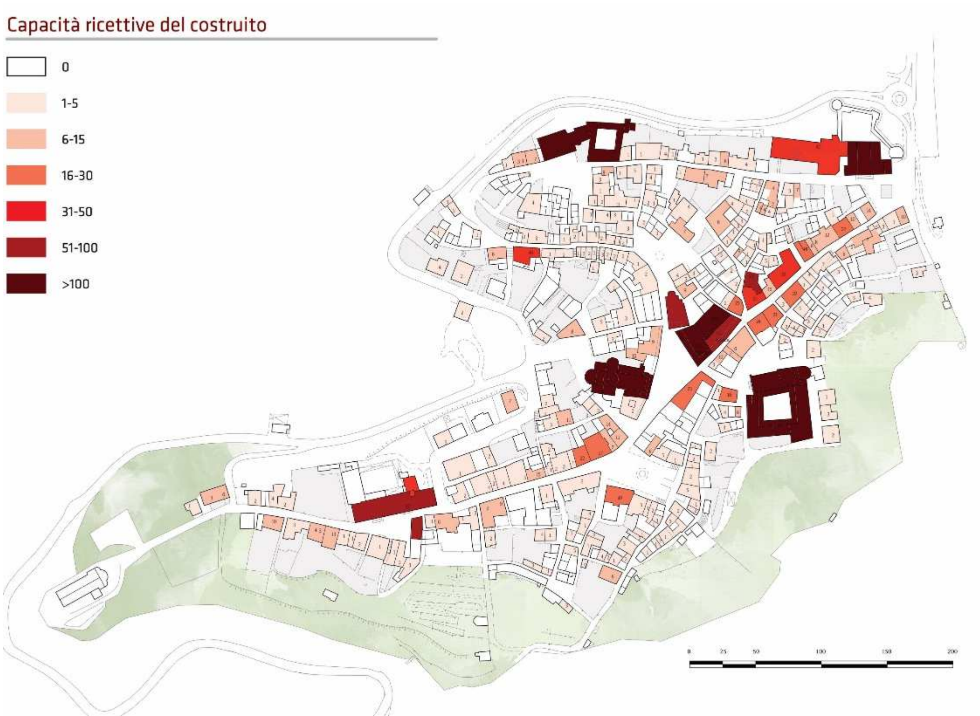


Figure 4-6. Map of the overall population capacity of the case study. The people contextualization is offered, according to Section 3.1, for each built structural unit according to the population and hosted people density analyses.

Mese	Agosto	
Giorno setttimana	Sabato	
Fascia oraria	Sera	
Spazi coperti		
Beni architettonici storici civili		-
Istituzioni Assistenziali		40
Edifici culturali e di intrattenimento		300
Edifici commerciali		-
Strutture ricettive		-
Esercizi ristorativi		189
Bar e caffè		47
Residenti - tutti		319
Spazi all'aperto		
Persone all'aperto		560
	totale	**1455**

Figure 4-7. Quantification of the crowding condition related to the Saturday evening. This hypothesis is resulted the highest for the considered case study.

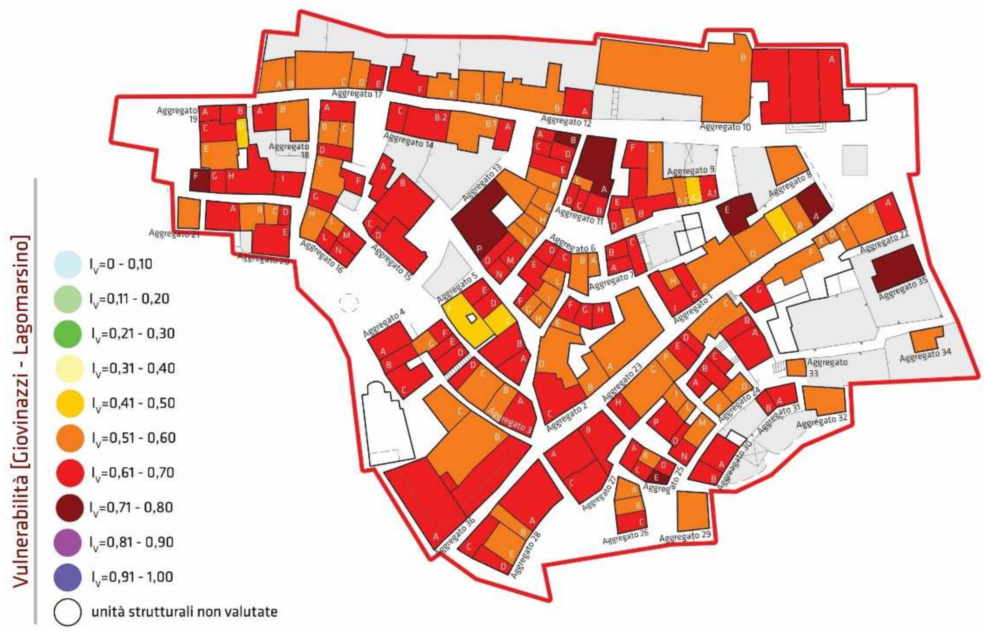


Figure 4-8. Map of the building vulnerability obtained by the application of the macroseismic methods (Lagomarsino and Giovinazzi 2006; Giovinazzi and Lagomarsino 2004) *to the interested areas.*

According to previous indicated methods, the building vulnerability is assessed by macroseismic methods (Lagomarsino and Giovinazzi 2006; Giovinazzi and Lagomarsino 2004)in order to quickly analyse large urban portions and have the possibility to correlate such vulnerability values with damage indices (measured by the EMS-98 scale (Grunthal 1998)). The map of the building vulnerability obtained for the case study, shown in Figure 4-8, highlights that the most of studied buildings own medium-high vulnerability values (range 0.5 - 0.7) while only few buildings own medium-low (0.4) or high (0.8) vulnerabilities.

Following the method proposed in Section 3.1.1, on the base of the obtained building vulnerability and of the observed geometrical features can be assessed the path network vulnerability indices (both in absolute and relative scales). (Santarelli et al. 2017). Figure 4-9 offers an overview of the normalized path vulnerability index for the case study. The normalized paths vulnerability values reveal that the lower vulnerable paths are the accessibility paths to the historical centre. Such results confirm the path choice for rescuers offered by the CLE analyses. Instead, the most of internal paths present a higher vulnerability, particularly the ones located into the most compact portion of urban fabric.

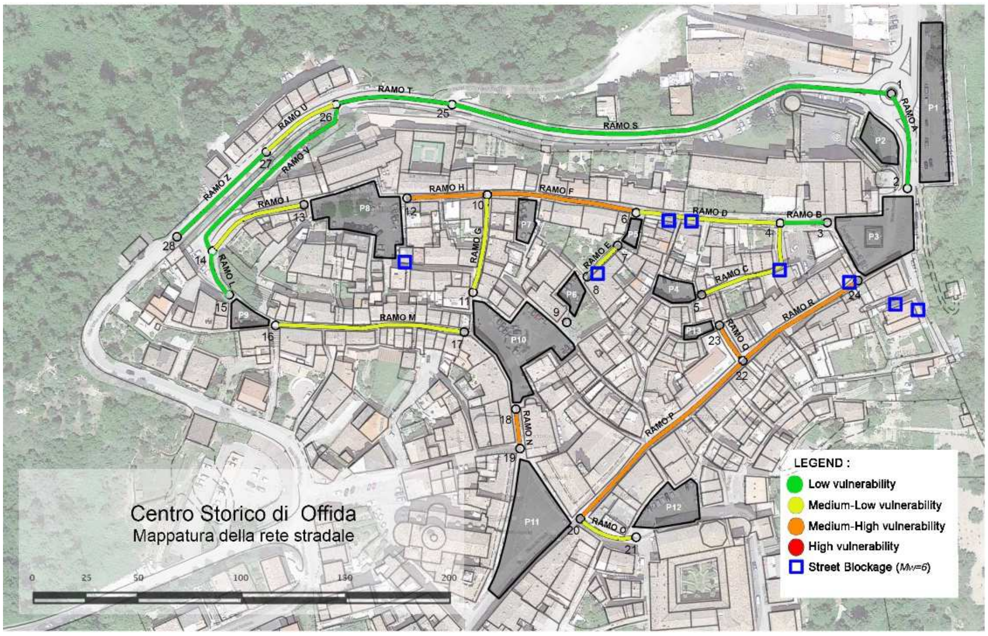


Figure 4-9. Map of the paths network vulnerability assessed for the case study adopting the proposed methodology.

The analyse of results offered by the path blockage index (see Section 3.1.1) highlights several street section blockages, some of these along the main ways to reach the planned safe areas. A quick comparison with the post-earthquake damage scenario offered through the experimental law for debris depth prevision (see Section 3.1.2) is also produced. Figure 4-10 offers a comparison between the two different damage scenarios assessed through these methods. According to the suggestions for application offered in Section 3.1.2, these two methods are also implemented on the simulation tool EPES in order to take advantage of experimental based method, specify for the historical heritage, for debris scenario definition. The observation of the two obtained damage scenarios reveals that the differences are substantial because of the very narrow paths network characterizing the case study (h/W generally higher than 2). In fact, the debris depth prediction method (Figure 4-10-b) generally produces a very high debris level whose represents an important obstacle for people motion during the evacuation. Contrarily, the in-paths obstructions method proposes, corresponding to the same earthquake intensity and building vulnerability, a scenario where only few paths are blocked and do not allow the evacuees' passage. The application of this second method evidences the effect of the relieved good quality of masonry but probably it offers an underestimation of path blockages, especially when the geometrical ratio is much higher than unity. In the considered context, this condition is verified for very narrow paths (width lower than 3 meters). Although both methods are based on experimental data, it could be conservatively supposed that the real post-earthquake scenario will be between these two limit conditions.

Finally, the map risk of the paths network, assessed for the case study and proposed in Figure 4-11, does not highlight significative differences between the analysed elements. This condition does not recommend any particular consideration about paths risk.

Figure 4-10. Comparison between the post-earthquake damage scenarios assessed through the two proposed methodologies: a) the in-path obstructions method; b) the debris depth prediction method (Santarelli, Bernardini, and Quagliarini 2018).

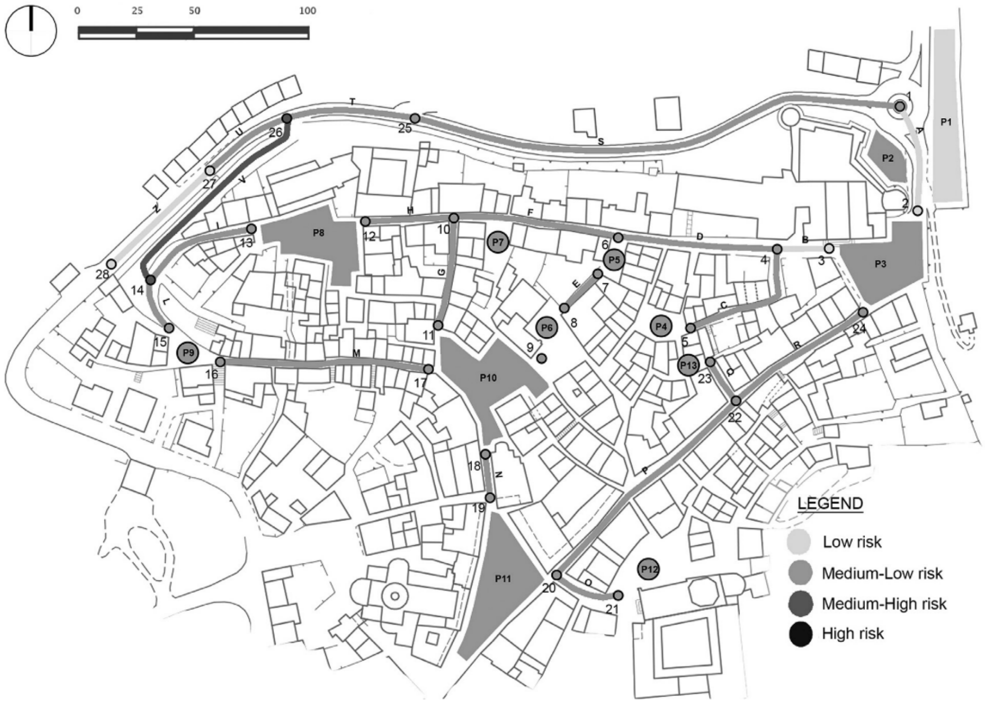


Figure 4-11. Risk map of the historical centre of Offida obtained applying the path risk assessment methods proposed in Section 3.1.3 (Quagliarini et al. 2018).

4.2.2 Definition of the alternative emergency layouts and research of the best-alternative

As defined in Section 3.3.1, starting from the municipal emergency plan and introducing the information related to the proposed pre-event analyses, the following suggestions and criteria for the proposal of alternative emergency layout could be summarized as follow:

- According to the path vulnerability, the safest access is the north one. Despite its low vulnerability, the link "V" presents a medium-high risk level since his intrinsic and typological aspects. This link represents one of the main connections between the connection path offered from the CLE and the internal safe areas;
- Concerning the accessibility of the safe areas for rescuers' operation, only three of the seven planned safe areas are directly reachable by rescuers and emergency vehicles. For that reason, further reachable areas should be located. Moreover, in case the KPIs evidence a scarce affluence to the not accessible areas, the introduction of guidance systems will suggest alternative codified areas if possible;
- According to the previous consideration and to the information deriving from the risk and the vulnerability analyses, when possible, to reach the safe area number zero is to prefer for evacuees;

These are preliminary considerations whose aspects should suggest several possibilities of improvement if jointly evaluated with the KPIs related to the three tested layouts. Figure 4-12 shows the alternative emergency layouts tested in this work.

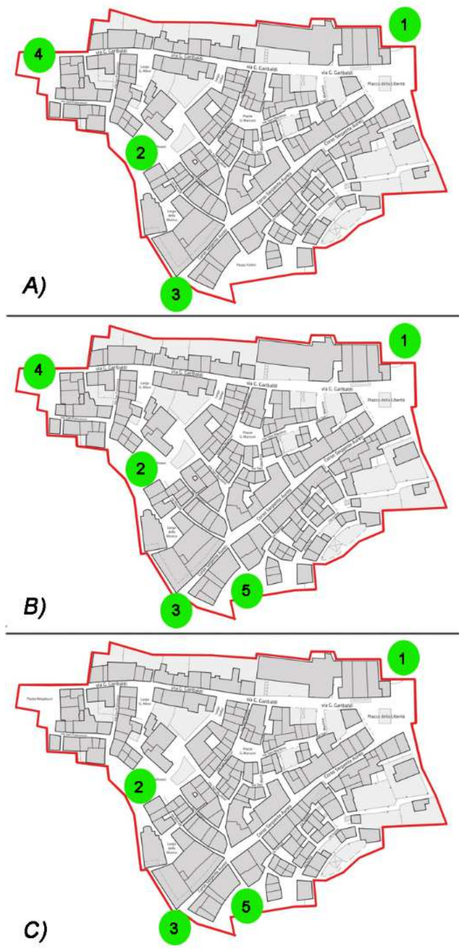


Figure 4-12. Several emergency layouts tested for the case study: A) municipal emergency plan; B) maximization of safe areas; C) optimization of safe areas.

Table 4-1, Table 4-2 and Table 4-3 show the basic KPIs, deriving from the output offered by the simulations, respectively related to the layouts A, B and C presented in Figure 4-12.

KPIs	*Safe area 1*	*Safe area 2*	*Safe area 3*	*Safe area 4*
$\overline{t_{evac,sa}}$ [s]	58.8	49.5	88.9	18.4
$t_{evac,sa}^{max}$ [s]	122.3	95.8	107.2	27.9

$\%_{p,sa}$ [%]	8.8	10.8	10.0	3.6

Table 4-1. List of the output offered by the simulation software for the emergency layout A - municipal emergency plan.

KPIs	Safe area 1	Safe area 2	Safe area 3	Safe area 4	Safe area 5
$\overline{t_{evac,sa}}$ [s]	44.4	58.0	82.5	12.2	29.1
$t_{evac,sa}^{max}$ [s]	83.9	109.0	91.5	18.8	41.6
$\%_{p,sa}$ [%]	9.6	9.2	6.8	2.4	5.2

Table 4-2. List of the output offered by the simulation software for the emergency layout B (related to the introduction of new safe areas).

KPIs	Safe area 1	Safe area 2	Safe area 3	Safe area 5
$\overline{t_{evac,sa}}$ [s]	53.2	64.1	87.9	32.6
$t_{evac,sa}^{max}$ [s]	104.3	110.8	99.7	101.4
$\%_{p,sa}$ [%]	9.3	9.7	6.4	4.7

Table 4-3. List of the output offered by the simulation software for the emergency layout C (related to the elimination of not optimized safe areas).

Table 4-4 shows the aggregate KPIs assessed for each tested layout. On the base of these indices it is chosen the best-alternative layout between the three assessed scenarios.

Kpis	Layout A	Layout B	Layout C
$\overline{t_{evac}}$ [s]	53.9	45.2	46.0
t_{evac}^{max} [s]	122.3	109.0	110.8
D_{evac} [s]	180	180	180
$\%_{p,na}$ [%]	68.3	68.3	69.9
$\%_{pzs,tot}$ [%]	31.7	31.7	30.1

Table 4-4. Comparison between KPIs related to the tested layouts for the iterative research of the best-performing emergency layout.

The offered analyses quantify the effectiveness of each emergency layout basing on the related evacuees' performances. They suggest that the introduction of further safe areas do not improve the number of safe people (see aggregate data) for the analysed case study. The phenomena is mainly due to the high number of not arrived people (about the 70% of the simulated population) and to the high impact that debris produce in term of practicable paths. Furthermore, the obtained data demonstrate that limiting the safe zones , avoiding those with a scarce affluence, is a delicate operation since its possible placebo effect. In fact, data show that the choice of most populated areas could led to a simple different distribution of safe evacuees that do not correspond to the improvement of the whole effectiveness of the emergency layout (in term of safe people). For the analysed case study, the data underline the relevance of the homogeneous distribution of the safe areas within the urban fabric respect to the choice of most populated areas.

At the end of this brief analyses can be clear that the layout A (corresponding to the actual Municipal emergency plan) can be considered the best-alternative layout. Hence, this planning solution will be used in the following as base for the introduction of the proposed guidance system. Moreover, in the following Sections, a consideration deriving from data about not arrived people is operated. As previously noticed, for the case study the high number of not arrived people strongly influences the evacuation effectiveness indices. Analysing the phenomena is possible to observe that not arrived people can be distinguished between trapped people and people out of safe areas. The trapped people category concerns the individuals that cannot exit from buildings because of the debris presence and so they do not participate at all to the evacuation process. Contrarily, people out of safe areas are agents that start evacuating but, for several reasons, they decide to stop before arriving to safe destinations. Some reasons of this behaviour, codified by literature and reproduced by the simulation tool, are related to the not individuation of a safe destination (safe area), to the decision to wait rescuers in temporary shelters within the urban context or to the situation where the individuals cannot choice or found a safe path to continue their evacuation. The maps of the probabilistic positions of not arrived people, obtained by the simulation tool, is offered in Figure 4-13. The image presents the obtained data in accordance with the adopted methods for post-earthquake scenario definition of Section 3.1.

In the following results of comparison between guided and not guided evacuations (Section 4.2.4), to appreciate a more sensible variation of numerical KPIs, the number of trapped people is subtracted from the total number of generated agents. In this way, the not arrived indicator $\%_{p,na}$ will concerns only the number of people out of safe areas and so it will be possible to assess the real impact of the tested guidance system, involving only wayfinding issues.

Figure 4-13. Probabilistic maps of case study for not arrived people (grey points), indistinctly between trapped people and people out of safe areas. The images show the cases of emergency evacuation simulation for post-earthquake scenario adopting: a) the in-path obstruction method; b) the debris depth prediction method (Santarelli, Bernardini, and Quagliarini 2018).

4.2.3 Introduction of the safety guidance system

Basing on the safety guidance methodology proposed in Section 3.2.2, the safe paths obtained for the case study and the analysed earthquake severity, are presented in Figure 4-14. The highlighted paths connect all the nodes of the paths network to the planned waiting areas by minimizing the safety cost associated to each edge of the network.

Figure 4-14. Map of the evacuation paths of the case study suggested by the safety guidance system. The scale of colours, as presented in the legend, represents the suggested paths minimizing the safety costs.

As remarked in the methodological Section 3.2.1, several devices could be adopted for the actuation of the suggested directions. The personal devices (e.g.: smartphones, smartwatches) have the advantage to be not invasive solutions, however the collective ones could be applied to the urban furniture and not directly on the built heritage. This last application could be a good compromise between the preservation of the cultural-artistic values and the necessity to introduce safety devices in the historical centre. In this study, the employ of collective devices is supposed and Figure 4-15 gives an example of application to street lighting system.

Figure 4-15. Example of the application of collective building components to the street lighting system of an urban centre. Taken from (Santarelli et al. 2018)

4.2.4 Evaluation of the safety guidance system and assessment of the best-performance layout

The comparison between the guided and the not guided performances of the considered emergency layouts are assessed in order to test the introduction of the safety guidance system. To this aim the scenarios described in Table 3-5, related to the best-performing layout, are simulated. As noticed in Section 4.2.2, in this part of the work the number of trapped people is subtracted from the total number of generated agents in order to consider only the individuals who are really able to evacuate. In this way, the corrected number of real evacuating people N_{evac}^{cor} is considered for the definition of Key Performance Indicators (KPIs) so as to evaluate only wayfinding issues and give relief to the impact of guidance systems. Then, the following numerical and graphical KPIs are produced and presented. Figure 4-16 and Figure 4-17 show the average evacuation curves comparing the guided and not guided evacuation performances respectively for the cases of post-earthquake scenario assessed by the debris depth prediction method (Santarelli, Bernardini, and Quagliarini 2018) and by the in-paths obstruction method (Santarelli et al. 2017).

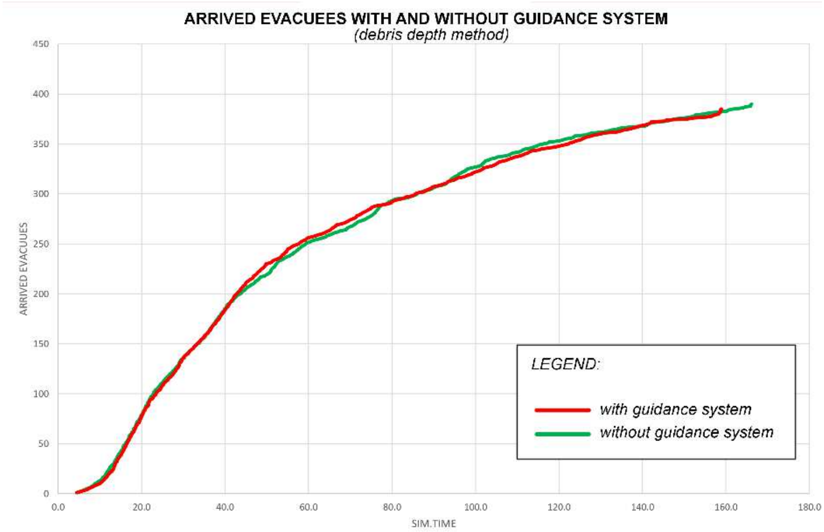


Figure 4-16. Evacuation flow curves related to the post-earthquake damage scenario produced by the debris depth prediction method. Comparison between the evacuation performances with and without the guidance system facility (layout I and II of Table 3-5).

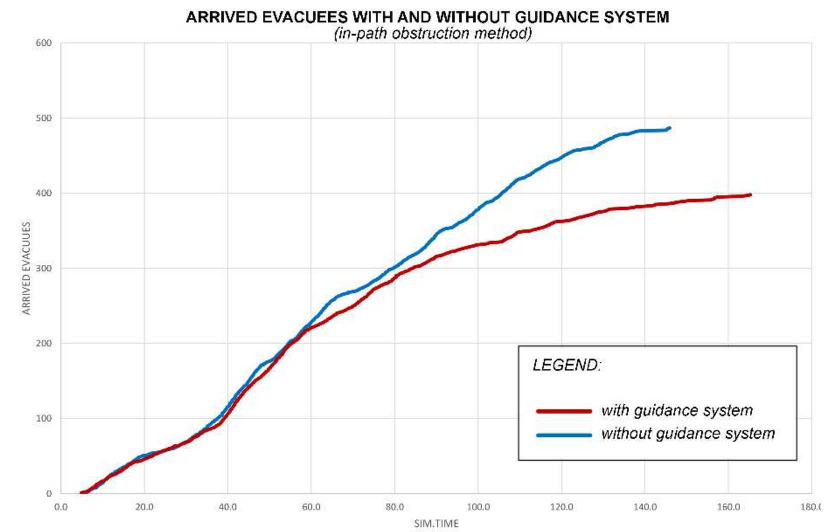


Figure 4-17. Evacuation flow curves related to the post-earthquake damage scenario produced by the in-paths obstructions method. Comparison between the evacuation performances with and without the guidance system facility (layout III and IV of Table 3-5).

The average trends shown in Figure 4-16, obtained by the simulation set concerning guided and not guided evacuations in debris depth post-earthquake scenario, do not highlight a substantial difference between guided and not guided evacuations. The phenomena relates both to the number of agents arrived to safe areas that to the time they spent to reach them. Data present that in the not guided case 390 agents arrive to safe areas while 385 individuals can do so in the guided case (-0.9%). The substantial invariance of arrived people can be mainly due to the scarcity of free paths within the damage scenario, comporting the increasing of people spread into the path network of the centre (about the 65% for both the guided and not guided performances).

Figure 4-16 considers the most severe damage scenario, assessed by the debris depth prediction method proposed in this work. Comparing data of Figure 4-16 with those of Figure 4-17, it can be observed that the use of a such conservative damage scenario strongly interfere with the number of people arrived (and not arrived) to safe areas. In fact, adopting a more realistic method for damage scenario in term of paths practicability the number of safe people increases of about the +25.8% passing from a 34.8 % to a 60.6% (mean values). Obtained results, calibrated on the average values of simulations, present that in general terms the percentages of not arrived agents is significantly lower than the previous scenario (about the 39%). However, 507 people reach safe areas in not guided evacuation while only 398 of them arrive adopting the guidance facility (-13.5%). Furthermore, the average evacuation lasting sees an increase of about the +3.8% in case of not guided evacuation but, this trend, can be due to the minor number of arrived people. These trends underline that, when paths are generally available for evacuation, adopting a guidance system can delay the arrival of agents to safe areas, also improving the probability they stop in temporary shelters and reducing the number of people who reach safe areas. This last represents a not obvious result of the work and surely it will need a further exploration of potentialities, criticalities and limits of adopting guidance systems for emergency evacuees in historical centres. Table 4-5 offers a summarization of the previous discussed issues together with the obtained numerical KPIs.

KPIs	*Best alternative layout considering the debris depth prediction method* (Santarelli, Bernardini, and Quagliarini 2018)		Best alternative layout considering the in-path obstructions method (Santarelli et al. 2017)	
	without guidance (layout I)	with guidance (layout II)	without guidance (layout III)	with guidance (layout IV)
N_{evac}^{cor} [s]	1104	1120	752	738
$\overline{t_{evac}}$ [s]	55.9	54.6	70.0	63.2
t_{evac}^{max} [s]	172.3	176.0	176.4	179.1
D_{evac} [s]	180	180	180	180
$\%_{p,na}$ [%]	64.7	65.6	32.6	46.1
$\%_{pzs,tot}$ [%]	35.3	34.4	67.4	53.9

Table 4-5. Numerical KPIs computed on the outputs of the simulation software. The emergency layout deriving from the best-alternative analyse are evaluated with and without the introduction of the proposed guidance system.

An interesting information can be observed by the evacuation lasting: in case of practicable paths (layouts III and IV) both the average that the maximum evacuation time are higher than the layout I and II. This condition, common to the guided and not guided performances, reveals that also people from the farest and deeper points of urban fabric can reach safe areas. This consideration suggests that, to maximize the effectiveness of the emergency guidance system (or other facility) a combination of behaviour strategies and building strengthening should be adopted in the most critical points of the historical centre.

Another not obvious consideration from results is that the obtained analyses are strictly correlated to the features of the analysed centre, underlining the performance-based designing policy of the work. Moreover, it can be observed that the proposed method can be suitable also to assist planners in the assessment of the introduction of facilities (as for example the guidance system one) or the targeted intervention on historical heritage.

Other interesting considerations, not directly object of the current work, could be done about the safety of paths suggested by the guidance system. In fact, a higher safety during the evacuation process could justify a (quite) longer path to reach safe areas. A safety lecture of the obtained values could suggest a further and sensible interpretation of the founded results: the paths travelled by guided evacuees are less damaged than those of not guided ones and the preferential reached safe areas are those easily accessible by rescuers. The presented are some of the safety advantages advised by the obtained data. However, the develop of synthetics Key Safety Indicators (KSIs) could be surely a future improving of the presented work of thesis.

Chapter V

5 Conclusions and future developments

The historical centres suffer considerably high earthquake risk because of their several disadvantages (e.g. buildings vulnerabilities, high human concentration on restricted territory and unfavourable urban fabric conformation). Mitigating this risk and reducing losses for the population are significant necessities. However, conventional solutions can be inadequate in these scenarios because of several unavoidable obstacles as historical-artistic constrains, economic issues, etc. Therefore, the preventive emergency planning and the first emergence management are key activities for the safety of citizens and the effectiveness of evacuation.

In this work of thesis new solutions for the emergency analyses, planning and the evacuation management (focused on the historical centres peculiarities) are proposed. To tis aim, several fields of study are defined and investigated (i.e.: buildings and paths vulnerability, the preventive evaluation of post-earthquake damage scenarios and the related effects on the evacuation process; the evacuees' emergency wayfinding). Similarly to how done by the most advanced emergency analyses techniques for the indoor environment, a Behaviour Design (BD) approach is adopted by the work. For each noticed field, new experimental or BD based methodologies and tools are offered in order to work with compatible variables and avoid the lack of analysed aspects. Furthermore, a traditional-innovative emergency planning method is offered in order to organize all the proposed studies in a unique procedure. The proposed methodologies are applied to a real case study in order to clarify the obtainable results and highlight the capabilities of adopting a performance-based approach for evacuation problems in earthquake outdoor scenarios. Basing on the relevance of the self-help strategies, as fundamental practice for evacuees' safety immediately after a seism, the further improvement of the emergency plan through the introduction of guidance systems is also analysed and tested.

The obtained results demonstrate that:

- The pre-event methodologies proposed by the work can effectively help safety planners to have a wider perspective of the environmental and human factors;
- Taking advantage of the proposed analyse level can help the emergency planners to design alternative emergency layouts to test;
- Adopting a BD-based strategy for the designing and test of emergency solution (e.g.: emergency layout, interventions of buildings and paths, introduction of guidance systems) could be optimized both the available resources and the evacuative performances.

Several are the possible future developments of the work. Some of them can concern the consolidation of the application of the proposed methodologies for the vulnerability, damage and planning to others case of study. In this context an expansion of the employed dataset and the following testing of the reliability of the proposed methodology can be useful too. The set of Key Performance Indicators adopted for the emergency designing and for the test of the introduced guidance system could be enlarged to other factors as for example the safety aspects (measure of the safety of followed paths or of the reached safe areas). Accordig to a Behaviour-Based approach and to a optimization strategies, the combination of innovative and traditional solutions for risk reduction in historical centres could be analysed to suggest further improvements.

Finally, the proposed approach and methodologies could be modified in order to refer to other kinds of emergencies in outdoor environment (e.g.: multi-hazard, terroristic attack, application to the safety of public events).

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7 Appendix

A. Notation table

Symbol	Measure	Description
$(h/W)_a$	-	Geometric ratio assessed for the building "a"
$(h/W)_b$	-	Geometric ratio assessed for the building "b"
$\%_{p,na}$	[%]	Percentage of population that stops in temporary opportunistic shelters (overall data)
$\%_{p,sa}$	[%]	Percentage of population that reaches the interested waiting area over the time D_{evac}
$\%_{psa,tot}$	[%]	Percentage of population that reaches the waiting areas over the time D_{evac} (overall data)
$\overline{t_{evac,sa}}$	[s]	Average time taken by evacuees to reach the interested waiting area
$\overline{t_{evac}}$	[s]	Average time taken by evacuees to reach the waiting areas (overall data)
$C_{P,i}$	-	Safety cost Index related to the i-th path of the network
B_{link}	-	Link Blockage Index evaluating probable street section complete obstructions
D_{evac}	[s]	Duration of evacuation, computable for the entire process or for a partial component (e.g.: a section of the evacuation route)
I_R	-	Risk Index of Paths
I_R^N	-	Normalized Risk Index of Paths
$L_{link,n}$	m	Length of the link n (from node to node)
N_{evac}^{cor}	[ppl]	Corrected number of evacuating people excluding trapped agents
$N_{p,na}$	[ppl]	Number of people not arrived to planned emergency safe areas
$N_{p,sa}$	[ppl]	Number of people arrived to a given safe area
$N_{p,tot}$	[ppl]	Total number of people
Sp_{iK}	-	Value of the alternative respectively associated to factors and parameters defined for path risk assessment
V_I	-	Building Vulnerability Index
V_{link}	-	Seismic vulnerability of the link, related to "intrinsic" and "extrinsic" elements

V_{link}^{N}	-	Normalized Link Vulnerability Index, assessed for the case study
Wc_K	-	Weights associated to the defined factors for path risk
Wi_K	-	Weights associated to the defined parameters for path risk
a_j	-	Value of the alternative assumable by variables for the IEGS method
$l_{build,j}$	m	Length of the building j façade along the link
$t_{evac,sa}^{max}$	[s]	Maximum time taken by evacuees to reach the interested waiting area
t_{evac}^{max}	[s]	Maximum time taken by evacuees to reach the waiting areas (overall data)
t_f	[s]	Value of final time corresponding to the arrive to safe zone or to the end of simulation time
t_i	[s]	Value of initial time corresponding to the evacuation starting
w_{j}	-	Weight of each variable in the safety cost index
μ_D	-	Mean damage grade
E	-	Seismic exposure, related to the presence and the 'value' of buildings and other objects and to the possible consequences on human life
H	-	Seismic hazard, related to the possibility of future seismic actions
h	m	height of building façade (measure corresponding for each building along the link)
h/W	-	Geometric ratio between building height and the related facing street width
I	EMS-98	Macroseismic intensity
i	-	Geometrical incidence of the building in the link (ratio between building and link lengths)
IEGS	-	Intelligent Emergency Guidance System
K	-	Value associated to the unacceptable conditions for safety variables in the considered scale
k	-	Damage level of building proposed by the EMS-98 scale
k95	-	Damage level of building corresponding to the 95th percentile of its cumulative distribution
LCE	-	Limit condition for Emergency
LOS	m^2/pp	Level Of Service for pedestrian motion
M_w	MMS	Seismic Moment Magnitude
PGA	m/s^2	Peak ground acceleration
P_k	-	Probability that a building with a certain μ_D will suffers a damage level *k*
Q	-	Ductility index of buildings

QX	%	External ruins area related to a building
R	-	Seismic risk, related to the number of people killed or injured, the damage to property and the impact on economic activity due to the occurrence of the disastrous event
V	-	Seismic vulnerability, related to the 'weakness' of the element
*V**	-	Modified Vulnerability Index (adopted in debris prediction)
W	m	Link width (measure corresponding for each building along the link)
W_a	m	Link width corresponding to the building "a" facade
W_b	m	Link width corresponding to the building "b" facade

Table 7-1. Notation table for the acronyms and indices employed by the work.