How to create seismic risk scenarios in historic built environment using rapid data collection and managing

POSTPRINT OF Quagliarini E, Lucesoli M, Bernardini G (2021) How to create seismic risk scenarios in historic built environment using rapid data collection and managing. Journal of Cultural Heritage 48:93–105. https://doi.org/10.1016/j.culher.2020.12.007

How to create seismic risk scenarios in historical built environment using rapid data collection and managing

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ABSTRACT:

The Historical Built Environment (HBE) is constantly prone to natural disasters because of its complexity. Resilience-increasing strategies in such a context should be defined at both preserving the cultural heritage and making the hosted communities safe. Earthquakes represent critical disasters because of the interactions between HBE elements (i.e.: buildings, open spaces, urban paths) and its inhabitants. Hence, the practical development of emergency plans and related risk reduction strategies should consider the induced effects of the earthquake on the HBE and the spatiotemporal variation in the number of exposed people. This goal needs propaedeutic methods to define relevant scenarios in view of the possible characterization of risk-related factors at the HBE scale. To this aim, this contribution tries to arrange a first sustainable, holistic, easy-to-use, and replicable framework. The paper innovatively provides planners with a unique scheme to reach available data from reliable sources concerning seismic hazard, vulnerability and damages, and exposure (i.e. related to human presences). Results on a case-study application (a typical Italian HBE) demonstrate the framework capabilities, by including the critical HBE damage-related conditions and crowding phenomena (in a multi-hazard perspective, based on the probable number and typologies of exposed individuals). Then, specific solutions can be advanced. The proposed holistic framework can be easily replicable

and adaptable due to the possibility to update the employed tools as well as to replace them with other existing and validated ones, giving the same inquired parameters as results. Hence, the methodological framework could constitute an effective support for risk scenarios creation at the HBE scale to be used in risk-assessment and emergency plans actions (e.g. basing on typological analyses on buildings/urban tissue, and simulation-based studies including human behaviours) by guaranteeing rapid data collection activities.

Keywords: Urban risk assessment, Historical Built Environment, Seismic risk, Data collection, Risk-reduction strategies, Urban emergency planning.

Highlights:

- A methodological framework to collect and manage seismic risk-affecting factors is developed;
- Wide-scale replicability for historic city centres is pursued;
- Factors to be evaluated, related data collection and organization are discussed;
- Historical Built Environment elements and their criticalities are inquired;
- Obtained framework constitutes the first step for effective simulation approaches.

1 Introduction

Natural disasters seriously affect cities and their community by causing serious threats to society as a whole, by affecting their building heritage as well [1]. A major risk is surely represented by SUdden-Onset Disasters (SUODs), which are "triggered by a hazardous event that emerges quickly or unexpectedly"[1]. Recent real-world SUODs-related events have revealed how: 1) it is important to extend emergency management at a wider scale, rather than focusing on single buildings [2,3]; the current operational methods must be improved to face these emergencies [4]; strategies for rapid

[1] compare to the UNISDR definition given at https://www.unisdr.org/we/inform/terminology (last access: 06/07/2020)

data analysis and collection are useful to risk-assessment and mitigation actions to also deal with multi-hazard conditions and other emerging topics on cities at risk (including climate change-related disasters, e.g.: floods) [3,5–7].

In this general context and among the SUODs, earthquakes are surely one of the most critical for the city safety and resilience, especially in historical contexts. In such scenarios, the specific features of the Historical Built Environment (HBE) should be preserved since the HBE is intended as an integral part of the cultural heritage [8]. Minimization criteria for risk-reduction interventions should be combined with the conservation principles and the reduction of architectural heritage losses, which contribute to the weakening of the communities' identity [8,9]. These scenarios are conditioned by the interactions among the high-vulnerable buildings (generally, ancient masonry constructions), their post-event modifications (i.e. damage levels), and the hosted community [9–11]. Such interactions seriously affect the community's safety during the first emergency phases, i.e. during the evacuation process (mainly involving the individuals who try to reach safe areas where they can receive the rescuers' support) and in the immediate aftermath (e.g. first responders' arrival and related actions in the earthquake-damaged scenario) [12–15]. Moreover, the seismic HBE risk due to buildings vulnerability and compact urban tissue can be strongly increased, from a multi-hazard perspective, depending on the HBE use, especially when crowding conditions are present (e.g.: in conjunction with mass-gathering events or touristic destinations) [3,7,16,17].

In general terms, the HBE can be defined as a network of (1) *buildings* (that could be *monumental*, with historic-artistic-cultural features e.g.: govern palaces, churches, monasteries, bell towers, obelisks, theatres, castles, triumphal arches and arch bridges, or *ordinary*, embodied by common dwellings or modern public facilities [18]), (2) *open spaces* (that are the main urban voids, such as squares) and (3) *urban streets* (connecting facing buildings to open spaces, which can be used as paths by evacuees and rescuers to move into the earthquake-damaged scenario) [14,19–21]. In case of an emergency, each of these elements can assume a strategic role [22–24]: (1) the *strategic buildings*, and (2) the *emergency areas* (hosted by open spaces), can host fundamental functions in the emergency scenarios, and they are linked together by (3) *strategic streets* and *evacuation paths* to be used by the population and the rescuers in the first emergency phases. Their seismic response, their mutual relationships and other aspects related to their use in ordinary conditions have to be collected because they could heavily influence the efficiency of the emergency plans [25,26].

The seismic risk of the HBE is conventionally composed of three components: Hazard (H), Vulnerability (V), Exposure (E) [27]. H relates to the expected event severity (in intensity or magnitude terms), within a given period, and is also connected to the topographical and soil characteristics of the site [28–31]. V is intended as its propensity to suffer damages during a seismic event, because of the HBE elements features (e.g. typological, construction-related, geometric) [32,33]. H and V factors are widely debated in literature and methods to collect data are well addressed and structured. Several works inquire how they can support the developed quantification methodologies in seismic risk scenario creation through the definition of influencing factors [34–36]. Furthermore, they are also included in some official guidelines and national regulations (e.g. [23]). Researches [37,38], including recent EU-Projects (e.g.: PERPETUATE [39] and Syner-G [40]), tried to develop reliable methodologies for V and related damage assessment. Nevertheless, their application seems to generally need significant efforts by designers (e.g. technicians of local administrations), who may be untrained and therefore unable to apply them (e.g. fragility curves). Quick methodologies based on Macroseismic approaches were previously developed and validated to move towards less time-consuming efforts both in data collection and in methodologies application by designers [1,41]. For this reason, they could be useful for quick HBE applications towards emergency simulation, preparedness and planning [13].

Finally, E is mainly oriented towards the human presence in the scenarios (e.g. to determine the impact in terms of human losses) [26,42]. It seems to be limitedly included in main research activities [43], e.g. due to the complexity in codifying human presences in the scenarios and behavioural issues (e.g. population risk awareness and response) [14,19,27].

Few studies tried to develop a methodology able to combine all the factors from a holistic point of view [21,44–48], quantifying the seismic risk of the HBE as a whole. Some others instead were oriented on a single part of the urban system such as open spaces [21] or paths networks [20]. Hence, it is essential to promote a unique framework or a guideline on how to collect and manage data for risk scenarios creation, by: 1) jointly considering the aforementioned factors [32,47,49–51], 2) relating them to the specific HBE elements, and 3) focusing on those that play a fundamental role in emergency conditions [22,23,52,53].

Databases from national statistical organizations allow retrieving many of the needed data (e.g.: building construction age, number of floors, structure type, hosted inhabitants) by including an urban-scale oriented approach. Recent works tried to provide bases for survey methodologies by jointly leading to buildings vulnerability and exposed population assessment towards emergency scenarios definition [42]. However, other requested data (e.g.: on evacuation procedures, mass gathering events) are more difficult to be obtained and they require specific collection methodologies or field surveys [13,26,54,55]. Such frameworks can make designers prone to leave out their evaluations where sources do not permit them to answer certain requests.

2 Research aim

This research is aimed at creating a unique methodological framework for scenarios creation of HBE prone to earthquakes, by jointly combining the risk-affecting components (i.e.: hazard, vulnerability, and exposure) from a holistic standpoint.

The novel proposed framework adopts specific literature-based methods in a combined, cooperative, and structured way. According to adaptability criteria, these methods are not exclusive, but they could be replaced by other existing and validated ones. Quick methods collecting data from easily available data sources are preferred to: 1) avoid costly in situ surveys; and 2) permit to reproduce the workflow by non-expert technicians. Reliable vulnerability assessment methodologies and damage state predictive algorithms are combined to quickly assess the impact of hazard conditions. Specific attention is paid to exposure issues, by introducing different HBE users' typologies (i.e. inhabitants, tourists), also considering time-dependent variations. In this sense, the framework provides the possibility to rapidly detect possible peak scenarios by overlapping ordinary conditions to mass gathering events from a multi-hazard point of view.

This way, this work constitutes a supporting tool for risk-assessment and emergency planning (e.g.: also towards the adoption of simulation-based methodologies).

3 Methodological framework

Figure 1 summarizes a consolidated methodological framework [20,56] to collect and manage data and dependencies between the scenario creation tasks (as the core of the work), in view of the three basic components (seismic hazard, vulnerability and layout, exposure assessment). This framework is oriented towards the application of existing methods for risk-assessment tools (i.e. simulation-based ones) [13,26,42]. In the following, for each factor of the framework core (grey areas concerning basics and advanced scenario creation tasks) reported in Figure 1, the data collection and management methods are discussed by introducing the main related works. The methodology is applied to an Italian case study (see Section 3.5). Hence, some specific data sources and regulations concerning the Italian case-study are evidenced in the methodologies description.

Nevertheless, the overall framework can be applied to other Countries depending on the specific national sources.

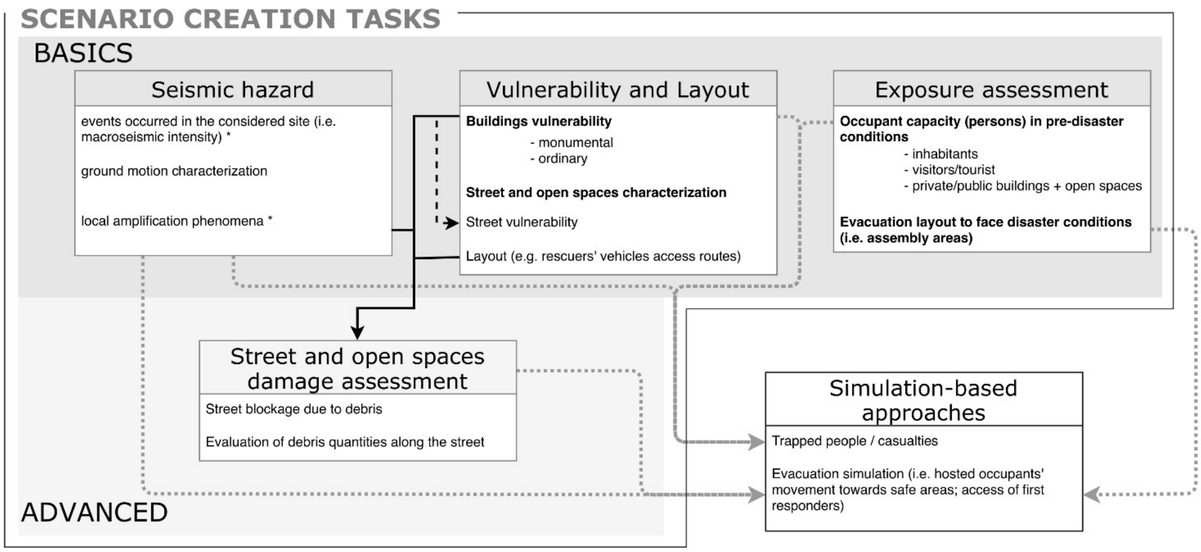

Figure 1 Dependencies between the scenario creation factors (including the related tasks) and the application of retrieved data in simulation-based and planning approaches. Dependencies are distinguished by: internal to each factor (black dashed line); producing data for another factor (black continuous line); providing data for the simulation-based approaches (grey dotted line).

3.1 Seismic hazard: possible earthquakes occurrence

Seismic Hazard data should be chosen to define probable earthquake emergency scenarios. According to this standpoint, the adoption of hazard values can take advantage of statistical data concerning historic seismic events that occurred in the considered site. In this term, they can be easily described in terms of macroseismic intensity (MCS). Global, national, and regional networks recording earthquakes provide the database that can be used to this end[2]. The selection of significant seismic intensity values can be preferred if combined with the application of rapid building vulnerability assessment methods [57]. However, other damage prediction algorithms

[2] e.g.: at European Level https://www.emsc-csem.org/#2 ; in Italy INGV emidius.mi.ingv.it/CPTI15-DBMI15/ ; for USA, the "Search Earthquake Catalog" of the USGS https://earthquake.usgs.gov/earthquakes/search/ or the "Northern California Earthquake Data Center" http://ncedc.org/anss/catalog-search.html finally, https://www.usgs.gov/natural-hazards/earthquake-hazards/monitoring (last access: 06/07/2020)

require moment magnitude (Mw). The conversion from MCS to Mw can be qualitatively obtained according to [58].

3.2 *Vulnerability and layout*

The analysis of the HBE can be essentially associated with the characterization of buildings and open spaces/streets network [59,60]. Buildings vulnerability assessment methods can focus on the single structural unit or the whole building aggregate [1]. The typological classification given in Section 1 that distinguishes *ordinary buildings* from the *monumental* ones is adopted [18]. *Monumental buildings* and the medieval urban tissue identification can be supported by the evaluation of the HBE evolution during the time (by available historical maps, e.g. Cadastral maps, General Land Office [61]).

Considering a wide urban application scale, macroseismic methods for building vulnerability assessment can be preferred because of their quick application [1]. Furthermore, they can be used together with hazard characterization approaches based on the adopted macroseismic intensity scale (see Section 3.1). The approach is valid for each structural typology. Specific methods can be employed for masonry constructions [62] and other structural typologies (e.g. reinforced concrete[63]).

However, in HBEs, masonry buildings are the more recurring typologies, thus we refer to them in the following. Their seismic vulnerability assessment is performed according to [63] for *ordinary buildings* and according to [64] for *monumental buildings*. For both ordinary and monumental buildings, data to be collected should concern the typological building features [33,64–67], e.g.: structural typology, connections among vertical and horizontal elements, roof typologies, eventual interventions, conservation state, position inside the aggregate.

All these vulnerability-affecting data can be retrieved by statistic databases from the public administration. Hence, the data collection process can be speeded up by using data from census databases integrated with GIS tools [56,68].

Streets and open spaces characterization consider geometric (layout-related) and vulnerability features depending on the interferences with the HBE elements. Firstly the related analysis has to consider the HBE access paths, paying special attention to rescuers' vehicle passage to ensure the intervention in the damaged city area [23,42]. Physical barriers, bottlenecks (e.g.: staircases, arches) and geometrical aspects (i.e.: buildings height and streets width) are considered to evaluate possible interferences between buildings and streets system [23,69,70]. Analyzing each structural unit can improve the effectiveness in the evaluation of local damage on streets and open spaces facing the buildings [69,71,72].

The street vulnerability can be evaluated according to the V_{link} method, which is one of the quickest ones [72]. Although other existing and validated tools can be adopted, this tool considers the sum of Macroseismic vulnerability of each building facing the street depending on its incidence on the total street length, as shown by Equation 1:

$$V_{link} = \sum V_i \, i \qquad (1)$$

where: V_i is the vulnerability value of each building (structural unit) along the street evaluated using the methods reported in Section 3.2; i is the ratio between the considered building length facing the street and the total length of the street itself. Since V_{link} can range from 0 to 1, street values can be quickly organized in i.e. four classes: low (0 to 0.25), medium-low (0.25 to 0.5), medium-high (0.5 to 0.75), high (0.75 to 1).

3.3 Exposure assessment

As reported in Section 1, the main exposure-affecting factors can be related to the occupants' presences, distinguished by *pre-disaster* [26,42] and *disaster conditions* [13].

The main exposure data concerning *pre-disaster conditions* is the people's presence in the HBE by distinguishing possible different typologies: inhabitants versus tourists. We can assume that the resident population, including workers who are used to frequent the HBE, have familiarity with it and with the emergency dispositions. On the contrary, daily visitors and tourists can be considered unaware. Critical pre-disaster conditions can be defined in terms of the maximum human presence, to consider the maximum impact on direct (e.g. casualties due to buildings damage/collapse [42,73]) and indirect (e.g. evacuation related ones [19]) losses.

The most rapid exposure evaluation could just consider the density of people (pp/km^2 where *pp* stands for the number of people) according to [74] and census databases referred to the considered HBE (e.g.: national on-line census, local municipalities or tourist office) [26]. In some cases, census databases can be linked to the detailed position of the population (e.g. street survey-based; integrated with GIS tools), by mainly focusing on standard occupancy levels, e.g. residents [26]. However, the number and position of exposed people vary over time and space essentially depending on the variations of factors collected in Table 1.

Table 1 Time and space issue influencing the human presence variation in the HBE.

Human presence typologies and their combinations	**Visitors**	**Inhabitants + neighbouring of the local municipality area**	**Inhabitants + visitors**	**Visitors presence in mass gatherings events**
People familiarity with places and emergency plans	Scarce familiarity with the urban spaces and with the emergency plans	Satisfying level of familiarity with spaces depending on their (frequent) HBE attendance	Different familiarity levels	Generally scarce familiarity with the urban spaces and with the emergency plans

Time issue	By considering visitors' flows during the year: critical conditions in exposed individuals' presence (e.g. monthly) correspond to the periods with the higher number of tourists' presence (considering both daily visitors and holidaymakers).	By considering inhabitants and neighbours during the week: estimating critical conditions in exposed individuals' presence (e.g. weekly)	By considering inhabitants and visitors during the day: these analyses allow considering the variations during the working time and between night and day (e.g. sleep time, working time, working, and resting time).	Critical conditions characterized by a high crowd density can occur in the urban tissue (e.g. concert venue, festivals).
Space issue	Visitors can be mainly placed in accommodations (e.g. hotels, tourist homes, such as for night-time periods) depending on their effective capacity, or even according to a homogenous dispersion (including public buildings, as for day-time periods).	Local markets, recurring fairs or festivities hosted by the HBE bring in town habitual visitors from near towns or peripheral areas that populating open spaces.	For some municipalities (e.g.: tourist cities/areas), further evaluations should consider the daily presence of individuals spending their time in some urban attraction.	Specific risk-increasing HBE features (e.g. in historical scenarios, the crowd in narrow spaces) have to be considered. Such an event in the HBE can be overlaid to the critical conditions for resident people obtaining overcrowding conditions among narrow urban environments.
References	[75]	[16]	[26]	[16]

The capacity [pp] estimation and the related people positioning in the HBE layout can be jointly assessed through census databases and municipal tourism promotion companies, regional tourism management bodies, trade organizations[3]. The capacity estimation can take advantages of standard data from occupant load [pp/m^2] assessment as follow (the methodology and specific references for the Italian case-study are shown in Table 2):

1. *identification of buildings open to the public,* and their use, especially if they can be affected by potential high occupants' density/overcrowding conditions. Occupants' capacity of such public buildings [pp] is rapidly determined: the occupant load factors ([pp/m^2] or [m^2/pp]) provided by the code of practice for Fire Safety Design is applied to the building area

[3] E.g.: for Italy, the National Institute of Statistic http://dati.istat.it/Index.aspx?DataSetCode=DCIS_POPRES1, for USA, United States Census Bureau https://www.census.gov/data.html (last access 06/07/2020)

extension depending on the hosted functions (see Table 2). Specific national sources can be used to this end[4];

2. *evaluation of the capacity of residential buildings by determining the number of inhabitants [pp].* General Land Office[5] surveys can provide a detailed map of residents, by additionally reporting additional data (e.g. age, gender) for each housing unit identified by the own civic number. Moreover, data about disabled people can be collected according to the Privacy Act by local healthcare agencies or civil protection bodies (that have to intervene in case of emergency to rescue them) [76]. Inhabitants' presence in their house has to be considered in relation to the time-dependent assumptions in Table 1 and the building use in Table 2 [26];

3. *evaluation of occupant capacity of public spaces [pp] susceptible to overcrowding phenomena* in case of temporary mass gatherings. According to a conservative approach, the maximum crowding-related occupant load range[6] of assembly areas could be reasonably considered from 2 to 4 pp/m^2. In case of local markets, the occupant load can be considered equal to commercial buildings data (compare to Table 2). The occupant capacity can be precautionarily esteemed in reference to gross (including parking, events stages, stands, and other urban furniture) or net area of the public spaces. In a general hypothetical situation, occupants leave their buildings and occupy public spaces by overlapping to mass gathering events, thus constituting a multi-hazard scenario due to the merging of occupants' presence conditions. Thus, it can be esteemed through the evaluation of the crowding density [pp/m^2] of overall public spaces. This data can be also expressed in terms of capacity [pp], so as to

[4] E.g.: in England https://bit.ly/2JcT6Vi, in the United States https://bit.ly/2UweLwX, and in Canada https://bit.ly/3dmj6v8 last access 06/07/2020.

[5] (.g. http://www.protezionecivile.gov.it/resources/cms/documents/Manuale.pdf, last access 06/07/2020

[6] e.g. from Italian regulations such as DM 19/08/1996; Circolare ministeriale (Ministero dell'interno) 18-07-2018, n. 11001/1/110/(10)

outline the effective maximum exposure scenario for simulation-based methodologies [13,26,42].

Table 2 Evaluation of the crowding density in buildings opens to the public in relation to the Italian fire safety codes due to their connection with the case-study application. In case of historical buildings hosting the intended use, regulations could be integrated, from a general point of view, according to the rules provided by Ministerial Decree (DM): DM 3/8/2015, DM 8/6/2016, DM 9/8/2016, Circular letter n° 3181 del 15/3/2016

Intended use	**Methodology**	**Quick occupant load factor**	**References to Italian regulations**
Residential buildings	The crowding density for private dwellings is related to their surface	0.05 pp/m² (imposed by regulations)	For residential buildings: DM 3/8/2015
Institutional buildings including architectural and historic ones used as offices, museum, and art gallery	Infield survey to trace information about the number of the occupant (personnel) with a precautional increase of 25% rounded to the upper bound-. The number of possible visitors has to be added by considering the area extension of public office In the absence of further information, use the quick occupant load factor.	Office close to public: 0.1 pp/m² Office open to public: 0.4 pp/m² Areas gathering public: 0.7 pp/m²	Generally, assimilable to the crowding of working place: DM 10/3/1998, DM 3/8/2015; for other public exhibition places, i.e. hosted by historical buildings: DM 20/5/1992, DPR 30/6/1995; for areas hosting cultural events with the public: DM 19/8/1996, DM 6/3/2001, DM 3/8/2015;
Religious buildings	For each building, the number of seats has to be counted adding the number of standing places	0.7 pp/m² applied to the available area extension	For this intended use, assimilable to entertainment and public exhibition places: DM 19/08/1996, DM 6/3/2001, DM 18/12/2012;
Hospital and healthcare buildings	Infield survey to trace the information regarding the number of available beds. The number of in-service personnel is added and the variation due to visitors esteemed through the average data of at least three typical days	Ambulatory and similar: 0.1 pp/m² Spaces for visitors: 0.4 pp/m²	For this intended use, assimilable to the crowding for working places: DM 10/3/1998
School buildings	The number of seats for each classroom and eventual annexes (e.g.: refectory, gym) has to be collected in relation to the number of students, teachers, and personnel, according to the headteacher declaration	Refectory and gymnasium: 0.4 pp/m² A maximum of 26 individuals can be considered for each classroom	DM 26/8/1992, DM 12/5/2016, DM 3/8/2015
Cultural and entertainment buildings (public exhibition and sports facilities)	Evaluation of the main activities and the presence of seats for the public (number of seats)	In a precautional way: ballroom - 0.7 or 1.2 pp/m²; theaters parterre -3 pp/m², standing places - 3.5 pp/m² Sports facilities: 2 pp/m²	DM 18/3/1996, DM 6/6/2005, DM 19/8/1996, DM 18/12/2012
Commercial buildings	The crowding index is related to the surface of the overall floor	0.4 pp/m²	DM 27/7/2010, DM 3/8/2015
Accommodation facilities	Data about a general scale could be provided by tourism organizations subdivided for periods or	0.4 pp/m² (i.e. common spaces)	DM 27/7/2010, DM 3/8/2015

	seasons (e.g.: the municipal tourism promotion companies, regional tourism management bodies, trade organizations). Infield surveys are necessary to obtain the single structures maximum capacity, the number of beds and personnel (increased by 20%)		
Public shops such as restaurants bars and cafes	The crowding values can be reasonable esteemed in relation to the extension of the area, for bars and cafes infield surveys are desirable to esteem the number of costumers during each time slot	0.7 pp/m^2 (precautionary evaluations)	For this intended use, assimilable to public exhibition places: DM 19/8/1996, DM 6/3/2001, DM 18/12/2012; from a general point of view: DM 3/8/2015

Disaster conditions concerning exposure-related factors regard the individuation of areas where the population can gather and wait for the rescuers' arrival [23,69,77]. Such assembly areas should:

- *be reached and usable by pedestrians.* The free entrance to the area (e.g. no access gates closure) over time, as well as the absence of obstacles related to particular space uses (e.g. spaces used to host fairs and exhibitions; parking areas) should be always guaranteed;
- *host the evacuees in adequate crowding conditions,* by avoiding the possibility of physical contact among evacuees (i.e., maximum Level of Service D according to [78]). In this sense, related occupant load values can essentially range from about 2 pp/m^2 to about 3.5 pp/m^2 [79]. The individuated assembly areas A_a [m^2] should be estimated by excluding some parts, i.e.: (1) potentially affected by buildings debris; (2) small prefabricated structures (including temporary ones) and fixed urban furniture; (3) parking lots (precautionarily considered as occupied); (4) carriageway reserved to emergency vehicles access (3.5 m, considering the width of the heavy rescue vehicle).

3.4 Street and open spaces damage assessment

Street and open spaces should guarantee the mobility of evacuees and rescuers in the immediate aftermath. In general terms, the street availability assessment can be performed according to two levels of details [20,69,80–82]: (a) possibility that the street can be blocked by the debris; (b) evaluation of the debris quantities along the street, to estimate the available free-of-debris street width. Quick methodologies and experimentally validated ones are preferred to this end in this work.

The approach of [72] defines a street as blocked by debris if there is at least one building along the street for which, contemporarily: A) the ratio between the building height and the street width is equal or higher than 1 (potential façade overturning); B) the suffered damage by the aforementioned building reach the 4th grade of the EMS98 scale (heavy structural damages or collapse [57]) according to the Macroseismic approach [63]. Otherwise, the street can be available.

The external (i.e. along the streets) debris percentage Qx [%] is defined as the ratio between the external debris area and the street area facing the building. This value can be rapidly estimated according to [32]. This work provides experimental-based relations as function of the building vulnerability (calculated according to [63]), the earthquake moment magnitude and the ratio between the building height and the street width. Then, Qx is combined to the mean street width W_b [m] facing the considered building to evaluate the effective debris depth on the street d_{debris} [m], according to Equation 2:

$$d_{debris} = Qx * W_b \tag{2}$$

Then the available width of the street can be easily evaluated by subtracting d_{debris} (for each facing building) to W_b.

3.5 Case-study application

The proposed framework is applied to the historical city centre of Offida (Lat. 42.93, Long. 13.70), Italy, which is representative of Italian historical settlements highly affected by earthquake risk because of these main three aspects:

1. *typological and settlement issues*: the urban tissue follows a medieval compact layout characterized by building aggregates (masonry buildings with irregular shape and age

construction) merged into a narrow streets network system. Moreover, the Historic Centre is confined within the ancient defensive walls system that makes difficult the interconnection with the outside areas in case of emergency;

2. *seismic hazard*: Offida is involved in the frequent seismic activity of its region due to the geomorphological configuration of the Central Apennine mountains. Moreover, relevant earthquakes have been occurred over the time because of the presence of a well-known seismogenic source[7] in the adjacent territories.
3. *exposure*: many tourist attractions are hosted by the HBE from the cultural and architectural points of view and several numbers of mass gathering events are organized during the year bringing in town a considerable number of tourists.

The HBE application area is marked in Figure 2.B: it corresponds to the more complex historic part of the whole historic centre in terms of buildings vulnerability, street/open spaces layout, and crowding conditions.

[7] http://diss.rm.ingv.it/dissGM/; https://goo.gl/3Tbrbd; last access: 06/07/2020

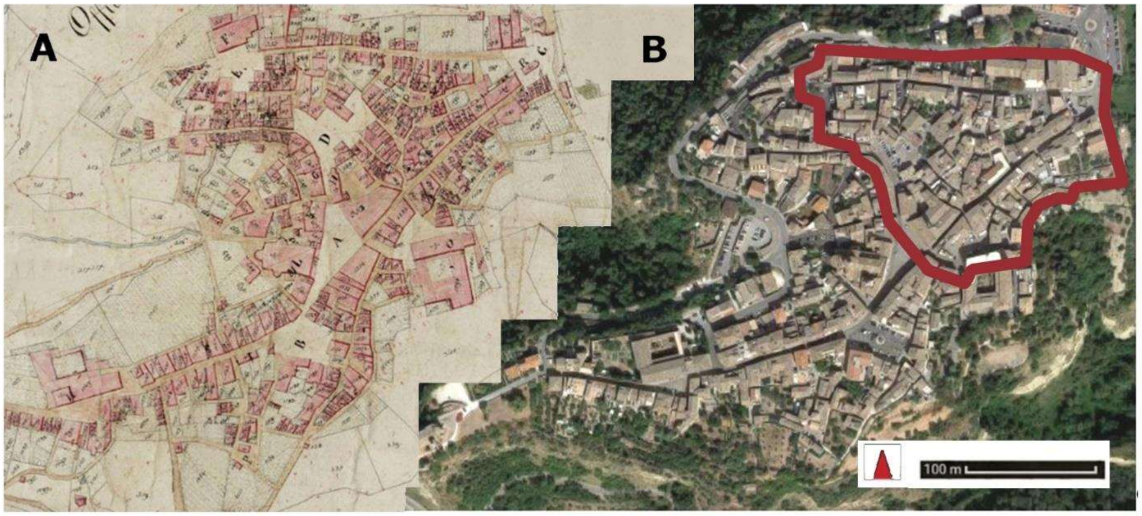

Figure 2 The part of the historic centre (red-marked) of Offida taken as case study. The figure compares: A) the historic map (Gregorian Cadastral maps of 1835 available at http://www.cflr.beniculturali.it/Gregoriano/mappe.php); B) the current settlement (source: Google Maps). Last access to websites 06/07/2020.

4 Results

4.1 Seismic hazard: earthquake characterization

Seismic Hazard characterization concerning the case-study application provides the following data according to Section 3.1 methodologies. Macroseismic data from the INGV database[8] are organized to provide statistics of historic seismic events. Figure 3 graphically traces the related results. Two main events are considered in the following (intensity values are expressed as next whole number): MCS=IV, that is the mean value, as for the 2003 earthquake, corresponding to Mw=4.0; MCS=VIII, that is the maximum value, as for the 1943 earthquake, corresponding to Mw=6.0.

[8] https://emidius.mi.ingv.it/CPTI15-DBMI15/query_place/ last access 06/07/2020

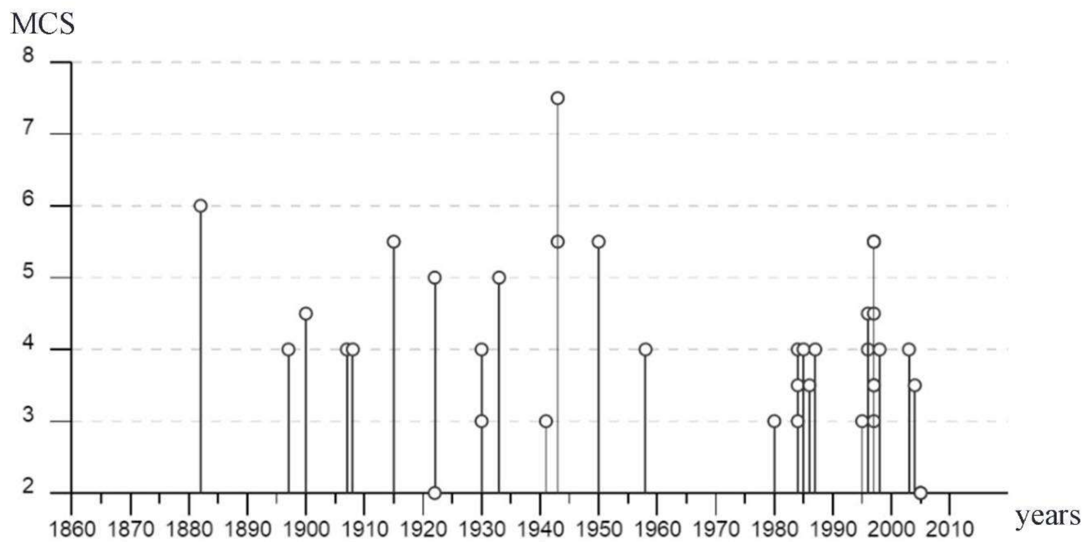

Figure 3 Historic seismicity of Offida according to the INGV database from 1860 to 2017 (https://emidius.mi.ingv.it/CPTI15-DBMI15/query_place/; last access: 06/07/2020). The stronger event (between VII and VIII MCS scale) refers to the 1943 earthquake with the epicentre in the municipality of Offida.

4.2 Vulnerability and layout

The evaluation of the historical evolution of the urban tissue is implemented thanks to the availability of historic maps (see Section 3.2). According to Figure 2, the current urban tissue structure is comparable to the one of the 1835. Figure 4 traces the building and street vulnerability within the selected area of the HBE. The vulnerability of monumental and ordinary buildings is shown in Figure 2-A (for the statistical distribution of ordinary buildings, see Figure 4-B). *Street and open spaces* analyses are provided in Figure 4-C and concern the identification of both the access points for rescuers' vehicles and the pre-defined Assembly Areas (AS) for the selected area (according to the Municipality Emergency Plan). Moreover, the same figure outlines the street vulnerability, by overlaying it to the buildings vulnerability data.

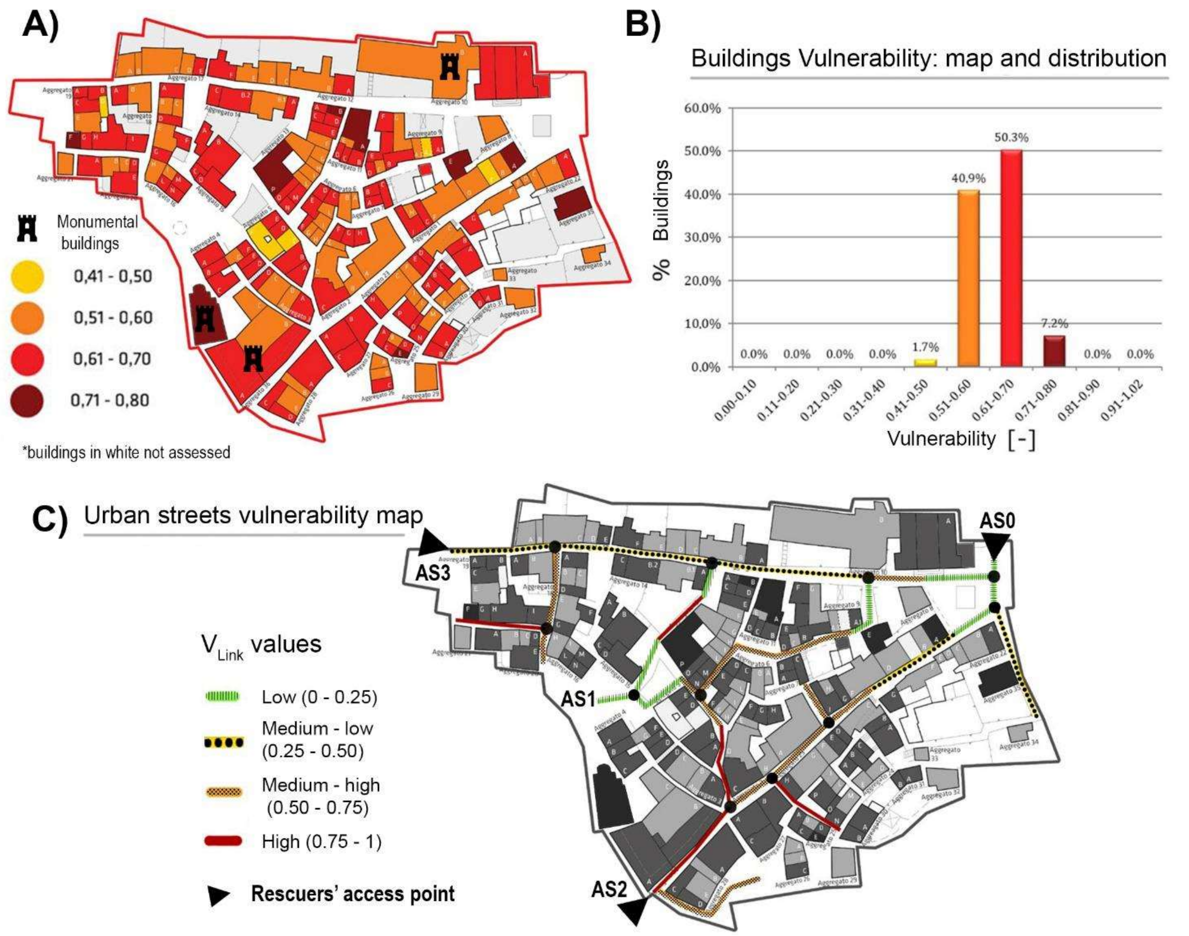

Figure 4 Buildings vulnerability (based on [63,64]) for the selected part of the Historic Centre of Offida: A) vulnerability map by pointing out the monumental buildings and the not evaluated structural units (in white; they do not face on the main evacuation street); B) statistic distribution of ordinary buildings vulnerability; C) vulnerability map of the main streets, where black dots highlight the nodes among streets (nodes referring to dead-end streets or assembly areas are not marked). Four assembly areas (defined by the emergency plan and identified by the code AS and a number 0 to 3) and three rescuers vehicles' access points are reported for emergency planning issues.

4.3 Exposure assessment

To establish the maximum daily presences [pp] *in pre-disaster conditions* according to Section 3.3 methodology, the visitors flow during the year is firstly assessed by using monthly data from the

Regional Observatory of the Tourism[9], as shown by Figure 5-A. Daily visitors' presences are directly retrieved according to databases from museums and tourist attractions[10], as shown by Figure 5.B. These surveys allow considering the daily presence of visitors. Results of Figure 5 highlight how a sensible increase in population occurs during the summer (i.e. in August, due to the holiday season in Italy).

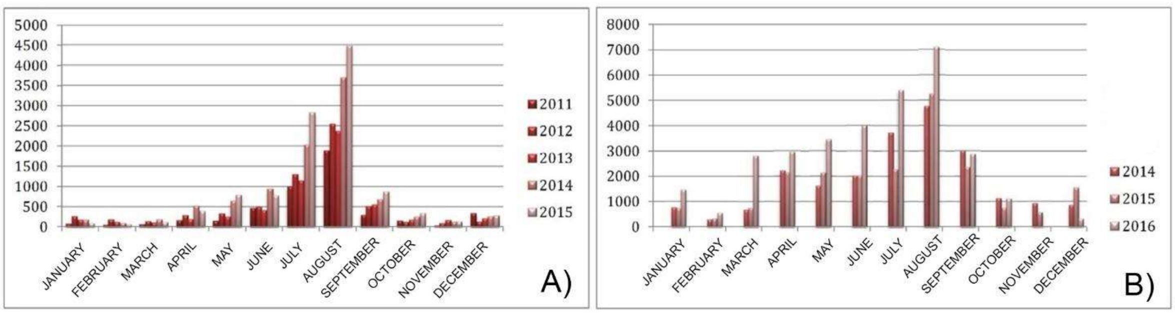

Figure 5 Monthly presences related to: A) visitors (tourist flows; years 2011-2015) of the whole historic centre (source: http://statistica.turismo.marche.it/DatiTurismo; last access:06/07/2020); B) daily visitors (years 2014-2016) to museums and tourist attractions (source: http://www.fabbricacultura.com/socio/oikos; last access 06/07/2020).

Then, Figure 6 resumes the number of inhabitants of the Historic Centre. It is obtained from the municipal database in association to: a) each residential unit, that is, by including information related to the citizens' age, subdividing them into different age-related ranges [83] (i.e.: 0-14 years, parent-assisted children; 15-19 years, autonomous young people; 20-65 years, adults; >65 years, elderlies including those with potentially reduced motion abilities); b) the resulting value for each building aggregate, in terms of the total number of inhabitants. A total of 750 inhabitants can be considered for the overall HBE and 319 only within the case-study area (black line in Figure 6).

[9] http://statistica.turismo.marche.it/DatiTurismo, last access:06/07/2020
[10] http://www.fabbricacultura.com/socio/oikos, last access: 06/11/20

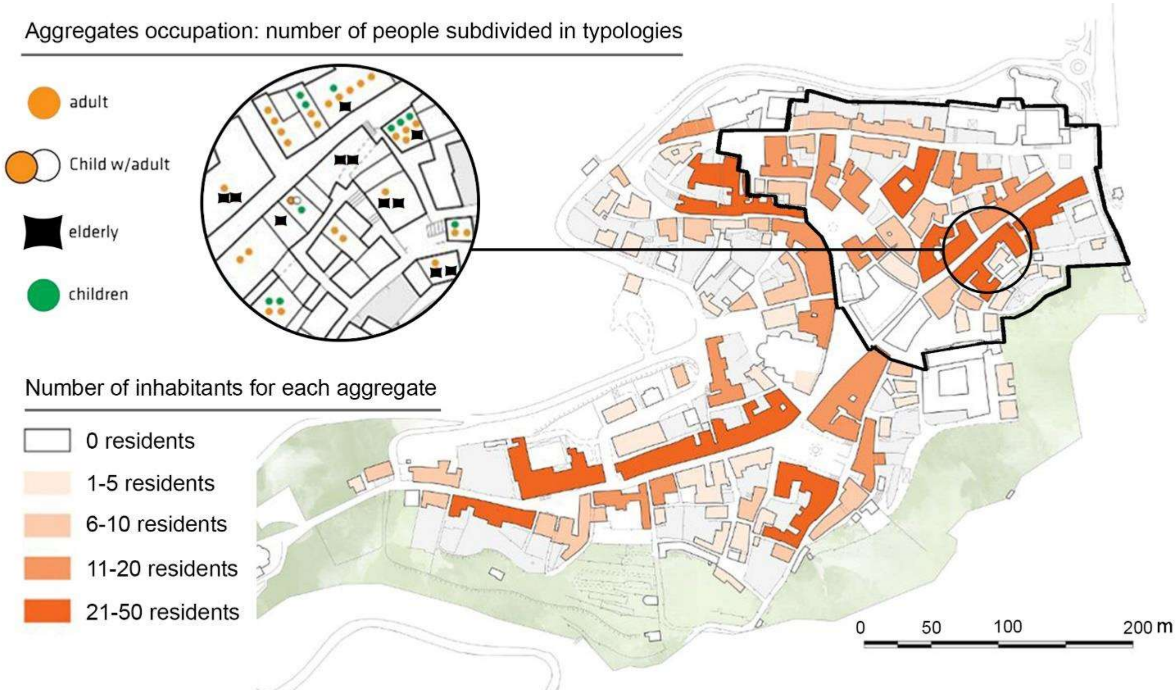

Figure 6 Characterization of inhabitants for the historic city centre by outlining the number of inhabitants for each aggregate (the black line evidences the case-study area). The detailed planimetry excerpt (inside the circle) focuses on aggregates occupation in terms of the number of people by distinguishing them in four typologies according to [27]*: parent-assisted child, young people, adult, and elderly.*

The assessment of the public building occupant capacity is performed by considering the indications summarized in Table 2, according to a quick evaluation of the occupant load [pp/m^2] and to the related building intended use (compare to Section 3.3). The results are graphically shown in Figure 7. These data are merged with those of outdoor public spaces occupant load to define the crowding density (pp/m^2) in open spaces and streets, as shown by Figure 8. In this way, the main areas that are susceptible to mass gatherings (multi-hazard condition) are those of the main street named "Corso Serpente Aureo" (i.e. due to the local market on Thursday) and of the square named "Piazza del Popolo" (i.e. hosting additional festivals).

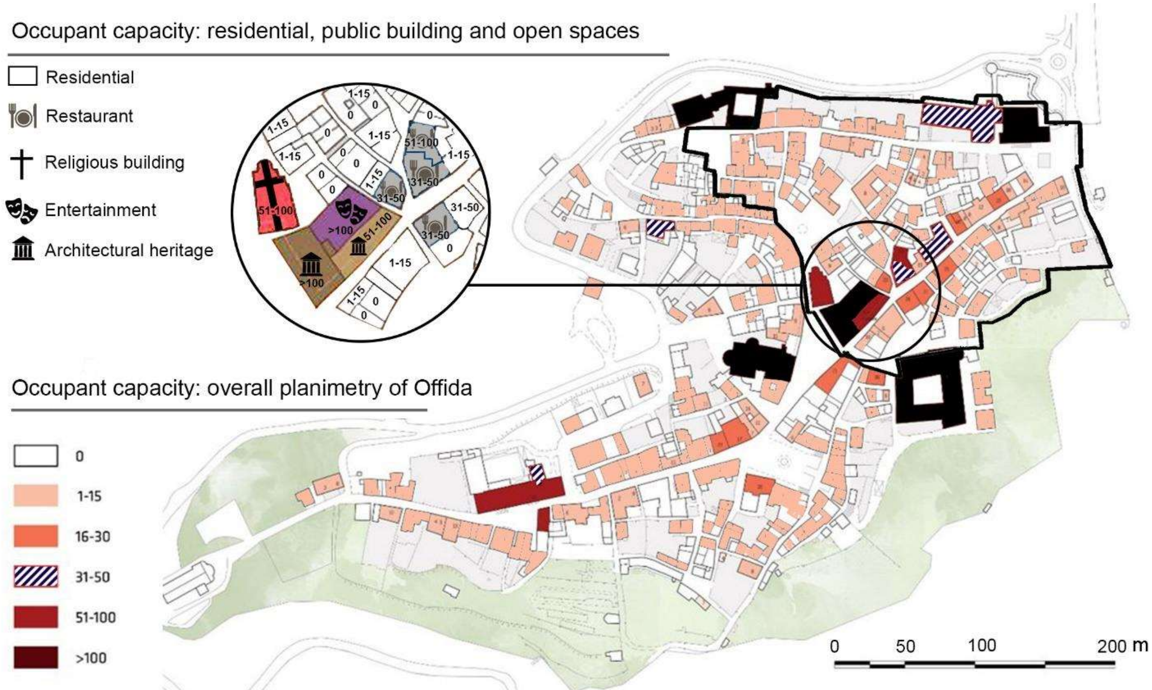

Figure 7 Overall planimetry of Offida with the individuation of the total occupant capacity of buildings, expressed in terms of the number of hosted people (the black line evidences the case-study area). The upper circle shows an excerpt from the analysis in terms of building typologies.

The overlapping of previous data allows defining critical scenarios in terms of occupants' presence in the case-study area. Concerning the selected area marked in Figure 2.B (black perimeter line), the scenarios described in Table 3 can be assumed as representative of recurring maximum achievable crowding conditions all over the year.

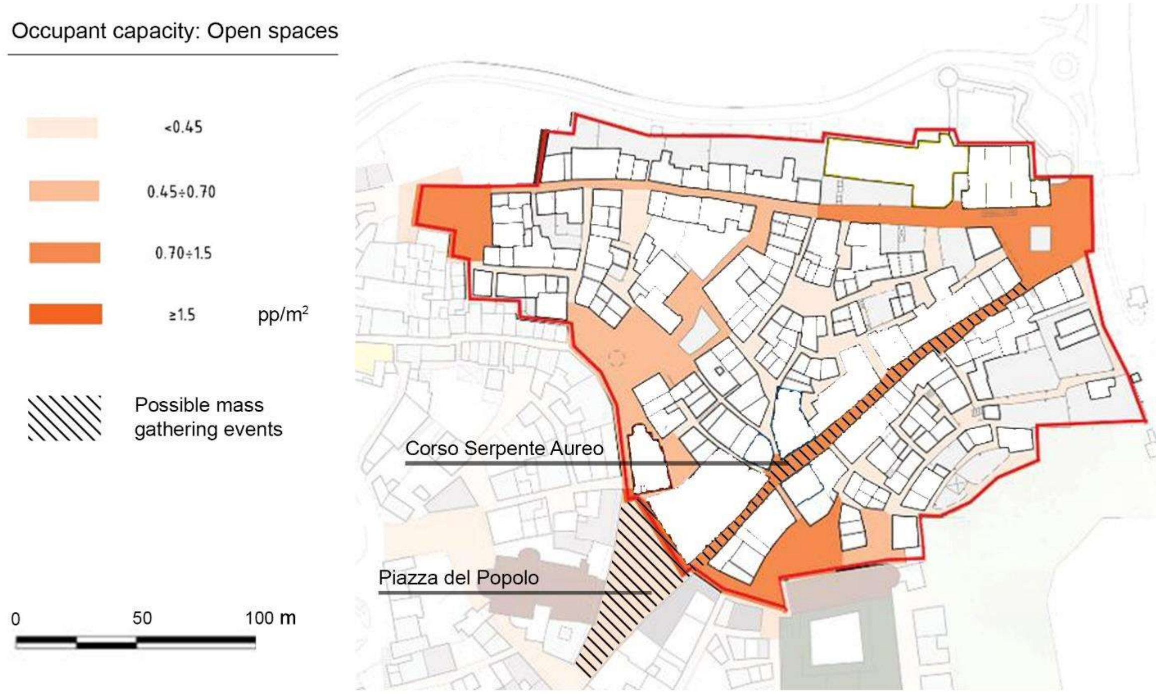

Figure 8 Planimetry of the case-study area in Offida with the evaluation of the crowding density (pp/m²) in public spaces, by evidencing the selected area border. The areas that can host mass gathering events are also evidenced by the hatching texture.

Table 3 Case-study maximum crowding scenarios

	Thursday (9-12 a.m.)	[pp]	Saturday (8-11 p.m.)	[pp]
Building intended use:				
Building heritage (museums, churches)	considering offices in the municipal buildings	121	considered as closed	-
Hospital and healthcare buildings	both personnel and patients	110	long term care	40
Cultural buildings (i.e. theatres)	cultural activities normally held during evenings and weekends	-	cultural activities held imply maximum crowding conditions	300
Commercial buildings	holding maximum occupant loads	176	are closed	-
Tourists accommodation	closed due to day-time activities	-	empty due to evening-time activities	-
Restaurants	are closed because of out of the lunchtime	-	maximum crowding conditions	189
Bars and café	holding maximum occupant loads	47	maximum crowding conditions	47
Inhabitants	people between 20 and 65 years old are supposed out of the Historic Centre, at work	143	dwellings are occupied by residents at the dining time	319
Open spaces:				
Pedestrians	crowding conditions in open spaces of the HBE hosting the weekly market along the main street “Corso Serpente Aureo” considering 0.4 pp/m²	560	HBE could host additional events (e.g. other local markets), assuming an occupant load equal to 0.4 pp/m²	560
Total:		**1157**		**1455**

Additionally, the “Saturday evening” scenario could be characterized by the possibility of *mass gatherings* within the open public spaces in the HBE. In particular, the central urban square “Piazza del Popolo” (Figure 8) that is able to host a maximum level of crowding equal to 3200 people on a limited gross area of 1600 m^2 (by considering a density of 2 pp/m^2, according to Section 3.3). In such conditions, the local theatre could be considered reasonably empty. Finally, in both the scenarios, the tourists’ presence (during the summer, according to Figure 5Figure 5) can be added to the overall capacity of the considered area by summing up 150 individuals, which represents the average value of daily presences (calculated by dividing the maximum monthly tourists' presences for 30 days).

According to the municipal emergency plan, four assembly areas (AS0, AS1, AS2 and AS3) are positioned to host evacuees to face the *disaster conditions* (their position is reported in Figure 4). However, for each of them, the available area A_a [m^2] can be evaluated only by estimating the area occupied by ruins (see next Section 4.4).

4.4 Streets and open space damage assessment

The streets availability in the first phases of the evacuation is based on the debris depth estimation approach as described in Section 3.4. The estimation is provided for both the considered earthquake magnitude values Mw equal to 4.0 and 6.0 (see Section 4.1). d_{debris} [m] values are discretized in homogeneous classes with an approximation of 0.5 m to be reasonably comparable to the individual’s width. The results are shown in Figure 9.

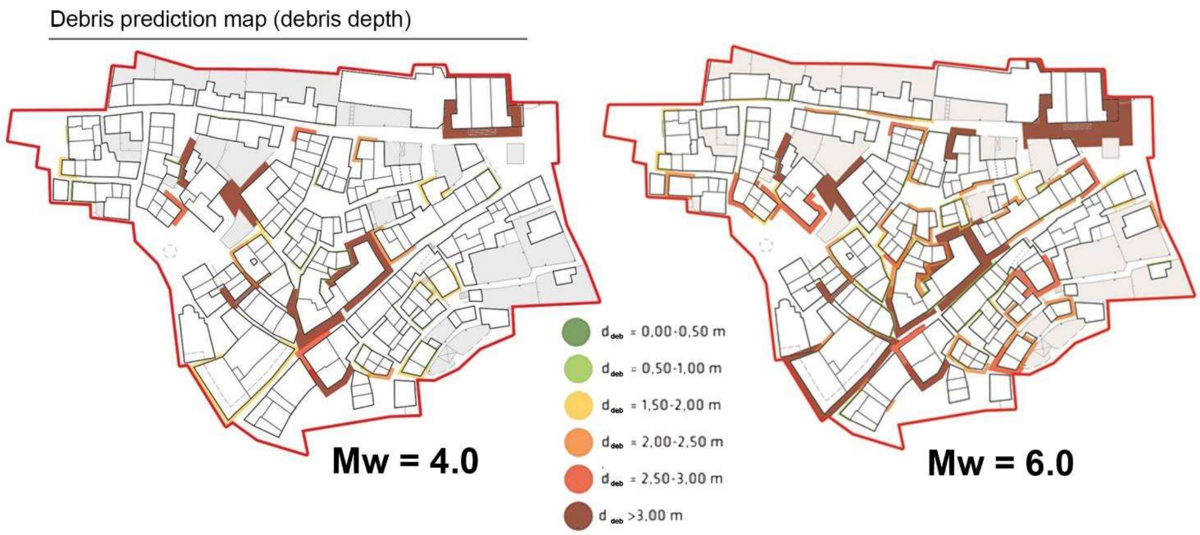

Figure 9 Debris prediction map on the paths network for Mw=4.0 and Mw=6.0.

This approach quickly allows evaluating the probable free-of-debris street width. Figure 10 outlines the maps for the two earthquake scenarios in terms of magnitude to propose a rescuers' access scheme and the distribution of people towards the related assembly areas (compare to "assembly area influence"). These planning elements can be easily proposed depending on the probable streets blocked by debris, and the eventual presence of potential isolated areas during the evacuation process and the immediate aftermath. In both the considered earthquake scenarios, the central area of the settlement is characterized by narrow streets with vulnerable facing buildings thus leading to unavailable streets. Hence, suitable risk mitigation interventions through the reduction of building vulnerability should be planned in this area, also according to the basic vulnerability-related results shown in Figure 4.

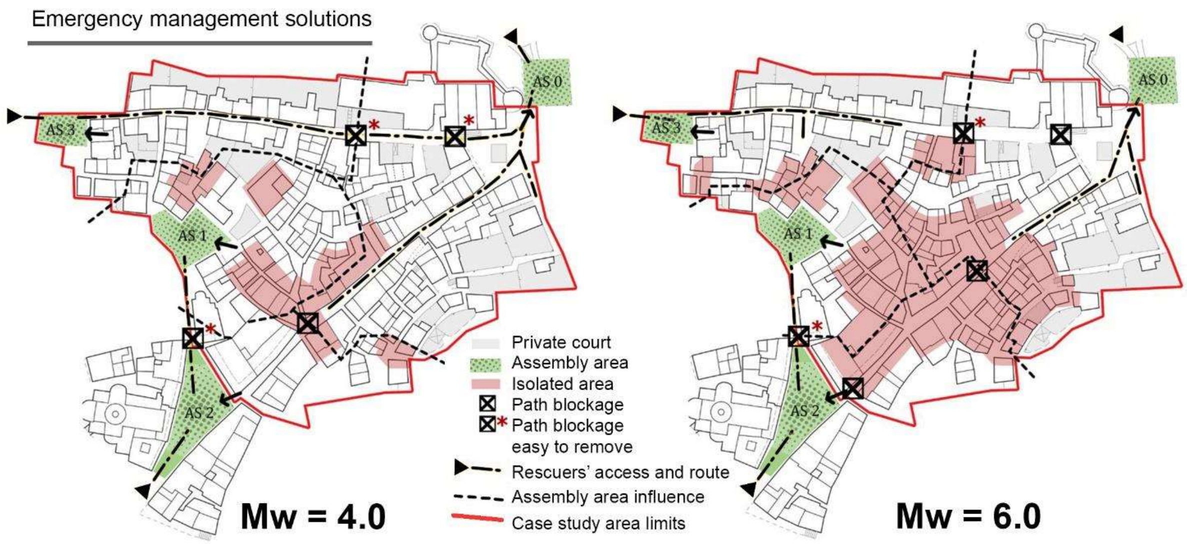

Figure 10 Streets and open spaces damage assessment for Mw=4.0 and Mw=6.0: criticalities and main solutions for emergency management focused on the rescuers' vehicle access and the assembly areas. The unavailable streets marked by "" refer to possible occlusions for the vehicle's transit that could be rapidly reopened in the first emergency phases.*

The debris depth estimation is also performed to evaluate the available area A_a [m²] of each assembly areas according to Section 4.3 depending on the earthquake magnitude. Table 4 shows A_a values excluding the area occupied by possible debris.

Table 4 Extension of assembly areas (rounded at 10m²) in pre-disaster conditions and as a function of the earthquake magnitude. the pre-disaster area of the assembly area 2 is considered equal to 1/3 of the total square area ("Piazza del Popolo") to conservatively consider the possible affluence of people coming from surrounding areas.

Mw	A_a [m²]			
	0	1	2	3
- (pre-disaster)	1020	950	580	540
4.0	990	890	520	500
6.0	920	830	470	470

5 Discussion

The Offida case-study shows how the novel proposed framework allows creating risk scenarios by quickly and effectively detecting the significant HBE risk-affecting factors, i.e. those typical of historical city centres contexts.

Specifically, Offida embodies the typical Italian Historic Centre located in a frequent earthquake-prone region, due to its narrow streets network and highly vulnerable buildings which developed over time according to the HBE evolution. About exposure-related factors, the settlement is strongly affected by a sensible variation in the number of the hosted population (inhabitants and visitors), during both the week and the different periods of the year (i.e. because of the tourists' flow). The most critical conditions of overcrowding (that constitute a multi-hazard condition) are recorded during the summer, on Thursday morning (due to the presence of the local market) and Saturday evening (due to the crowd in pubs, restaurants, and the city theatre). The two damage scenarios for the considered earthquake events (Mw=4, Mw=6) describe high earthquake-affected modifications to the urban environment (e.g.: debris effects due to buildings collapse, also along the streets) which would cause significant impediments to the rescue system if they were not preventively taken into account in the emergency plans. Although differences in earthquake effects on the built environment exist because of the earthquake severity, the method application results evidence that (see Figure 10):

- the area of the main street "Corso Serpente Aureo" must be the "hot-spot" in the urban tissue for seismic retrofit interventions on buildings, to reduce the total amount of debris along the street and limit the streets unavailability considering the evacuees;
- the assembly areas AS are generally accessible by rescuers (from the outside of the considered area perimeter), except for the AS1, in both the earthquake intensities scenarios (an immediate intervention is required to remove the debris along the AS2 to AS1 access path);
- the AS0 is marginally affected by buildings collapse mainly because of its wide dimension, and so it can be used as the main AS to host evacuees coming from the highly-dense populated areas of the main street "Corso Serpente Aureo";

- these risk-reduction interventions effectiveness could be increased only if the evacuees are aware of the urban context, e.g. they should be properly guided towards the best evacuation paths and AS during the emergency evacuation.

Therefore, the case-study application demonstrates how the proposed framework is: *holistic,* since it handles input data on seismic hazard, HBE vulnerability, exposure, and emergency response; *structured,* because it combines data to define emergency scenarios to move towards advanced methodologies (such as those based on simulation-based approaches); *quick-to-apply and sustainable,* since it is mainly based on existing and quick-to-access databases, by integrating local data with rapid on-site survey methodologies; *reliable,* due to its *experimental-based* approach; and finally *oriented towards a human-centred perspective*.

The proposed framework introduces some significant novelties in view of risk assessment and emergency management actions in HBEs.

Contrarily to other studies on the same topic, this work takes into account and widely debates the exposure issue introducing several users' typologies hosted by the HBE at different times and for different purposes. For instance, the determination of exposure parameters is based on a single source on census data (number of inhabitants) (e.g. [48]). In human-centred studies based on emergency simulation (e.g. [13]), the input scenarios are randomly populated by the individuals. On the contrary, in this work, inhabitants are counted considering punctual residential information by also inquiring their ages. Furthermore, the crowd density of HBE outdoor spaces and buildings are considered to determine the presence of tourists and daily visitors. Buildings with specific intended uses (e.g.: hotels, hospitals, theatres, restaurants) are considered to this end. In this way, the framework easily allows to overlap different effects of ordinary conditions and mass gathering events (also including the open spaces in the HBE), thus investigating critical scenarios from a multi-hazard point of view. All these kinds of data will be considered to create more detailed scenarios on hosted populations in simulation-based risk assessment.

Concerning vulnerability-related aspects, the previous studies declare the necessity to conduct in-situ surveys on materials quality and constructive techniques by trained personnel (e.g. [40]). On the contrary, here the involvement of reliable easy-to-use methods pursues the rapid applicability by non-expert technicians as well.

Finally, the proposed framework adopts punctual existing methods in literature to determine single risk components within its practical implementation. Such methods are not exclusive, but they could be replaced by other ones giving the same inquired parameters (also in the view of future methodological improvements). This adaptability criterion enriches the framework innovation, contrarily to other existing methods that seem to establish the adoption of a unique model to collect and manage data (e.g. [37,39]).

6 Conclusion

The improvement of urban resilience against seismic disasters should be aimed at risk reduction strategies based on an effective knowledge of the scenario's conditions. Historical Built Environments and their users are strongly affected by such disasters, because of the high vulnerability of the first and the high exposure due to the second ones (over time and space). Thus, defining risk scenarios is a priority item to determine critical conditions of such contexts and then provide risk-reduction strategies, including pre-disaster interventions and emergency response. This paper firstly provides a novel framework to collect and manage seismic risk-affecting factors and organize risk scenarios, by using current and validated tools. The significant case-study application demonstrates the framework capabilities, thus evidencing that the proposed approach constitutes the first step for a sustainable emergency planning process based on an overall perspective of the most problematic HBE elements in case of a certain seismic event. In particular, results show that easily available data and accessible sources can create a reliable input scenario for HBE risk assessment and emergency management analyses, thus avoiding costly in situ surveys (e.g.: interviews, practical verifications) and guaranteeing a rapid implementation process. Thanking to the easy-to-use employed tools, the entire framework can be implemented by non-expert technicians, too. The inhabitants' distribution is punctually investigated providing more detailed scenarios on hosted populations. Moreover, the framework provides the possibility to also determine exposure "peak" conditions in the scenarios, including the effects of mass gatherings into the HBE from a multi-hazard point of view. In this sense, future integration with GIS-based procedures will boost the application process.

From a holistic point of view, this work contributes to evidence the connections between vulnerability-related issues (including heritage preservation) and the safety of individuals hosted in the HBEs. The main issues concerning the data collection are gathered in a unique methodological framework, thus constituting the first step towards emergency analysis (i.e. simulation-based) approaches. Hence, this novel proposed framework can be employed with other disaster typologies (e.g. further multi-hazard conditions and climate change-related disasters). To do this, some adjustments will be required on the definitions of risk-related factors connected to different disaster sources to face off. Future works for numerical and objective quantifications of the risk in urban areas could take advantage of this provided organization for dataset creation. From this point of view, urban planners and Civil Protection Bodies can base their risk reduction solutions connected to management actions and physical interventions on the HBE elements. Future efforts will start to jointly combine the results of this work with evacuation simulation outcomes, to deeply comprehend the effects of human behaviours in the HBE in an emergency scenario. In particular, the investigations on users' typologies traced in this framework will provide exhaustive data for populating the HBE at a different time, by also including possible inhomogeneous features related to exposed individuals' motion disabilities and familiarity with evacuation procedures.

Acknowledgments

The authors would like to thank Eng. Alighiero Lucidi for the support in the case-study application activities.

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