1

URBAN GRID AND SEISMIC PREVENTION

A CONFIGURATIONAL APPROACH TO THE EMERGENCY MANAGEMENT OF ITALIAN HISTORIC CENTRES

VALERIO CUTINI[1]; ANNA DE FALCO[2]; FRANCESCA GIULIANI[3]

ABSTRACT

Italy is located in one of the most earthquake prone areas in Europe with one of the richest cultural legacy in the world. In the last decades, a series of seismic events caused considerable casualties and damage to the built environment in Italy, highlighting the need of undertaking proactive measures to limit the impact of any potential earthquake on the urban system. The most vulnerable areas are historical city centres whose complex current morphology is the result of a centuries-old processes of aggregation, space saturation and adaptation to the territory. Besides, the great number of historical buildings contributes to the built-up of high exposure to hazard.

Since 2009, after the dramatic L'Aquila earthquake, the Civil Protection Department introduced and consolidated a disaster relief system based on top-down policies to deepen knowledge about site-specific hazard and address preventive planning, providing funding and assistance to local urban planners. Although the programme is still in progress, three points still emerge in the experience. First, the actions have been partially implemented with important shortcomings in the nationwide development of studies and plans. Secondly, the preventive planning has involved so far only strategic buildings while no initiative has been undertaken to improve the capacity of the urban system to cope with the consequences of the event. Third, emergency management plans do not encompass historical centres, thus neglecting their peculiarities and complexities.

This paper introduces an interdisciplinary approach to implement the post-seismic emergency management into Italian historical centres and consequently address their preventive planning. The procedure combines space syntax techniques and vulnerability analyses to evaluate their resilience to earthquakes. The first step is the survey of the present-day configuration, with its historical assets, aggregates, critical infrastructures, urban functions and strategic activities. Then, the vulnerability analysis of the urban fabric supports the prediction of post-seismic damage scenarios, detecting possible debris that can obstruct routes causing their loss of accessibility. Finally, assuming that human behaviours are influenced by the townscape, the syntax analysis offers a measure of the resilience of the grid and allows selecting the "sensitive paths", namely the more attractive routes of the configuration in terms of movement.

This exploratory study considers different historical settlements in Tuscany, taking into account the influence of the spatial elements on urban resilience. For each case study five scenarios have been investigated, providing the routes that inhabitants or rescue teams would most likely follow during an emergency. The comparison between the spatial properties offers a measure of the influence of the configuration on the emergency management and is the starting point for the development of mitigation

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strategies. On this basis, it will be possible to rank priority intervention into a preventive plan in order to ensure free escape routes and clear access for the emergency services during the post-seismic phase.

KEYWORDS

Historical centres, configurational analysis, seismic vulnerability, emergency management, urban planning

1. INTRODUCTION

1.1 Background and aim

When dealing with disasters, the main question in vulnerable areas is not so much "if" but "when" catastrophic events will occur. Such events might be frequent or rare but, in any case, they require attention in order to limit their social, economic and physical impact. Therefore, it is indispensable to investigate the relationship between each risk and the urban structure with the aim of identifying scenarios and priorities of action at urban scale.

In the last decades, the idea that 'disasters are not natural' has been largely discussed and many researchers argue that disasters – even if caused by natural events - result from the interaction of several factors related to social, economic and political vulnerabilities (O'Keefe et al. 1976) (Wisner et al. 2012). Within this holistic approach, several studies have been conducted to identify strategies for risk assessment and disaster management. The approach is indeed officially encouraged by the agencies of the United Nations and other international bodies (UNISDR 2009) (UNISDR 2011) (UNISDR 2015).

The evaluation of risk in built-up areas is the probability of occurrence of an event with a certain intensity on a fixed site; so it depends on three main measures: the hazard of the site; the vulnerability of people, buildings, and infrastructure that make them susceptible to the damaging; and exposure that refers to people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses. According to this definition, urban areas are highly under threat, especially where there is a great and diffuse presence of cultural heritage that contributes to increase the vulnerability and exposure in the site. Consequently, historic centres require attention to avoid loss of human life while preserving the authenticity and values of the ancient landscape. The topic will be further detailed in section 1.2.

On the other hand, disaster risk management (DRM) entails three main phases of pre-event, emergency and response, and post-event (Jha et al. 2013) (Alexander 2002), as summarized in the cycle in figure 1. According to Alexander (2002), there are two types of risk management strategies, short-term and long-term ones; they are both equally important but among the long-term actions spatial planning plays a key role. When dealing with seismic risk, it is impossible to avoid the hazard or predict the occurrence of a shock. Risk mitigation is therefore determined by the multi-level vulnerability and exposure, ranging from the building scale to the urban and territorial ones. Despite the vulnerability of the built environment is today studied by seismic engineering, a neglected area is the relation between urban planning and disaster risk management. Since it is impossible to predict the timing of impacts of hazards, mitigation planning and prevention are the best strategies to reduce costs and losses through structural and non-structural measures. Structural measures commonly refer to engineering solutions that reduce or avoid the expected impacts of hazards. Instead, non-structural measures pertain to urban planning and development (Chmutina et al. 2014) and are useful in difficult areas characterized by several constraints connected to the value of the built environment, for instance historic centres. In such cases, evacuation planning, land use control, emergency access organization and community engagement are paramount.

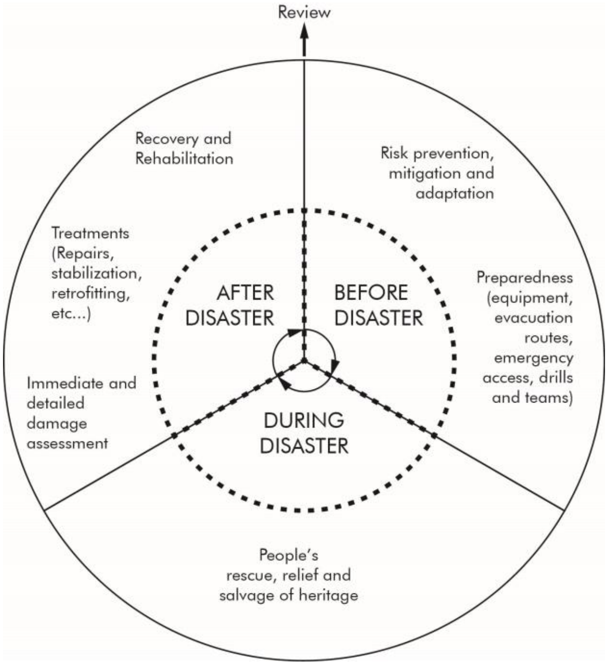

Figure 1 The phases of the disaster risk cycle

This study focuses on the second phase of the DRM cycle and applies space syntax analysis to support emergency management in case of earthquake. The main assumption, according to literature in space syntax research, is that the urban grid has a primary role in urban dynamics (Hillier and Hanson 1984) (Hillier 1996) with a strong relationship between the topological aspects of the network and the distribution of 'natural movement' (Hillier et al. 1993) (Hillier and Iida 2005).

In this paper, a specific emphasis will be given to historic centres in order to enhance their response and recovery capacities in case of earthquake. The heterogeneous characteristics of the built-up areas, with their complex morphology and irregular form, do not provide general indicators to compare different systems or scenarios. Conversely, the topology of space and its representation with Space Syntax techniques can provide mathematical and non-arbitrary information on account of its capacity to internalise irregularities and evaluate the relations between the spaces of the system.

The first question addressed in this study regards the capacity of the configurational indexes to provide a correlation between the grid configuration and emergency management, with reference to emergency routes and functions. The second question entails an evaluation of the impact of earthquakes on the systems, comparing scenarios characterized by disruptions and failures that can obstruct the street network. The collapse of portions (or even the totality) of the urban fabric can cause debris and road blockages with consequent limitations in the evacuation or access to the centre. Literature distinguishes between two types of road damage (Argyroudis 2003), direct and indirect damage. According to Caiado et al. (2012), direct damage mainly affects regional roads and is caused by ground subsidence, soil liquefaction, sliding of embankments and slopes, and all the phenomena which result in surface ruptures and pavements cracking. Instead, indirect damage refers to fallen obstacles such as debris from collapsed buildings or non-structural elements, or damage caused by lifelines ruptures (e.g.: gas or water distribution network); such damage commonly involves urban roads. Dealing with historic centres, this study considers only indirect damage.

Starting from the analysis of the emergency in the earthquake scenarios, the study serves as a tool to identify long-term prevention measures oriented by spatial planning and policy actions. In this way, the whole risk management process may benefit from the optimization of the emergency response phase.

The remainder of the paper is organised in four sections: section one introduces previous and current procedure for emergency management in Italy and provides a discussion on the key problems of historic centres, with reference to the case studies; section two examines the methodology and the use of space syntax approach; section three reports the results of the analysis and provides a preliminary discussion; section four draws conclusions and future developments of the research.

1.2 Historic centres and emergency management: the Italian situation

Italy is one of the most earthquake-prone countries in the Mediterranean area so that seismic hazard is considered as one of the greatest challenges. The highest seismicity is concentrated in the south-central part of the peninsula, along the Apennines, from Tuscany to Calabria, as well as in Sicily and in some northern areas, such as Friuli, Veneto and part of western Liguria. These areas have been urbanised in ancient times and today host a number of borgoes and historic settlements with unique assets that contribute to their integrity and heritage values. Nowadays, historic centres are cultural resources and their distinct morphology, urban fabric, architecture, community structure and boundaries progressively evolved through a century-old process.

During the last decade, several historic centres have been severely damaged by earthquakes, and the vulnerability of historic buildings has been largely investigated through methodologies pertaining to different disciplines (seismic engineering, risk management, urban planning) and different scales (national, territorial, urban, building). Despite the sectorial studies conducted during the past years, not many advancements have been carried out combining the disciplines of seismic engineering and urban planning. In practice, the interdisciplinarity have been neglected so that the actual strategy and tools to cope with disaster risk mitigation in urban areas are sector-centred.

The current National Seismic Prevention Programme, promoted by the Italian Department of Civil Protection (DCP), is conducting microzonation studies and interventions for seismic retrofitting of strategic buildings, as well as funding private initiatives for local strengthening of properties (Dolce 2012). At the municipal level, only the Limit Condition for Emergency (LCE) deals with the urban settlement, identifying a damage scenario in which most of the urban functions are interrupted. Only the strategic functions for the emergency management are preserved, as well as their internal connection and their access routes from the external territorial context. The approach developed from the Augustus Method that is the major reference for emergency management in Italy (Galanti 1997); it acknowledges the importance of the road network in the relief system, locating 'emergency areas', namely meeting points, shelters and first-aid zones. During the emergency, the safeguarding of human life is of upmost importance; then temporary shelters and deposits are endowed to host citizens, material and, sometimes, cultural heritage.

Even though historic centres have been identified as a priority among the research needs (Dolce and Manfredi 2005), the necessity to improve their disaster risk management has been so far neglected. According to estimates by the DCP, the ratio between damage and energy released during earthquakes in Italy is higher than other seismic countries around the world. The main causes are the high population density and the fragility of the built environment, as well as the lack of interventions and awareness. For example, in the last 3 years, the long seismic sequence in the Central Italy caused considerable damage. Regrettably, the high vulnerability of the local infrastructure, the presence of a vulnerable buildings stock and the shallowness of the largest events (depth around 8 km) resulted in a great number of casualties and homeless, with difficulties in the post-disaster management. Besides, the aftermath of the 1980 Irpinia earthquake included huge human losses and damage to cultural properties in historic centres, with half of the building stock collapsed. The event had an interesting breakthrough: for the first time it was clear that the main cause of such disaster was the location of settlements on slopes or ridges (De Paoli 2012), namely the traditional use of the territory had become a vulnerability tearing apart the idea of a harmonious co-existence between the local communities and their environment. Paradoxically, the long periods during which disastrous earthquake in Italy does not occur make the settlement even weaker because of the citizens tendency to underestimate or even remove the possibility of a new disaster. This tendency results in insufficient prevention activities and emergency preparedness throughout the country which is caused by the great distance between National authorities and Local Governments. Besides, in such areas, the lack of resources and the poor planning can cause widespread damage to cultural assets and loss of identity for local communities.

As a matter of fact, the reality is more complex and disasters in historic centres resulted (and still result) not only from the location, but from a series of practices processed over generations, such as unmanaged stratifications, change of use and appearance in buildings and aggregates, lack of maintenance, mixed construction types with a misuse of modern constructive materials on vernacular architecture. Italian towns show common features such as the absence of linearity and regularity within the urban fabric, or the presence of narrow, winding streets often linking squares. Originally, the settlements were characterized by a rarefied urban fabric looking very different from the nowadays compact centre; then the existing buildings were sided by other constructions moving towards the saturation of the urban space. Besides, several elements have been added on facades or openings have been varied in order to comply with changes in living standards. Despite the present-day ‘chaotic’ appearance, the development of the block and its growth had modularity and a specific layout with modules perpendicular to the longitudinal axe of the roads (Caniggia and Maffei 1984); the latter followed the orography of the site creating spontaneous irregular paths with different connectivity in relation to the dimension of the block. Many historic centres are still enclosed into the defensive walls with a limited number of gates that hinder the evacuation in case of emergency.
In conclusion, as highlighted by Maffei and Caniggia (1984), there is a close interdependence between constructive techniques, typologies and morphologies in Italian historic centres. The challenge is to link this interdependence with risk assessment and management in order to ensure it does not turn into an interference for the road network during the emergency.

1.3 Case studies

Two historic centres have been selected for the analysis and comparison: San Gimignano and Lucignano. Their urban configuration is characterized by similarities despite the differences in the adaptation to the territory. The case studies are located in Tuscany, an Italian region known all over the world for its golden grain, vineyards and ancient borgoes. The cities sit on a height of land, dominating the surrounding landscape and clearly visible in the distance. In spite of their different morphological development, both the historic centres treasured their architectural homogeneity and original urban layout over time, retaining their feudal atmosphere. Indeed, it is this reason that led to the inscription of San Gimignano in the UNESCO World Heritage List in 1990.

The historic centres developed around the main public buildings, representing the religious and civic powers, with the adjacent squares serving as important meeting places for the population. Besides, they are characterized by a particular pedestrian orientation, typical of medieval cities, that provides a sense of enclosure thanks to the continuity in the building line. Lucignano still presents a peculiar configuration in elliptic shape with concentric rings of narrow streets whose layout follows the orography of the terrain; several radial roads link the outer ring to the top of the hill, where the public functions are located. San Gimignano grew with an intricate layout around the castle and a core composed by the Cathedral, the Town Hall and three adjacent squares. The perimeter of the two hilltowns is defined by the defensive walls with gateways still preserved. In case of Lucignano the city walls have been progressively incorporated in private houses and historical buildings, while the gates are still visible. San Gimignano medieval walls are well-preserved, and five gates allow to access the ancient settlement.

Nowadays, the historic towns are vulnerable to disasters and prone to several hazards, particularly seismic hazard which is higher in areas in close proximity to the Apennines. San Gimignano and Lucignano are located in a seismic-prone area classified as zone 3, characterized by a maximum PGA of 0.15g. Between the 1804 and the 1998, 20 earthquakes are registered in the area and a VII-degree earthquake (MCS scale) VII-degree earthquake occurred on September 1869. Besides, the effects of the increasing tourism and the related pressure on modifications to the traditional use of buildings pose relevant conservation and safety issues. San Gimignano shows signs of unsustainable congestion due to the increase of touristic flows (De Ascaniis et al. 2018), so that there is a great presence of people that are unaware of risks and are not prepared to face emergency situations.

Figure 2 Location of the historic centres in Tuscany, Italy. Number 1 is Lucignano, in province of Arezzo, while number 2 is San Gimignano, in province of Siena.

2. DATASETS AND METHODS

In recent years, space syntax research emphasised the correlation between the syntactic properties and the concept of resilience (Koch and Miranda Carranza 2013), paving the way towards disaster risk management. The main advantage in the application of syntactic analysis is in the possibility to determine and quantify the pattern of movement, interpreting the natural tendency of people to move into urban grid privileging some spaces and paths (Hillier et al. 1993) (Hillier and Iida 2005). In fact, approaches based only on the calculation of geometrical distances can't be representative of the way people use the space, especially during emergencies when human behaviour is strongly guided by space perception and previous experience. When selecting 'sensitive paths' the shortest are not always the ones that people will walk, thus space syntax techniques can provide indicators regarding the movement in the urban spatial structure.

Many authors approached the topic comparing urban grids pre and post-disasters, referring to flood (Abshirini et al. 2017) (Esposito and Di Pinto 2015), typhoon (Carpenter 2013), volcano (Cutini and Di Pinto 2015) or seismic (Cutini 2013) (Sari and Kubat 2012) hazards. However, a neglected research area regards the relationship between the emergency functions and the spatial properties of the grid. Space syntax assumes that the activities within the urban grid can amplify the natural movement, acting as configurational attractors (Hillier et al.1993) (Hillier 1996). Thus, the notion of centrality is intended as attractiveness which depends only on the spatial relations between the elements within the urban layout. Several studies (Cutini 2001a) (Cutini 2001b) proved that the integration index can reproduce the location of free market activities (or non-monopolistic) with a narrow correspondence on the grid. In front of them, the monopolistic activities can be assumed as non-configurational attractors because they can influence the movement independently from the grid.

Common syntactic properties adopted for the description of the grid during disasters are choice and integration, which are also known to represent the *through-movement (*or *betweenness centrality)* and *to-movement (*or *closeness centrality)*, respectively (Hillier and Iida 2005).

Choice reproduces the potentials of a spatial element to be on the shortest paths connecting all the others, a very important aspect that can be related to evacuation. Besides, *integration*, as a closeness measure, identifies the urban spaces where people tend to direct, intentionally or not, when moving into the city. Another parameter is the *connectivity* that is the number of directly connected elements. Based on these configurational indexes, other parameters have been introduced to measure the impact of change caused by disruptions.

Koch and Miranda Carranza (2013) introduced the topic of 'syntactic resilience' by analysing a building that is assumed as an 'interface' where several link interruptions can happen. The authors focus on the interior wayfinding which is measured by the *integration*. The authors compare the integration values in two configurations, before and after the change, and measure the degree of change in terms of *sameness* and *similarity*. The main weakness in this study relates to the dependency from the number of segments which indeed is one of the variables of the problem.

Another approach to urban resilience has been proposed by Cutini (2013), who introduces three indicators: the *mean connectivity* (C_m), the *frequency index* (v) and the *synergy index* *(R^2)*. The first represents the number of alternative paths between the edges of the segments within the grid; the values of C_m range from 2 to n, being n the number of segments, and are high in case of a dense presence of alternative paths even in case of disruption. The second parameter is the ratio between the maximum actual choice and the maximum value it could virtually reach (equation 1), representing the distribution level of the shortest paths.

$$v = \frac{I_{choice,max}}{n^2/_2 - ^3/_2 + 1} \qquad (1)$$

The index is between 0 and 1, representing a vulnerable system when *v* tends toward 1 and resilient otherwise. The last parameter refers to the so-called synergy (Hillier 1996) and is the correlation between global and local integration values, with radii n and 3 respectively. High values of synergy stand for a higher resilience of the system.

Carpenter (2013) considered the coastal area hit by Hurricane Katrina in 2005 and compared the resilience of the settlement in relation to the urban changes caused by the disaster. The study evaluates several parameters, among which the syntactical properties are metric and angular reach that depend on the direction changes and the distances. Esposito and Di Pinto (2015) examined the changes in the angular segment properties of three flood scenarios, adopting the three configurational-based indexes proposed by Cutini (2013). Given the limited variations in the values, the authors conclude that the networks of the studied city retained the same functional structure before and after the disaster and is therefore resilient to floods. A further study by Cutini and Di Pinto (2015) measured the resilience of the cities in the Vesuvius area and highlighted the higher vulnerability associated to the new urban development. An interesting discussion on vulnerable settlements and earthquakes has been proposed by Sari and Kubat (2012) whose study aimed at prioritizing interventions on the basis of the necessity to limit road blockages.

Based on the existing knowledge, this paper presents a methodology to improve emergency management by means of space syntax analysis. Through the application of the configurational approach in support of emergency planning, the methodology can be a valid tool to finally piece together the two disciplines, while dealing with the fragility of historic centres. In fact, the results allow identifying proper risk mitigation actions aimed to minimize the impact of earthquakes, prepare for a crisis situation and be able to immediately respond. The evaluation of emergency scenarios starts from the grid characterization and considers the possible invariants and interferences for the emergency management. The methodology is based on three main layers: i) land uses for emergency; ii) specific vulnerabilities of the built environment and; iii) network and flow analysis. The physical data derived from the layer (i) are combined with the results of layer (iii); this allows to evaluate whether there is a correspondence between the configurational properties and the location of strategic functions.

The layer (ii) represents the starting point for the definition of disruption scenarios associated to the collapse of one or more vulnerable elements.

Before detailing the contents of each layer, table 1 summarizes the datasets and their use in this work. The data regarding urban plan of the historic centres are available from the Carta Tecnica Regionale (CTR), the open source regional technical map. The Structural Plan and the Emergency Plan of the two cities have been consulted to collect information on public buildings and emergency services. Then, on-site surveys are necessary to verify the consistency of the maps and gather additional information regarding strategic functions or vulnerabilities. Furthermore, several institutional databases provide data on the built environment (height of the buildings, inhabitants) and cultural heritage.

Table 1 Datasets of the research.

	Layer	Data sources	Actions
i	Land uses for emergency	Structural Plan Open data (Geoscopio[4], Vincoli in rete[5]) Emergency Plan	Map strategic functions, emergency or empty areas
ii	Specific vulnerabilities	On-site survey Historical data	Map local vulnerabilities
iii	Street network	CTR On-site survey	Edit maps Space Syntax analysis

Firstly, the land uses layer identifies all the critical and strategic functions in case of emergency, with respect to the LCE which entails the identification of the structures for the emergency management. The layer maps strategic buildings inside the boundaries of the historic city, such as operative centres, town hall, hospitals, schools, and shelters. In the emergency scenario simulation, the connection between the strategic functions and the urban centre should be preserved in order to guarantee access to emergency services and limit human losses. According to the August Method (Galanti 1997), other important areas for this layer are emergency areas that can serve as meeting points, temporary shelters or deposits; a preventive location of such spaces could improve the intervention and increase the preparedness of services and citizens. For this reason, these areas should be easily reachable even by trucks, and should have basic supplies, i.e. power and water. Empty urban spaces are generally rare in historic centres so that paths and squares should remain in safety conditions.

The second layer analyses the specific vulnerabilities of the historic centres and introduces a site-specific measure of the built-environment. Even though this research does not consider damage scenarios of the historical building stock, it is necessary to identify in a separated layer the vulnerable elements that can interfere with the road network, limiting the capacity of the settlement to cope with the emergency. As stated by the DPC, more than 25% of the casualties during earthquakes are caused by the collapse of non-structural elements, so that it is important to survey these elements on each building of the centre. In particular, the mapped non-structural deficiencies that can potentially cause road obstruction are infilled panels, chimneys, cantilevers, cornices and other heavy elements on facades, dangerous in case of fall. Besides, the urban scale of the problem requires the adoption of a wider perspective so that other vulnerable elements can be towers and vertical elements (i.e. water tanks), retaining walls, small bridges and underpasses (De Paoli 2012). In this regards, walled cities present inherent vulnerabilities associated to the limited number of gateways and the impossibility to guarantee

[4] http://www.regione.toscana.it/-/geoscopio
[5] http://vincoliinretegeo.beniculturali.it/vir/vir/vir.html

alternative exit from the historic centre. Consequently, gates are both constraints and interferences, and their collapse can significantly impact on the emergency capacity.

The last layer introduces the analysis of the historic centre from a network perspective, referring to the urban grid and the patterns of movement. The urban grids of the two case studies entail only the historic centres, corresponding to the area within the ancient walls. The systems have been studied with the Angular Segment Analysis (ASA) provided by the UCL Depthmap. In ASA, streets are represented as intersecting segments whose cumulative angular measure is considered in the processing of the syntactic properties. This aspect is particularly relevant in the analysis of historic centres that are characterized by narrow and winding streets with a wide variation in the segments' cumulative angle. According to the literature review, the syntactic properties that are relevant for the purpose are connectivity, radius n choice and radius n integration, where radius n corresponds to the historic area. Although previous studies consider local measures (commonly with radius 3) as relevant parameter, our only referral to global analysis is due to the generally small size of the grid network corresponding to the observed historic centres.
For each case study, the present-day configuration has been studied in terms of integration in order to identify its core and centrality. The results provide information on the sensitive paths, namely the ones that could be critical due to the presence of great flows and lack of alternative routes. Such situation requires the implementation of proper strategies aimed at reducing the closure probability, avoiding the isolation of streets or districts. By comparing the integration core with the location of the strategic functions and emergency services identified in layer (i), it is possible to understand whether there is a correlation or not. Strategic functions that are located in segregated areas can represent a further element of vulnerability that affects the efficiency of the emergency response.
In addition to the pre-seismic scenario, four post-event configurations have been associated to disruptions, hypothesised considering the likelihood of streets closure according to layer (ii). The new maps have been created by removing the streets that could not be accessible by vulnerable categories of people and by emergency trucks, or that could be blocked by the collapse of the gateways. According to the literature review on resilience, the comparative analysis is based on the two configurational-based indexes, the mean connectivity (C_m) and the frequency (v), thus neglecting the synergy that does not seem suitable for providing useful information when applied to small systems.
Scenarios have been created on the basis of some general considerations. Given the inherited capacity of historic centres to be pedestrian-oriented, a space syntax analysis of their complete grid provides information on human accessibility or evacuation. However, the map includes stairways and very steep roads that can limit the evacuation of people with disabilities. Thus, a separated analysis should be performed on a second grid that excludes the paths that can't be accessible by these groups because of the slopes, slippery surfaces, stairs. Similarly, not all the streets are accessible to emergency trucks and services due to the lack of the minimum passing space. The third grid is obtained by removing the streets that: i) are less than 2,50 m in width, ii) host urban stairways, and iii) present obstacles in height (i.e. low balconies, low-covered passages). Furthermore, two other grids are obtained by simulating scenarios according to the specific vulnerabilities mapped in layer 2, with particular reference to gateways whose collapse can significantly alter the syntactic properties.
To summarize, the analysed scenarios are the following:

- Scenario 1: it considers the whole grid and the space syntax analysis provides its pedestrian capacity whereas historic centres are pedestrian oriented.
- Scenario 2: it considers a grid tailored on the needs of elderly or disabled people, such as wheelchair users, that struggle to walk through the winding streets with changes in level.
- Scenario 3: it takes into account the vehicular accessibility for trucks and emergency services, thus excluding stairways, low-covered or cantilevered passages.

- Scenario 4 – 5: they consider the collapse of the gateways and depend on the case study.

3. RESULTS

The results of the analysis on the two historic centres, Lucignano and San Gimignano, are presented in the following sections, where some special emphasis will be given to space syntax and to the configuration of urban space. The city walls are assumed as the limit of the ancient settlements and thus the analysis is based on the hypothesis that all of the gateways conduct to safe areas.

3.1 Land uses for emergency and specific vulnerabilities (layers i and ii)

The historic centre of Lucignano (figure 3) presents four accesses, three of them coincide with the historic gates, while the north-east passage has been realised with the demolition of a portion of the city walls. It is characterized by the location of several emergency services within the boundaries of the historic centre. The town hall (TH) is hosted in an ancient building on top of the hill, close to the main church, the Collegiata of San Michele Arcangelo, and the Church of San Francesco which are both listed as heritage according to National Protection laws. Next to the town hall there is a primary and secondary school. Other strategic uses for the emergency management are the police (P) and healthcare (H) functions, both located into the historic centre of Lucignano. The squares and the open spaces are identified as temporary emergency areas and meeting points to gather population, especially vulnerable groups.

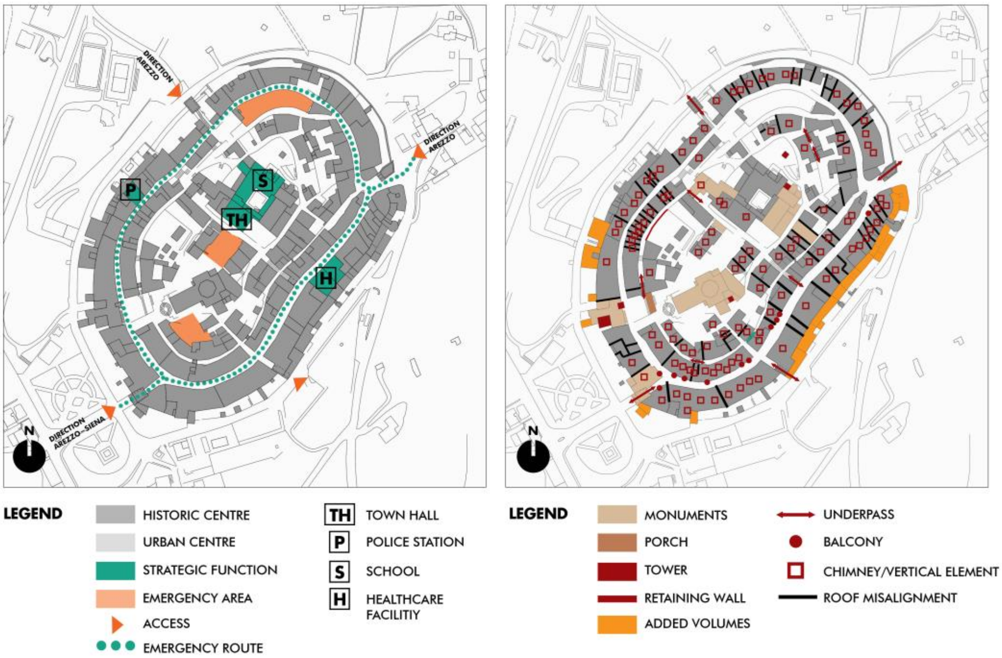

Figure 3 Historic centre of Lucignano. On the left, map of the land uses for emergency; on the right, map of the specific vulnerabilities of the built environment.

San Gimignano (figure 4) has a different organization, in fact some emergency functions, such as the police station and the healthcare services, are located outside the historic city. Only the town hall is inside the historic walls and is still hosted its original building. There are five gateway and two more pedestrian accesses. Most of the constructions around the three main squares (Piazza delle Erbe, Piazza del Duomo and Piazza della Cisterna) are listed as heritage; the squares are the only open spaces in the town, so they are identified as meeting areas where emergency services can rescue people.

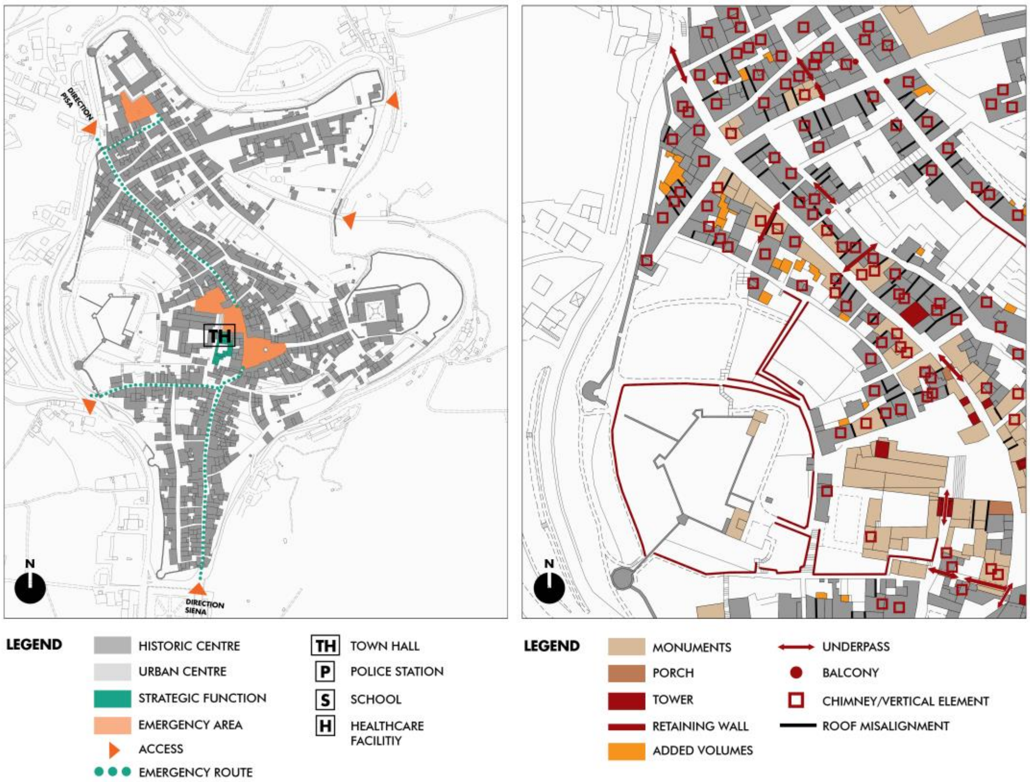

Figure 4 Historic centre of San Gimignano. On the left, map of the land uses for emergency; on the right, map of the specific vulnerabilities of the built environment.

3.2 Space syntax analysis (layer iii)

This layer is paramount to consider the orientation of people and their pattern of movement into the urban grid. The maps are obtained with the application of the ASA to the segment maps of the two historic centres. Each segment map has been constructed including all the accessible spaces so that the grids internalise the presence of slopes. Depthmap provides a chromatic representation of the configurational indexes: high values are highlighted by the red hues, low values by the blue ones.

Given the interpretation of the integration index as a to-movement parameter, we can assume that the most integrated segments identify ‘sensitive’ routes. With this term, we refer to those streets that may be chosen as evacuation routes from residents or visitors to escape from the historic centres. This appears as a realistic condition because an integrated street generally presents great flows according to the wayfinding behaviour. The global analysis of the segment map for the historic centre of Lucignano (figure 5) shows that there is an integration core in the south eastern area; the western part is more segregated and presents a lower potential of accessibility. Instead, the radius n integration of San Gimignano (figure 6) proves that the north-south and west-east axes can be key-routes for the emergency planning.

With reference to the emergency functions, the methodology refers to the interpretation of centrality as a form of attractiveness so that we can relate configurational properties to the location of the activities. We evaluated the integration index for the historic centres and compared the results with the emergency functions in layer (i) (figures 5 - 6). These functions (town hall, school, hospital, police station) refer to monopolistic activities and present a poor correlation with integration. An example is provided by Lucignano (figure 5), which is characterized by the location of strategic activities, namely the police station and the school, into segregated areas. Since the grid configuration does not affect the location of such monopolistic activities, they could either be moved or considered as a vulnerability in the planning phase. However, we can likely assume that a change would involve high costs and provide very little effect of the attractiveness of the urban areas. For this reason, in the emergency planning, the information should be considered crucial, and proper emergency routes should connect each strategic function to the safe areas outside the city.

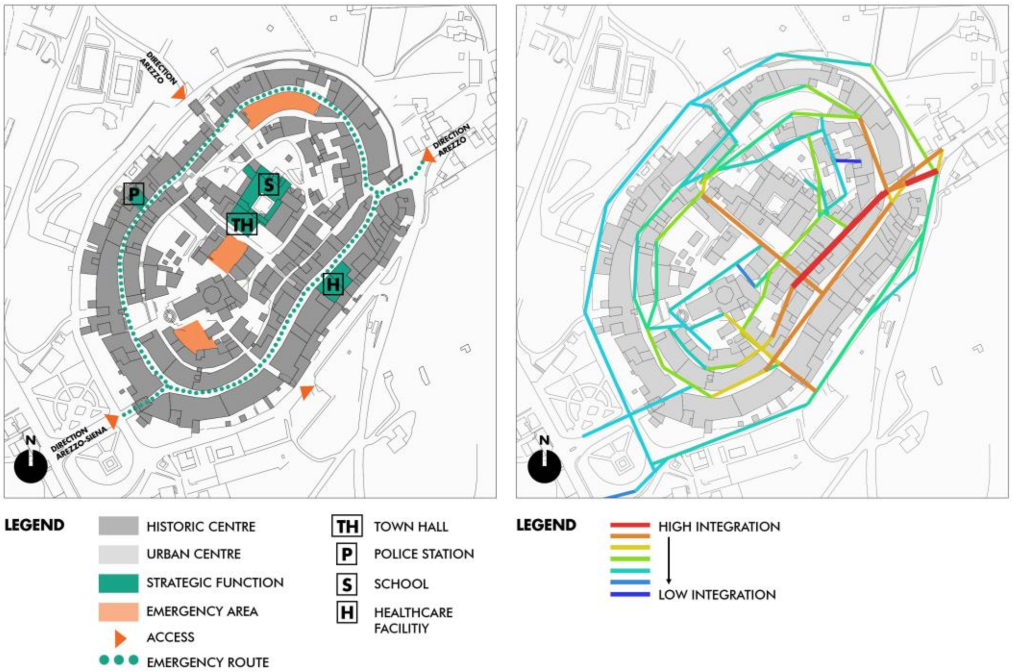

Figure 5 Historic centre of Lucignano: visual correlation between the location of emergency functions and the integration values of the grid.

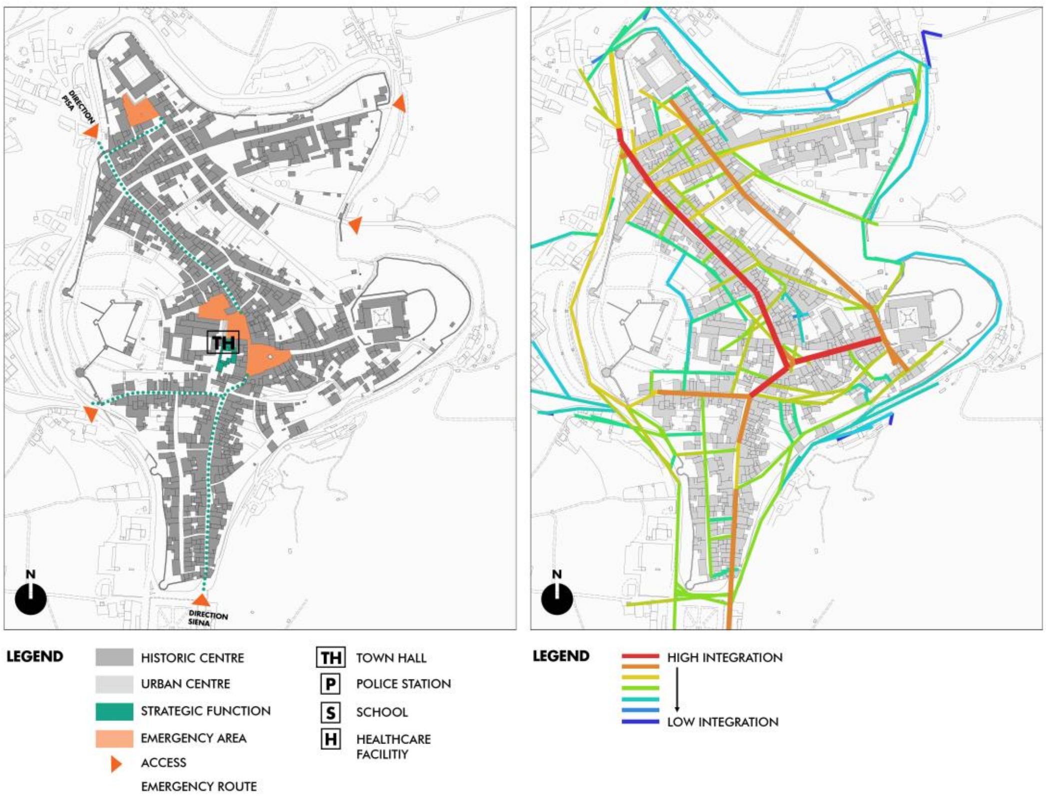

Figure 6 Historic centre of San Gimignano: visual correlation between the location of emergency functions and the integration values of the grid.

A further step in the analysis entails the evaluation of emergency scenarios, as described in section 2. The comparison of the five scenarios (figures 7 and 8) allows to identify common aspects in the configurational properties:

- the connectivity values are higher in proximity of the gates that act as sensitive points confirming the common intuition that they represent key elements in the urban system.
- the integration core tends to remain unchanged in the disrupted scenarios confirming that it can provide an effective criterion to select sensitive routes. Consequently, a prioritization of interventions based on the integration values could effectively improve the emergency management.
- whereas the integration values are significantly altered by the disruption, we can assume that the scenario is likely to cause a high impact on the system, reducing the reliability of the network. In this regard, for example, we can consider the north gate of Lucignano (figure 7) as a key access, while the eastern as secondary because it gets more integrated in case of disruption of the others. The latter is represented by the scenario 5 in which we can observe higher values of integration on the transverse line that connects the outer route rings with the top of the hill where the town hall is located. In the historic centre of San Gimignano (figure 8), the collapse of the north and south gateways (scenario 5) alters the integration values of the whole system so that they can be assumed as key passages for the historic centre.
- the great presence of routes with limited width is a problem for historic centres because, as shown by the third scenario, the integration index is reduced (table 2) with respect to the first scenario. Such situation requires attention in the emergency planning because it could result in the impossibility for rescue to teams to reach several areas with emergency trucks or ambulances.

Table 2 Maximum values of connectivity, choice and integration for the 5 scenarios of the case studies.

	Historic centre	Lucignano	San Gimignano
	Province	AR	SI
Scenario 1	n	155	525
	Connectivity $_{max}$	6	6
	$I_{choice,\ max}$	1847	37493
	$I_{integr,\ max}$	88.4265	231.536
Scenario 2	n	121	495
	Connectivity $_{max}$	6	6
	$I_{choice,\ max}$	1575	33649
	$I_{integr,\ max}$	73.7667	213.722
Scenario 3	n	107	321
	Connectivity $_{max}$	5	6
	$I_{choice,\ max}$	1306	13241
	$I_{integr,\ max}$	50.7455	147.026
Scenario 4	n	135	491
	Connectivity $_{max}$	6	6
	$I_{choice,\ max}$	1862	36882
	$I_{integr,\ max}$	78.4455	211.514
Scenario 5	n	135	521
	Connectivity $_{max}$	6	6
	$I_{choice,\ max}$	1714	41676
	$I_{integr,\ max}$	61.4818	208.951

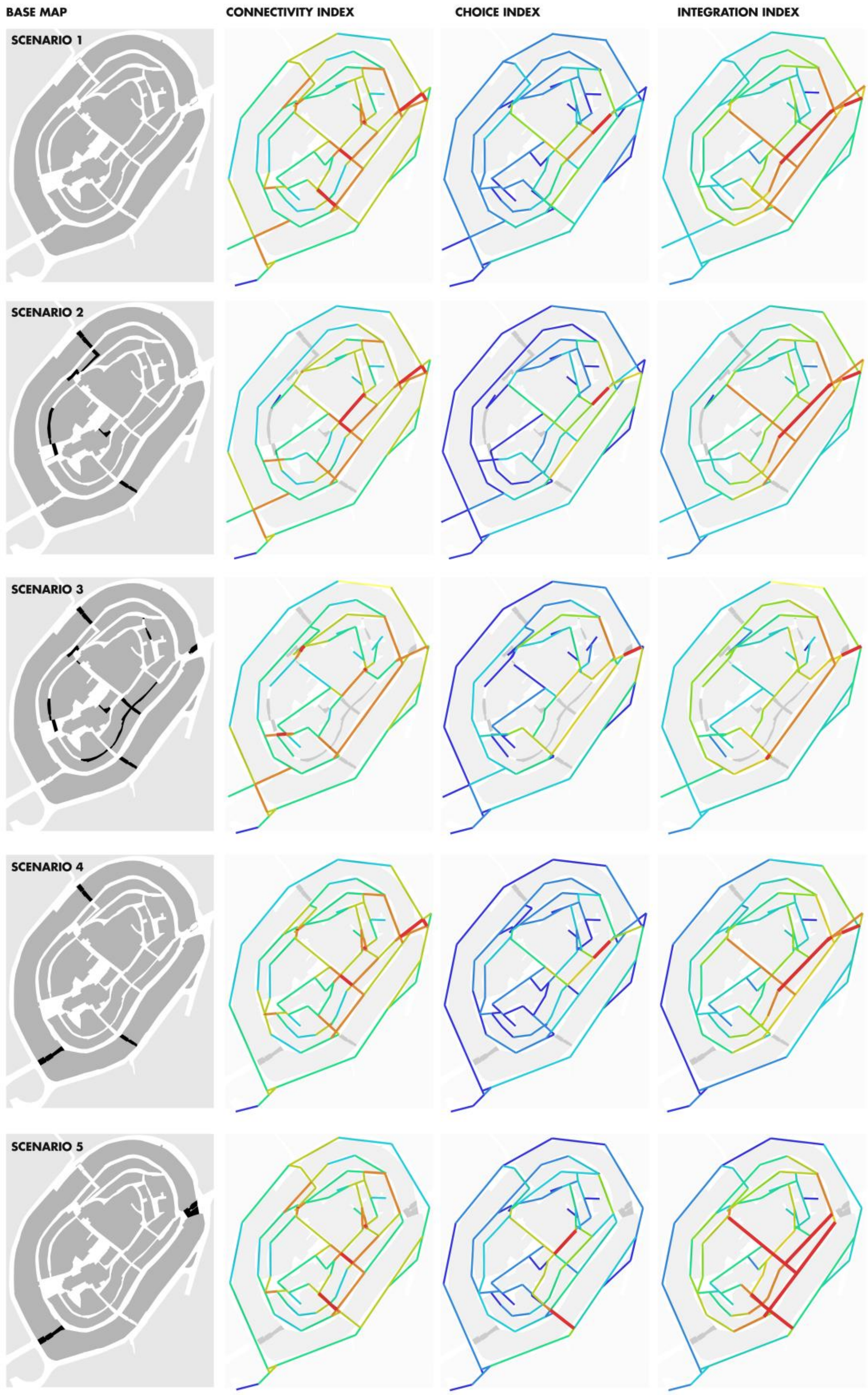

Figure 7 Historic centre of Lucignano: scenario maps with their connectivity, choice and integration.

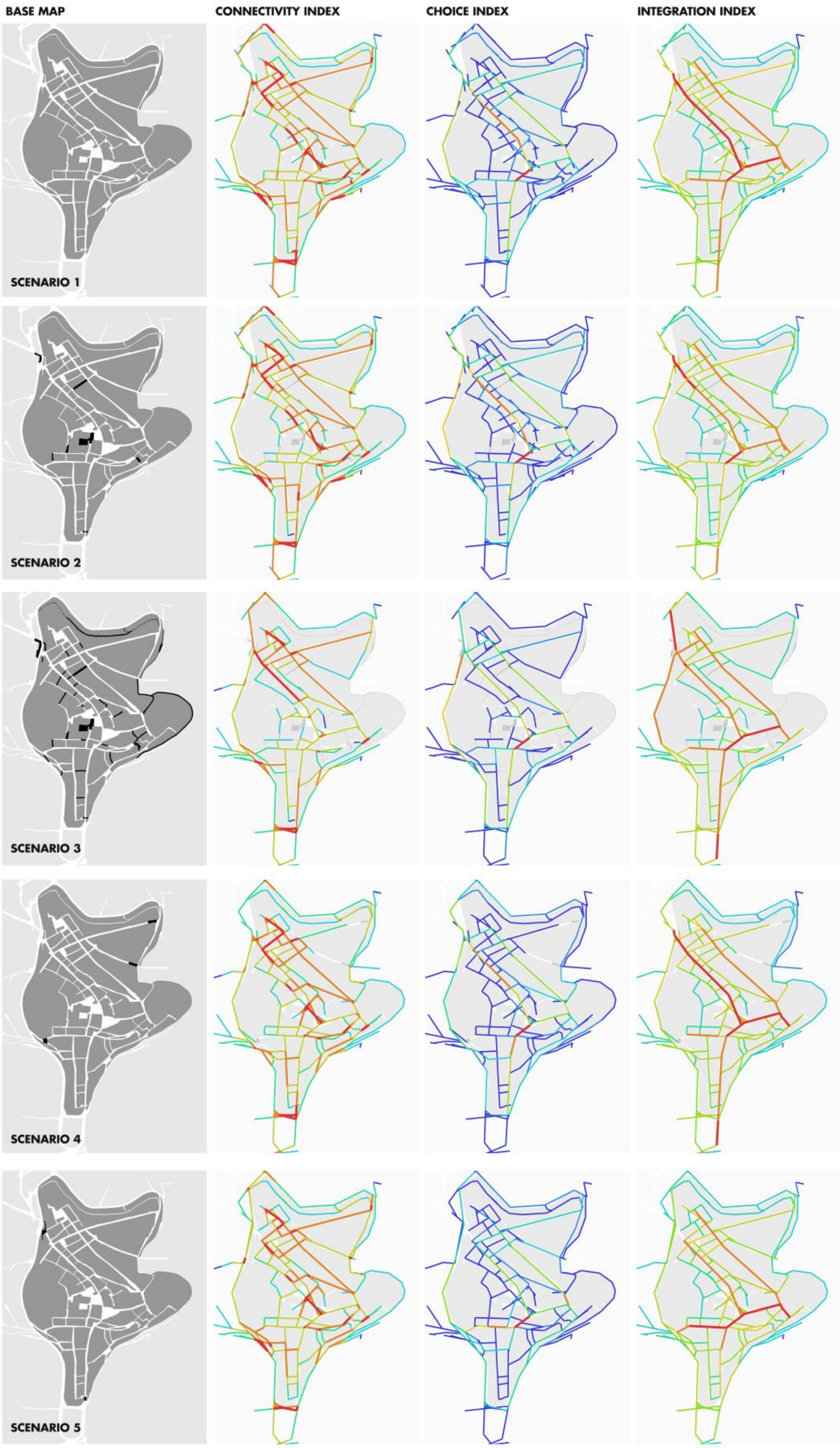

Figure 8 Historic centre of San Gimignano: scenario maps with their connectivity, choice and integration.

The evaluation of resilience is based on the mean connectivity and the frequency index, summarized in table 3. For each index, the percent difference (ΔC_m and Δv) from the first scenario, corresponding to the initial configuration, has been calculated. This indicator measures the impact of the disruptions on the system and allow to assess the resilience of the observed cases.
As expected, the exclusion of roads causes a decrease in the mean connectivity and an increase in the frequency index. In other words, the number of alternative paths is higher, while the uniformity in the distribution of choice decreases. Although all the five situations result in more vulnerable conditions, there is a slight difference that can address the emergency planning by suggesting priorities. For example, the indicators show that Lucignano is mostly affected by the second and third scenarios, corresponding respectively to the evacuation of people with disabilities and to the vehicular accessibility. In this case, interventions should aim to guarantee alternative ways to access the centre with trucks or to prepare local groups to rescue people with disabilities, conducting them to safe areas within the historic centre. Instead, the fourth and fifth scenarios have a great impact on San Gimignano, so that the disruption of the gates limits the resilience of the settlement, both on the north-south axes and the west-east ones. A possible intervention strategy should prevent the occurrence of damage on the structures, promoting the seismic retrofit of the historic buildings.

Table 3 Values of the resilience indexed for each scenario of the two case studies.

	Historic centre	Lucignano	San Gimignano
Scenario 1	C_m	4.10	4.26
	v	0.154	0.236
Scenario 2	C_m	3.92	4.23
	v	0.215	0.275
	$\Delta C_{m\,\%\,(2\text{-}1)}$	-4.39	-0.70
	$\Delta v_{\%\,(2\text{-}1)}$	39.93	16.51
Scenario 3	C_m	3.81	4.12
	v	0.228	0.257
	$\Delta C_{m\,\%\,(3\text{-}1)}$	-7.07	-3.29
	$\Delta v_{\%\,(3\text{-}1)}$	48.39	9.02
Scenario 4	Cm	3.93	4.19
	v	0.204	0.306
	$\Delta C_{m\,\%\,(4\text{-}1)}$	-4.33	-1.67
	$\Delta v_{\%\,(4\text{-}1)}$	32.90	29.80
Scenario 5	Cm	3.94	4.25
	v	0.188	0.307
	$\Delta Cm_{\%\,(5\text{-}1)}$	-3.90	-0.23
	$\Delta v_{\%\,(5\text{-}1)}$	22.33	30.26

4. CONCLUSIONS

This paper adopts the Space Syntax approach to investigate the street network of Italian historic centres from a syntactic perspective in order to evaluate their safety in the emergency. Historic centres in Italy present great differences one from another, depending on history, orography, traditional uses, dimensions. When dealing with such contexts, critical aspects of the emergency management can be recognised in their orography - which does not allow great freedom of movement in open spaces due to the presence of steep paths -, in the town-walls -

whose limited number of gates, if obstructed, can severely hinder emergency operability – and in the presence of great flows of residents and visitors.
Given the heterogeneity in the urban fabric, the study adopts space syntax analysis to study the configuration and identify the potential critical issues by means of a mathematical procedure, aimed at predicting the distribution of centrality, both in terms of attractiveness or accessibility. However, emergency management has a strong dependency from non-configurational parameters, such as: the presence of strategic functions that behave as monopolistic activities, the unequal demographic density of the historic centre, the necessity to reach specific equipment for emergency and the presence of local vulnerabilities.
In particular, the location of emergency functions in segregated areas should be carefully considered to avoid critical situations, such as the impossibility for emergency services to access some areas due to road blockages.
The results corroborate the role of configuration in assessing sensitive routes in case of earthquake. In fact, the integration maps show that the centralities resulting from the ASA are preserved in each scenario. Once these sensitive routes are identified, proper mitigations measures should be adopted in order to guarantee the street safety; among other actions on the exterior elements of the buildings, efforts should aim to remove obstacles, reinforce vertical elements and chimneys. Besides, in spite of the differences in the grids, the results of both case studies show that gateways are sensitive points in both the case studies confirming the necessity to evaluate scenarios hypothesizing their collapse. The comparison between the scenarios can contribute to the evaluation of the key access/gate to the historic centre. Finally, the impact of disruptions on the grid can be effectively expressed by the mean connectivity and the frequency index, that provide a prioritization criterion to design and plan proper preventive measures. To date, the investigations are limited to two historic centres and a limited number of scenarios. However, further analyses should consider a wider set of case studies and entail different scenarios.

In conclusion, the methodology offers an approach to bring the geography of risk into space syntax research, bridging the gap between spatial planning, disaster risk management and seismic engineering. The results are encouraging and suggest that spatial analysis can be a valid tool to support emergency planning. Intervention measures can be designed starting from the identification of the sensitive routes, the key gateways and the most critical scenarios in terms of configuration. By implementing such measures preventively, the concept of 'active preservation', presented by Giuffrè in 1995, could finally be put into practice at an urban scale.

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