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A simplified methodology for risk analysis of historic centers: the world heritage site of San Gimignano, Italy

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Abstract

Purpose – Worldwide, natural hazards are affecting urban cultural heritage and World Heritage Sites, exacerbating other environmental and human-induced threats deriving from deterioration, uncontrolled urbanization and unsustainable tourism. This paper aims to develop a disaster risk analysis in Italian historic centers because they are complex large-scale systems that are cultural and economic resources for the country, as well as fragile areas.

Design/methodology/approach – A heritage-oriented qualitative methodology for risk assessment is proposed based upon the formalization of risk as a function of hazard, vulnerability and exposure, taking into account the values of cultural heritage assets.

Findings – This work provides a contribution to the body of knowledge in the Italian context of disaster risk mitigation on World Heritage Sites, opening for further research on the monitoring and maintenance of the tangible heritage assets. The application to the site of San Gimignano proves the effectiveness of the methodology for proposing preventive measures and actions that ensure the preservation of cultural values and a safer built environment.

Originality/value – The application of a value-based simplified approach to risk analysis is a novelty for historic centers that are listed as World Heritage Sites.

Keywords Historic centers, Disaster risk reduction, Cultural heritage, Resilience, Vulnerability, World heritage

Paper type Research paper

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1. Introduction

Cultural Heritage (CH) is a key resource in building resilience to disasters because of its ability to foster the post-event response and recovery of communities (Jigyasu, 2016; UNISDR, 2013). Worldwide, the great number of cultural and natural heritage sites that are exposed to natural hazards and human-induced threats are posing significant conservation problems (Bosher *et al.*, 2019). The recent fires in the Notre-Dame Cathedral (2019), the widespread bushfires in Australia (2019–2020), the water level rising in Venice (Markham *et al.*, 2016) and the rainfall-induced erosion of the Palatine Hill in Rome (De Paoli *et al.*, 2020) or the earthquakes in Mexico (2017) and Central Italy (2016) are few of the many cases. These disasters showed that the loss of heritage, both tangible and intangible, of a country, can affect the international community. For this reason, the conservation of CH has been promoted in international standards and conventions such as the Athens Restoration Charter (1931), the Venice Charter (1964), the World Heritage Convention (1972), the Convention for the Safeguarding of the Intangible Heritage (2003), the Faro Convention on the Value of Cultural Heritage for Society (2011).

Risk analysis for CH is a complex task because of the inability to obtain adequate knowledge and to calculate the true costs of damage and loss. Moreover, historic centers require to account for several assets, ranging from architectural to landscape features, which include ordinary buildings. In situations where data, time or expertise are limited, qualitative analyzes are particularly suitable to identify those situations where a more detailed assessment is needed (Romão *et al.*, 2016). The importance to reduce risk on CH has been recognized by UNESCO (2007) within the "strategy for reducing risk at world heritage properties" that, among other actions, calls for building a culture of disaster prevention and promotes risk assessment activities for sites that are inscribed on the World Heritage List. ICOMOS and UNESCO are monitoring World Heritage properties and periodically report on monuments and sites in danger (Colette, 2007; Markham *et al.*, 2016; Machat and Ziesemer, 2017; Machat *et al.*, 2014). Moreover, the UN's Sendai Framework for Disaster Risk Reduction 2015–2030 encourages the identification of strategies for risk assessment and disaster management in cultural properties (UNISDR, 2015).

In the context of CH, it is important to briefly present the Italian theoretical and legal background, which the term conservation refers to. Conservation is intended as an active measure to understand, safeguard and protect CH in its intangible and tangible assets. Hence, it includes all the efforts to limit the aging of materials and the failure of the structure, as well as actions for the enhancement and promotion of its symbolic values. According to Italian regulations, conservation is ensured to monuments, landscapes and collections, in the application of the Code of Cultural Heritage and Landscape (D.Lgs. 42/2004). Historical buildings or monuments are listed as architectural heritage, while historic centers and natural landscapes are under large-scale protection because of the notion of landscape heritage. This vision is in line with the notion of "historic urban landscape" introduced by UNESCO (2011) to extend the concept of heritage from architecture to the urban environment, strengthening the relationship with the embedded intangible values. Other than National heritage registers, a great number of Italian cultural properties have been included in the World Heritage List, as the adoption of the World Heritage Convention (1972). Due to their Outstanding Universal Value (OUV), the disappearance of a World Heritage Site (WHS) would be an irreplaceable loss for all peoples of the world.

In Italy, national regulations have also been issued to improve the structural safety of heritage-listed monuments and historical buildings, in compliance with the Building Codes. The Italian Ministry for Infrastructure and Transport and the Italian Ministry of Cultural Heritage and Activities released guidelines on the seismic risk assessment and reduction for heritage structures (DPCM, 2011; NTC, 2008). The document provides a path of knowledge for assessing the safety level against earthquakes and designing interventions for listed CH. In its turn, the new Italian Building Code (NTC, 2018) explicitly refers to the Guidelines as a reliable source of guidance that can be used for the vulnerability assessment of heritage buildings under seismic loads (Torelli *et al.*, 2020).

This paper explores the theoretical and methodological aspects of risk assessment in historic centers listed as WHSs. It adopts a simplified heritage-oriented approach, thus evaluating hazards and vulnerabilities with attention to the exposed multi-layered values (e.g. historic, architectural and artistic). The simplified methodology herein proposed can be applied to any type of CH asset threatened by any type of hazard. Its general format can be used as a screening procedure for the preliminary risk analysis, to establish risk mitigation priorities or to identify assets requiring more detailed and resource-demanding analyzes. The proposed methodology applies multidisciplinary analytical tools, combining heritage studies, civil engineering and risk analysis. The approach moves from the international guidelines on Disaster Risk Management (DRM) for CH (Jigyasu and Arora, 2013) and (Jigyasu *et al.*, 2010), to develop site-specific expert-based investigations on the vulnerabilities of the historical fabric. Novel elements derive from the prediction of post-disaster losses in CH value by means of the Nara grid for authenticity. The methodology has been validated on a case study, the historic center of San Gimignano, in Central Italy. The results represent the starting point for the proposal of intervention measures.

2. Method and materials

2.1 Methodological framework

A mainly qualitative multi-step methodology has been formalized for the research scope, as this allows diverse sources of evidence to be collected and analyzed. The approach builds on the investigation of the cultural significance of heritage (UNESCO, 2004), which involves the identification of the attributes of the site and then evaluates risks in a multi-hazard framework. Being historic centers' complex systems that host different heritage assets, there is a preliminary question on what should be preserved and why. In this regard, the notion of authenticity has a key role, especially when dealing with WHSs. Principles of conservation based on the concept of authenticity and the importance of maintaining the historical and physical context of historic buildings and sites are clearly expressed by the Venice Charter (1964), which is a reference for many later charters and documents. Among them, the Nara Document on Authenticity (1994) has a broad meaning that accounts for a great variety of tangible and immaterial attributes (Boccardi, 2019), including: (i) form and design, (ii) materials and substance, (iii) use and function, (iv) location and setting, (v) traditional techniques and management systems, (vi) location and setting, and finally (vii) spirit and feeling of the place.

Urban cultural heritage can be analyzed by means of the specific attributes on which people place value. This idea has been discussed by several authors (Mason, 2002; Van Balen, 2008; Eshrati *et al.*, 2017), who agree on the presence of diverse typologies of values whose characterization can inform conservation and management processes. A first attempt to develop a tool that would help to better grasp the concept of authenticity is represented by the multi-layered evaluation grid proposed by Van Balen (2008). The authenticity judgments of a site are formulated accounting for two sets of features: the "aspects" that are classified as in the Nara Document (points (i) to (vii)) and the "dimensions," namely, the artistic, historic, social and scientific types of value.

In this study, the Nara grid is applied in two steps. First, it is a preliminary knowledge tool to evaluate and rank the authenticity attributes of the site with the objective to describe the current state and to prioritize risk analysis on the most significant attributes. Then, it is applied to re-assess the attributes in a post-disaster situation altered by the occurrence of the most likely hazardous events. In this way, we can explore how disasters are expected to impact the authenticity of the site and also estimate the expected loss of value for each attribute. Attributes are associated with typology-based classes of CH units accounting for their response to the different types of hazards. A similar approach was adopted in previous studies (Lagomarsino and Cattari, 2015; Romão *et al.*, 2016) that propose several architectural classes based on the technological and morphological features of historical constructions. Each class is linked to a description of the expected damage and vulnerability to different hazards (Section 2.2) based on a literature review of past events that affected similar typological classes.

For each i-th attribute, the Nara grid becomes an evaluation matrix ($m \times k$) in which "aspects" represent rows ($m = 7$) and "dimensions" are the columns ($k = 4$). Cells can be scored by one or more evaluators with a rating scale from 0 to 3 that expresses the relevance of each aspect-dimension description in relation to the others. Once each cell of the Nara grid is assessed, individual scores (n_{mk}) are summed up to obtain a final rate (N_i), as expressed in equation (1).

$$N_i = \sum_{m,k} n_{i,mk}, N_i \leq 72 \tag{1}$$

Scores depend on the stakeholder judgment, and in this study have been assigned by the authors on the basis of a detailed site analysis at the territorial, urban and building scales. Regulations, periodic reports required by UNESCO for any WHS and secondary data has been collected with the purpose of building a comprehensive knowledge framework on the historic center.

Risk can be defined as the potential loss of exposed elements, and it is expressed as the probability of exceedance of a fixed level of economic, social or environmental negative consequence – or impact – in a specific site and during a given period of time (Carreño *et al.*, 2007). The evaluation of risk can be qualitative or quantitative, deterministic or probabilistic and the selection of the most suitable approach depends on the context (Blaikie *et al.*, 2014; Aven, 2016). The debate on the definition of risk is still ongoing, however, risk assessment commonly involves three main factors: hazards, vulnerability and exposure (Welle and Birkmann, 2015). Hazards are natural or human-induced events that have the potential to cause losses of life, injuries, loss of CH, property damage, loss of livelihood and services, socio-economic disruptions. A growing body of literature is developing multi-hazard studies that analyze cascading or interacting effects between the most likely events (D'Ayala *et al.*, 2004; Kappes *et al.*, 2012). Hence, hazards can be classified as primary if they are the triggering cause of the chain of events or secondary if they are a consequence of the primary ones. Vulnerability is the susceptibility of physical assets to suffer direct or indirect damage, as well as the inability of social, economic and institutional assets to withstand adverse impacts (Blaikie *et al.*, 2014; Romão *et al.*, 2016). The latter deals with the lack of coping capacity which affects the ability to reduce the negative consequences of a hazardous event (Welle and Birkmann, 2015). As such, the coping capacity can be measured by the repairability of the expected damage to CH assets. Finally, exposure refers to people, heritage-listed assets (collections, artifacts or ancient buildings) and properties within the hazard zone that can be adversely affected. In this study, the emphasis is given to the loss of OUVs that are central for WHSs, as embodied in the notion of authenticity.

In this study, risk assessment is based on a mainly qualitative simplified methodology entailing expert judgments that allow for defining the most likely risk scenarios. A scenario consists of photography of all that can potentially happen under a given action, defined, for instance, as a repetition of a known past (also referred to as conventional) event which is representative of possible future phenomena (Gavarini, 2001). Scenarios are requested to be structured consistently and logically starting from the acquisition of hazard maps and history. By way of example, useful data regards the geomorphological characteristics, local amplification, instability areas, seismic history. Once hazards have been defined, vulnerabilities and exposure are qualitatively evaluated by means of site surveys, visual inspections and secondary data from institutional databases.

The procedure for risk assessment herein proposed is adapted from the framework developed by Romão *et al.* (2016) but it is differently organized to better meet the need for distinguishing risk factors and grading risk levels on account of OUVs. The model (Figure 1) considers vulnerability together with exposure, thus obtaining five classes of Exposure-Vulnerability (EV) ranging from EV_1 (low EV level) to EV_5 (high EV level). The EV level results from three qualitative evaluations regarding the expected damage, the repairability capacity and the expected post-repair loss of value of the CH unit under

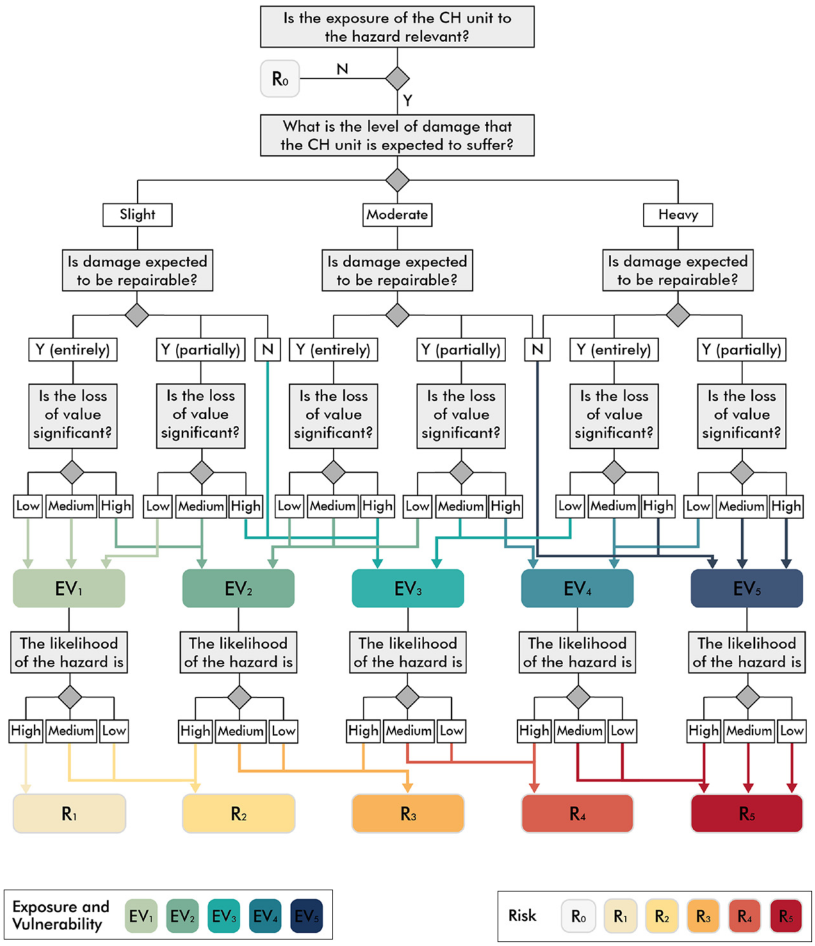


Figure 1.
Flowchart or risk assessment for CH assets

investigation. Damage can be slight, moderate or heavy, depending on the affected elements (structural or nonstructural) and the presence of people or movable CH into the units. Slight damage involves nonstructural elements, decorations, as long as the stability of CH assets is not compromised and human life is not threatened. Moderate damage corresponds to CH units showing local failures that do not compromise the overall stability but can cause injuries or loss of heritage artifacts hosted into the main unit.

Finally, severe damage involves relevant local or global failures that critically threaten human life and affect the stability of CH units with incipient collapse or destruction of structural elements. The evaluation of the expected damage is driven by expert judgments supported by a critical review of past events, as described in the following sections.

The repairability expresses the capacity to restore the physical and material integrity of a damaged CH unit, preserving authenticity. It can be possible, partially possible or not possible in relation to the entity of damage, costs or any other external factor.

Differently from previous proposals (Romão *et al.*, 2016; Romão and Paupério, 2019), losses of CH value are assessed by comparing pre and post-disaster scenarios (S_j) that are both evaluated through the Nara grid. The number of scenarios (j) depends on the hazards under analysis. In fact, if N_i^0 is the value of the i-th attribute in the pre-disaster situation and N_i^{Sj} is the value in post-disaster scenario, then the expected loss of value is determined by an index ${I_{Ni}}^{Sj}$ that is expressed in equation (2).

$$I_{N_i}^{S_j} = \frac{N_i^0 - N_i^{Sj}}{N_i^0}, \quad 0 \le I_{N_i}^{S_j} \le 1 \tag{2}$$

The loss of value associated with I_{Ni} can be low, medium or high. It may be conventionally assumed as low if the index is between 0 and 0.33, medium if it is between 0.34 and 0.67 and high if it varies between 0.68 and 1.

Each EV measure is then combined with the expected likelihood (low, medium, high) of a given hazard to obtain the risk index. The likelihood of an event is set on the basis of hazard maps that are realized considering historical data on past events and the return period of the event with reference to its intensity. Basically, a higher likelihood of the hazardous event is expected to have low intensity and vice versa. In Italy, seismic zones are defined in terms of Peak Ground Acceleration (PGA) associated with different return periods of the ground motion. Moreover, the Italian Macroseismic Database (DMBI15) provides the seismic history of municipalities in terms of MCS macroseismic intensity (Locati *et al.*, 2019; Rovida *et al.*, 2020). Instead, Italian geomorphological hazard maps identify five categories of hazard-prone areas, from low to very high, in which landslides or instability phenomena are more or less likely to be triggered.

Six risk classes are established, from R_0 to R_5 (Romão *et al.*, 2016), corresponding to increasing risk levels. The class R_0 is assigned to CH units that are not exposed to any hazard. The classes R_1 and R_2 are associated with acceptable levels of risk. Instead, the class R_3 is at the limit of acceptability and therefore requires regular monitoring actions. Finally, the classes R_4 and R_5 are associated with unacceptable and critically unacceptable levels, respectively. Detailed investigations and risk analyzes are recommended for the classes R_3, R_4 and R_5 due to the great uncertainties of simplified risk assessment methodologies (Romão *et al.*, 2016).

Effective strategies of risk reduction in historic centers concern the mitigation of vulnerabilities and exposure. Measures are calibrated on the potential impacts of the most likely scenario on the WHSs to avoid losing authenticity and compromising the overall integrity.

2.2 Vulnerability of typological classes: lessons from past events

When dealing with large-scale risk analysis, the physical vulnerability assessment entails several interfering elements having direct and indirect components. For historical constructions, direct vulnerabilities derive from the structural characteristics of each building and the aggregate, namely, the quality of materials and the brickwork and the structural typology. Indirect vulnerabilities derive from the mutual interactions between adjacent buildings, and from any damage induced by a structural component to another or to nearby streets (Carocci, 2001). For open spaces, indirect vulnerabilities mainly refer to debris fallen from collapsed buildings or nonstructural elements or damage caused by lifelines ruptures (e.g. gas or water distribution network).

The parameters affecting the damage pattern of masonry buildings depend on the typological classes and the characteristics of the masonry material. The response of CH buildings in structural aggregates is influenced by the in-plan and in-height regularity, the position of the unit within the aggregate, the presence of soft stories. Their vulnerability to hazards is increased by lack of maintenance or inadequate conservation.

CH structures such as churches, towers and town walls are typical typologies of Italian historic centers and their vulnerability to different hazards is extremely different from ordinary-buildings, palaces and structural aggregates. Their response is strongly influenced by their peculiar constructive features, geometric shape and complexity, together with the nonlinearity and inhomogeneity of masonry (Ceravolo *et al.*, 2016; Fiorentino *et al.*, 2018): slender walls, large, heavy architectural elements such as domes and vaults, the lack of intermediate horizontal floors, together with the transformations during centuries.

These features make seismic damage to churches greater than to ordinary buildings, even under low intensity shaking (Lagomarsino and Podestà, 2004a). In addition, churches are also constituted by nonstructural elements like artistic assets, e.g. altars, cornices and statues, whose structural response and damage modes may also be considered independent from that of other structural elements and entail a notable cost of restoration. The vulnerability of churches stems not only from structural aspects but from their inherent historical and artistic value, as well as their functions, especially when they host other artworks and masterpieces such as paintings, sculptures and other heritage items.

Slender structures such as tower-houses and bell towers are characterized by a high sensitivity to environmental actions and, overall, to dynamic loadings such as earthquakes and vibrations induced by the bell sound, the traffic and the wind (Sepe *et al.*, 2008). This is often exacerbated by human-induced modifications in the tower's structural configuration across the centuries and by the lack of maintenance. On the other hand, under seismic shaking, towers sometimes suffer smaller spectral accelerations with respect to ordinary masonry buildings due to their larger vibration periods (Zanotti Fragonara *et al.*, 2017). However, slender structures are often a threat for adjacent constructions and a source of further induced vulnerability, due to partial collapses, fall of debris or punching effects, as their deformability is higher than ordinary buildings.

Finally, the vulnerability of town walls depends on their shape, degree of connection to towers or fortifications, quality of masonry, environmental or anthropogenic degradation and alterations suffered over time. The masonry walls may often exhibit significant out-of-plane mechanisms due to water-related issues (Giaccone *et al.*, 2020), lateral earth pressure, lack of maintenance (Andreini *et al.*, 2013), soil settlement, slope instability and seismic shaking.

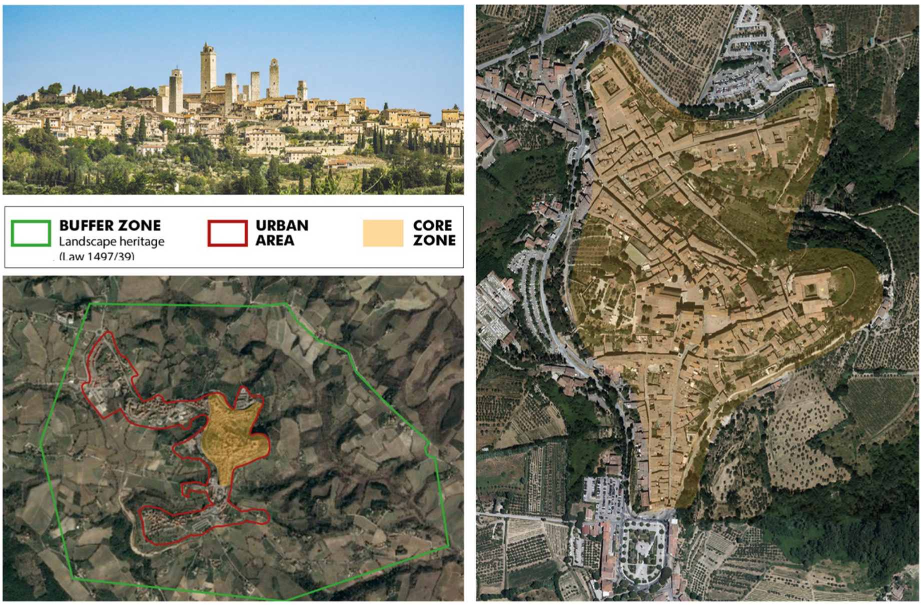
2.3 Case study: the world heritage site of San Gimignano, Italy

San Gimignano is a medieval hill town located in Tuscany. It dominates the surrounding rural landscape and is clearly visible in the distance because of its many stone towers

(Figure 2). The historic center retained the feudal atmosphere and appearance, for this reason, it was listed as UNESCO WHS in 1990 under criteria (ii), (iii) and (iv).

The foundation of San Gimignano dates back to ancient times, but the city fully developed during the Middle Ages when it was considered an important relay point for pilgrims traveling on the Via Francigena to or from Rome (Giorgi and Matracchi, 2019). The town and the urban structure grew with an irregular layout around two main squares: the triangular Piazza Della Cisterna and the Piazza Duomo, hosting the majority of public and private monuments, as well as the religious buildings. Towers and town walls are symbols of San Gimignano (Giorgi and Matracchi, 2017), both providing authenticity and integrity to the town. From the end of the 12th century, towers were lowered and sided by other buildings of lower height. Despite the century-old transformations, the center has retained its integrity and the remaining 13 towers still witness a past when families had power over public institutions. The perimeter of the historical town is defined by two concentric rings of town walls, the inner ring was constructed in the late 10th century and it was reinforced with the outer walls in the 13th century.

Nowadays, the historic center is at risk due to geological hazardous events and shows signs of unsustainable tourism congestion (UNESCO, 2014). The main geological problem concerns landslides because the town is built on limestone rocks and sandy substratum, as identified in the geo-morphological hazard map. However, landslides may be triggered by heavy rainfalls and earthquakes, causing a chain of events that can be disastrous for the CH and the city. On December 20, 1982, a fall caused damage to the Parco Della Rocca and to the tower of the Town Hall. Landslides reactivated on March 28, 1985, because of the geological conditions: the nature of substratum and the variation of the aquifer. Besides on April 4,



Notes: On the top left: view of the historic center; at the bottom left: boundaries of the buffer and core zones and the built-up urban area; on the right: map of the historic center

Figure 2.
Historic center of San Gimignano

2018, a 20-meters section along the Eastern side of the historic town walls abruptly collapsed due to a landslide and steady rains, with water undermining the solidity of masonry. The same causes brought to the partial collapse of the terrace under the Rocca di Montestaffoli. Further threats derive from the potential occurrence of earthquakes. San Gimignano is located in a seismic-prone area classified as zone 3, characterized by a maximum PGA of 0.15 g. Between 1804 and 1998, 20 earthquakes are registered in the area and two VII-degree MCS macroseismic intensity earthquakes (i.e. the DBMI15's scale) occurred in 1804 and 1869. The local amplification map is still under investigation, but the preliminary results show the location of potential earthquake-induced instability-prone areas in the historic center (Peruzzi *et al.*, 2013).

3. Results and discussions

The investigation starts from the definition of the attributes of the WHS that requires an in-depth contextual knowledge deriving from the preliminary site analysis. The main attributes of the historic center are considered as typological classes, which include towers, squares, churches, town walls and gates, the Rocca di Montestaffoli, the via Francigena and finally the set of heritage-listed palaces. According to the Nara Document on Authenticity, each attribute can be evaluated by scoring the "dimensions" and "aspects" of CH (Van Balen, 2008), taking into account the intangible assets such as social practices, rituals or public festivals. Table 1 presents an example of the completed Nara grid for the set of towers. It reports both the descriptions of the significance and the assigned scores that are summed up according to equation (1). The pie chart of Figure 3 shows the percentage scores of each attribute over the total sum. In detail, "churches" are the most relevant attribute with a total score of 55. This achievement is owed to their religious vocation and the presence of masterpieces of the 13th and 14th centuries. Other relevant attributes are "towers" (Table 1) and "squares" that are paramount for the feudal atmosphere of the historic center, creating a great setting for traditional celebrations and historical events. Towers embed values related to the physical features (original material, form, design), as well as historical and social traditional aspects. The set of listed "palaces" presents a score of 38, the "town walls and gates" are scored 35 and the ancient "Rocca di Montastaffoli" is rated 28. Finally, the "via Francigena" is rated 27 because of its historical and social significance in orienting the urban development (Giorgi and Matracchi, 2019) and promoting intercultural dialogue and not only pilgrimages, across Europe. Since 2019, it is included in the World Heritage Tentative List on the initiative of the Italian National Commission for UNESCO.

Nowadays, the town is prone to several natural hazards, as proven by the events that occurred in the past years. Landslides are the main problem together with earthquakes. Landslides may be triggered by heavy rainfalls and earthquakes but tend to be localized where instability phenomena are more likely to occur, as identified in the geo-morphological hazard map of San Gimignano. Another secondary hazard that usually follows earthquakes is fire because of ruptured gas lines and arcing electrical wires. On these grounds, earthquakes and heavy rainfalls are considered as primary hazards, while secondary hazards are landslides and fire.

Vulnerabilities regard physical, environmental, social and economic aspects, as identified in tab 2. Physical vulnerabilities can be both direct and indirect and can be associated with the site attributes. Slender structures, single-sided retaining walls and town walls can be considered more vulnerable to geomorphological hazards. For instance, the town walls in San Gimignano have proven to be vulnerable to rainfall-induced landslides. Environmental vulnerabilities involve the historical built-up areas with their squares and open spaces. They derive from the potential fall of objects from buildings in case of an earthquake, which can

Table 1. Completed Nara grid for the "tower-houses" attribute in San Gimignano

Aspects	Dimension Artistic	Historic	Scientific	Social
Form and design	Towers present local Romanesque-Gothic architecture, with arches, cornices, merlons and coats of arms. **Score: 2**	Towers derive from medieval fortifications, developing in height due to the rapid urbanization of the city center. **Score: 3**	Towers illustrate the construction abilities and the recycling attitude of the medieval period. **Score: 3**	A tower's height reflected the prestige and importance of the merchant family that it belonged to and in fact, families competed to have the tallest tower. **Score: 3**
Material and substance	The original medieval stone masonry is visible in the massive structure of the towers. **Score: 1**	Some elements derived from the reuse of existing buildings, as common in medieval practice. Score: **3**	High quality of stone masonry towers. Arches, vaults, and narrow windows are typical elements. Score: **3**	**Score: 0**
Tradition, technique and workmanship	Specific expression of the ability of artisans to carve stones for these constructions. **Score: 1**	Ability of medieval artisans to reuse materials to raise high towers. **Score: 3**	Towers help to study traditional construction techniques. **Score: 3**	**Score: 0**
Location and setting	Towers are part of the urban landscape of the city. **Score: 2**	13 out of 72 towers survived and mark the city landscape, witnessing their history. **Score: 3**	The hilltop location of towers was strategic to control valleys and neighbors and to address the urban development. **Score: 2**	Towers were strategically located next to the main squares and roads to enhance public and private power. **Score: 3**
Use and function	**Score: 0**	The ground floor hosted the shop, and the basement was a storage. The upper levels have been modified overtime and their use is still uncertain. **Score: 1**	Score: **0**	The ground floor still hosts retail activities, and a few towers are open for cultural visits. **Score: 2**
Spirit and feeling	Towers and coat of arms on facades express power and wealth of ancient families. **Score: 1**	Towers are the symbol of the city and represent a time of struggle for private power. **Score: 3**	Towers witness the ability of craftsmen in building high-rise constructions in local style. **Score: 1**	Towers symbolize the power of the past and the greatness of the city during traditional festivals. **Score: 3**

be dangerous for human life. Moreover, vulnerabilities are also associated with the limited number of gates and open spaces, as well as the presence of slopes, stairs and narrow passages that may hinder the evacuation. Further issues are related to social and economic vulnerabilities. On the one hand, the touristic vocation of the center is scaling the demand for touristic services and for modifications to the traditional use of buildings, thus posing relevant conservation and safety issues. This phenomenon also influences the coping capacity, as local people move in the outer built-up areas and are not engaged in the active protection of CH units. On the other hand, the number of residents in the center is decreasing and no awareness-raising campaign is devoted to visitors. These issues ultimately result in a lack of risk awareness and risk preparedness.

Exposure involves several entities located in the hazard zone, namely, inhabitants, tourists, CH assets (movable or immovable, i.e. monuments, collections, decorations) and their CH values. The dataset on CH properties is well-defined because of the open-source repositories on listed assets developed by the Italian Ministry of Cultural Heritage. On the contrary, the estimation of human exposure is quite challenging due to missing or outdated data on the inhabitants and tourist flows.

The occurrence of the aforementioned chain of hazardous events, combined with the vulnerability and exposure factors, may seriously compromise the integrity and authenticity of the WHS, as well as the safety of people in the historic center. The expected impacts associated with a worst-case scenario are listed in Table 2 and proper risk reduction interventions should be introduced to prevent damage and improve the overall emergency operability.

Three risk scenarios are thereby investigated considering two reference seismic intensities and landslides. The latter can be activated either by the ground motion or by heavy rainfalls (Peruzzi *et al.*, 2013). Based on the seismic history of San Gimignano (DBMI15), the maximum seismic intensity is fixed to VII in the MCS scale, which has a low likelihood of occurrence. A further seismic hazard scenario is considered to account for earthquakes having a higher likelihood of occurrence, which are associated with an intensity less than or equal to V. Finally, the geo-morphological hazard map identifies areas having medium, high or very high hazard that corresponds to the medium and low likelihood of occurrence, respectively. Landslides may potentially occur next to the Rocca of Montestaffoli and along the eastern sections of the town walls where slopes are steeper and unstable. While landslides can be localized in specific areas, earthquakes have large-scale impacts and the response strongly depends on the structural characteristic of each typology. The risk scenarios have been identified by assigning risk levels to each CH unit, following the flowchart in Figure 1 that encompasses the qualitative evaluation of the expected damage, repairability and CH value loss (Equation (2)) for the three hazard scenarios. Figure 4 illustrates the risk scenarios in a target area that contains a greater number of CH assets. Damage levels are assigned because of typological considerations and rapid on-site visual surveys. Besides, the observation-based description of MCS scale degrees provides useful guidance for the assessment.

If a VII-degree intensity earthquake occurs (risk scenario 1 in Figure 4), we can likely assume that churches, towers and palaces with greater structural heterogeneity would be more damaged and the failure of masonry walls would cause the fall of elements on the streets. The main churches (C1 and C2 in Figure 3) are highly at risk (R_5 in Figure 4) because of the presence of artworks and masterpieces that would be damaged and may not be fully restored. Moreover, a number of towers (T2, T3, T7 and T12 in Figure 3) are classified as R_5 due to the presence of heavy-load elements at the top (e.g. bell chambers, spires) or the presence of large openings that may lead to the development of belfry mechanisms. The

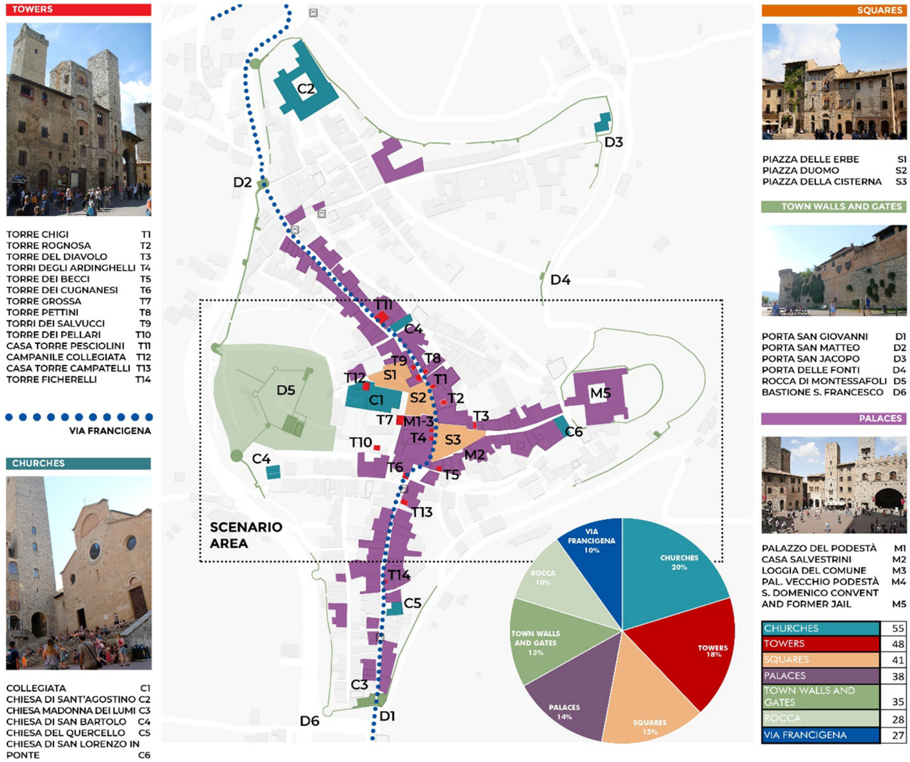


Figure 3. Identification and evaluation of the cultural heritage attributes

remaining towers are quite regular in the geometry, have a good stone masonry texture and state of conservation, thus their damage is supposed to be moderate and repairable. Although towers might be able to withstand the reference seismic action (Bartoli *et al.*, 2016), they could still be partially damaged with the consequent fall of debris in the narrow streets.

The occurrence of a V-degree intensity earthquake (risk scenario 2 in Figure 4) may induce slight or moderate damage to CH structures, however, nonstructural elements may be damaged and overturn on nearby open spaces and buildings. The main churches (e.g. C1 in Figure 3) present a moderate risk (R_3) because of their greater vulnerability with respect to other typologies. An R_3 risk level is the result of the analysis for palaces that are irregular or placed next to towers. According to Cifani *et al.* (2005), the mean damage of towers is lower than churches for low seismic intensities. However, several towers (T2, T3, T7 and T12 in Figure 3) are at risk level R_3 equal to churches because we take into account the potential damage of heavy elements connected to the structure and their subsequent fall. This situation can be seen as moderate damage, to be on the safe side.

In spite of these qualitative evaluations of seismic risk scenarios, detailed vulnerability investigations and assessments based on analytical or empirical methods are recommended to improve risk analysis. Several methodologies for large-scale damage assessment of structural typologies proposed for churches (Lagomarsino and Podestà, 2004a; Lagomarsino and Podestà, 2004b), ordinary buildings (Lagomarsino and Giovinazzi, 2006) and towers (Sepe *et al.*, 2008) allow for better evaluating the seismic response of buildings.

Table 2.
Hazards, vulnerabilities, exposure and impacts on the historic center of San Gimignano

Hazards	Vulnerabilities	Exposure	Impacts
Primary: Earthquake Heavy rainfall Secondary: Landslide Fire	Physical – CH assets – Masonry aggregates with poor quality materials, complex structural organization, heterogeneities in materials and stiffness, the difference in height, staggered floors – Typological peculiarities – Lack of earthquake-resistant design in buildings – Lack of maintenance – Insufficient drainage system Environmental – Nonstructural elements and heavy decorations – Lack of accessibility due to a limited number of gates – High-rise buildings and narrow roads – Type of soil and geomorphological features – Presence of slopes and stairs – Lack of wide-open spaces Social – Lack of risk preparedness of people – Lack of risk awareness of local government – Seasonal use of properties Economic – Rural areas located close to the city – Pressure on a modification to the traditional use of buildings (from residential to touristic)	– location into the hazard zone – CH assets – Inhabitants – Tourists	On local people – Loss of lives – Street blockage and lack of evacuation routes – Panic – Disruption of lifelines and supply systems – Displacement of residents On the local and national economy – Loss of economic activities, particularly cultural and touristic – Loss of jobs – Displacement of administrative functions On local identity – Loss of social, artistic, traditional activities On heritage assets – Damage to historical buildings, masterpieces, paintings and frescoes – Loss of integrity – Loss of natural and urban landscape of Outstanding Universal Value

The risk scenario associated with the geo-morphological hazard (risk scenario 3 in Figure 4) depends on the distribution of exposed CH assets among the hazard zones. Most of the historic center is located in a medium hazard zone where only slow ground subsidence phenomena are likely to occur. For this reason, the expected damage is deemed to be slight and – if necessary – repairable, with a low loss of CH value. All of these CH units are in R_1 class except for the main church (C1 in Figure 3) and convent (M5) that are in R_2 one due to their particular vulnerability to ground settlements and location. Particularly, the M5 unit is on the hilltop next to a steep slope in which landslides are potentially active. Instead, the CH assets prone to high and very high hazards are the town walls and the Rocca that are classified as R_5 and R_4. Their damage would be moderate or heavy in these areas, but either way partially repairable with low loss of authenticity. In this case, it is possible to safeguard the town walls by improving the drainage systems to reduce water pressure (i.e. pipes, weep holes) and planning interventions for soil and slope stabilization in areas where the geomorphological hazard is very high (e.g. tie rods anchoring). Additionally, monitoring systems can be implemented to verify the progression of deformations on CH units.

Through this case study analysis, several mitigations and emergency measures can be proposed and be the starting point for developing a DRM plan for the WHS of San

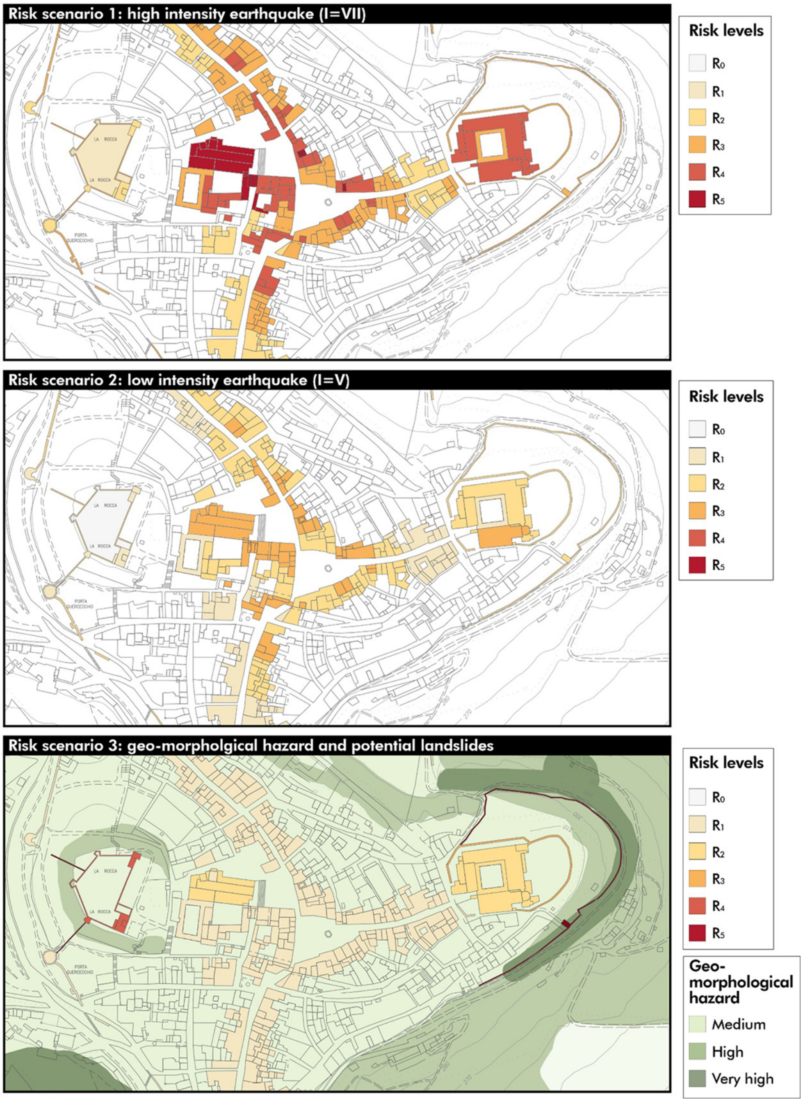


Figure 4.
Risk scenarios for the target area

Gimignano. One of the main proposals can be the engagement of communities in the decision-making process, not only educating to risks but also building on existing capacities and involving local actors in the risk reduction (Cutini *et al.*, 2019). This measure contributes to increase the coping capacity of communities and might be effective whereas the reduction of vulnerabilities might not be cost-effective (Pazzi *et al.*, 2016; Bandecchi *et al.*, 2019). The Municipality should foster the participation of citizens to establish and train a workforce able to rescue sensitive groups (i.e. elders, tourists, children) and salvage CH artifacts in the earliest post-disaster phase.

Technical measures can greatly reduce physical vulnerabilities by encouraging, for example, regular maintenance on public and private buildings (Giuliani *et al.*, 2019). Nevertheless, the great number of private historical properties and the lack of interest in the preservation of heritage assets is often an obstacle to the safety of historic centers. Today, there are funds and incentives for the maintenance and seismic retrofitting of private buildings, but they are assigned on a voluntary basis. Conversely, the introduction of mandatory interventions for achieving a minimum safety level on buildings along strategic routes (Giuliani *et al.*, 2020) would bring a significant advancement, especially if sided by governmental incentives for risk reduction.

4. Conclusions

This paper explored the topic of risk analysis on urban cultural heritage, with particular reference to WHSs, that are subject to natural hazards or human-induced threats. Dealing with large-scale systems, the heritage-based prioritization of interventions plays a key role in DRM, ultimately leading to their preservation in case of hazardous events. A simplified methodology for the qualitative risk assessment is proposed considering the heritage assets whose preservation is paramount. The main novelties are the creation of a simplified framework for risk assessment and the evaluation of CH losses. The procedure outlined in this paper recognizes the unique values of WHSs and is rooted in the evaluation of the specific attributes that contribute to their authenticity. The evaluation of values is based on the Nara Document on Authenticity that implicitly refers to a grid that has been re-interpreted according to the risk analysis conducted in this study.

The approach has been effectively applied to the WHS of San Gimignano that represents a significant Italian historic center threatened by multiple hazards. The study highlighted the values of the site and its criticalities from a risk perspective.

By and large, the proposed methodology is deemed to be effective for the DRM of historic centers listed as WHSs. The key elements for the success of this approach are that it is relatively simple to apply and all issues can be assessed as long as a good knowledge of the site is achieved. With reference to the Nara grid, the overall results are sensitive to the stakeholder's number and background, and thus the final ranking of attributes might vary accordingly. Nevertheless, the proposed results are deemed to be robust, as each component of the evaluation grid is well-defined (e.g. the sample table presented for the case study regarding towers) and scores derive from the relative comparison among the descriptions. Eventually, the definition of attributes can also be refined if heritage values are unevenly distributed in each architectural typology. Although simplified, the risk assessment methodology and the proposed flowchart are a step forward for the risk management of complex large-scale systems like historic centers.

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