Why should we bother about risk reduction at the urban scale? The Early Recovery System (ERS) framework to assess the impact of prevention instruments on post-quake urban functionality

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Abstract
Italian seismic risk management has traditionally prioritized post-disaster recovery instead of effective urban prevention strategies. This approach carries significant costs, and the speed of recovery plays a critical role in determining whether communities choose to rebuild or relocate permanently. To accelerate post-earthquake recovery and enhance urban resilience, effective disaster risk reduction policies centered on urban prevention strategies to safeguard territorial safety effectively, are needed.

In this work, we introduced the Early Recovery System (ERS) framework that identifies essential urban elements with potential for seismic retrofitting. Through the calculation of 18 indicators over different time intervals and across three hypothetical scenarios in the case study of L'Aquila post 2009 earthquake, we generated recovery curves that illustrate urban functionality loss and recovery trajectories, to establish the optimal prevention strategy to be adopted.

Keywords Seismic risk prevention; Early recovery; Urban functionality assessment

1. Introduction

Italy faces high seismic risk due to several factors, including a widespread seismic hazard, the high vulnerability of its built environment, and substantial exposure in terms of population density and historical-cultural heritage (Dolce et al., 2021). Since 1950, earthquakes have caused approximately 5,000 casualties and significant economic damage (Coviello and Somma, 2021).

Despite this evidence, the predominant approach to seismic risk management has focused mainly on emergency public actions and the physical restoration of individual assets rather than comprehensive urban prevention strategies. This "territorial compensation" approach entails very high costs in terms of financials and territorial equity (Balducci et al., 2021).

Catastrophic events can significantly impact local communities, and time plays a crucial role, as the speed of recovery is decisive in determining whether community members will decide to stay and rebuild or leave permanently (Arendt and Alesch, 2014). Recovery time, defined as the period needed to restore system functionality to the desired pre-earthquake level, is a variable with high uncertainty and typically depends on several complex factors: pre-event conditions, available resources, and governance (Terzic et al., 2021).

To accelerate post-earthquake recovery, policy initiatives such as the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) have emphasized the potential of stakeholders and communities to become more adaptable through practices and policies aimed at implementing Disaster Risk Reduction (DRR) programs and actions.

Since the 1980s, defining policies and actions for DRR has been the subject of intense technical and scientific experimentation throughout Italy. However, attention has often been limited to prevention interventions primarily implemented on individual buildings. However, protecting entire settlements is unrealistic due to the high costs of interventions, procedural complexity, and the long time required to achieve goals. The challenge, therefore, lies in identifying a minimum system of essential urban functions whose preventive safety measures could reduce urban vulnerability and enable recovery to begin.

The Italian approach to seismic risk prevention in urban areas began to take shape more concretely in this direction after the Abruzzo earthquake on April 6, 2009. Following the consequent massive urban damage, the Italian government introduced a significant funding program of approximately 1.2 billion euros to finance interventions for risk management in seismic-prone territories (Castenetto, 2024). Through the National Plan for Seismic Risk Prevention (PNPRS), the State embarked on an ambitious agenda of Seismic Microzonation investigations, Emergency Limit Condition (ELC) analysis, and structural interventions on buildings. Although the allocated finances represent a small fraction of the expected average annual cost of earthquake damages, the PNPRS is Italy's first national plan considering prevention from an urban planning perspective (Bramerini et al., 2013).

The ELC analysis, focused on validating the emergency management system defined in Civil Protection Plans, aims to verify the existence and consistency of strategic elements in the emergency management system, suggesting intervention priorities to administrators (Tomassoni et al., 2023). The ELC is significant because it represents a step towards reducing urban vulnerability by defining a minimum system of buildings, open spaces, and road networks to be safeguarded to maintain fundamental strategic functions for emergency management.

However, urban vulnerability is a multidimensional concept influenced by building features, functional systems (Braga et al., 2015), and socioeconomic factors (Blackwood and Cutter, 2023). It requires, therefore, a broader vision aimed at maintaining essential settlement functions (Fiore et al., 2018). Following this approach, the Urbisit Project (Cavinato, 2013) extended the concept of building limit states to urban settlements, formulating Urban Limit Conditions (ULCs) as a scale of prevention goals with increasing urban performance to guide seismic risk prevention policies (Bramerini et al., 2013; Basaglia et al., 2019).

In recent years, ULCs have been experimented at both local and national scales. Locally, the 'EQ-DIRECTION' procedure was developed to evaluate a specific ULC aiming to protect essential urban functions necessary for ensuring a rapid return to pre-earthquake conditions (Cattari, 2024). At the national scale, a methodology was proposed to map different ULCs for various earthquake scenarios, estimating the seismic resilience of large-scale communities (Anelli, 2023). Both methodologies, though valuable, have limitations: the first focuses on a specific case study and requires local political involvement, making it difficult to generalize nationally. The second considers only housing as a proxy for urban functionality.

Moreover, ULCs theory has difficulty quantifying performance levels, which range from the worst to the optimal condition—that is, the full recovery of the urban system. This complexity makes it challenging to translate the theory into actionable public policies.

Our work aims at contributing to the debate on urban seismic prevention by proposing i) a new planning prevention instrument for early recovery—the Early Recovery System (ERS)—inspired by ELC and a simplified conceptualization of ULCs, and ii) a methodology to introduce the concept of urban functional recovery assessment. This methodology compares the potential seismic retrofitting of different ERS configurations in a specific risk scenario and provides support for decision-makers.

In this paper, we present: the ERS instrument (Chapter 3) and a set of indicators to evaluate the best ERS configuration and visualize hypothetical post-event recovery trajectories (Chapter 4). We propose a counterfactual experimentation of our methodology on a pilot case study: the city of L'Aquila, severely affected by the 2009 earthquake (Chapter 5).

We want to demonstrate that seismic prevention from an urban planning perspective can guide decision-makers in assessing, a priori, the potential impact of prevention instruments on post-event urban functionality, helping to set intervention priorities and allocate financial resources towards territorial safety goals.

2. Switching paradigm: from building to urban functional recovery

Finding methods to reduce vulnerability and assess the capacity for post-disaster recovery over time is a key motivation for academics and policymakers in promoting community resilience and functional recovery concepts (Mayer, 2019; FEMA, 2021). Over the past few decades, community resilience has emerged as a compelling paradigm to advance DRR initiatives. Generally defined as the ability of a system to prepare for, respond to, and recover from disasters minimizing impacts and damage, the concept has been addressed in extensive literature through two predominant approaches: the socio-economic, focus on the characteristics of local communities (Cutter, 2014; Berke and Campanella, 2006) and the engineering centered on the physical properties of the built environment and its ability to restore functionality over time (Bruneau et al. 2003; Cimellaro, 2016). When applied to urban systems, the concept of resilience often extends beyond physical structures to include the capacity of social, cultural, and economic systems to recover and restore functionality after an earthquake (Burton, 2015; Zhang et al., 2021).

However, improving or building resilience is a process that requires comprehensive and long-term strategic planning. In recent years, the concept of functional recovery has gained attraction as a way to link resilience goals with the design, construction, and retrofitting of individual structures (EERI, 2019; FEMA, 2021). Functional recovery is defined as the post-earthquake state of a building or infrastructure in which its capacity is sufficiently maintained or restored to support pre-earthquake functionality (EERI, 2019). From a public policy perspective, functional recovery should serve as a mechanism for achieving broader community-wide goals. Recent studies (Zhang et al., 2021; Ren et al., 2021) have begun evaluating the functional recovery of building groups at the urban scale, considering both internal factors (building type, age, and function) and external factors (social systems). However, the literature notably lacks consideration of urban planning decisions and practices as a bridge between these internal and external factors.

The built environment plays a socio-spatial role in the urban space, embedded in the lives of local communities. Functional recovery at the urban scale should not be seen merely as the sum of individual buildings' post-disaster functionality. It must also take into account factors such as social networks, accessibility, and a certain level of urbanity, all of which encourage communities to remain in their territories after a disaster.

In this study, we extend the concept of functional recovery to the urban scale by considering an essential urban core of physical elements and their connections, which are necessary for recovery to begin. Given the limited financial resources available, one of the key priorities for decision-makers is identifying, through prevention plans, which buildings and infrastructure are critical for the very early stages of recovery. This selected urban core is treated as a minimum spatial unit to assess urban functionality, which we define as the ability of the urban system to maintain its pre-existing spatial, functional, and relational organization after a disaster. We do not focus on buildings' structural performance, allowing us to maintain a broader perspective on urban planning issues. We strongly believe that just as buildings have different functionality limit states, urban systems may also exhibit varying levels of functionality during recovery, indicating the system's capacity to function after an earthquake.

3. Towards an urban scale prevention instrument: the Early Recovery System (ERS)

Post-earthquake recovery is an evolving process, and while the end goals may be apparent, the path to achieving them is often uncertain. Much depends on how physical reconstruction is approached—whether as a collection of individual building restorations or as part of a comprehensive urban planning strategy. There is also a significant disconnection between response management, which is generally well codified, and the phases of the recovery process. The latter, from the construction of the so-called 'temporary city' to the beginning of recovery and the long-term reconstruction, is often the result of a complex system of decisions and actions, typically implemented on a case-by-case basis over a period ranging from the immediate aftermath to several years later (Coppola et al., 2021).

To bridge short-term response measures with medium- to long-term recovery programmes, the 'Early Recovery' (ER) paradigm (IASC, 2006; UNDP, 2008) was introduced. Although this concept has yet to be fully operationalized, it primarily focuses on the humanitarian aspects of post-disaster situations, often neglecting the urban planning dimension (Noureddine Tag-Eldeen, 2017). However, without integrating planning expertise into the ER framework, there is a risk of disjointed actions across different post-disaster phases, creating imbalances that could hinder urban development.

Adopting the definition of ER as a multidimensional process that aims at generating self-sustaining, resilient processes for post-crisis recovery, encompassing the restoration of basic services, livelihoods, shelter, governance, the environment, and social dimensions, including the reintegration of displaced populations (IASC, 2006; Cluster Working Group in Early Recovery, 2008), we aim to enhance the ER concept by developing its spatial dimensions. We focused on identifying key services and infrastructures whose immediate usability after an earthquake could be strategic for minimizing common post-disaster effects, such as losses, displacement, and relocation. Observing post-earthquake experiences, and considering that disaster impacts are often more severe in areas with fragile infrastructure, the continuous functioning of basic services, such as healthcare facilities and schools, plays a vital role in strengthening the community's capacity to respond effectively in the aftermath of an event (Burton, 2015; FEMA, 2016; Mutch, 2018; Fontana et al., 2020).

Global campaigns like Hospitals Safe from Disasters (ISDR, WHO, and World Bank, 2009) emphasize the importance of maintaining the functionality, accessibility, and high quality of healthcare facilities after a disaster. These facilities are not only essential for monitoring community well-being (Achour et al., 2014), but communities with a high concentration of primary care facilities generally exhibit better overall physical and mental health, making them more resilient in absorbing and recovering from disasters (FEMA, 2016).

Similarly, integrating the educational sector into DRR strategies is crucial for minimizing a disaster's impact on younger populations, which directly affects the entire community (Tong et al., 2012). Structural improvements to school buildings, combined with enhancing administrators' capacity to maintain cohesion in the school community after a disaster, are key factors (Mutch, 2018). Schools, often centrally located, not only support the well-being of children and young people but also serve as hubs for local social cohesion. As a result, they play a significant role in all phases of the risk management cycle (UNISDR, 2007; ADPC, 2007; GADRRRES, 2022).

Therefore, maintaining pre-existing basic services in situ and preserving their relationship with the territory as part of an interconnected functional system—along with temporary housing plans that respect pre-disaster spatial organization and social networks—form the basis of the Early Recovery System (ERS) concept. Inspired by the ELC prevention instrument, ERS defines a minimum core of elements common to all territories, whose functionality must be preserved to reduce urban vulnerability (Fontana et al., 2024).

Specifically, it comprises i) strategic functions for rescue operations, ii) healthcare facilities, iii) schools, iv) areas for temporary housing, v) the road network that connects these functions, and vi) 'interfering buildings', whose collapse could interrupt system connections.

To define ERS, the first step is to identify the elements and their interconnections on the cartography (Figure 1, Step 1). Depending on the complexity of the road network, the selection of these elements can generate diverse ERS configurations (Step 2), which may change urban functionality levels. To evaluate the best ERS configuration, the different configurations must be assessed on specific risk scenarios (Step 3): for each configuration, the urban functionality loss and the possible recovery trajectory are calculated through a set of indicators (Steps 4). Hypothesizing and assessing different ERS configurations is a way to support policymakers in planning risk reduction strategies and developing intervention programs. While Steps 1, 2, and 4 are the focus of this paper, Step 3 will be explored further in the research process.

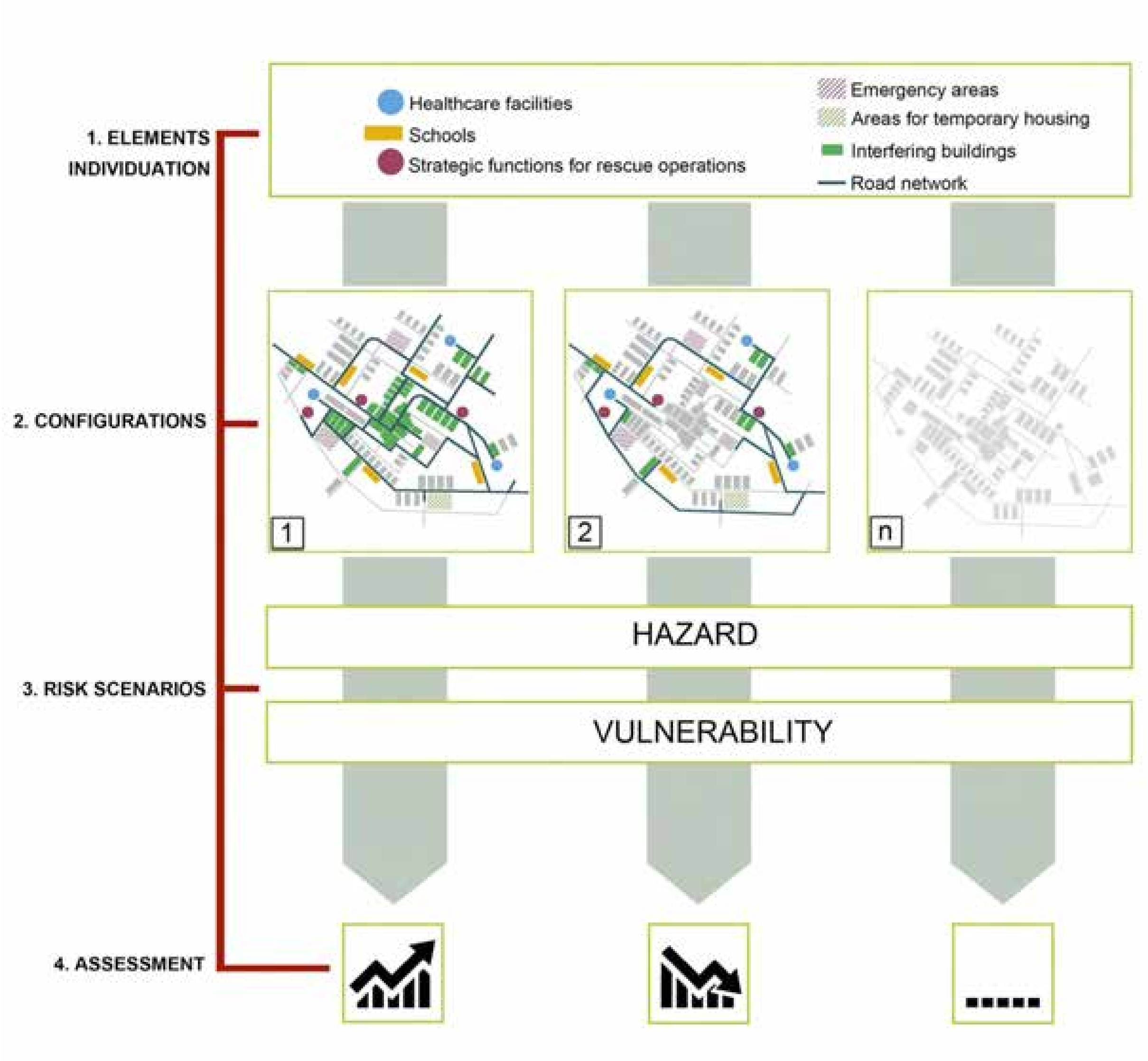

Figure 1. The four steps of ERS planning methodology.

4. A methodology to assess post-earthquake urban functionality

To analyze the urban system's capacity to respond to shocks, we divided it into different functional dimensions that reflect the complexity and multifaceted nature of society (Cutter et al., 2014; Singh-Peterson, 2014; Cimellaro, 2016; Kammouh et al., 2019; Fontana et al., 2020). We identified six dimensions: environmental, housing, school, healthcare, infrastructural, and socio-cultural. To assess the functionality of the urban system and its recovery trends over time, we developed a set of indicators.

According to us, these dimensions help identify the variables that have the most significant impact on the early recovery of a post-earthquake territory and can be directly (healthcare, school, housing, and infrastructural) or indirectly (environmental and socio-cultural) correlated with the ERS elements. To each dimension, we associated a specific urban damage proxy for the loss of functionality measured through 18 indicators (Table I).

For the environmental dimension, we measure the reduction of the environmental balance, a key aspect of the quality of life and human health. To calculate it, we consider two variables: 1) land consumption growth, amplified by the construction of temporary settlements and commercial and facilities areas, and 2) the volume of rubble produced over time from the collapse and/or demolition of buildings. Within the housing dimension, the loss of functionality is intended as the displacement of households, measured through variables that show the changes in the urban spatial structure due to temporary housing settlements and the consequent relocation of people. This can lead to a loss of community sense and social networks, encouraging the permanent abandonment of places. The school dimension is linked to its usability decrease caused by both service interruption due to building damage and its relocation to a different area. Similarly, the healthcare dimension is linked to the reduction of its usability. In this case, however, it is important to consider not only service interruption and its possible relocation but also the potential post-earthquake performance downgrade or upgrade. For the infrastructure dimension, we measure the reduction in accessibility caused by damage to road infrastructure and the perimeter extension of the 'red zones. ' Finally, for the socio-cultural dimension, fundamental to maintaining and consolidating community identity and sense of belonging, we calculate variables related to the unavailability of cultural heritage and social spaces to measure the loss of socio-cultural networks.

Table I: Selected indicators to describe the loss of functionality in the six dimensions.

URBAN FUNCTIONAL DIMENSIONS	LOSS OF FUNCTIONALITY	INDICATOR	DESCRIPTION	EFFECT
Environmental	Reduction of environmental balance	**Land Consumption**	Expansion of built-up areas, using Corine Land Cover data (hectares)	-
		Volume of Rubble	Volume produced by the collapse of public and private buildings, the demolition of unsafe structures, and public and private building interventions (tons)	-
Housing	Displacement of households	**Displaced Population**	Homeless resident population on total population (%)	-
		Change in the City's Spatial Structure	Average distance of the temporary settlements from the pre-event inhabited areas (meters)	-
		Temporary Settlements Delivery	Temporary settlements delivered to the displaced population (%)	+
		Population Displaced in Hotels	Population displaced in hotels on total homeless residents, weighted based on the distance (%)	-
School	Decreased usability	**Unavailability of School Facilities**	Condemned schools (%)	-
		Repair of the School Function	Reactivated schools, including delocalization and temporary schools (%)	+
		Change of the School service Spatial Organization	Average distance of the new schools from the existing ones (meters)	-
Healthcare	Decreased usability	**Unavailability of Healthcare Facilities**	Condemned healthcare facilities (%)	-
		Repair of the Healthcare Function	Reactivated healthcare facilities, including delocalization (%)	+
		Displacement of Healthcare Facilities	Average distance of the new healthcare facilities from the existing ones (kilometers)	-
		Performance of Post-Earthquake Healthcare services	Value based on the post-earthquake performance of the healthcare service: 0 (no service); 0.2 (medical clinic, ASL); 0.4 (First aid point); 0.6 (Emergency Room); 0.8 (second-level Emergency Admission Department); 1 (first-level Emergency Admission Department)	+

Infrastructural	Accessibility reduction	**Level of Inaccessibility**	Interrupted access to inhabited areas, weighted on residents' number (%)	-
		Red Zone Extension	Ratio of forbidden 'red zone' extension to total urban settlement area	-
Socio-cultural	Socio-cultural relationships loss	**Unavailability of Cultural Heritage**	Condemned cultural building heritage (%)	-
		Unavailability of Sites dedicated to Culture and Social network	Condemned sites dedicated to culture and social network (%)	-
		Repair of Sites dedicated to Culture and Social network	Reactivated sites dedicated to culture and social network, including delocalization (%)	+

4.1 Data collection, aggregation, weighting, and calculation time

After the development of the pre-established risk scenario, all the indicators can be calculated using secondary data sources obtained from open-access databases, primarily from institutional sources. Additionally, information can be extracted from earth observation data to supplement the primary dataset. Each variable is assigned a maximum and minimum value based on the indicator measurement. The calculations for each variable are performed at the local municipal scale. To assess urban functionality, each variable is normalized using a Min-Max rescaling scheme, which allows for the comparison of values across different scenarios and various urban dimensions. This normalization process scales values between 0 and 1, with 0 representing the worst rank and 1 representing the pre-earthquake functionality.

After normalizing the variables, the values are aggregated for each dimension through a simple average. All variables are equally weighted. This decision is based on two main considerations, as argued by Cutter et al. (2010) and supported by the authors: 1) such a method of aggregation is transparent and easier for other potential users to understand and use, and 2) there is no theoretical justification for attributing a hierarchy of importance across indicators. Moreover, all indicators are considered relevant for measuring urban functionality only if observed from an equal and systemic perspective.

The indicators are then calculated over four different time intervals: t=1 (from the earthquake to 1 year after); t=2 (from 1 year to 2 years after); t=3 (from 2 to 3 years after), and t=10 (10 years after).

The first three intervals represent the early recovery period, while t=10 provides an overview of long-term recovery. Calculating recovery at different time points allows for the generation of a recovery curve (see Chapter 5 as an example).

5. L'Aquila after the 2009 earthquake: a counterfactual hypothesis with and without ERS interventions

To test the methodology and evaluate the sensitivity of the chosen indicators to variations in the urban system functionality, the case of L'Aquila, severely damaged after the 2009 earthquake, has been selected as a pilot case study.

With a population of roughly 69,000 inhabitants spread over 470 square kilometers, L'Aquila exhibits a highly fragmented and unbalanced spatial structure. Rebuilt numerous times following earthquakes, its spatial organization has historically centered around two primary systems: a historic center of significant social and cultural value and a vast network of smaller villages.

On April 6, 2009, a seismic event with a magnitude of Mw = 6.3 occurred with the epicenter located approximately 6 km away from the city of L'Aquila. The earthquake severely impacted it and 56 additional municipalities, resulting in 309 casualties and displacing 60,000 inhabitants. A total of 37,000 buildings were damaged, including 34,000 private houses, 1,000 public buildings, and 2,000 buildings of significant historical value (OECD, 2013).

L'Aquila's highly damaged historical center was immediately evacuated, declared 'red zone', and placed under military control. Residents were rescued and relocated to camps managed by the Civil Protection body or to hotels along the coast. The reconstruction process of the historical center only started in 2012, three years after the earthquake. Consequently, many socio-economic and cultural activities were relocated, and people displaced into temporary settlements scattered and dispersed within the large municipality boundaries (Frisch, 2010).

In this context, we posed the question: To what extent could urban functionality have been preserved if ERS strategy had been implemented before the earthquake?

To address this complex question, we first calculated the indicators based on the current state, considering real damages. We then hypothesized to apply an ERS prevention strategy in a counterfactual manner and calculated the indicators for two hypothetical configurations:

1. ERS1 → connecting elements of the system through the historical town center and relocating temporary housing based on proximity criteria (compact system);
2. ERS2 → connecting elements of the system while minimizing or avoiding passage through the historic town center; temporary housing locations remain unchanged from reality (diffused system).

For each of these configurations and the generation of a recovery curve, we calculated the set of indicators across four different time intervals: t=1 from April 6th, 2009 to March 2010; t=2 from April 2010 to March 2011; t=3 from April 2011 to March 2012; t=10 from April 2019 to March 2020.

For the two hypothetical configurations, ERS1 and ERS2, we calculated the indicators for each interval by subtracting from the real available data the amount derived from the elements potentially retrofitted during the prevention phase to implement the ERS, assuming that the interventions were 100% effective and that there would therefore be no damages that could compromise the functioning of those elements.

For instance, the Red Zone Extension indicator was calculated by measuring the extent of the 'red zone' for each time interval, as defined in various municipal resolutions, in relation to the urbanized area. As the interventions for securing, demolition, and reconstruction proceeded, the boundaries of the restricted zones were updated over time. For the calculation of values in the two configurations (ERS1 and ERS2), the areas occupied by elements included in the ERS were subtracted from these surfaces, considering them as potential safe areas.

Individual values were then aggregated by urban functional dimension. The results for each dimension were visualized using linear graphs illustrating the initial loss of functionality due to the earthquake and potential recovery trajectories over time.

We are aware that the ERS is a complex system (i.e., a system of sub-systems) and that the aggregation of independently calculated indicators may be a forced approximation of reality. In any case, to compare the different configurations in the first instance, we considered ours to be an acceptable approximation.

5.1 Current state: no intervention

Figure 2 illustrates the repercussions of the L'Aquila earthquake on various urban dimensions. The socio-cultural dimension shows the most severe loss: in fact, the historical center, where all the social and cultural activities were concentrated, was completely evacuated and strictly controlled by the institution of the red zone. The historical center began reopening gradually only three years later, exacerbating the impact on social and cultural activities.

The school dimension shows a similar loss, having been heavily affected, with over half of the 36 public schools sustaining significant damage. Students were relocated to temporary school units, located outside the town center, scattered across the suburbs, and often distant from their original locations (on average 700 meters).

Additionally, the environmental dimension exhibits a notable negative trend between t2 and t3. This was primarily due to the extensive construction of the 'temporary city' and the relocation of businesses and services that increased land consumption. Moreover, the long-term physical reconstruction of the historical center resulted in a substantial accumulation of rubble.

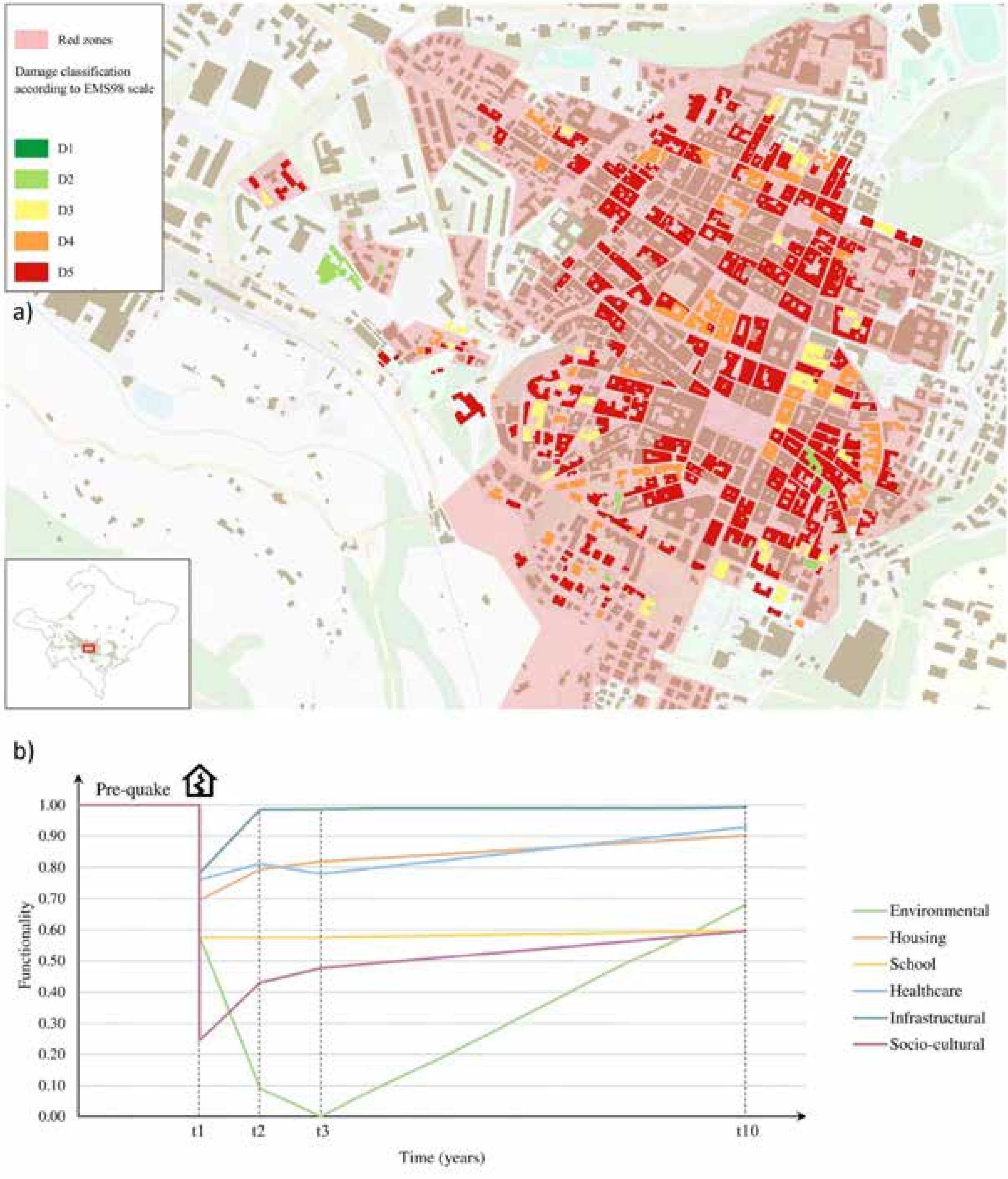

Fig. 2: Map of the damage of private buildings in the historical center of L'Aquila (a); Loss of urban functionality for the current state 'no intervention' (b).

5.2 Configuration 1: ERS1

The ERS1 configuration establishes a network of interconnected elements utilizing a road network through the town center. Figure 3 depicts an excerpt of ERS1, highlighting the elements classified by typologies and a revised demarcation of the 'red zone,' which considers the potential seismic retrofitting of buildings. Given the substantial number of historical buildings involved, implementing a similar intervention program will undoubtedly necessitate a comprehensive planning effort. However, this would promise significant community and financial benefits throughout the long process of post-earthquake reconstruction and recovery.

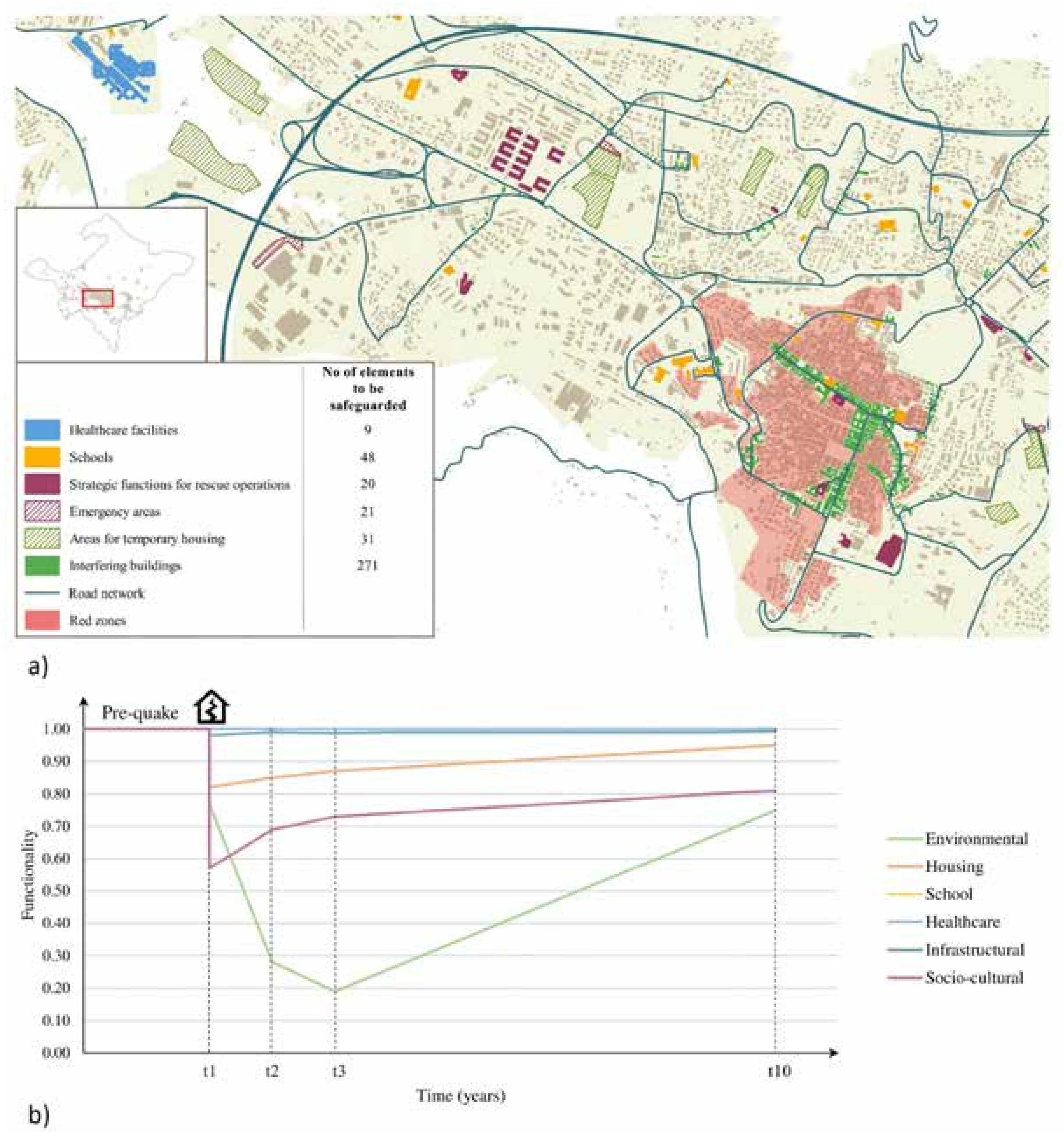

Fig. 3: ERS1. Excerpt of the historical center and surroundings (a); Loss of urban functionality for the ERS1 configuration (b).

During the prevention phase, the potential retrofitting of approximately 350 structural units (public and private buildings), 300 km of roads, and the identification of 31 suitable areas for temporary houses would have helped preserve a significant part of the spatial and relational urban organization. As illustrated in Figure 3, the school and healthcare dimensions would maintain their functionality, while the infrastructural dimension would experience only a minor loss of 0.02. The housing dimension shows a lighter loss compared to the current state (0.18 compared to 0.31) and demonstrates better recovery over 10 years (although the slope of the line remains relatively consistent). The socio-cultural dimension, which includes historical buildings and cultural and social venues, benefits from this configuration, reducing functionality loss from 0.76 to 0.43. The environmental dimension, despite still experiencing significant functionality loss, would also benefit from this configuration, particularly through fewer relocations due to the prevention planning of temporary locations and seismic retrofitting of schools.

5.3 Configuration 2: ERS2

The ERS2 configuration includes the same elements as ERS1, except for the relocation of two buildings for rescue operations outside the town and modified connections between elements outside the center (Figure 4). Additionally, the post-earthquake locations of temporary housing were maintained as determined by government decisions.

With this configuration, the number of potential seismic retrofitting interventions would be significantly reduced, decreasing from around 350 structural units in the previous configuration to approximately 270. The preservation of road infrastructures remains largely unchanged, except for those associated with the historic center.

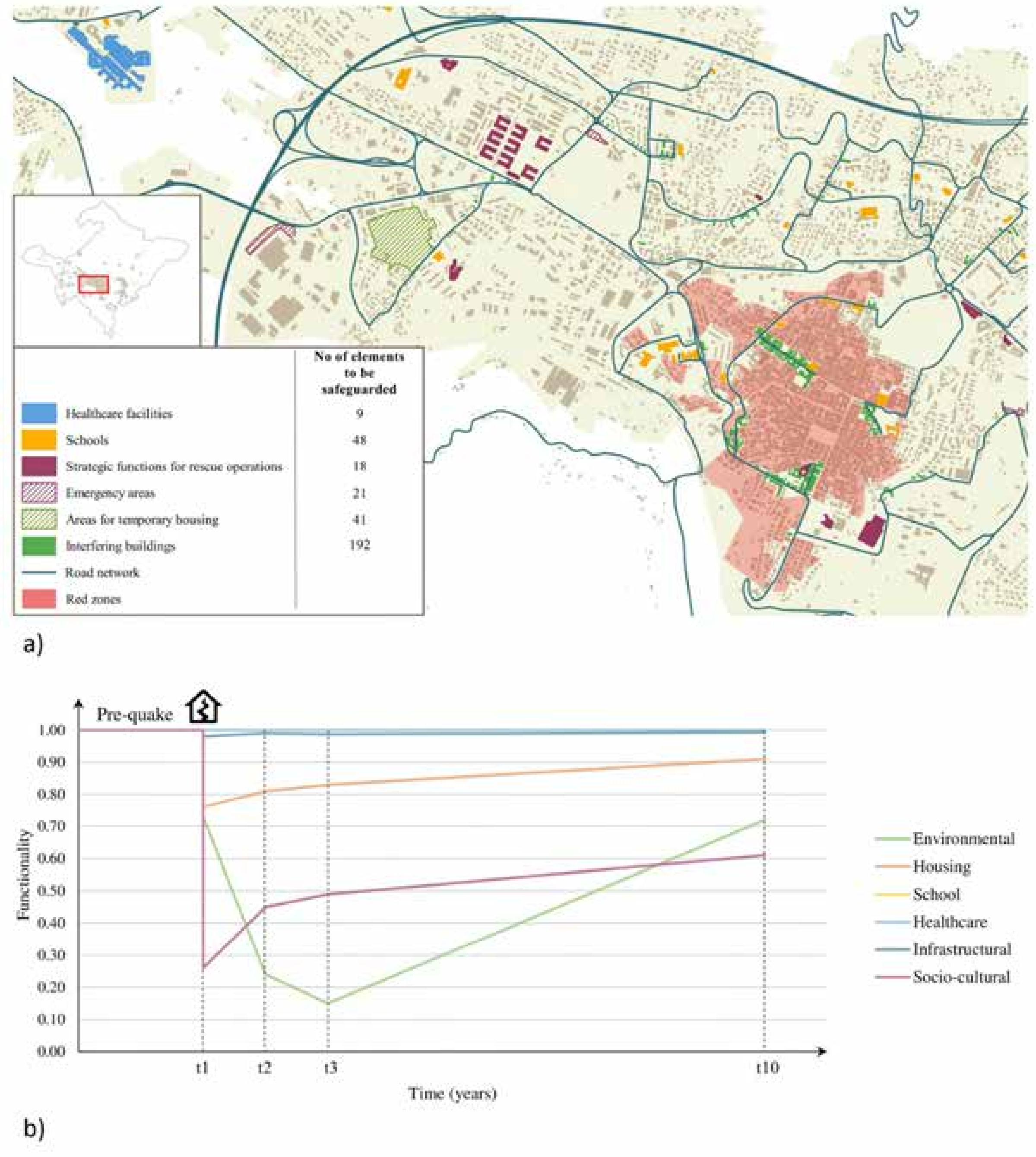

Fig.4: ERS2. Excerpt of the historical center and surroundings (a); Loss of urban functionality in the configuration ERS2 (b).

Like the ERS1 configuration, school, healthcare, and infrastructural dimensions would maintain their functionality in ERS2. However, there is a minor pejorative difference for the housing dimension compared to the previous configuration (functionality loss of 0.24 compared to 0.18). The most significant change occurs in the socio-cultural dimension. By not including the road network within the town center and thus not accounting for interfering buildings, many cultural and social venues would be excluded from ERS2. As depicted in Figure 4b, the socio-cultural functionality curve shows little difference from the current state (0.74 for ERS2 and 0.76 for current state).

5.4 Discussion

In summary, across both ERS configurations, the dimensions directly involved in the selection of system elements (school, healthcare, infrastructural) exhibit very little or no functionality loss. However, the ones indirectly involved still show some loss of functionality, albeit significantly less compared to the current state. Notably, the socio-cultural dimension continues to experience considerable functionality loss in the second configuration (ERS2) due to the absence of a road network within the historic center.

The effects of lacking seismic prevention urban strategies over time are supported by concrete facts. More than 15 years later, the region is still grappling with both physical and socio-economic recovery. L'Aquila's urban system has undergone profound changes in its functional and relational organization, and the overlap between the temporary city and long-term reconstruction has exacerbated socio-spatial imbalances. The reconstruction of public buildings has barely reached 50% of the planned interventions (USRA, 2023), resulting in a scarcity of socio-cultural spaces and the absence of schools within the historic town. The general spatial reorganization, which accelerated a depopulation process already underway before the earthquake, also had significant social impacts, generating collateral effects such as increased land consumption and traffic congestion.

Conversely, the ERS1 configuration suggests that implementing a seismic retrofitting program for the system's elements would have prevented significant damage to the school and healthcare sectors. Additionally, retrofitting the buildings within the historic center—many of which host important social and cultural spaces—would likely have mitigated the loss of functionality in the socio-cultural dimension. This approach would have allowed these functions to continue in situ, without disrupting the city's socio-spatial structure, and would have limited land consumption resulting from temporary relocations.

Regarding the loss of functionality in the housing dimension, since it is not feasible to secure all private residential properties, there is still an evident, albeit limited, loss. The real advantage, therefore, lies in the prevention planning for temporary housing areas, where the choice of locations for new settlements becomes a strategic issue to reduce abandonment processes and excessive new land consumption.

Experimentation on the specific case of L'Aquila post-2009 earthquake allowed us to highlight the strengths and weaknesses of the proposed methodology. Among the weaknesses is the difficulty in obtaining data for calculating the indicators, which did not allow us to detail the various functional dimensions equally and address all characteristic aspects. In addition, the lack of literature on indicators to measure urban functionality, as defined in this paper, made the choice of the indicator set highly experimental.

The absence of existing models in literature pushed us to test the methodology on a specific area already affected by an earthquake, with known effects on the short and long-term reconstruction and recovery processes, to validate the methodology and the set of indicators by comparing them with the state of the art. What emerged is that the proposed variables and the resulting recovery curves seem to reflect the recovery trajectory of L'Aquila. This result allows us to continue the research to abstract the methodology, applying it within a complex framework of risk scenario simulation to support public prevention policies.

6. Conclusions

In this article, we introduced a new prevention instrument for Early Recovery and a methodology to assess urban functionality by comparing different prevention spatial configurations, emphasizing the importance of viewing prevention from an urban planning perspective. Considering that retrofitting the entire urban settlement is unlikely, our approach aimed to identify a proto-system of essential functions, open spaces, and road networks to be preserved to guarantee a minimum level of urban vitality after a major event and foster recovery to begin. In analogy and continuity with the general structure of the Emergency Limit Condition (ELC) analysis, we developed the Early Recovery System (ERS) instrument. As for the ELC, identifying specific essential elements allows the methodology to be consistently applied across all territories at the national scale.

Through the calculation of a set of 18 indicators, framed into 6 urban dimensions, across four time intervals– t1, t2, t3, and t10 – we generated and compared recovery curves for different ERS configurations (ERS1 and ERS2), providing a visual representation of functionality loss and potential recovery trajectories over time.

The lack of existing models in the literature to measure post-earthquake urban functional recovery from a planning perspective prompted us to conduct a counterfactual experiment using the proposed methodology on a case study that had already been affected by a major event: L'Aquila post-2009.

By comparing the current state with the best ERS configuration (ERS1), we demonstrated the severe long-term impacts on L'Aquila's functionality. In contrast, ERS1 showed potential for significantly preserving urban functionality and reducing long-term disruptions.

The experimentation in a specific area with known effects on short- and long-term recovery processes allowed us to highlight the strengths and weaknesses of the proposed methodology. Despite limitations, the resulting functionality curves reflected L'Aquila's recovery trajectory, validating the methodology's potential.

Now that the assessment methodology has been tested, we aim to further this research by applying it to other Italian territories during peacetime and within a complex risk scenario simulation framework. The ultimate goal is to design an effective urban prevention path to support decision-makers in planning interventions and setting priorities, thereby mitigating long-term urban imbalances in the wake of seismic events.

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