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Resilience assessment of complex urban systems to natural disasters: A new literature review

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ABSTRACT

In parallel with the observed greater frequency of natural disasters worldwide, there has been an ever-increasing interest in urban resilience and its assessment. Experience obtained in recent extreme events (in particular, earthquakes and floods) has revealed that both the level of preparedness and the response of affected cities were insufficiently high, whereas the recovery process was long and expensive. For this reason improved pre-disaster mitigation actions, as well as smart and strategic urban planning in threatened areas (e.g. in earthquake-prone regions), is essential. For this purpose, a comprehensive review of the existing literature has been performed in relation to the holistic assessment of urban system resilience to natural disasters, with an emphasis on the effect of earthquakes. The main goal of the review was to try to determine how to best assess the resilience of urban systems as a whole, taking into account all of their components, i.e. both the physical components (i.e. of buildings, infrastructure, and open spaces) and the social components (i.e. of the community), as well as the dynamic interactions between them. Besides considering the commonly measured indicators (e.g. determination of the scope of actual structural damage caused by an earthquake), the paper tries to extend the discussion to some indicators which are not so commonly taken into account, by applying a quantitative resilience assessment approach. Based on the results of the described new literature review, a preliminary concept which could be used to assess the seismic resilience of complex urban systems, taking into account all urban components which have been identified as having an important impact on the latter, is presented. This concept consists of three different parts: (i) a probabilistic fragility analysis for each individual physical element (i.e. a building or an infrastructure element), (ii) a composite index methodology for the measurement of community disaster resilience, and (iii) a complex network approach (graph theory) for the assessment of the resilience of urban systems as a whole. Since, in the existing literature, there is a lack of consideration of urban open space, which can have a significant role in the recovery process, it is suggested that, in future research of seismic resilience assessment, such open space should be taken into account, and that an in-depth study of possible recovery strategies be performed.

1. Introduction

In recent decades the frequency of occurrence of natural disasters, and the extent of their devastating impacts, both economic and to humankind, have, according to [1–3], shown almost exponential growth. These facts can be mostly attributed to poor urbanization strategies, and the worsening effects of climate change. Worldwide, between 2006 and 2015, natural disasters, on average, annually affected approximately 224 million people, killing almost 70,000 of them, and simultaneously causing more than US$ 135 billion in damage [4]. As the present trends of population growth and urbanization continue, it can be expected that more and more people will be exposed and that assets will be more concentrated in risk-prone areas. Today, more than half of the world's population lives in cities, and it is expected that, by 2050, up to 75% will do so [5,6]. This means that there is an ever-increasing need for special attention to be paid to risk mitigation and the adaptation of urban systems.

As a result of the above-mentioned threats, the notions of urban resilience and resilient cities have recently raised interest among both practitioners and researchers. The term 'resilience' is derived from the Latin word 'resiliere', which means "to bounce back" [7,8]. With its roots in physics and mathematics, the concept was originally used to indicate the capability of a material or system to return into balance after being displaced [9]. Holling [10] used the term resilience to describe the capacity of a natural ecosystem. He defined ecological resilience as the persistence of relationships within a system and a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist. Later the term

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resilience was more widely applied to other scientific fields (ecology, materials science, social science, economics and engineering), and today it is still evolving. Thus, during the last few years several interpretations of resilience have been proposed, depending on different scientific approaches and the fields involved. Researchers and theorists dealing with resilience try to find answers to the fundamental questions: resilience for whom, what, when, where and why [11,12]. In the literature two dominant theoretical perspectives have been identified: socio-ecological and engineering. While the socio-ecological perspective considers resilience as a process-oriented phenomenon (a dynamic concept), the engineering perspective views resilience as a result-oriented concept (a static premise). Based on this aspect, the engineering approach understands the term resilience as bouncing back to the same (stable) condition before an adverse event, whereas the socio-ecological approach denotes adaptive resilience, such as how to respond to, recover from, and adapt to new conditions. As such, an ecological approach allows the existence of different equilibrium conditions achievable by the system after potential disruptions [3]. According to the study by Asadzadeh et al. [12], the theoretical background of disaster resilience measures can be distinguished based on their semantic completeness (why resilience), measurement focus (resilience for when), and operationalized domain (resilience of what):

– The semantic completeness of disaster resilience frameworks is characterized by a distinction between their attitudes toward the term resilience (a static or result-oriented vs. dynamic or process-oriented concept);
– The measurement focus of resilience frameworks can be classified into: (i) measuring the recovery and stability of communities by focusing on the return time and efficiency of characteristics (*engineering resilience*), (ii) capturing the persistence (robustness) level of communities by focusing on buffering capacity, withstanding shocks, and maintaining functions (*ecological resilience*), and (iii) measuring adaptive capacity, as well as learning, and transformability (*socio-ecological resilience*), which enable communities to respond successfully to, recover from, and adapt to new conditions;
– The operationalized domain of disaster resilience measurement frameworks endeavour to measure either (i) the characteristics of systems (evaluation of the unique quantities of some attributes in communities without any evaluation of quality that makes them different from others) or (ii) the capacities within them (evaluation of quality performance or the ability of systems or community elements).

A general definition of resilience was published by the National Academies Press referring to resilience as "the ability to prepare and plan for, absorb, recover from and more successfully adapt to adverse events" [13,14]. Another definition was proposed by the United Nations: "Resilience is the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner including through the preservation and restoration of its essential basic structures and functions" [2,15,16]. Social resilience is understood as the capacity or ability of a community to anticipate, prepare for, respond to, and recover quickly from the impacts of disaster [16]. One recent engineering-based approach has defined resilience as a system's coping capacity and ability to withstand or adapt to external shocks, along with the effects of pre-disaster preparedness and adaptive response actions that can be quickly taken in the disaster's aftermath in order to recover efficiently and effectively [17,18].

The concept of a "resilient city" combines both of the above-mentioned aspects, i.e. the engineering-based aspect and the socio-ecological-based concept. According to Godschalk [19], a resilient city is a sustainable network of physical systems and human communities, capable of managing extreme events; during disaster this network must be able to survive and function under extreme stress. Bozza et al. [20] defined urban system resilience as the capacity of a complex system, composed of non-homogeneous components interacting and coexisting, to withstand an external stress and bounce back to an equilibrium state or bounce forward to new equilibrium states (improved conditions). Whether bouncing back to a pre-disrupted condition is the most favoured option or not is a matter for debate. The interpretation of resilience as bouncing back as a positive outcome can be identified as "elastic" resilience, whereas the recent approach of resilience implementing uncertainty and adaptation can be defined as "ductile" resilience [3]. In accordance with the mechanical definition of elastic behaviour of a material (the elastic branch in the stress-strain diagram), "elastic" resilience interpretation seeks to regulate a return to the pre-existing equilibrium (the static concept of resilience). Conversely, the "ductile" resilience interpretation – in parallel with the nonlinear behaviour of the material exhibiting large deformations at a certain level of stress – is no longer about returning to the equilibrium or maintaining the status quo, but is seen as a process of on-going self-transformation that can be likened to bouncing forward (the dynamic concept of resilience). According to Chandler and Coaffee [21], the first generation of resilience thinking (i.e. the static concept) could be understood also as a "homeostatic" approach, whereas the second generation of resilience (i.e. the dynamic concept) can be recognized as a "autopoietic" approach. In the latter, bouncing back is not the aim but rather growth and development, through an increased awareness of interconnections and processes.

Based on all of the above-mentioned different approaches and definitions, it is clear that the notion of resilience has a broader meaning than just the capacity to resist an external disturbance. This means that it should therefore be distinguished from the concepts of "resistance", which refer to the force required to displace a system from equilibrium, whereas resilience refers also to the time required for the system to return to equilibrium once displaced [9,22]. The time dimension [2,9,22–24] is essential when considering the concept of resilience as a process before a disaster occurs, at the time of disaster occurrence, and after the disaster (corresponding to the different phases of: preparedness, response, recovery and adaptability). Besides the time scale, also other scales (e.g. spatial and functional) do matter when resilience is discussed. According to Young [25], scales are the levels at which phenomena occur both in space and time. The literature review recently performed by Cerè et al. [3] highlighted a strong contrast between extremely broad analyses (involving broad-scale networks without any particular focus either on buildings or infrastructures) and limited-scale methodologies (e.g. those addressing building-scale or urban-scale resilience in relation to a single typology of disruption). Building an understanding of urban resilience across multiple scales requires an awareness of both spatial diversities in adaptive capacities, and trade-offs in resilience between different scales [24]. It should, however, be noted, that, according to the analysed spatial scale (i.e. the urban macro level), the level of accuracy of an individual component's characterization is, in general, lower than in the case of the analysis of just one element (e.g. a selected building) among the studied urban subcomponents. Consequently, the accuracy and applicability of the results strongly depends on and is limited to the considered urban scale. If an assessment of resilience from the holistic perspective is desired, the used resilience indicators should be able to capture the change in resilience at different scales, and should not be limited to individuals, communities or even cities [26].

Because the concept of resilience has been used in various research fields, it has several definitions with different meanings, and different approaches have been proposed for its assessment. In order to obtain a clearer picture and overview of the topic, a more exact review and in-depth analysis of the existing literature is needed. Several such review articles taking into account different resilience research fields and topics have been published. Some of them are focused on community resilience [9,12–14,26–28], whereas others have approached this question from the engineering perspective [3,8,29,30].

Sharifi [13] analysed a total of 36 selected tools for the assessment of community resilience. An analytical framework was developed which was able to identify six criteria for the evaluation of the performance of resilience assessment tools. The percentage distribution of the frequency of criteria belonging to each dimension was analysed. In his conclusions Sharifi exposed the weaknesses of the investigated resilience assessment tools, as well as listing the challenges and opportunities which are available for their improvement. He found that only limited success has so far been achieved in addressing these criteria, and that, in terms of comprehensiveness, the environmental dimension has received relatively less attention in spite of its significance for building community resilience. He also emphasised that these tools should not be developed in isolation from each other, and that cross-fertilization is needed in order to create more comprehensive and better-informing assessment tools. In a similar fashion Sharifi and Yamagata [14] evaluated the suitability of the same 36 selected assessment tools for guiding communities towards disaster resilience. A framework which identified various measures addressing each of the four resilience abilities (planning, absorption, recovery and adaptation) was developed. The results of the evaluation indicated that only a few of them are reasonably suitable for addressing the measures which are related to the four resilience abilities.

Hosseini et al. [8] published a review of definitions and measures of system resilience, with a focus on engineering systems, and provided a classification scheme of the approaches, focusing on qualitative and quantitative assessment and their subcategories. Four domains of resilience were identified: organizational, social, economic, and engineering. On the other hand Weber Righi et al. [29] restricted themselves to papers which considered resilience from the engineering perspective. Their research was based on a systematic literature review of 237 studies which were published between 2006 and 2014. Six research areas were identified: the theory of resilience engineering, the identification and classification of resilience, safety management tools, analyses of accidents, risk assessment, and training. Finally, based on the literature review a research agenda for further investigations was proposed. Similarly, Bozza et al. [30] focused on urban resilience from a civil engineering perspective, but the review was limited to existing methodologies which can be used to quantify urban resilience. In particular, articles that could be used to assess resilience according to graph theory were analysed, taking into account combinations from the engineering and human centric perspectives. The reviewed literature was classified by system model and resilience metric.

The purpose of this study is to provide a critical and comprehensive review of the existing literature as related to the holistic assessment of urban system resilience to natural disasters, with an emphasis on the effects of earthquakes. In the literature selection process priority was given to recent publications and achievements in this field. The main body of the work consisted of an overview of scientific journal papers and of selected research programs supported by national and governmental organizations. An analysis of the applied resilience assessment methods was performed, and the distinction between qualitative and quantitative approaches was made. Referring to the literature review, the paper attempted to find answers to the following research questions:

– Which urban components have a substantial impact on overall urban resilience to natural disasters?
– How to model urban systems as a whole?
– What are the possibilities for assessing urban system resilience?
– What are the particular factors which have to be taken into account when assessing urban system resilience to earthquakes?
– How does social capital and urban open space affect urban system resilience in the case of an earthquake?
– How large is the potential of urban open space in the preparation of recovery strategies?

This paper is organized as follows. In Section 2, the theory of urban system resilience is first analysed. In Section 3, we focus on resilience assessment. This section is divided into two subsections, analysing qualitative (Section 3.1) and quantitative (Section 3.2) resilience assessment. The latter has a further division into sub-subsections considering the quantitative assessment of individual urban components, i.e. buildings, infrastructure, the community, open space, and the urban system as a whole. In Section 4, the reviewed papers are critically discussed, and the authors' proposed new concept for the seismic resilience assessment of a complex urban system is presented. Section 4 is concluded by a short discussion on the operationalisation challenge of resilience assessment frameworks. In the last section, Section 5, the authors' concluding remarks and recommendations for future studies are given.

2. Urban system resilience

A complex urban system consists of a number of interdependent networks which are made up of different physical and social components. There are dynamic interactions between individual components which enable efficient system performance [19,23]. The physical components act as the body of the system, its skeleton, veins and muscles. The social components function as the brain of the city, directing its activities, responding to its needs and learning from its experience [19]. It is impossible to evaluate the resilience of any observed city without considering different relevant systems and their interdependency. Before performing urban system resilience assessment, it is necessary to understand the concept and properties of a resilient urban system, as well as how to plan and manage resilient cities. Many theoretical papers and initiatives discussing these issues have been published [2,6,9,19,23,31–33].

Norris et al. [9] looked for a definition of community resilience, and a set of capacities and strategies for a resilient community. Community resilience was presented as a process which is reflected in population wellness. A resilient community includes a network of adaptive capacities (resources with dynamic attributes) which is capable of adaptation after a disturbance. Three dynamic attributes of resources were recognized: robustness, redundancy, and rapidity. The fourth attribute, resourcefulness, proposed by Bruneau et al. [34], was omitted. Four primary sets of adaptive capacities were recognized (economic development, social capital, information and communication, and community competence) which together provide a strategy for disaster readiness. Norris et al. [9] distinguished between resilience and resistance, as well as between the engineering and the ecological approach to resilience. Godschalk [19] introduced the notion of a resilient city, and proposed a comprehensive strategy of urban hazard mitigation. He recommended a major resilient city initiative, including expanded urban systems research, education and training, and increased collaboration among professional groups involved in city building and hazard mitigation. The following attributes of resilient cities were exposed: redundancy, diversity, efficiency, autonomy, strength, interdependency, adaptability and collaboration. The public and private organizations of a resilient city should both plan ahead and act spontaneously. Desouza and Flanery [23] proposed a conceptual resilience framework for the evaluation of cities as complex adaptive systems. The framework serves as a holistic approach to design, planning, and management for resilience by including an evaluation of the interaction of social and physical elements. Physical and social processes can be understood as spatial and temporal interactions across networks. Four types of stressors (natural, technological, economic, and human) and three types of damage (destruction, decline, and disruption) were defined. The impact of stressors acting on a city is mediated by enhancers (which cause an increase in the intensity and/or duration of a stressor) and suppressors (which reduces the intensity and/or duration of a stressor).

Lu and Stead [31] examined the awareness and understanding of urban resilience on the case study of Rotterdam's urban planning system. In the paper particular attention was paid to the issue of climate change and water risk managing. Resilience was considered as an adaptive cycle which is focused on the dynamics of systems that are neither stable nor in equilibrium, but repeatedly pass through four characteristic phases: growth and exploitation, conservation, collapse or release, and renewal and reorganization. The proposed analytical framework includes the evaluation of six characteristics of resilient spatial planning.

Harrison and Williams [2] considered the observed recent increase in the frequency of natural disasters and suggested a system approach to the mitigation and adaptation of these risks and to recovery from such events. They described an urban system as being neither a purely social system nor a purely infrastructure system, but rather as a myriad of interactions among the inhabitants, between the inhabitants and the natural and built environments, and between the natural and the built environments. The differences between resilience and sustainability were demonstrated since both notions often interact, and can sometimes be in conflict.

In practice, however, there have been relatively few attempts to incorporate resilience research concepts into actual urban development strategies. Prominent among these was the Rockefeller Foundation's initiative "100 Resilient Cities", which has helped cities worldwide to build better and build back in order to improve the lives and well-being of an urban population [6]. As a result of the support provided by the Rockefeller Foundation to the ARUP International Development research team, a City Resilience Index (CRI) was developed. It enables the measuring and monitoring of the multiple factors that contribute to urban resilience. Its primary purpose is to diagnose strengths, weaknesses, and priorities for action, and to measure relative performance over time. This provides a holistic articulation of city resilience, structured around 4 dimensions, 12 goals and 52 indicators, that are critical for the resilience of cities (Fig. 1). It is envisaged that the CRI will primarily be used by city authorities who are in the best position to gather administrative data, but it can also be used by other interested organizations and individuals. Similarly, within the context of the campaign "Making cities resilient" the UNISDR has adopted a practical standpoint, that the way to building resilient cities is through the actions of mayors and local governments [33]. In order to accelerate implementation of the Sendai Framework for Disaster Risk Reduction (2015–2030) at the local level, the campaign devised a list of "Ten Essentials for Making Cities Resilient". These essentials are the critical and independent steps that need to be undertaken to build and maintain resilience. This steps emphasised the need for the participation and collaboration of local government decisionmakers, various officials and departments, academia, business and citizens in all disaster risk phases (prevention, mitigation, preparedness, response, recovery and rehabilitation).

To sum up the reviewed literature (Table 1), most of the abovementioned papers are focused on urban system resilience, whereas only a few are focused on social resilience. An urban system can be described in several different ways, depending on the importance of individual networks and their components. All studies make a primary distinction between physical and social components, but they also include some subdivisions [2,9,23]. The authors of this paper propose an extension of the existing divisions of urban systems to include four basic components, which in their opinion significantly affect the resilience of urban systems in the case of natural disasters: buildings, open space, infrastructure, and community [35,36]. The whole relevant urban content could be captured by the proposed four components and their subcomponents (Fig. 2). However, it should be noted that the proposed division could be extended by means of one or more additional components or united into two basic components – physical (buildings, open space, infrastructure) and social (the community) – depending on the aim and priorities of the urban system analysis.

3. Resilience assessment

A holistic assessment of urban system resilience should be able to obtain answers to questions about system preparedness, the ability to absorb disturbances, the ability to efficiently respond, and the ability to adapt to new conditions. For this purpose, in the first phase of the presented study a comprehensive literature review was performed. There are several studies considering different approaches to resilience assessment, which are presented in the following sections. In Section 3.1 the studies that apply the qualitative resilience assessment approach are summarized, whereas in Section 3.2 different attempts of quantitative resilience assessment are presented and classified according to the observed system components. It should again be noted that for further research purposes the selection of the analysed papers was based on the seismic resilience preference.

3.1. Qualitative resilience assessment

The qualitative approach to resilience assessment is preferred by urban designers and spatial planners. The spatial characteristics are assessed by conceptual frameworks, which are based on experts' assessments of different qualitative aspects of resilience that offer best practices. Rich descriptions and discussions of observed urban systems enable different (subjective) interpretations and solutions for the enhancement of their resilience.

Lu and Stead [31] proposed a qualitative assessment framework of planning and managing resilience. After an extensive introduction of resilience theory (reviewed in Section 2) the proposed framework of six resilience attributes (Table 1) in relation to planning for climate disturbance and flood risk was implemented on the case study of the city of Rotterdam. *Based on policy reviews and interviews with planning officials, the framework assessed the use and significance of the notion of resilience in a wide variety of planning documents from the local, regional and national levels.* The empirical study of Rotterdam illustrates that the assessment framework is applicable for examining planning strategy and decision making.

A recent attempt towards the better measuring of resilience – particularly for localised infrastructure at the community level – was presented in a study by Woolf et al. [26]. They developed a qualitative framework for assessing resilience considering numerous characteristics of a safe and resilient community, divided into four main categories: *external resources, assets, capacities* and *qualities.* For each category a set of indicators was evaluated, and their average scores graphically presented (by means of radar graphs): (i) the external resources were described by 3 indicators (connections and information, services, natural resources); (ii) the assets were assessed by 5 indicators (physical, economic, environmental, human, and social assets); (iii) the capacities were considered in terms of 3 characteristics (resourcefulness, adaptivity and flexibility, learning); whereas (iv) to describe these qualities 5 indicators were observed (strong/robust, well-located, diverse, redundant, equitable). The authors consider that the proposed prototype framework would enable community-based agencies and local stakeholders to assess the resilience of projects through a rapid appraisal process, with no need for extensive household interviews. Since the assessment relies on user perception and judgement, its objectivity might be questionable. In order to minimize the framework's dependence on user subjectivisms, the authors suggest another (additional) independent revision following the first phase of such an assessment. They conclude that the full potential of the proposed tool would be realised by utilising it for project planning as a way to *promote thinking about the interconnected and multi-dimensional nature of resilience, and to move project thinking away from a techno-centric approach to one of holistic social, economic and environmental inclusivity.*

The disciplines of recovery planning and urban design have a common interest in providing for the health and safety of urban communities. However, they appear to be often contradictory. Many

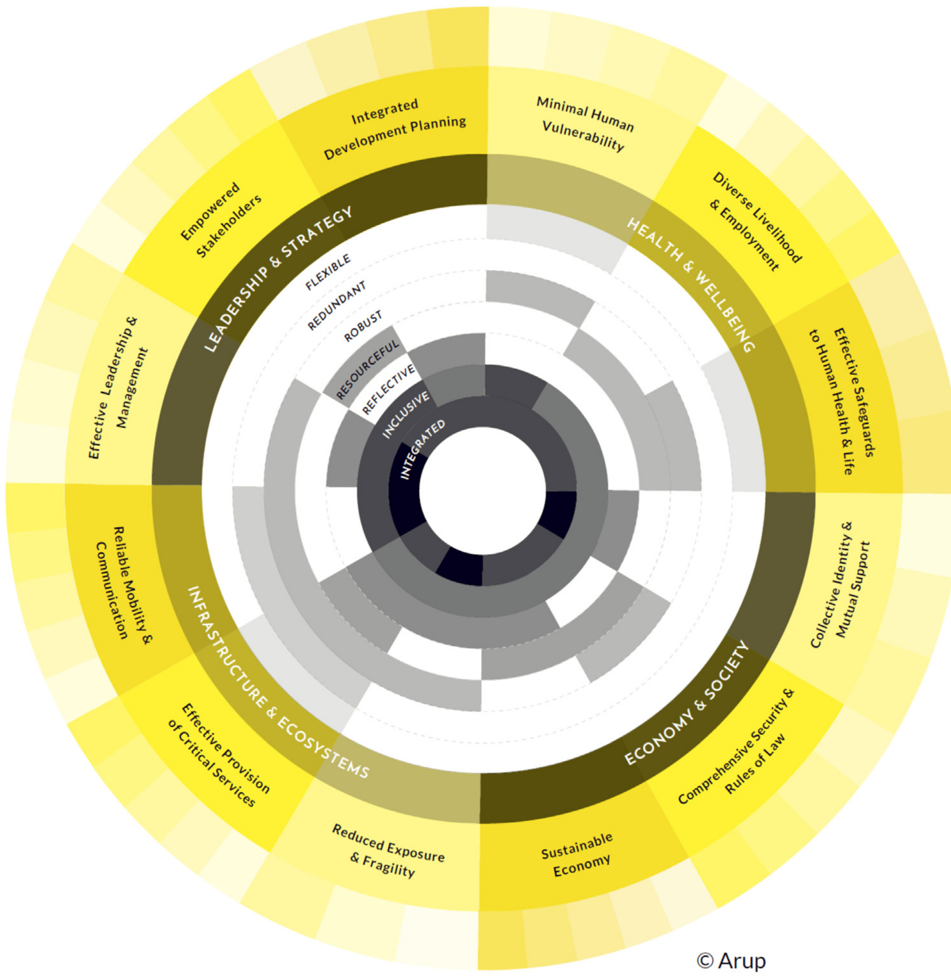

Fig. 1. Structure of the City Resilience Index developed by Arup with support from the Rockefeller Foundation [6].

earthquake planning recommendations, including the provision of large quantities of unstructured open space, can result in dispersed rather than compact urban forms, making it difficult to achieve liveable, diverse and sustainable urban environments. Allan and Bryant [37] proposed resilience as a framework for the successful integration of recovery planning and urban design. Two case studies were analysed: San Francisco (California) after the 1906 earthquake, and Conception (Chile) after the 2010 Maule earthquake. The assessment framework consists of the resilience attributes which appeared in urban design theory: diversity, modularity, innovation, tight feedbacks, overlap in governance, ecosystem services, social capital and variability. Through a qualitative evaluation of both case studies a link between a city's urban structure and its capacity to recover after an earthquake was recognized. *The idea that an urban environment - not just the buildings but the spaces between buildings - could be designed to influence recovery was presented. The disaster was recognized as an opportunity to build back better.* In their later study [38] Allan et al. continued with the idea of the influence of urban morphology on the resilience of cities following an earthquake. The paper explores these ideas by examining the relationship between the community's adaptive behaviour and the spaces of the city of Concepcion after the 2010 earthquake. Qualitative assessment of the spatial characteristics of the studied city was used. In the first step, the urban structure of Concepcion's greater metropolitan region was mapped. Its urban structure and support for recovery after the earthquake was then examined. Finally, these data were evaluated using *four qualitative resilience attributes: modularity, diversity, ecosystem services, and variability.* Analysis of the activities of individuals and communities after the earthquake occurrence revealed some important relationships between urban structure, recovery, and resilience. *The authors concluded that spatial and functional diversity has a positive effect on urban resilience, especially in the phase of recovery. The balance between modularity (the autonomy of individual city areas) and connectivity was recognized as significant for system functionality. Finally, it was shown that redundancy and efficiency are reflected in redundant space (urban voids), and that the variety of available ecosystem services is crucial for successful recovery of the system.*

In the paper by Brand and Nicholson [39] post-earthquake urban space projects in Christchurch, New Zealand, were investigated in order to evaluate the recovery of the city after the 2010 and 2011 earthquakes. Through qualitative evaluation the potential contribution that the urban structure and public space can make to resilience planning was discussed. Five core characteristics of a resilient urban system were defined: (1) spare capacity, (2) flexibility, (3) limited or safe failure, (4) rapid rebound, and (5) constant learning. *The importance of open public spaces and public buildings was recognized as the locus of the civil defence emergency response, with centres swiftly established in parks and sports or community buildings. The city grid street pattern enables a flexible network of alternative routes and appears as a flexible and redundant system.* In the aftermaths of the two disasters two different recovery strategies were observed: the first one, a council-led planning process, and the second one, a community-led bottom-up process. Both strategies provided for an enhanced network of green open space and mixed-use development. A sustainable transportation system and a reduction in the height of buildings were planned by the city council. Several community initiatives implemented different actions at open public places in order to increase the quality of city life. Public space in Christchurch is set to

Table 1
Comparison of the main definitions and characteristics in the theory of urban system resilience.

Ref.	System components	Urban system definition	Resilience definition	Resilience attributes
[19]	Physical and social	Cities are complex and dynamic metasystems in which technological components and social components interact.	A resilient city is a sustainable network of physical systems and human communities, capable of managing extreme events; during disaster; both must be able to survive and function under extreme stress.	Redundancy, diversity, efficiency, autonomy, strength, interdependency, adaptability and collaboration
[9]	Built, natural, social and economic	Not defined	A process linking a set of adaptive capacities to a positive trajectory of functioning and adaptation after a disturbance.	Robustness, redundancy and rapidity
[23]	Physical (resources, processes) and social (people, institutions, activities)	Cities are complex adaptive systems which are in constant disequilibrium.	Resilience in terms of cities generally refers to the ability to absorb, adapt and respond to changes in an urban system.	Not defined
[31]	Not defined	Not defined	Resilience is the ability of a city to absorb disturbance while maintaining its functions and structures.	Attention to the current situation, attention to trends and future threats, ability to learn from previous experience, ability to set goals, ability to initiate actions, and ability to involve the public
[2]	Natural, human and mechanical	Urban systems consist of a myriad of interactions among the inhabitants, between the inhabitants and the natural and built environments, and between the natural and the built environments.	The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (UNISDR).	Not defined
[6]	Health and well-being, the economy and society, infrastructure and the environment, leadership and strategy	Cities consist of individuals, communities, institutions, businesses and systems.	City resilience describes the capacity of cities to function, so that the people living and working in them – particularly the poor and vulnerable – survive and thrive no matter what stresses or shocks they encounter.	Reflectiveness, resourcefulness, robustness, redundancy, flexibility, inclusiveness, integration

become larger, greener, more creatively expressive, flexible and transformative, with a blurring of public private boundaries.

The role of open spaces in relation to earthquake resilience and risk perception has been recently discussed also by Shrestha et al. [40]. In this study the authors tried to discover whether an individual's perception of seismic risk is correlated with the availability of open spaces, their attributes and surroundings. In the described case study the actual response of people during and after the 2015 Nepal earthquake in two selected communities within the city of Kathmandu was analysed. *The qualitative (land use, services available, ownership), as well as the quantitative (i.e. number, size, surrounding built density) attributes of open spaces* were assessed. To identify the possible relationships between open spaces and seismic risk perception, a Risk Perception Index (RPI) was developed and calculated for each household. It combines aspects of the psychometric and the cultural theories of risk perception. The results of the study indicate that *the attributes of open spaces are significant for developing risk-sensitive land use plans that facilitate adaptive responses and cater to the needs and perceptions of people.*

3.2. Quantitative resilience assessment

The need for a generic quantitative approach for resilience assessment was recognized by several authors [34,41,42]. They offered a fundamental concept of resilience represented by a performance curve showing the variation of the functionality of the system over time (Fig. 3). Resilience was graphically defined as the area under the performance curve (Eq. (1)):

$$R = \int_{t_0}^{t_0+T_{RE}} [100 - Q(t)]dt, \tag{1}$$

where $Q(t)$ is the functionality of the system (within the range between 0% and 100%).

It should be mentioned that in the terminology there is often confusion between the concept of resilience and other related concepts such as vulnerability, sustainability, durability and risk [42]. All of these concepts are interdependent with the resilience dimension, but there are some important differences in the applied approaches. For instance, when running on a limited budget, a resilience analysis is used to prioritize the recovery strategies, whereas risk analysis is used to prioritize the mitigation strategies (Fig. 3).

Bruneau et al. [34] proposed a conceptual framework of quantitative measures for the seismic resilience assessment of communities, where a community was meant to be not just a social network but a whole urban system consisting of different urban physical and social components. The proposed framework relies on the complementary performance measures of resilience: "reduced failure probabilities", "reduced consequences from failures", and "reduced time to recovery". Four dimensions of resilience (*TOSE:* Technical, Organizational, Social, and Economic) and four resilience properties (the "four *Rs*") were identified:

- *Robustness*, which indicates the ability of a system to withstand a given level of stress maintaining its functionality (Fig. 3);
- *Redundancy*, which refers to alternative resources in the recovery process when the principal ones are insufficient;
- *Resourcefulness*, which accounts for the human factor and, in particular, the capability to forecast dangerous events without over-relying on technological devices;
- *Rapidity*, which is the capacity to contain losses and avoid future disruption. It represents the slope of the performance curve during the recovery time (Fig. 3).

Bruneau et al. [34] defined the main critical facilities for system resilience as follows: water and power lifelines, hospitals, and organizations with responsibilities for emergency management. However, it should be noted that decisions about which facilities are of key

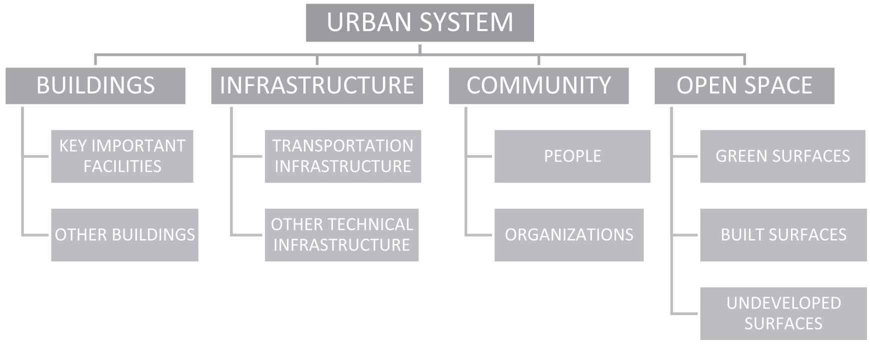

Fig. 2. Division of an urban system as proposed by the authors.

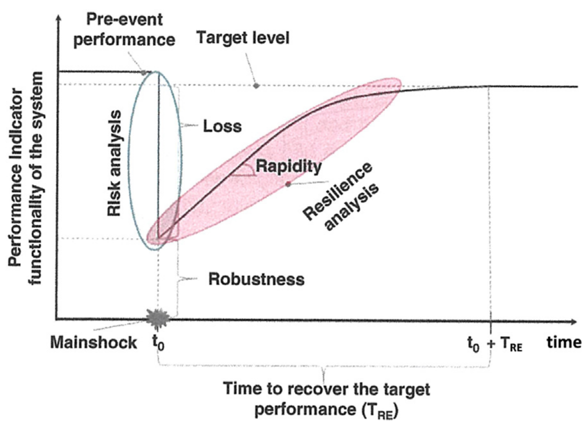

Fig. 3. Graphical illustration of resilience presented by means of a performance curve (source: Cimellaro [42]).

importance depend on the urban risk management priorities, and the main activities (functions) of the city, as well as on its structure and complexity.

Henry and Ramirez-Marquez [41] upgraded the conceptual framework by proposing the use of generic metrics for the quantification of system resilience as a time dependent function based on Bruneau's definition [34]. This means that system resilience could be considered as an attribute of a system's delivery function. Three distinct states of the system's lifetime cycle were recognized: the original state (S_0), the disrupted state (S_d), and the recovered state (S_f). There are two transitions: system disruption (from S_0 to S_d), and system recovery (from S_d to S_f), and two events that trigger and enable these two transitions: a disruptive event and a resilience action. The key parameters which are needed to analyse system resilience were described as follows: disruptive events, component restoration, and overall resilience strategy. In order to quantify the system resilience a time-dependent system delivery function or figure-of-merit should be defined. In reality, it is common for multiple figures-of-merit to be studied for a single system under consideration. Thus, for a holistic analysis of system resilience, the system must be analysed with respect to all figures-of-merit that are recognized as relevant and important. The proposed quantitative approach was illustrated on the simple network example of the Seervada Park Problem. Multiple figure-of-merits were proposed (shortest path, maximum flow, and overall health of the road network) because some disruptive events may not affect all of them. The recovery action was predicted and the optimal restoration strategy was analysed. For future research work an extension to the probabilistic scenario taking into account component restoration times as stochastic was proposed.

In the following subsections different quantitative approaches depending on the subject of interest are discussed. The focus is on the four main urban components defined in chapter 2: buildings, infrastructure, open space, and the community. The final review is related to research into urban systems as a whole.

3.2.1. *Resilience assessment of building stock*

Many papers have been published in connection with the assessment of the seismic fragility of selected building typologies [43–51]. However, we were focused on the resilience assessment of a whole building network as a complex building portfolio, consisting of various building types [52–56].

The conceptual framework which was proposed by Bruneau et al. [34] for quantitative resilience assessment formed the basis for the study by Cimellaro et al. [57], which addresses the analytical quantification of resilience related to earthquakes. The graphical definition of resilience as the area underneath the performance function of the system, together with the four characteristics of resilient systems (rapidity, robustness, redundancy, and resourcefulness), was adapted from Bruneau et al. [34]. The framework is upgraded by means of time-dependent dimensionless measures of rapidity and robustness, as well as formulae which include the losses in the disaster and the recovery path. The loss function is defined including direct and indirect losses as well as economic and casualty losses. Losses are assessed by applying the fragility function which indicates the structural response to earthquakes in a probabilistic way. The recovery process usually depends on available technical and human resources, societal preparedness, and public policies, and may take different forms, which can be estimated by using simplified recovery functions (linear, exponential, or trigonometric) or else more complex organizational and socio-political models. This framework was implemented on two case studies: (1) a loss estimation study of a specific hospital, and (2) a regional loss estimation study of a hospital network.

An important contribution to the seismic risk assessment of European cities was made by the RISK-UE project, which was entitled: "An advanced approach to earthquake risk scenarios with applications to different European towns" [58,59]. The project offers a framework for the seismic vulnerability assessment of direct and indirect damage. Modular methodology for the creation of earthquake scenarios enables the identification of weak points within an urban system. The approach focuses, however, on physical urban components (buildings and infrastructure) taking into account the distinctive features of European cities. The proposed methodology consists of seven work packages: (1) European distinctive features are analysed in order to create a matrix of 23 different building types, (2) Assessment of seismic hazard with both a probabilistic and a deterministic approach on the local and the regional level, (3) Analysis of urban systems in order to highlight critical buildings, services and their interactions, creating maps with GIS tools, (4) Vulnerability assessment of buildings using fragility curves, (5) Vulnerability assessment of old town centres, historical monuments and buildings, (6) Vulnerability assessment of lifeline facilities and essential structures, (7) Implementation of seismic risk scenarios by assessing direct damage, the likely number of victims, economic impact, the likely number of homeless, and recovery time. However, the project did not fully address the notion of resilience. It is orientated towards structural vulnerability and damage assessment, but does not consider a time-dependent recovery process.

In the study by Lestuzzi et al. [60] the RISK-UE methodology was used for seismic vulnerability assessment at an urban scale for two typical Swiss cities: Sion and Martigny. A field survey of buildings was conducted in order to define their main structural characteristics, generally divided into unreinforced masonry and reinforced concrete buildings. Evaluation of the physical vulnerability of buildings took into account typical Swiss building features, which differ from the Mediterranean features studied in the RISK-UE research. Different types of structures were classified in a building typology matrix. Two different methods were used for vulnerability evaluation. They were: the empirical method LM1, and the mechanical method LM2. The empirical method LM1 is used where no specific site seismic hazard studies or detailed seismic intensity information are available. The vulnerability of a building belonging to a given typology is defined by a vulnerability index (V). The second, mechanical method LM2 is suitable for studying existing buildings or built sites in areas where local seismicity data are available (preferred in the form of response spectra in ADRS format). For each building type, a capacity curve is required. Comparing the results obtained by using both methods, the mechanical method LM2 provided results that were globally one degree of damage level higher than those obtained when using the LM1 method. Furthermore, the damage distributions due to historical earthquakes in the examined region were fitted better in with the results of the LM1 method. However, both methods lead to the same identification of the most vulnerable parts of the two investigated cities. From this it can be concluded that both methods are able to identify the most vulnerable parts of a city, and the most vulnerable city among a group of investigated cities, but such quantitative results should be treated with care.

In order to mitigate the consequences of severe seismic motions on physical structures (buildings as well as the technical infrastructure) different programs supported by national and governmental organizations have been established: Hazus [61,62], CAPRA [63], Syner-G [52,53,64], and RISK-UE [58,59] etc. The programs offer software for probabilistic seismic fragility analyses, except for RISK-UE. Whereas Hazus and CAPRA are designed for use in North and Central America, Syner-G and RISK-UE are European research programs. Nevertheless, all programs aim to be applicable to any country, with some adjustments. Syner-G and RISK-UE are focused just on seismic vulnerability assessment. On the other hand, the scope of Hazus and CAPRA extends to multiple hazards including earthquakes, hurricanes, cyclones, floods, tsunamis, landslides and volcanic hazards. All the programs are based on fragility functions and use GIS tools in order to obtain data and map the results.

3.2.2. Resilience assessment of the infrastructure

The infrastructure supports and connects together urban components. It consists of a transportation infrastructure and other technical infrastructure (water supply, sewage system, electricity network and telecommunications). In this sub-subsection the focus is on the transportation infrastructure. The street patterns represent the basis for other technical infrastructure, which is normally located along streets [65]. Papers addressing infrastructure resilience usually use a network approach. The importance of interconnections and connectivity of the whole are considered to be more important than the resilience of a single element.

Kermanshah and Derrible [66] proposed a geographical and multi-criteria vulnerability assessment method to quantify the impacts of extreme earthquakes on road networks. Vulnerability was measured as a percentage drop in four families of metrics: overall properties (length of the remaining system), topological indicators (betweenness centrality), accessibility, and travel demand using Longitudinal Employment Household Dynamics (LEHD) data. The various metrics were plotted on a Vulnerability Surface (VS), from which the area could be assimilated into an overall vulnerability indicator. The proposed method couples together the GIS approach and network science (graph theory). A complex transportation system is presented as a topological network. After that, freely available transportation GIS data and USGS (United State Geological Survey) ShakeMaps are used to define damaged road sections which are then removed. The method was applied to two US cities, Los Angeles and San Francisco. The latter was recognized as less vulnerable to a strong earthquake. Finally, it should be noted that the research addressed system "robustness" and not "resilience" as a time dependent function.

Chang [67] attempted to assess the performance of urban transportation systems in the different time phases which follow a disaster. A performance measure was proposed considering the concept of accessibility and using a probabilistic approach. The assessment method is based on social criteria considering travel demand patterns. The transportation system was presented as a network by using GIS technology. The proposed method was applied to two case studies. In the first case study the proposed accessibility performance measure was used to assess the performance of a railway system in Kobe after the 1995 earthquake. Different restoration strategies were analysed. In the second case study the methodology approach was improved by measuring the potential loss of roads in Seattle. Accessibility loss in terms of changes to modelled travel times rather than in terms of approximated travel distances was considered. Travel times and accessibility loss were evaluated for three post-disaster damage conditions: the immediate post-earthquake situation and two partial restoration states.

Zhang and Wang [18] introduced a novel metric based on system reliability and network connectivity to measure the resilience-based performance of a road transportation network. The performance metric, referred to as WIPW, systematically integrates the network topology, redundancy level, traffic patterns, structural reliability of a network's components (i.e. roads and bridges), and the functionality of the network during the community's post-disaster recovery. The WIPW metric is the weighted average number of reliable IPWs (independent pathways) between all O–D pairs in the road network. It is based on graph theory using Dijkstra's algorithm to search for the shortest independent paths. In order to quantify the WIPW it is important to properly assign link (i.e. road segments with or without a bridge) reliabilities. The reliability of an individual bridge or road segment can be probabilistically evaluated using fragility analyses. A project ranking mechanism for identifying and prioritizing retrofit projects as well as a decision methodology which could be used to select optimal solutions among possible alternatives was introduced. The use of the proposed WIPW metric was illustrated on a hypothetical road network exposed to a severe earthquake.

Soltani-Sobh et al. [68] focused on the reliability of the transportation infrastructure and on the pre-positioning of recovery centres for the efficient repair of bridges in the case of a disaster. The objective was to cluster the bridges and locate a recovery centre for each cluster by considering operational costs and system reliability. Backup recovery centres were determined in the case of a disrupted primary centre. The transportation system was presented as a graph, where the nodes are the road cross-sections and all possible positions of recovery centres, whereas the links refer to road segments and bridges. The reliability of the transportation system is based on the most reliable path instead of the shortest path. The methodology was applied to the Sioux Falls (USA) real transportation network. The results demonstrated a trade-off between operational costs and reliability, and discuss the possibilities of substantial improvements in reliability with minimal increases in operational costs.

The concept of ‘emergency resilience’ and a framework for assessing this kind of resilience in the emergency recovery stage of urban lifeline systems (i.e. the critical infrastructure) was recently presented in the research of Zhao et al. [69]. In this work emergency resilience is defined as the short-term resilience of a lifeline system currently constrained by local budgets (e.g. funds, repair materials, and other consumables) and resources (e.g. human resources, equipment repair resources, and other non-expendable items) which would be available in the few days or weeks following a disaster. Beside the features which are commonly used to describe resilience (occurrence probability, disaster consequences, and recovery time) a new feature is introduced: that of the 'recovery degree', which can be used to specify the final performance level that a system can achieve after recovery. In the paper the newly developed 'recovery degree' feature is integrated with a performance response function (PRF) [34], based on network equilibrium theory. The procedure includes four steps: (1) probability assessment of the extent of damage to each unit in the lifeline system (seismic fragility curves), (2) assessment of the extent of damage to the entire system, (3) simulation of the recovery process and determination of PRF curves, recovery time, and recovery degree, and (4) comprehensive assessment of system emergency resilience using time-dependent PRF curves. Finally, the variation of the emergency resilience with changes to the recovery budget and recovery resources is discussed by means of trade-off curves.

Network topology is an abstract representation of a transportation system as a network of nodes and interconnecting links. Zhang et al. [17] investigated its role in transportation network resilience. Their study refers to a definition of resilience that takes into account not only the network's inherent coping capacity, but also its ability to efficiently adapt after the event. Based on graph theory, three resilience measures for assessing the throughput, connectivity, and compactness of transportation networks are proposed: average degree, diameter, and cyclicity. Resilience is considered in terms of preparedness and recovery actions. The results indicate that resilience level is relatively strongly correlated with the average degree and less significantly with cyclicity. Diameter is negatively, although weakly, correlated with resilience. The authors found that complete networks showed the highest values of resilience, whereas ring networks showed the lowest. In order to enhance network resilience, they recommended that network structures should be transformed by the careful addition of redundant links, central connections, secondary or tertiary hubs, and similar.

3.2.3. Resilience assessment of the community

The social vulnerability index, SoVI, proposed by Cutter et al. [70], was used as a basis for several studies of community resilience [12,15,16,71]. This index of social vulnerability to environmental hazard was based on socioeconomic and demographic data that applied to the USA. It was defined as the summary score of 42 different variables united in independent dimensions of social vulnerability (personal wealth, age, density of a built environment, single-sector economic dependence, housing stock and tenancy, race, ethnicity, occupancy, and infrastructure dependence). Some of these dimensions can increase vulnerability, whereas others can moderate it.

A widely accepted holistic framework for measuring the resilience of communities to extreme events or disasters is the PEOPLES Resilience Framework [42,72]. The acronym PEOPLES stands for the seven dimensions of community resilience: (1) Population and demographics, (2) Environmental/Ecosystem services, (3) Organized governmental services, (4) Physical infrastructure, (5) Lifestyle and community competence, (6) Economic development, and (7) Social-cultural capital. Each dimension is characterized by a corresponding performance metric that is combined with the other dimensions using a multi-layered approach. When assessing the Population and Demographics dimension, the SoVI index is adopted as a measure of performance metric. The suggested framework (Fig. 4) can be used for resilience-based design at different spatial levels (local, regional, etc.) and at different temporal scales (emergency response, reconstruction phase, etc.).

A framework which could be used to assess community resilience to natural disasters in Indonesia was proposed by Kusumastuti et al. [16]. A resilience index (*RI*) was defined as the ratio between preparedness (*PI*) and vulnerability (*VI*) of the area under consideration (Eq. (2)):

$$RI = \frac{PI}{VI} \tag{2}$$

In order to determine the dimensions of preparedness and vulnerability, in-depth interviews and focus group discussions were conducted. Preparedness was calculated as a composite indicator of five different dimensions: social, economic, community capacity, institutional and infrastructure. Similar dimensions were applied to vulnerability, with the additional dimension of hazard. The goal for the community is to maximize the preparedness potential and minimize its vulnerability. The preparedness and vulnerability scores are determined using pairwise comparisons by means of the AHP method [73]. The preparedness score (*PI*) is calculated as the sum of the weighted score of all the dimensions' scores, whereas the dimension score is calculated as the sum of all the weighted sub-dimensions' scores. Lastly, the sub-dimension score is calculated as the average score of its indicators. Data about the indicators are obtained by means of secondary data or questionnaires. All the indicators are scored between zero and one, using different statistical techniques.

A humanitarian risk index, named *InfoRM*, or *In*dex *f*or *R*isk *M*anagement, was introduced as the result of a project organized by the Joint Research Centre of the European Commission (JRC) [15]. The goal of the project was to identify countries which have a high risk of the occurrence of a humanitarian crisis and are more likely to require international assistance. Three dimensions of risk are identified in this index: hazards and exposure, vulnerability, and lack of coping capacity. Each dimension includes different categories that are combined into a single framework (Eq. (3)):

$$\begin{aligned} \text{Risk} = {} & (\text{Hazard \& Exposure})^{1/3} \times (\text{Vulnerability})^{1/3} \\ & \times (\text{Lack of coping capacity})^{1/3} \end{aligned} \tag{3}$$

Different aggregation methods (making use of arithmetical and geometric averages) and statistical analyses (normalization, rescaling, and other procedures) were proposed in order to obtain a composite index scoring from 0 to 10 for risk and all its components. Such risk needs to be regularly monitored, so that yearly reports are provided [74].

Frigerio et al. [71] proposed a GIS-based approach for the evaluation of social vulnerability to seismic hazard in Italy. In the first step, socioeconomic indicators based on Cutter et al. [70] and adapted to Italian conditions were used to calculate a social vulnerability index. The weighted scores of each factor were combined into a single measure using different aggregation and statistical methods. In the next step, the obtained values of the social vulnerability index were mapped using GIS tools. Finally, the social vulnerability map was combined with the seismic hazards map using a risk matrix in order to obtain an exposure map, which presents the social vulnerability exposure to earthquake hazard (Eq. (4)):

$$Risk = (Hazard)x(Vulnerability) \tag{4}$$

Although the approach used by Frigerio et al. [71] is a relatively simple, and provides interesting and straightforward results (maps), its main shortcoming seems to be the overall accuracy of the vulnerability assessment. The proposed risk exposure matrices are quite rough (only four classes of social vulnerability combined with four levels of seismicity – Fig. 5), and the physical vulnerability of the built environment is completely ignored. Thus, the proposed exposure maps do not provide any information about overall vulnerability, which is strongly related to the overall resilience of the investigated area.

3.2.4. Resilience assessment of open space

A number of researchers have attempted to quantify open space, but only a few have addressed the concept of resilience. Most of these studies were focused on the evaluation of green open spaces [75–78]. FRAGSTATS, which is software for the quantification of landscape structure, was developed by McGarigal and Marks [76] as a product of

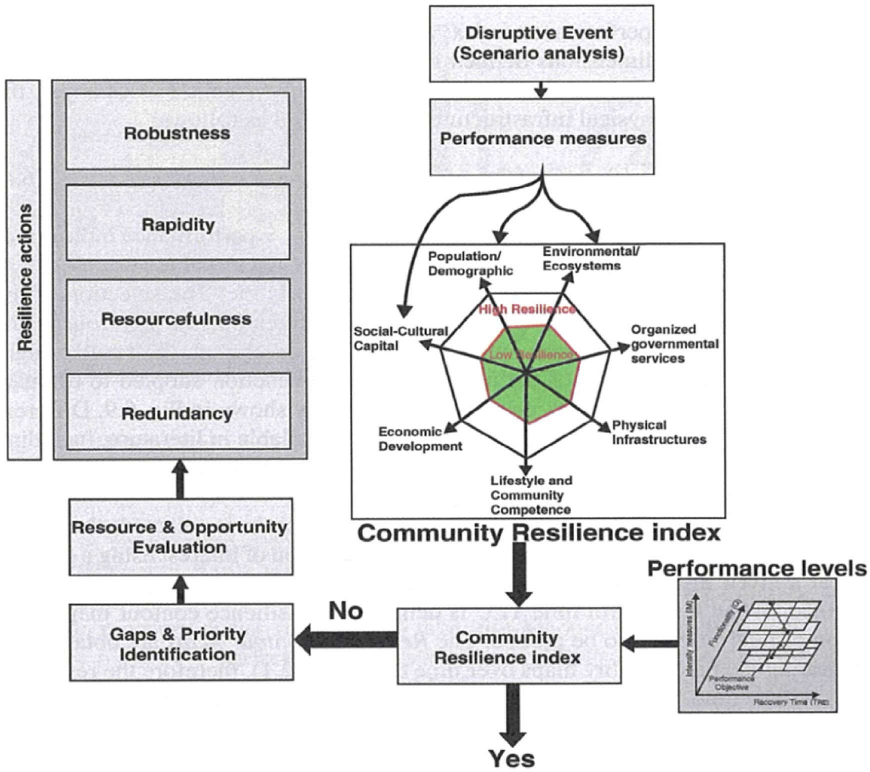

Fig. 4. The PEOPLES resilience framework: a methodology for resilience-based design (source: Cimellaro [42]).

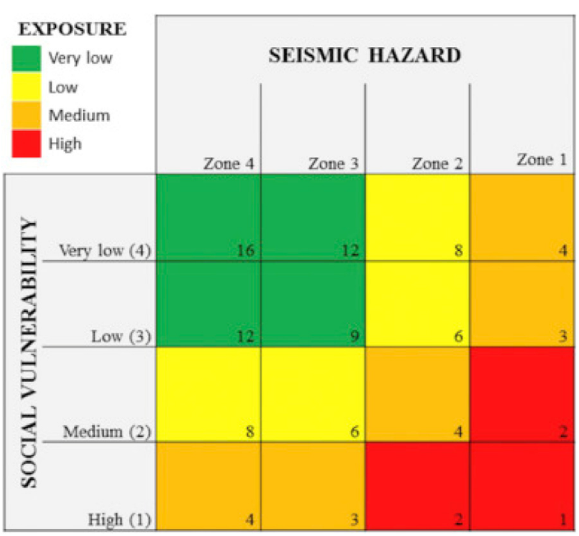

Fig. 5. The risk matrix used by Frigerio et al. [71].

the Coastal Oregon Productivity Enhancement Program. Several metrics and algorithms for spatial pattern analyses are divided into patch, class and landscape indices. The program was used in later research work [75,77,78].

Urban green spaces have an important influence on the well-being of the population, which is highly correlated with community resilience and sustainability [37–39,79]. These spaces contribute to quality of life by providing ecosystem services. In order to evaluate and better plan the location and quality of green spaces in urban areas, a set of different indicators at city and local level was proposed [75]. These indicators take into account the following parameters: (i) the total area of green spaces in relation to the population and urban context, (ii) the quality of green spaces based on their size, shape and vegetation cover, and (iii) the spatial distribution and accessibility of green spaces. Only public green spaces with free access were evaluated, whereas private parks and gardens with restricted access were neglected. The assessment framework was applied to three municipalities, belonging to the Metropolitan Area of Santiago (Chile), with different household incomes. A correlation was observed between the spatial distribution of green spaces and the income level of the area.

Xu et al. [78] studied how the spatial pattern of urban green spaces influences the realization of their ecosystem service value. Their specific spatial characteristics, which included richness, accessibility, distribution, and shape configuration, were examined. The Hedonic Price Model (HPM) was used to evaluate the "green space premium" of real estate prices, and the spatial characteristics of urban green spaces were evaluated by Landscape Ecological Metrics (LEM). A positive correlation was found between the quality and accessibility of green spaces and real estate value. The proposed method was tested on a case study of the city of Beijing. The GIS database was used as a source of information about the location and shape of all major urban green spaces in the city, as well as other geographical features such as administrative boundaries, streets, roads, and public transportation. According to the currently valid land use classification system, only first-order land use urban green spaces were identified.

Multifunctional green infrastructure enhances urban resilience and ecosystem services [77,79]. Green infrastructure is defined as an interconnected network of green space that conserves natural ecosystem values and functions, and provides associated benefits to human populations. It fosters urban resilience by increasing diversity, flexibility, redundancy, modularization, and decentralization. In order to identify ecosystem service trade-offs, synergies and hotspots, Meerow and Newell [77] introduced a Green Infrastructure Spatial Planning (GISP) model as a support tool for decision-making. GISP is a GIS-based multi-criteria approach that integrates six benefits of green infrastructure: (1) storm water management, (2) social vulnerability, (3) green space, (4) air quality, (5) urban heat island amelioration, and (6) landscape connectivity. The model includes the weighting priorities of stakeholders by means of three methods: rating, ranking, and pair-wise comparison (the AHP method). The framework was applied to Detroit, where priority areas for these six criteria were individually mapped, and then combined, taking into account the planning priorities of local stakeholders.

3.2.5. Resilience assessment of an urban system as a whole

In contrast to previous subsections which consider the resilience of a single urban component, in this subsection references to the resilience assessment of urban systems as a whole are given. Duzgun et al. [80] focused on the seismic vulnerability of urban systems in a holistic and multidisciplinary manner. They divided overall vulnerability into two categories. The first category (type I vulnerability) deals with the seismic vulnerability of physical structures (e.g. buildings, infrastructure, and lifelines), whereas the second category (type II vulnerability) deals with socio-economic vulnerability and accessibility to critical services. The Type I and Type II weighted vulnerability indices are combined together into an overall urban vulnerability index (Eq. (5)):

$$V = w_1 v_s + w_2 v_{12} + w_3 v_{22};\ \sum_{i=1}^{3} w_i = 1, \tag{5}$$

where: v_s = the structural vulnerability index,
v_{12} = the socio−economical vulnerability index,
v_{22} = the vulnerability index for accessibility to critical services, and
w_i = the weight of a vulnerability component i ($i = 1,\ 2,\ 3$).

The methodology integrates a total of nine components: (1) Seismic hazard analysis, (2) Soil response analysis, (3) Tsunami inundation analysis, (4) Probabilistic structural vulnerability (fragility) analysis, (5) Socio-economic vulnerability analysis [70], (6) Vulnerability for accessibility to critical services (zone-based, isochronal-based, raster-based), (7) Overall vulnerability assessment, (8) GIS-based mapping of vulnerabilities for neighbourhoods, and (9) Visualization of vulnerabilities in a 3D virtual city model. The proposed framework was applied to Eskisehir, Turkey. Different vulnerability patterns in terms of the treated structural, socio-economic and accessibility aspects, were considered.

Carreño et al. [81] also proposed a framework for urban seismic risk assessment from the holistic perspective, but with a different methodology. The proposed method takes into account the expected physical damage (hard risk) as well as the contextual conditions (soft risk), such as socio-economic fragility and lack of resilience. The total risk is expressed by Moncho's equation (Eq. (6)):

$$R_T = R_F(1+F), \tag{6}$$

where R_T is the total risk index, R_F is the physical risk index and F is the aggravating coefficient. This coefficient is a composite indicator and depends on the weighted sum of a set of aggravating factors related to socio-economic fragility and a lack of resilience. The physical risk is calculated starting from a probabilistic risk scenario developed within the scope of the framework of the Risk-UE project [58,59]. This method is based on fuzzy set theory and uses experts' opinion where needed data are not available. The proposed methodology enables identification of critical zones, and has been applied to two case studies: Barcelona (Spain) and Bogota (Colombia).

Based on the previous discussed method [81] with some modifications, Salgado-Gálvez et al. [82] researched an urban seismic risk index (USRi) for Medellín, Colombia. They used the CAPRA software platform [63] in order to calculate the USRi index and to identify critical zones in the city (Fig. 6). The USRi index is a composite indicator based on Moncho's equation (Eq. (6)). The new indicators for calculating the aggravating factor are the calculation of public areas and of the distance to the closest hospitals and other health centres. As the USRi index is a composite indicator, after obtaining the final result it is possible to disaggregate it and to see the contribution of the different descriptors related to the physical risk and/or social fragility and lack of resilience [83]. From the results, the descriptors for social fragility and lack of resilience that most contribute to the aggravating coefficient F are the population density and the amount of public areas, respectively.

Cavallaro et al. [84] considered urban systems as a whole, based on complex network theory. They proposed a methodology for the assessment of urban resilience to catastrophic events, which combines engineering and ecosystem approaches to resilience. The framework is based on the representation of a city as a complex network [85]. The efficiency of a city as a whole depends on the topological properties of its street pattern. The structure of a city's street network is strongly connected to the availability of services and facilities, and thus also to the overall quality of life as perceived by the city's citizens. For this reason the concept of *Hybrid Social–Physical Networks* (HSPNs) was introduced. Such a network consists of a city which is modelled as a graph, consisting of street network links and nodes, which represent the city's citizens, buildings and facilities (Fig. 7). Three different types of weighted HSPNs are proposed, as follows: a residential HSPN, a goods HSPN, and a services HSPN. GIS software is used for data acquisition and for the modelling of the HSPNs.

The global efficiency of different networks can be measured by means of algorithms contained in graph theory. The global efficiency of a spatial network is defined as the average of the normalized pairwise efficiency over all possible pairs of nodes [86]. It is normalized over the interval [0,1] and can be used to compare the efficiency of different systems in a consistent way (Eq. (7)):

$$E = \frac{1}{N(N-1)} \sum\nolimits_{i,j \in N, i \neq j} \frac{d_{ij}^{eucl}}{d_{ij}} \tag{7}$$

where: E = the global efficiency,
N = the number of nodes,
d_{ij}^{eucl} = the Euclidean distance between node i and node j,
d_{ij} = the length of the shortest path between nodes i and j.

Several earthquake simulations were performed using the Monte Carlo technique. The damage probability for each building was estimated by applying fragility analyses. If a building is significantly damaged, then its failure could also make any street next to it inaccessible. The road interruption probability (P_r) is defined by Eq. (8):

$$P_r(h,\ l) = \begin{cases} 1 & if\ h \geq l \\ \frac{h}{l} & otherwise \end{cases}, \tag{8}$$

where h is the height of the building and l is the width of the road. The inaccessible street segment is removed from the street network, which affects the global efficiency of the system. The main idea presented in the article was to use the efficiency measures on HSPNs in order to quantify the resilience of an urban system, by comparing their corresponding values before and after a catastrophic event, and during the subsequent restoration. For the recovery assessment any explicit dependence of resilience on time was removed. A recovery function $Y(C) = E(C)/E_{pre}$ was defined as the ratio between the efficiency $E(C)$ of the urban system when C citizens have been relocated, and the efficiency E_{pre} before the disaster. Six different reconstruction strategies were analysed, as follows: (1) the status quo down-up, (2) the status quo up-down, (3) new sites down-up, (4) new sites up-down, (5) status quo inwards, and (6) status quo outwards. The down-up and inwards relocation strategies were recognized as being the most efficient. It should be stressed that the proposed methodology was tested only as a function of the number of reallocated citizens, without accounting for the availability of financial resources, restoration rates, or emergency management issues. In order to quantify the resilience of an urban system as the area under the recovery curve, the following measure was defined (Eq. (9)):

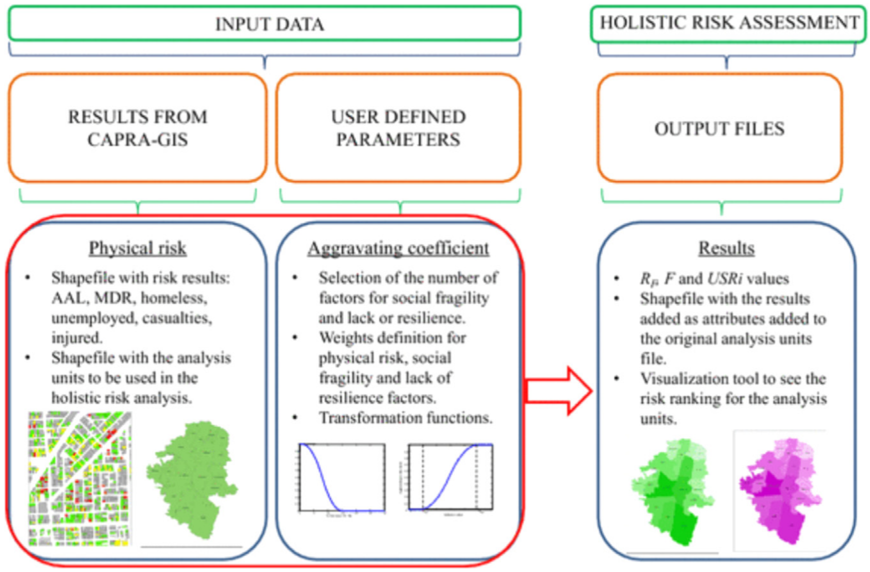

Fig. 6. CAPRA's holistic risk assessment module flowchart (source: Salgado-Gálvez et al. [82]).

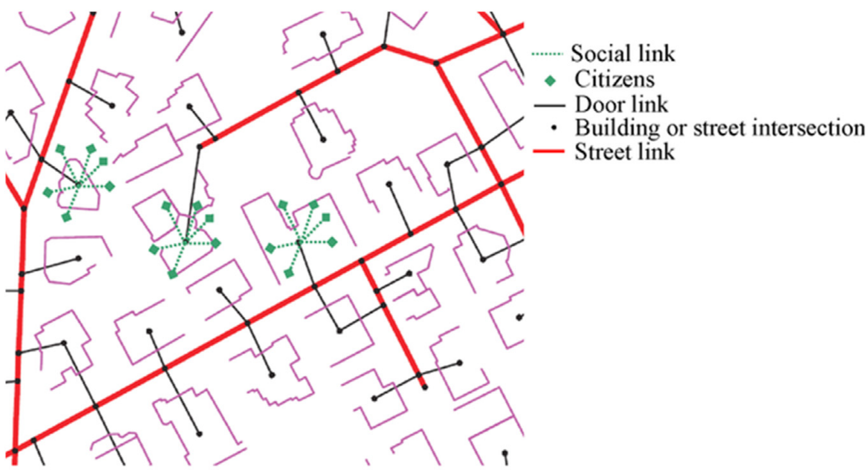

Fig. 7. HSPN model proposed by Cavallaro et al. [84].

$$R = \frac{\int_0^{C_{max}} y(C)dC}{C_{max}}, \tag{9}$$

where $C_{\max}$ is the total number of people to be relocated after a certain event.

Several recent studies [20,65,87,88] were based on Cavallaro's research [84]. In the study [87] Bozza et al. were focused on the social aspect of urban systems. Besides the efficiency measure, they evaluated quality of life indicators in order to measure inhabitant happiness and environmental sustainability. A correlation between resilience and sustainability was recognized as a quality of life and equilibrium condition between the natural and physical environment. Social sustainability measures were used as key indicators of system functionality, assuming that they represent the level of satisfaction of its citizens. An initial transformation function based on fuzzy logic was implemented in order to integrate different indicators into a unified measure.

Bozza et al. [65] continued their research with a study of different topological structures and geometric shapes of cities, focusing on the efficiency of the cities themselves, and their resilience. The methodology proposed by Cavallaro et al. [84] was adopted when evaluating four different hypothetical city shapes: circular, rectangular, hexagonal and star-shaped. The results showed some differences in resilience levels, with the star shape being in every case the most efficient, and the circular shape the worst. In a recent study by Bozza et al. [20] the just-mentioned methodology was applied to a real case study of the city of Sarno (Italy), as well as to 16 artificially modelled HSPNs with diverse shapes and sizes.

In their most recent paper Bozza et al. [88] proposed four alternative synthetic resilience indices based on the results of previous studies [20,65,84,87]. In order to compare different urban systems that are prone to the same hazards, the proposed index, R_1 (Eq. (9)), can be effectively used to compute resilience in the case in which no dependence on the state of damage is considered. On the other hand, R_2 is highly influenced by the damage level soon after the event occurrence. R_3 and R_4 are both damage-dependent measures. R_4 puts a particular focus on the urban damage from a human perspective. Whereas R_2 is defined over an open interval $[1, +\infty]$, R_1, R_3 and R_4 are defined over a restricted interval [0, 1]. Such an approach shows the advantage of having an upper boundary, which makes comparative analysis between diverse cities and diverse event typologies easier. Time-independent global indicators of system connectivity were tested on the real case of the city of Sarno, which is threatened by multiple hazards (earthquakes and landslides).

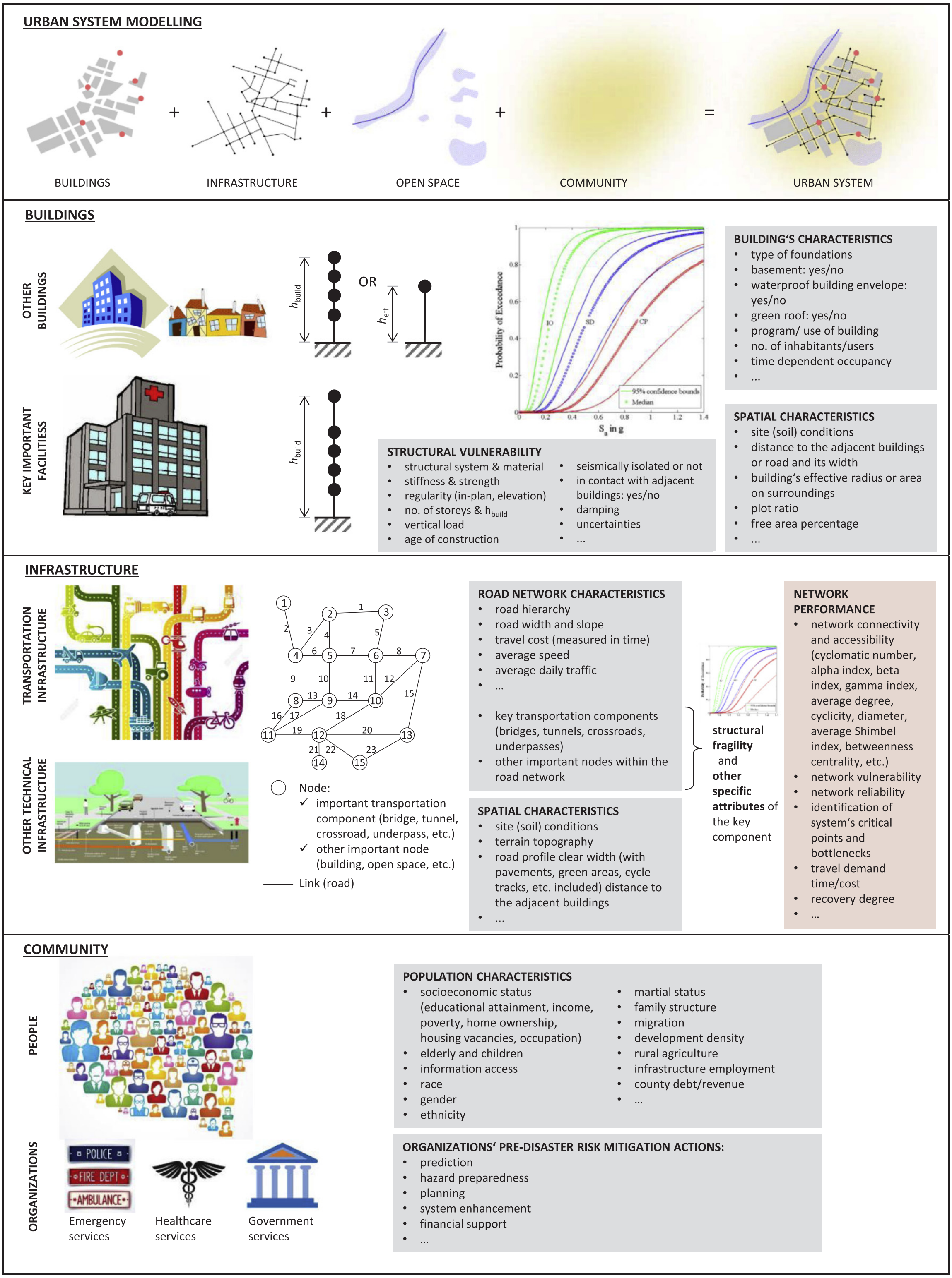

Fig. 8. The authors' concept for the modelling of an urban system, its (sub)components and their attributes.

4. Discussion

The main purpose of the review is to answer the question: how should the resilience of an urban system as a whole be assessed, taking all its components and their interactions into account. It should be noted that the reviewed papers were selected according to further research, focussing on urban system resilience to earthquakes.

4.1. Modelling of urban systems and urban resilience assessment approaches

An urban system is commonly understood as a complex interdependent network consisting of different urban components and the dynamic interactions between them. The primary distinction is between physical and social components, both of which can be divided into subcomponents. For the purpose of further research, based on the literature review the authors of this paper have extended the existing

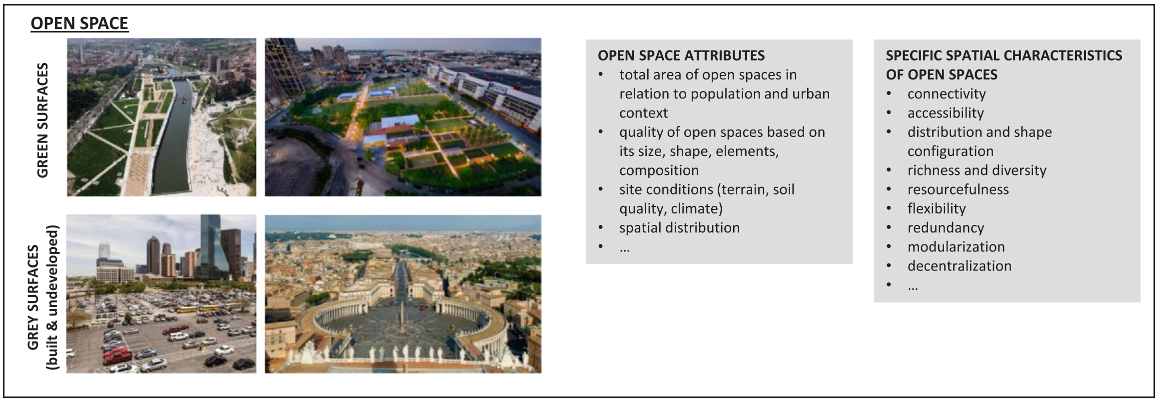

Fig. 8. (*continued*)

divisions of urban systems to four basic components (Fig. 8): buildings, open space, infrastructure and community [35,36].

Since the resilience of a complex system usually touches many disciplines, several definitions of resilience can be found in the literature. However, the time domain is essential when considering the concept of resilience as a process before a disaster, at the actual time of the disaster, and after the disaster (these are the phases of preparedness, response, and recovery) (Fig. 9). Limited to the review of existing literature addressing the engineering perspective of resilience only, there are four dimensions of resilience: technical, organizational, social, and economic. According to the literature engineering-based resilience frameworks tend to view resilience as bouncing back to the same condition (result-oriented) and to the achieving of a certain outcome. Furthermore, engineering-originated measurements concentrate on measuring pre-event (inherent robustness) and during-event (constancy/recovery) conditions. However, for resilience in general its ecological (environmental) dimension is also very important, since it focuses on the system's adaptive capacity and enhancement in order to obtain an effective response, adaptation to new conditions, and learning from previous events (process-oriented). Asadzadeh et al. [12] distinguish between ecological resilience (capturing the robustness level of communities to withstand external shocks and maintain functions) and socio-ecological resilience (quantifying the ability of human communities to absorb perturbations, the degree of self-organization, the degree of learnability, and the capacity for innovation). Socio-ecological-originated measures often focus on operationalizing post-event (i.e. adaptive capacity) and preventative (i.e. inherent robustness) conditions. In the literature primarily related to the engineering perspective of resilience, four attributes of resilient systems exist: robustness, redundancy, resourcefulness and rapidity. Analysing resilience from the ecological perspective, many other attributes such as efficiency, flexibility, capacity, diversity, autonomy, strength, interdependency, adaptability, and collaboration might also be taken into consideration. Based on both perspectives, resilient cities demonstrate

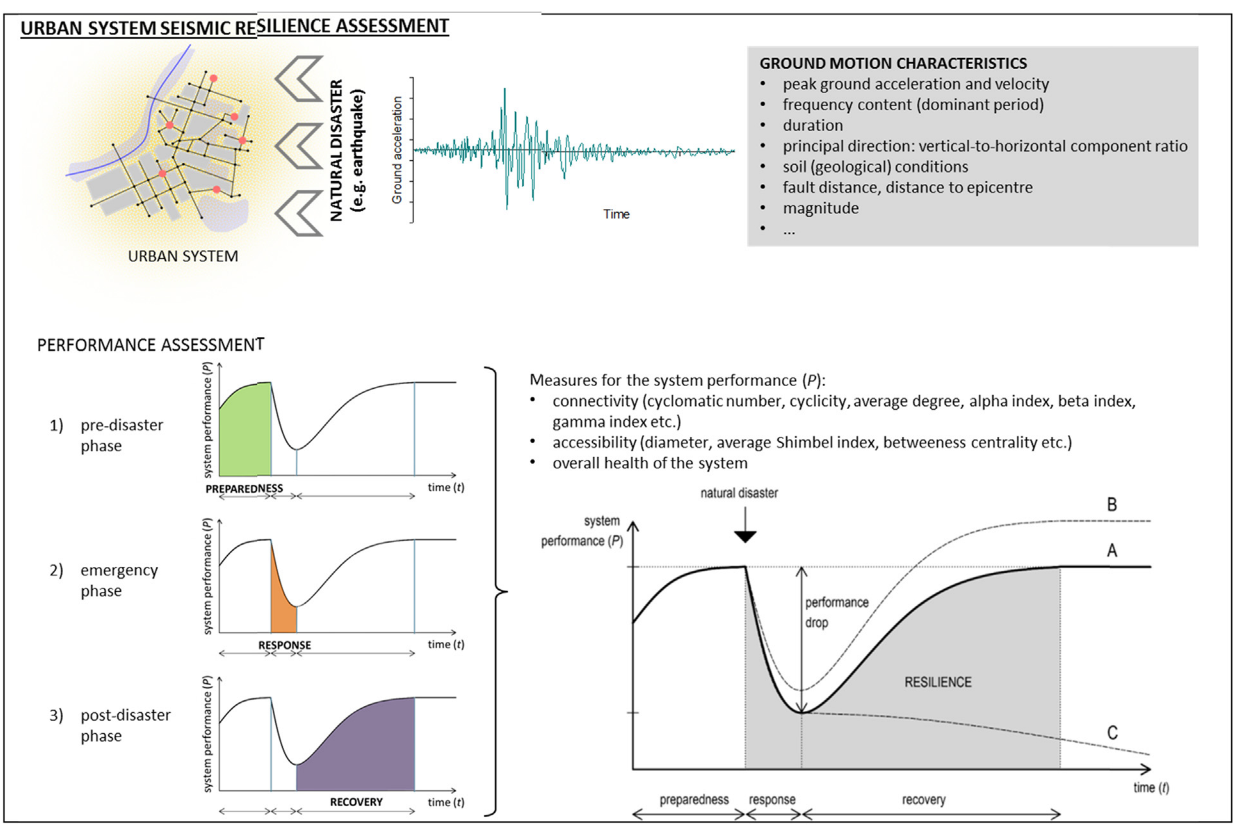

Fig. 9. The authors' conceptual framework for quantitative seismic resilience assessment of an urban system: time-dependent system performance analysis.

seven qualities [6]: reflectiveness, resourcefulness, robustness, redundancy, flexibility, inclusiveness, and integration (Fig. 1).

Resilience assessment should be able to provide answers to questions about system preparedness, the ability to absorb disturbances, the ability to efficiently respond, and the ability to adapt to new conditions. From the time aspect, we can distinguish between the short- (i.e. recovery), medium- (i.e. adaptation) and long-term (i.e. transformation) perspectives of resilience [24]. However, it should be noted that these stages of resilience cannot be understood as isolated, since in reality they often overlap.

Two different approaches of resilience assessment are recognized, i.e. qualitative and quantitative resilience assessment. *Qualitative resilience assessment* includes conceptual frameworks which offer the best practices, and expert assessments of different qualitative aspects of resilience. The most important part of qualitative assessment is its explicit descriptive evaluation of a case study. For this purpose, frameworks including different resilience attributes are usually used for discussion on a real case. Some other studies, e.g. [39] have been based on observing and explaining the case study, and then go on to reveal the resilient urban elements and characteristics. In the reviewed literature different resilience attributes are recognized: diversity, modularity, innovation, tight feedbacks, overlap in governance, ecosystem services, social capital, variability, spare capacity, flexibility, limited or safe failure, rapid rebound, and constant learning. However, the authors have some scruples about the application of the qualitative approach only for resilience assessment. Their main doubts are related to the objectivity and expertise of the involved "experts", the relevance of data provided with the aid of different questionnaires and interviews (the reliability of user perception and judgement), the reliability of the resulting reports based only on the observation of system functionality after a natural disaster, the limitations of applying the descriptive evaluation of a case study only, etc. Existing studies using the qualitative approach often use scoring systems with quite rough scale levels, different weighting methods, and radar graph presentations [26].

Quantitative resilience assessment is usually focused on just a single urban component. Most research in connection with the resilience assessment of buildings has been focused on the seismic vulnerability of specific building types [43–51], whereas not much research has been focused on networks of building stock [56–58,60]. Usually just the first two phases of resilience (preparedness and response), which refer to robustness, are analysed. For this purpose, probabilistic fragility analysis can be implemented. On the other hand, in the case of the holistic resilience assessment of buildings the use of fragility functions as well as a recovery function has been proposed [57]. It should be noted that, in reality, the recovery function depends on available technical and human resources, societal preparedness and public policies. Thus, there is a need for further research of recovery function and strategies.

Resilience assessment of infrastructure is usually performed using the network approach and applying graph theory. System interconnections and connectivity of the whole are investigated based on the vulnerability of a single element. In first step the vulnerability of such an element (e.g. a road segment, a bridge, or a road junction) is assessed by applying probabilistic fragility analysis. Different weights can be assigned to individual elements, which indicate specific characteristics (e.g. length, hierarchy, or travel time). After this, a resilience assessment of the whole network is performed using performance measures based on graph theory. In the literature, the most frequently observed phases of resilience are preparedness and response, whereas the recovery phase is rarely investigated. This is because there are numerous difficulties in the measurement and obtaining of relevant data in order to be able to analyse the recovery process. The measure of 'recovery degree' proposed by Zhao et al. [69] indicates the final performance level that a system can achieve after recovery. It is constrained by local budgets (e.g. funds, repair materials, and other consumables) and resources (e.g. human resources, equipment repair resources, and other non-expendable items), and therefore presents an optimization problem, although there is no suggestion about the identification of a specific time-dependent recovery curve. However, new research is needed which should be focused on the assessment of system recovery, providing analyses of different recovery strategies.

Community resilience is commonly assessed by means of a composite index. Social vulnerability indices (such as SoVI, which was proposed by Cutter et al. [70]) can be measured as composite indices consisting of different dimensions, sub-dimensions and primary indicators. Various aggregation methods (using both arithmetical and geometrical averages), statistical analyses (for normalization and rescaling) and weighting are used in order to get the score of the final index. Based on the authors' experience, an excessively complex multitude of differently interrelated indices, in combination with differing systems of weighting factors, can in practice allow the user to influence the result and fit it to his own expectations and desires. For this reason, aggregation methods should be simple, and the treated area not too large in order to ensure that the average index still makes sense. Usually the obtained results are mapped using the GIS technique. However, most studies are focused on social vulnerability and do not address comprehensive time-dependent community resilience. The response and recovery phases are often neglected, although the social structure has an important impact on system recovery. For instance, an agile, aware, and financially stable population would react better in crisis situations than a weak, poor, and uneducated population. The most important attributes of population with impact on urban resilience are: age, employment, education, ethnicity, economic situation, family structure, migration, and information access. Besides this, strong community organizations including emergency, healthcare, and government services are the driving force for the recovery of other urban components and the entire urban system. For further research, the social capital needed for the recovery action should be taken into account [35].

Open space has been recognized as a very important element for resilient urban systems in the phase of emergency as well as for system recovery [35,37–40,82]. Although there have been no serious attempts to include open space in the quantitative assessment of seismic resilience, assessment frameworks for the quality evaluation of open green spaces have been proposed [75,76,78]. Different indicators for the assessment of green open spaces have been proposed which could, with some modifications, be included in resilience quantification. Open space, including built, green and undeveloped surfaces, contributes to the quality of urban life and system performance. It is important for system recovery because, in the aftermath of a disaster, it can provide an alternative for disrupted transportation connections, spare capacity for temporary shelters, and space for building reconstruction [40]. Additionally, green open space provides ecosystem services which enhance the sustainability and resilience of the whole urban system, whereas built open space is often related to important historical and cultural monuments [89]. The green infrastructure was assessed in terms of climate resilience by Meerow and Newell [77], but the proposed framework does not suit seismic resilience assessment. The impact of open urban space on urban seismic resilience should be comprehensively investigated by both approaches (quantitative and qualitative).

4.2. Holistic assessment of urban system resilience

When assessing urban resilience, a holistic approach including the whole system lifecycle is preferable. However, the resilience assessment of urban systems as a whole is still a new research field. Three main methodologies with some modifications within individual categories were recognized in the reviewed papers (Table 2). Whereas the first two methods [80–82] are related to system vulnerability and risk evaluation, the third method [20,65,84,87,88] comprehensively assesses resilience, including all phases of preparedness, response, recovery, and adaptation. The social and physical components of urban systems can

Table 2
The main methodologies used for the resilience assessment of urban systems as a whole.

Ref.	Observed resilience phase	Resilience metric	Assessment technique	Application
[80]	Preparedness, response	$V = w_1 v_s + w_2 v_{12} + w_3 v_{22};\ \sum_{i=1}^{3} w_i = 1$	Weighted composite index, fragility analyses, GIS tools	Eskisehir, Turkey
[81,82]	Preparedness	$R_T = R_F(1 + F)$	Weighted composite index, fragility analyses, GIS tools, fuzzy set theory	Barcelona, Spain; Bogota, Colombia; Medellín, Colombia
[20,65,84,87,88]	Preparedness, response, recovery and adaptation	$R = \frac{\int_0^{C_{max}} y(C)dC}{C_{max}}$	Network and graph theory, fragility analyses, GIS tools	Accera, Italy; Sarno, Italy; hypothetical urban networks

be assessed separately, i.e. into soft and hard risk, respectively [80–82]. On the other hand, both components can be integrated in the same system as a complex network. The performance of the whole network considering the relationships and interactions of different social and physical components can be assessed applying graph theory [20,65,84,87,88]. A complex network is described as a graph consisting of a set of nodes (e.g. buildings, open spaces, people, and road junctions) and connecting edges (e.g. road segments and virtual connections). In order to include the different properties of individual components, a weighting method [12,90,91] could be used. When calculating composite indices, each indicator has its own weight. On the other hand, when considering a graph, weights (e.g. length, travel time, and cost) can be assigned to each edge in order to obtain a weighted graph. Most of the reviewed studies used probabilistic fragility analyses of physical structures and GIS tools. They were focused on seismic risk and applied to real case studies or for artificially modelled (hypothetical) cities.

Urban systems are complex networks which cannot be assessed just as the sum of individual separately evaluated components (Fig. 8). The performance of a city as a whole depends on the topology of its street patterns which enable efficient connections between each component and define reachability of the city services and facilities [92]. For this reason the resilience assessment of an urban system as a whole should include an assessment of individual components as well as of their relationships and interactions. The method proposed by Cavallaro et al. [84] and modified in further research [20,65,87,88] is the closest to achieving this goal. However, it still needs improvement and critical consideration. It should be noted that these studies were based on the engineering approach whereas the ecosystem approach was considered only partially.

Even though, the examined studies [20,65,84,87,88] promise consideration of the social aspect, this aspect is not completely included in the proposed metrics. The human aspect includes just the number of inhabitants of each building. Although it is suggested that social indicators should be included [87], this is not implemented in the latter's proposed integrated framework. In future research the social indicators referring to the SoVI index [70] should be included in the proposed metrics.

Furthermore, in the abovementioned studies, when modelling an urban system as a residential Hybrid Social-Physical Network (HSPN), the number of inhabitants is not based on real census data. It is just an estimate depending on the average number of inhabitants per square metre of the buildings' floor area. If real data for each building were available, the accuracy of the results obtained by the proposed framework would increase. In the study by Cavallaro et al. [84], when modelling goods HSPN, the weights for commercial buildings depend on the proportion of available goods which is defined just as a building area. The Services HSPN is a relationship between the inhabitants and one type of services (e.g. schools). In future research it should be extended to a more complex network including different types of services which play an important role in the case of a natural disaster (especially healthcare and emergency rescue services).

The metric of global efficiency [20,65,84,87,88] which is the basis for overall resilience assessment includes just one figure-of-merit, i.e. characteristic path length, which is normalized by Euclidean distance. Normalized values enable consistent comparisons to be made between two distinct systems.

In the case of a natural disaster the severely affected (useless) nodes and edges should be removed from the network model, since they do not contribute to the system's performance, and could indeed impede or reduce it. On the other hand the area around a removed node (e.g. a building) could present a new resource since it could become an area of new activity. If the complete removal and revitalization of useless nodes is done in time, such an approach might enhance the recovery process. However, in the methodology proposed by Bozza et al. the affected nodes and edges are removed from the network, but this is not noticed by the proposed metric. While comparing the level of the system's efficiency at different times (before, at the time of, and after the disaster), in the proposed methodology the absolute number of nodes (buildings, people, services) and edges (road segments, virtual connections) changes but it does not affect the overall network resilience (connectivity). It should be noted that the absolute number of network elements could be an indicator of the system's overall health [41]. A handicapped system has a lack of services (i.e. nodes, edges). As can be read in [41] some disturbances might not affect the proposed metric, but could still have an impact on the system resilience. For this reason, in addition to the proposed metric, some other metrics based on graph theory could be included in the framework in order to assess the system in a more comprehensive way (Fig. 9). System connectivity could be measured by cyclomatic number, cyclicity, average degree, alpha index, beta index, gamma index, etc. Measures for accessibility could be diameter (i.e. the maximum distance among all shortest distances between all O–D pairs in the network), the average Shimbel index (i.e. average of the sum of the lengths of all shortest paths connecting all pairs of nodes in the network), and betweenness centrality (i.e. number of times a node is crossed by shortest paths in the graph) [17].

The resilience measure is based on the definition of the recovery function as the area under the recovery curve [34]. It depends on time, the recovery budget, and the available human resources, data about which is hard to obtain. In order to avoid the necessity for this data, the resilience metric proposed by Cavallaro et al. [84] was defined as time-independent. However, the general definition of resilience is based on the time dimension, so that future research should try to include the time aspect in the assessment of recovery (Fig. 9).

There is a wide range of opportunity for new research into the planning and analysing of different recovery strategies. Whereas the reviewed papers [20,65,84,88] offer 6 different strategies for recovery after the occurrence of an earthquake, they could be modified or replaced by alternatives. Especially, a *new-site* strategy could be designed completely differently by carefully choosing the most suitable open spaces for new urban development. Contrary to the findings of the reviewed studies, it is assumed that smart recovery planning could contribute to more sustainable and more resilient urban systems.

4.3. The operationalisation challenge of resilience assessment

Based on the performed literature review, the authors agree with the statement made by Cerè et al. [3], that existing resilience framework research is still quite fragmented and the links behind various studies are not straightforwardly accessible. Moreover, although a lot of attempts to assess the resilience level of selected cities have already been carried out, most of them have applied only a limited (i.e. partial) approach in terms of the addressed perspectives of the notion of resilience (engineering, social, ecological, environmental, etc.). In the majority of studies dealing with the assessment of urban system resilience in the case of a selected type of natural disaster, only selected urban components have been considered. Thus, the final result does not actually reflect the real resilience level of the analysed city. The reason for this might be the practical application aspect of existing frameworks for resilience assessment which – due to their costly and time-consuming data collection and data hungry modelling methods – often focus on a few components only, whereas some other (important) urban components are excluded from the analysis.

Discussion about appropriate conceptual frameworks for disaster resilience, and how to apply resilience approaches operationally in disaster planning, response and recovery is still on-going. There are some studies addressing this operationalisation challenge seeking for practical operational approaches out of the diversity, complexity and subtlety of resilience thinking [12,26,93]. Bridging the gap between theory and practice, and responding effectively to natural catastrophes, requires detailed planning which addresses the relevant complexities and uncertainties [93]. The authors of this study agree that there is a need for a resilience measure which can be applied easily by local organizations [26]. One of the possible ways to improve the operational domain of resilience assessment frameworks could be the establishment of local or national governmental authorities responsible for different urban (sub-)components (building stock, infrastructure, social capital, green space, etc.). Such municipal agencies would be able to provide (collect and compile) the additional data required for selected urban components. It is a fact that more detailed and accurate input data could provide more reliable results, but in this case considerably more computational effort and more time is needed [36]. Of course, the basis for preliminary analyses could be existing data obtained from national databases, such as those provided by national institutes of statistics. However, building stock census data and population census data about the demographic and social structure of the population residing in the investigated city/region should be updated and/or upgraded. For reliable resilience assessment, detailed census data are required (Fig. 8), such as data about the actual number of users/inhabitants of a selected building, evidence of the whole building stock with its structural vulnerability characteristics, data about the actual number of users of an observed infrastructure component (e.g. average daily traffic on a selected road segment), and quantitative and qualitative data about existing (sub-)urban open spaces (using GIS tools). A good concept which can provide reliable data about selected urban (built) components seems to be the *Building Information Modelling* (BIM) approach and documentation [94,95]. Due to its wide application (its use is already obligatory in several countries), in the future complete data for the whole built environment will be available. In relation to the practical aspect of striving for resilient communities, John Twigg, in his guidance note for government and civil society organizations [28], considered that the focus on resilience should be about putting greater emphasis on what communities can do for themselves, rather than concentrating on their vulnerability to disasters or environmental shock.

5. Conclusions

Rapid population growth, climate change, and natural and man-made disasters require new design approaches. Getting ahead is our greatest opportunity. This is why the authors of this paper have tried to think more critically about how people should take more care of each other, including, in particular, the resilience of the urban environment. Forward-looking design can profoundly impact health in people and communities. Researchers of this topic face the frightening complexity of the whole problem in which the forgotten or not adequately addressed details might trigger completely different risk event development. There is a drawback that the resilience assessment of an urban system as a whole, by the averaging of indexes, might exclude some important data and it might be that such a holistic approach will never go well in hand with more technical, narrowed approach risk response studies. It is, however, our opinion that in risk management even a small step in the right direction and at the right time during the pre-disaster phase (such as the identification of possible bottlenecks in the analysed system) could make a significant contribution to the response and recovery phase, by saving numerous lives and assets in the case of a natural disaster.

The authors of this paper extended the existing division(s) of urban systems from the relevant literature using four basic components and their subcomponents (Fig. 8): (1) buildings as important key facilities and other buildings, (2) infrastructure as transportation and other technical infrastructure, (3) open space as green and grey (built and undeveloped) surfaces, and (4) the community as people and organizations. A set of attributes, which are recognized as having a substantial impact on urban resilience in the case of selected natural disasters (e.g. earthquakes), is allotted to each component.

From the reviewed literature on urban system resilience assessment it has been found out that the consideration of partial approaches (e.g. those which consider the physical urban components only) provides only an incomplete view of a system's resilience level. Furthermore, a holistic assessment of urban system resilience should include an evaluation of system preparedness, as well as of the system's ability to absorb disturbances, to efficiently respond, and adapt to new conditions. Such resilience assessments can be qualitative or quantitative. Whereas qualitative approaches are reliant on user perception and judgement, and hence they are more subjective, quantitative approaches can provide objective comparisons of individual systems over time, as well as resilience comparisons between different urban systems. A generic quantitative metric defines resilience as the area under a performance curve.

Based on the newly performed literature review, the following findings can be made:

- Only a few studies deal with the resilience assessment of an urban system as a whole, taking into account the relationships and interactions between multiple urban components;
- There is a lack of studies of the system recovery phase;
- Given the available metrics, time-dependency of the system resilience is often neglected;
- As a measure for system performance, only one figure-of-merit is usually used;
- In existing quantitative approaches to the resilience assessment of urban systems the social aspect is frequently considered in a very simplified or limited way, which means that some important issues may be neglected;
- Open space and its potential are usually ignored in the case of studies about the quantitative assessment of the seismic resilience of urban systems.

In the authors' conceptual framework for the quantitative seismic resilience assessment of urban systems as a whole, the application of complex network theory is proposed. In this way a city can be represented by a mathematical graph. Buildings are considered as a set of nodes which are connected together by a set of edges representing the infrastructure. The basis for the infrastructure network is the street pattern, since the technical infrastructure is usually located on the streets. The community is considered as the inhabitants of residential buildings which are classified by social indicators based on the use of the SoVI index. Open spaces are defined as nodes which are determined by weights representing their properties (e.g. area size, area shape, typology, and ecosystem resources). In order to completely assess the resilience of an urban system, the system performance in all three phases has to be analysed (Fig. 9), i.e. (1) preparedness, (2) response, and (3) recovery.

– Firstly, the phase of preparedness is evaluated by a generic metric for the global efficiency of the system before the disaster occurs. For global efficiency the use of multiple figures-of-merit considering the algorithms of graph theory is proposed.
– The second phase of response includes vulnerability assessment of buildings, using fragility analysis for key facilities (e.g. hospitals and other health centres, rescue services, governmental facilities, and educational facilities) and other buildings (e.g. residential buildings, manufacturing facilities, and commercial facilities) and infrastructure components. Structural damage due to the effect of a disaster contributes to downtime and damage costs. The expected structural damage and impact on infrastructure should be evaluated using a probability approach. Global efficiency after the disaster should be measured in order to evaluate the corresponding performance drop of the system after the disaster. As well as this, the interdependencies between the damage state of urban built components and their users or inhabitants have to be taken into account. The level of usability or habitability of urban built components is strongly correlated to the overall system performance, as well as to shelter needs assessment immediately after the disaster. The latter directly affects the recovery process of the whole system.
– In the third phase of recovery different scenarios and recovery strategies should be considered in order to obtain the most efficient one with respect to system performance. Recovery depends on time, the recovery budget, and available human and space resources. All these components should be included in order to be able to predict the recovery function. While searching for appropriate locations for the organization and erection of temporary shelters, data about the available urban open space and its potential are needed [40,96]. Thus, the inclusion of urban open space and its evaluation within the scope of the analysis of urban systems and their resilience is of great importance. Furthermore, the importance of open space in the case of new reconstruction should be included in *new-site* strategies. It is assumed that smart recovery planning would contribute to more sustainable and more resilient urban systems.

The described research is the authors’ first step towards the development of a framework for the holistic assessment of the resilience of urban systems. The proposed framework presented in this paper is still in its conceptual phase, not a final tool/method, and as such it seems to be data-hungry. Further optimization of data selection is needed. However, the operational domain (how to collect data) was not our primary goal, the main question under investigation in this review paper was how to assess resilience if the data required are available. Generally, in the proposed conceptual framework for the seismic resilience assessment of urban systems it is possible to take into account input data of arbitrary accuracy and reliability. The quality of input data depends on cost and time resources, as well as on the expertise of the authorities responsible for the collection of data/attributes of selected urban components. For a holistic assessment of urban system resilience, it is essential that all important urban components, and the interactions between them, are taken into consideration.

It should be mentioned that the presented study is mainly focused on the engineering perspective of resilience and the different available quantitative resilience assessment approaches. Furthermore, the study is limited to selected literature which has its primary focus on seismic resilience. Nevertheless, it contains a few examples of other natural disaster studies. For a wider and deeper knowledge of the existing literature the selection could be expanded to other types of natural disasters (e.g. floods, hurricanes, and landslides). It should be emphasised that in the study a natural disaster is understood as a threat with a negative connotation. However, it is a fact that for a community or region a disaster might, in some cases, result in a positive outcome.

The authors' future studies will address test models where the concept proposed in this paper will be developed further, and applied to the seismic resilience assessment of selected smaller and/or artificial urban systems. After this, the methodology will be applied to more complex (real) urban systems. Our primary goal is to deepen the perception of urban system seismic resilience while simultaneously raising the level of community awareness, so that people can more easily understand the interventions that are needed to establish and sustain it.

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