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Research Article

Integrating "Hard" and "Soft" Infrastructural Resilience Assessment for Water Distribution Systems

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Cities are highly dynamic systems, whose resilience is affected by the interconnectedness between "hard" and "soft" infrastructures. "Hard infrastructures" are the functional networks with physical elements providing goods or services. "Soft infrastructures" (culture, governance, and social patterns) encompass the social networks, make the hard infrastructures work, and are vital for understanding the consequences of disasters and the effectiveness of emergency management. Although the dynamic interactions between such infrastructures are highly complex in the case of the occurrence of hazardous events, it is fundamental to analyze them. The reliability of hard infrastructures during emergency management contributes to keep alive the social capital, while the community, its networks, and its own resilience influence the service provided by infrastructural systems. Resilience-thinking frameworks overcome the limits of the traditional engineering-oriented approaches, accounting for complexity of socio-technical-organizational networks, bridging the static and dynamic components of disasters across pre- and postevent contexts. The present work develops an integrated approach to operatively assess resilience for the hard and soft infrastructural systems, aiming at modeling the complexity of their interaction by adopting a graph theory-based approach and social network analysis. The developed approach has been experimentally implemented for assessing the integrated resilience of the hard/soft infrastructures during the L'Aquila 2009 earthquake.

1. Introduction

Critical infrastructures (CIs) have an increasingly pivotal role for modern societies, providing services which are paramount for the welfare of citizens [1, 2]. They are vital systems, services, and assets, whose disruption or destruction may have severe impacts on the health, security, safety, or economic well-being of a community. Both human actions and natural disasters threaten the proper functioning of CIs, increasing the concerns about their reliability and safety level and making their improvement a key requirement in the field of crisis management [1]. Among the CIs, water supply infrastructures are crucial for both public health and economic reasons, and the assessment of water distribution network performance in case of disruptive events is thus a relevant research topic [3].

The analysis of CIs shows extraordinary complexity, mainly due to the interdependence inherited from their technological, social, and economic properties [4]. Particularly, the occurrence of disasters is characterized by interdependent and systemic risks that can trigger hardly predictable effects. Both risk identification and risk management tools are limited because they rely upon foreseeable factor analyses of steady-state systems with predictable hazard frequencies and severities ([5, 6]). These approaches are unsuitable to cope with unpredictable risks. Therefore, a shift from risk management toward resilience management is crucial, since a resilient system is capable of coping with not-expected/not-forecasted risks [2, 6, 7].

Resilience-based approaches have gained increasing recognition particularly in the field of infrastructural systems, given that infrastructure assets represent significant financial investments and provide essential societal value [8, 9], considering their increasing complexity and interdependency [4] and the importance of "black swan" (i.e., unanticipated or unpredictable) events [7]. Although multiple definitions of disaster resilience exist (see, e.g., [10]), a broad one identifies resilience as the property of a system impacted by a hazard to (i) resist the stresses, by withstanding hazards and limiting damage, and (ii) recover or be strengthened, thus returning within a given period time into acceptable levels of use and serviceability [8, 10]. Specifically referring to infrastructural systems, resilience accounts for resistive and adaptive capacities that support infrastructure functionality in times of crisis or stress, such as natural hazards [9, 11], even in the case where the stress is uncertain or not defined.

During a crisis, emergency management of CIs is even more complex due to the presence of different decision-makers (e.g., government, first responders, and community members), characterized by a dense network of interactions among them and with the system of infrastructures [1, 4]. The analysis of past disasters led researchers to investigate and model the connections between physical ("hard") infrastructures (e.g., buildings, infrastructures, and utilities) and social ("soft") infrastructures (e.g., social bonds between citizens and emergency management systems) (e.g., [12–15]). The importance of integrating social and physical components to properly model resilience attributes of infrastructural systems, using a human-centric perspective, is crucial to understand and describe system performances [16, 17]. The need for integrated approaches has been introduced by Checkland's framework [15] and also echoed by the Hyogo Framework for Action of the United Nations [18].

Among the available approaches for resilience assessment, the TOSE approach, stemmed from the activities carried out at the Multidisciplinary Center for Earthquake Engineering Research (MCEER), seems to be suitable for analyzing the hard/soft infrastructure interaction. According to this framework, resilience should be conceptualized as the joint ability of both physical and social systems to withstand external stresses and to cope with impacts through situation assessment, rapid response, and effective recovery strategies [19]. The TOSE approach is based on the integration of four dimensions: technical, organizational, social, and economic [19, 20]. Examples of the TOSE implementation in actual cases are available in [1, 21].

Although the need to address resilience through a multidimensional and integrated approach is widely accepted (e.g., [17, 22]), it is still challenging to develop quantitative measures and indicators in complex systems such as urban environments [17]. Most of the resilience-building principles defined in the literature do not cover all the dimensions that make up resilience, and there is still a gap between theory and practice in integrated resilience [1].

Starting from such premises, this work aims at operationalizing the TOSE approach to resilience, with specific reference to water distribution systems (WDS), proposing a quantitative framework to measure its dimensions. The basic assumption is that the urban system can be modeled as a set of interrelated networks (i.e., the "hard" infrastructural system and the "soft" one), which is capable of generating a collective behavior through the combination of simple local mechanisms, resulting in a complex behavior [22, 23]. The hard infrastructure is represented by the urban WDS, whereas the soft infrastructure is the social network for emergency management. A graph theory- (GT-) based approach is implemented in this work to assess the properties influencing the integrated resilience of CIs. The methodology is developed with specific reference to the well-known case of the 2009 L'Aquila earthquake, one of the most severe in the recent history of disasters.

2. Resilience Dimensions and Attributes

The present section aims at providing an overview of the main concepts related to resilience, according to the scientific literature, mainly focusing on its key properties, dimensions, and attributes. Particularly, based on the available literature, a conceptualization of resilience is proposed and used to build a framework to develop an integrated model to assess the resilience of CIs.

Several definitions of resilience currently exist. The National Academy of Sciences [24, 25] defines resilience as "the intrinsic ability of a system to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events." This definition becomes more articulated if a set of system properties is considered (e.g., [26, 27]): (i) absorptive capacity, that is, the resistance to shocks; (ii) adaptive capacities, connected to the possibility of meeting different demand/service levels; and (iii) restorative capacities, that is, the capability to return to, or beyond, equilibrium [9].

Resilience literature often highlights the need to understand and consider multiple contributing dimensions (e.g., [9, 20, 27]). For what concerns the resilience of complex networked systems, four dimensions should be particularly considered, that is, technical, organizational, social, and economic (TOSE approach, [19, 22]), which help describe both physical and nonphysical aspects. The four dimensions are described in detail:

(i) The "technical" dimension of resilience focuses on the ability of the built environment to withstand and recover from disruptive events [19, 26]. It describes the capability of a system to perform adequately.

(ii) The "organizational" dimension of resilience pertains to the function of organizations in managing facilities and postdisaster response activities [19]. It refers to the capacity of crisis managers to make decisions and take actions that lead to the avoidance of a crisis or at least to a reduction of its impact [1]. It typically encompasses measures of organizational capacity, planning, training, leadership, experience, and information management that improve disaster-related organizational performance and problem solving.

(iii) The "social" dimension of resilience emphasizes the capacity of social ties and networks in limiting negative impacts from hazards [19, 28, 29]. It explains the response of society to disasters.

(iv) The "economic" dimension of resilience refers to the capacity of systems to minimize, and rebound from, direct or indirect economic losses.

Opdyke et al. [9] underlined that among these dimensions, the most prevalently analyzed in literature are organizational, technical, and economic. A smaller number of works refer to social indicators. Several authors also argue that these dimensions are often studied separately without taking into account their interrelationship. An analysis of independent resilience dimensions could indeed be satisfactory, but crisis could also originate due to the lack of integration of these dimensions—for example, a valve could be the right one but operators might not have the required training for its proper use [1].

Given the multidimensionality of resilience, and the need for integrated approaches, system performances may be quantified in a number of ways, depending on the type of system under investigation. MCEER's resilience framework consists of a set of attributes ("4R") such as *robustness*, *redundancy*, *resourcefulness*, and *rapidity* and enables the characterization of system functionality (performance level) of the system at a particular time (e.g., [19, 20, 22]). Specifically:

(i) *Robustness* is the "strength or the ability of elements, systems, or other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function" [19], that is, the inherent resistance of a system.

(ii) *Redundancy* is "the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e. capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality" [19]. It describes the availability of alternative resources.

(iii) *Resourcefulness* is "the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis" [19]. It mainly depends on human skills and improvisation during the event.

(iv) *Rapidity* is the "capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption" [19], that is, the speed of the recovery phase.

Referring specifically to CI resilience assessment, a broad overview of the available tools and methods includes, for example, probabilistic methods, graph theory methods, fuzzy methods, and analytical methods [30]. However, such models have limitations in their implementation [1]. Because of the theoretical nature of current resilience frameworks, crisis managers have difficulties determining which activities or policies should be carried out to improve the resilience level of CIs [1]. In addition, most of the current sets of principles underestimate the role of external agents and their influence on improving the CIs' resilience. Furthermore, most of the frameworks only define principles for improving organizational aspects without taking into account economic or social aspects, which are also influential in the resilience-building process [1]. Although there are several promising trends in resilience analysis, the landscape of resilience indicators is confusing and increasingly hard to navigate [22, 27]. A comprehensive and widely accepted model to quantify resilience is thus still missing, due to the complexity of the issue [30], and there is no single or widely accepted method to measure it. The challenge is to adopt a comprehensive methodology mixing both qualitative and quantitative resilience metrics or indicators, capable of describing multiple dimensions [9]. Among the available methods, the use of GT-based approaches is particularly relevant with the aim of providing an integrated and multidimensional insight into resilience. As detailed in Section 3, it is a flexible methodology, capable of being used both in hard and soft infrastructure analysis, with strongly quantitative roots and an explicit focus on topological and connectivity aspects of systems.

Starting from the available scientific literature and the widely acknowledged gaps in it, the present work aims at operationalizing resilience for CIs according to the following assumptions: (i) from a theoretical perspective, the TOSE framework is used to describe the multidimensionality of resilience; (ii) the "4R" set of attributes is used to characterize the main features of all such dimensions; (iii) an integrated approach is used to jointly assess resilience for the hard infrastructural system (i.e., the physical infrastructure, focusing specifically on drinking water supply) and the soft infrastructural system (i.e., the social network of agents, resources, tasks, and knowledge available during emergency); and (iv) GT is used to operationalize all the dimensions and attributes of resilience, and specific metrics are used to characterize hard and soft systems.

3. Methods: Graph Theory Metrics to Operationalize the TOSE Approach to Resilience

Complex systems can be interpreted and analyzed as networks, that is, abstract mathematical structures consisting of objects and their connections, and by the associated attributes. The analysis of the topology of networks is crucial since it is well known that the structure affects function [31, 32]. Network science therefore has important implications for understanding complex sociotechnical systems because, as discussed by several scholars (e.g., [31, 33]), complex systems' properties and behavior are strongly affected by the network of connections among the different system elements [34].

Following the conceptual framework provided by the TOSE approach [19], resilience is conceptualized according to four dimensions (i.e., technical, operational, social, and economic), each one described through four key attributes, namely, robustness, redundancy, resourcefulness, and rapidity. Globally, 16 performance criteria are used to characterize the resilience of CIs, which are described in detail in Table 1.

Table 1: Performance criteria according to the TOSE approach (adapted from [19]).

	Performance criteria			
	Robustness	Redundancy	Resourcefulness	Rapidity
TEC	Damage avoidance and continued water supply provision	Backup or duplicate water supply systems	Diagnostic and damage detection technologies and methodologies	Minimize time to return to preevent infrastructural functional levels
ORG	Continued ability to carry out designated function (i.e., water supply in emergency)	Backup resources to sustain operation (i.e., alternative sites and water supplies)	Plans and resources to cope with damage and disruption	Minimize time needed to restore services and perform key response tasks
SOC	Avoidance of casualties and disruption in the community due to the interruption of water supply	Alternative means of providing water for community needs	Plans and resources to meet community needs	Minimize time to return to preevent functional levels
ECO	Avoidance of direct and indirect economic losses	Untapped or excess economic capacity to provide water in case of loss of functionality	Stabilizing measures (e.g., capacity enhancement and demand modification, external assistance, and optimizing recovery strategies)	Minimize time to return to preevent functional levels

Selected metrics of graph theory (GT) are used in the present work to operationalize the TOSE framework: (i) referring to the hard infrastructural system, a set of metrics capable of modeling the key aspects of resilience of WDS is identified; (ii) referring to the soft infrastructural system, social network analysis (SNA) is used to map and analyze the network of interactions among the different emergency responders, both institutional and noninstitutional.

The analysis of the hard infrastructural system mainly originates from the existing scientific knowledge, since some GT metrics were already associated to specific resilience dimensions/attributes for WDS (further details in Section 3.1). Results obtained in other systems (both benchmarks and real networks) were used for the purpose of comparison with the L'Aquila case. Starting from these evidence, the local water utility technicians supported identifying the most significant subset of metrics. As far as the soft infrastructure is concerned, the process of model building and validation was performed integrating SA (storytelling approach) and PSM (problem-structuring methods), to structure and analyze salient knowledge (as in [29]). Both expert (i.e., policymakers and first responders) and local community member knowledge was elicited, mainly concerning (i) the emergency management procedures, (ii) the role of information exchange, and (iii) the interactions taking place during a crisis. Focusing on the metrics, a broad set of suitable measures was identified by the authors among those available in ORA© software. Among the different available SNA methods, we referred to organizational risk analysis because it allows detecting the central elements in the network but also identifying and analyzing the main elements affecting the vulnerability of the network, that is, those elements whose failure could drastically reduce the effectiveness of the emergency management network, as discussed in [29]. The comparison among the resilience dimensions' definition and the ORA measures' definition allowed identifying the most suitable GT measure (see Sections 3.2 and 3.3 for further details).

3.1. Technical Dimension: Water Distribution System Modeling Based on the Graph Theory. Referring to CIs, resilience is the degree to which the system minimizes the level of service failure magnitude and duration over its design life when subject to exceptional conditions. This definition is particularly suitable for water distribution systems (WDS) [35].

Several research projects underlined the role of GT to provide a framework for the assessment of water infrastructure system performances, through the analysis of subsystem connections, topological redundancy, and identification of critical components [36]. Indeed, WDS can be basically represented as networks of n nodes connected by m links (e.g., [37]). Physical and hydraulic attributes (e.g., diameter, pressure, and flow rate) may be added to better characterize system components. GT-based approaches for water distribution systems are particularly important in the reliability field, supporting the identification of topologies minimizing service disruptions (e.g., [36–39]) and the analysis of operation and failure conditions [36, 40].

In general, topology-based approaches to WDS pipe network analysis are less data-dependent and more computationally efficient to support initial assessments of WDS performance and reliability [38]. Referring to the wide set of GT metrics that are suggested in the scientific literature to describe the behavior of WDS, a direct connection with resilience dimension was already identified for the ones included in Table 2. A short description of such metrics is also provided, mainly in order to underline the specific relevance for WDS analysis. Starting from the measures included in Table 2, and referring also to literature evidence for both real and benchmark networks, the experts from the water utility supported in the selection of the most significant measures (highlighted in light grey in Table 2). Specifically, the technical robustness can be described referring to the density of bridges (D_{br}), which estimates the percentage of the links/pipes whose failure may potentially disrupt water delivery by isolating a part of the network. The redundancy can be

Table 2: GT metrics used for the analysis of the technical dimension of resilience. The number of WDS nodes and links is denoted by n and m, respectively.

Resilience dimension	Metric	Formula	Description
Robustness	Density of bridges	$D_{\mathrm{br}} = N_{\mathrm{br}}/m$	A bridge is a link whose removal isolates part of the network. It relates the number of bridges (N_{br}) to the edges m [44].
	Central-point dominance	$C_b = 1/(n-1)\sum_i (b_{vm} - b_{vi})$	It is based on the betweenness centrality of each network node, b_{vi}, and of the most central node, b_{vm}. C_b ranges from 0 (regular network) to 1 (star topology) [44, 45].
	Spectral gap	$\Delta\lambda$	Difference between the first and second eigenvalues of the adjacency matrix. A small spectral gap would probably indicate the presence of bridges [44, 45].
	Algebraic connectivity	λ_2	The second smallest eigenvalue of the normalized Laplacian matrix of the network. A larger value indicates enhanced fault tolerance against efforts to cut the network into isolated parts [44, 45].
Redundancy	Meshedness coefficient	$R_m = (m-n+1)/(2n-5)$	Ratio between the total and the maximum number of independent loops in a planar graph. It ranges between 0 and 1 and is based on the existence of alternative supply paths [37, 38, 46].
	Clustering coefficient	$C_c = 3n_\Delta/n_3$	Based on the ratio of the number of triangular loops n_Δ to the number of connected triples n_3. It is usually smaller in grid-like structures while higher values indicate a more clustered network [44].
Rapidity	Network efficiency	$E = 1/(n(n-1)) \cdot \sum_{i,j\, i\neq j}(1/d_{i,j})$	It is the harmonic mean physical distance between nodes. It ranges between 0 for least-efficient and 100% for most-efficient networks and may be used as proxy for average water travel time [38].

expressed using the meshedness coefficient (R_m), which is typically a measure of network connectivity. The rapidity is described using the network efficiency E, under the assumption that a more efficient network is also capable of recovering more rapidly from disruption. The technical resourcefulness, following the definition by [19], is considered either 0 or 1 according, respectively, to the absence or availability of monitoring and assessment systems.

It is worth remarking that the selected metrics can provide a global description of network properties and a general assessment of the expected response to extreme events regardless of local aspects and of the specific hydraulic operation of the system. Detailed hydraulic simulations and modeling activities (see, e.g., [41–43]) should be implemented in order to better investigate system performances.

3.2. Organizational and Social Dimensions: Social Network Analysis for Emergency Management. Evidence demonstrates the need for a coordinated involvement of experts and organizations from several fields for effective response to disasters [29, 47]. Nevertheless, understanding and managing the complex network of interactions involving the different responders—both formal and informal—is not a trivial task.

Emergency management networks are more emergent than planned [48]. Moreover, organizational structures, procedures, and responders' roles could be altered in order to meet the demands of an exceptional event, such as an emergency situation [49]. Finally, interactions are activated, with noninstitutional actors (e.g., the society) playing crucial roles in responding to the emergency [29]. Therefore, the analysis of emergency management network cannot be based exclusively on existing and formalized relationships. Keeping track of the interactions taking place during an emergency management is difficult, hampering the capabilities of analysts and researchers to implement quantitative methods for the analysis [48].

Following Giordano et al. [29], quantitative social network analysis (SNA) and problem structuring methods were integrated in order to collect responders' narratives and to structure them in a graphical map of interactions. Among the different methods available in the scientific literature for modeling and analyzing social networks (e.g., [50–52]), the organizational risk analysis (ORA) approach was implemented in this work [53].

The underlying assumption is that an organization could be conceived as a set of interlocked networks connecting entities such agents, knowledge, tasks, and resources [54]. The interlocked networks can be represented using the metamatrix conceptual framework, which accounts for the role of knowledge and tasks and of the interconnections among the key elements (i.e., agents A, knowledge K, tasks T, and resources R) considering their specific weight/importance. Additional details on the methodology are available in Giordano et al. [29]. Following Carley [54] and Giordano et al. [29], the following metamatrix was used (Table 3).

The map was developed using the ORA© software [54], developed by the Centre for Computational Analysis of

Table 3: Metamatrix framework showing the connections among the key entities of social network (adapted from [54]).

	Agents	Knowledge	Resources	Tasks
Agents	*Social network*: map of the interactions among the different actors involved	Knowledge network: identifies the relationships among actors and information or skills	Resource network: describes the access to resources	*Assignment network*: defines the role played by each actor
Knowledge		*Information network*: map the connections among different pieces of knowledge	*Resource usage requirements*: identifies the knowledge needed to use resources	*Knowledge requirements network*: identifies the information used, or needed, to perform a certain task
Resources			*Interoperability and co-usage requirements*: defines connections among resources	*Resources requirements*: describes the resources needed to perform a specific task
Tasks				*Dependencies network*: identifies the workflow, that is, the relations between tasks

Table 4: GT measures for the analysis of the organizational dimension of resilience.

Metric	Description	Meaning for the organizational dimension	Resilience dimension
Agent knowledge congruence	The number of knowledge that an agent lacks to complete its assigned tasks expressed as a fraction of the total knowledge required for the assigned tasks	Agent with high knowledge congruence can be capable of carrying out the assigned tasks, even if some connections become unreliable in case of emergency.	Robustness
Out-degree centrality	In an agent by knowledge network, the out-degree centrality identifies the actors connected to a high number of pieces of knowledge.	A high out-degree centrality means that the actor could activate different sources or connections in case of crisis.	Redundancy
Cognitive demand	Individuals who are strong emergent leaders are likely to be not just connected to many people, organizations, tasks, events, areas of expertise, and resources but also are engaged in complex tasks where they may not have all the needed resources or knowledge and so have to coordinate with others or have other reasons why they need to coordinate or share data or resources.	Emergent leaders in emergency management are the actors that, because of their connections with agents and knowledge, are capable of mobilizing crucial resources.	Resourcefulness
Closeness centrality	Closeness reveals how long it takes information to spread from one node to others in the network. High-scoring nodes in closeness have the shortest paths to all others in the network. It would follow that such nodes could monitor the information flow in an organization better than most others that have a lesser closeness value.	Nodes with the highest value in this measure will have the best picture of what is happening in the network as a whole. An actor with short paths can rapidly distribute information and have rapid access to pieces of information, thus minimizing the time needed to perform key response tasks.	Rapidity

Social and Organizational Systems of the Carnegie Mellon University. According also to GT, the strength of edges is analyzed considering the weights for the links. In this work, the metamatrix approach was used to unravel the complexity of interactions in the soft infrastructural system, particularly identifying the key properties affecting resilience according to the cited approach.

Among the different GT measures available for analyzing social networks (e.g., [55, 56]), we referred to the measures described in Tables 4 and 5. The organizational criteria of the TOSE approach refer to the water utility characteristics (Table 4), whereas the social criteria refer to the local community characteristics in the network of interactions (Table 5).

With specific reference to the water utility, the assumption is that its position in the map of interactions affects its capability to mobilize resources, both economic and informational, needed to cope with an emergency. The social dimension of the resilience accounts, instead, for the capability of the local community to access important information and to interact with important responders.

The robustness of the water utility (organization) relies on the organization's capability to access important information for carrying out the required tasks, even in case of

Table 5: GT measures for the analysis of the social dimension of resilience.

Metric	Description	Meaning for the social dimension	Resilience dimension
Capability	Detects entities with high connection degree relative to other entities (agent × agent network)	A community with high capability can be capable of activating alternative connections in case of emergency, thus limiting problems and disruption.	Robustness
Hub centrality	An agent is hub-central if its out-links are to agents that have many other agents sending links to them.	Having access to a high number of sources of information and being capable of interacting with central actors make the community's network redundant and capable of identifying alternatives.	Redundancy
Cognitive demand	Individuals who are strong emergent leaders are likely to be not just connected to many people, organizations, tasks, events, areas of expertise, and resources but also engaged in complex tasks where they may not have all the needed resources or knowledge and so have to coordinate with others or have other reasons why they need to coordinate or share data or resources.	A community well connected to agents and knowledge is capable of mobilizing crucial resources to meet the needs.	Resourcefulness
Closeness centrality	Closeness reveals how long it takes information to spread from one node to another in the network. High-scoring nodes in closeness have the shortest paths to all others in the network. It would follow that such nodes could monitor the information flow in an organization better than most others that have a lesser closeness value.	Nodes with the highest value in this measure will have the best picture of what is happening in the network as a whole. An actor with short paths can rapidly distribute information and have rapid access to pieces of information to quickly return to preevent functional levels.	Rapidity

Table 6: Economic dimension of resilience: GT measures related to the hard infrastructural system.

Metric	Formula	Description	Resilience dimension
Critical breakdown ratio f_c	$f_c = \frac{1}{k^2/k - 1}$ (k = degree)	It provides a theoretical value for the critical fraction of the nodes, which need to be removed in a network to lose its large-scale connectivity [36, 45]. It is a measure of *robustness* to failures and can be adopted to estimate the magnitude of losses.	Robustness

failures of part of the interaction network (e.g., some connections could not be available in a critical situation). Therefore, referring to Table 4, the agent-knowledge congruence measure was adopted. Similarly, we considered the water utility as organizationally redundant if it has access to multiple sources of knowledge to perform its tasks (out-degree centrality in the agent × knowledge network). The water utility could be considered as a resourceful actor if it could be listed among the emergent leaders in the social network, that is, if it is capable of mobilizing critical resources during a crisis (cognitive demand). Finally, the water utility could rapidly react (rapidity) to a crisis if it has fast access to information and resources (closeness centrality).

Concerning the social dimension of the resilience framework, GT measures were selected in order to assess the capability of local communities to change behaviors—as water users—and to affect positively the infrastructure resilience. We assume here that the community behavior is influenced by the interaction with the other agents and thus if it could activate alternative connections in order to gather useful information to cope with the emergency (capability). A community could be considered redundant in the resilience framework if it has a high degree of hub centrality. This means that it receives information from different sources and shares information with well-connected nodes. The community is a resourceful agent if it has a high degree of cognitive demand. Finally, the community could rapidly react to a crisis if it has a high closeness centrality.

3.3. Economic Dimension of Resilience. Following [19], the economic resilience measures can be defined referring to the ability of the system to limit losses and recover quickly performances after disasters. The economic impacts concern both the hard and the soft infrastructural systems, thus requiring the adoption of a hybrid set of GT metrics, which are summarized in Tables 6 and 7. Particularly, the economic resilience takes into account features of the system that either guarantee a limitation of damages or increase the accessibility

Table 7: Economic dimension of resilience: GT measures related to the soft infrastructural system.

Metric	Description	Meaning for the economic dimension	Resilience dimension
Hub centrality	A node is hub-central to the extent that its out-links are to nodes that have many in-links. Individuals or organizations that act as hubs are crucial in the interaction with a wide range of others.	It supports identifying the centrality of specific resources (i.e., economic resources) in order to complete all the tasks that are needed during emergency management, including particularly water supply in case of loss of functionality.	Redundancy
Capability	Detects entities with high or low degree relative to other entities. The formula discounts for the fact that most elements have some connections and assumes that there is a general discount to having large numbers of connections.	It helps assess the capability of economic resources to enhance capacity, limit damages, and optimize recovery.	Resourcefulness
Closeness centrality	Closeness reveals how long it takes an element to spread from one node to another in the network. High-scoring nodes in closeness have the shortest paths to all others in the network.	If economic resources have short paths, they can rapidly be used to activate other resources needed in emergency management, to quickly return to preevent functional levels.	Rapidity

to resources that are useful in supporting emergency management operations.

4. Overview of the Case Study: The 2009 L'Aquila Earthquake

L'Aquila province (central Italy) was struck by a severe earthquake on the 6th of April 2009. The magnitude was relatively moderate (6.3), but it revealed the very high vulnerability of lives, livelihoods, building stock, and institutions [57, 58]. The L'Aquila old city was declared unsafe and made off-limits with military control, and the community was moved out of destroyed and damaged buildings. A complex recovery phase characterized the whole area [59, 60].

Focusing on the infrastructural systems, the emergency management of CIs guaranteed a rapid and effective response to the earthquake [61, 62]. With specific reference to the water supply systems, an important water pipe within the "Gran Sasso Aqueduct" failed due to the presence of a fault activated during the earthquake [61, 62]. Furthermore, some minor damage on the supply system (slippage/breakage of the joints and breaking of cast iron pipes) was also observed [63]. Individual interviews with the technicians working for the local water utility (Gran Sasso Acqua SpA) confirmed that one of the most critical points in supporting the operation of the whole system was the distribution of several local breaks (e.g., in pipes serving single buildings), which caused severe functionality issues [21]. The urban WDS showed only a partial flexibility and limited adaptation capacity to provide the required service to citizens, considering the change in population distribution (e.g., people moved to temporary shelters or to other cities) and the need to close entire districts of the network (due to high ratio of volume lost). It is worth mentioning that, as a consequence of the high level of damage that occurred and of the changes in urban asset, the WDS was completely redesigned and is currently being rebuilt, after the earthquake.

The L'Aquila earthquake got a great interest worldwide also due to a series of scandals and controversies that are still ongoing. One of the most controversial issues related to the earthquake was the trial and prosecution of seven functionaries of the Italian National Department of Civil Protection (DPC), mainly due to the kind of information on the event shared with the community. Some citizens had acted on that information and consequently had lost their lives [58]. In general, in the aftermath of the disaster, the centralized emergency management has been debated [60].

The analysis of the L'Aquila earthquake thus represents an interesting opportunity to analyze in detail the interconnectedness of hard and soft infrastructural systems and to prove the importance of jointly assessing their resilience.

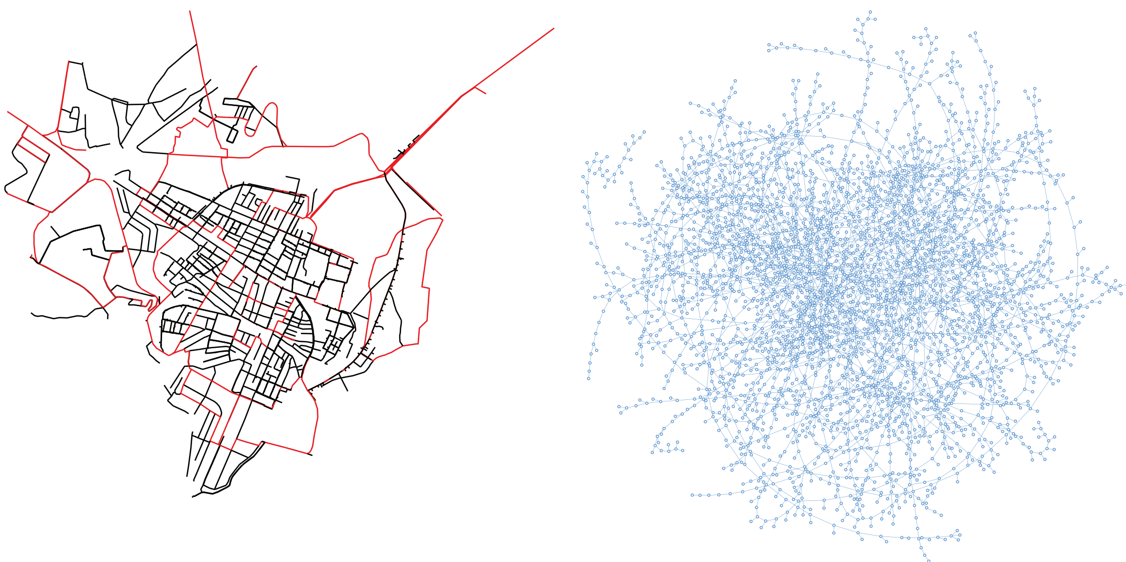
5. Results

According to the methodology description proposed in Section 3, Table 8 summarizes the GT measures used in the present work in order to characterize the dimensions of resilience according to the TOSE approach. The measures refer either to the hard (GT(h)) or to the soft (GT(s)) infrastructural system. Particularly, referring to the soft system, it also made explicit reference to the agent/resource or the specific matrix the measures are computed for. All the measures included vary between 0 and 1, denoting increasing values of resilience. Full details on the results and the values obtained for the case study are included in the following subsections. More specifically, Sections 5.1, 5.2, and 5.3 provide a detailed analysis of the results of the methodology in the "baseline" condition, that is, with specific reference to the earthquake in 2009, whereas a scenario analysis is proposed in Section 5.4.

5.1. "Hard" Infrastructural System: L'Aquila WDS. The following Figure 1(a) represents the urban WDS of L'Aquila, as it was before the earthquake. Figure 1(b) is the representation of the same system according to GT convention. The key

Table 8: GT measures used to assess the performance criteria according to the TOSE approach.

	Performance criteria			
	ROB	RED	RES	RAP
TEC	GT(h): $1 - D_{br}$	GT(h): R_m	Monitoring/control systems (0-1)	GT(s): network efficiency
ORG	GT(s): 1 – agent knowledge congruence (WU)	GT(s): out-degree centrality (WU) in A × K	GT(s): cognitive demand (WU)	GT(s): closeness centrality (WU)
SOC	GT(s): capability (C) in A × A	GT(s): hub-centrality (C) in A × A	GT(s): cognitive demand (C)	GT(s): closeness centrality (C)
ECO	GT(h): f_c	GT(s): hub centrality (R3) in R × T	GT(s): capability (R3) in R × T	GT(s): closeness centrality (R3)



(a) (b)

Figure 1: (a) Representation of L'Aquila WDS. The elements in red represent the main pipes of the system, whereas the elements in black are part of the distribution network. (b) Representation of L'Aquila WDS according to GT metrics.

Table 9: Summary of a selected subset of characteristics of the WDS of L'Aquila according to GT.

Measure	Value
Number of nodes n	3636
Number of edges m	3901
Density of bridges D_{br}	0.31
Meshedness coefficient R_m	0.037
Critical breakdown ratio f_c	0.127
Network efficiency E	0.034

characteristics of the system, along with the selected metrics, are summarized in Table 9. According to the definitions of the metrics proposed in Section 3.1 and considering for the purpose of comparison the values available for other networks in the cited literature, the high density of bridges D_{br}, along with the low value of the critical breakdown ratio f_c, contributes to suggest a low resilience of the network. The value of the meshedness coefficient R_m assimilates the network to a tree-like structure, which is in general easier to control but also characterized by lower adaptation capacity and flexibility.

5.2. "Soft" Infrastructural System: L'Aquila Emergency Management Network. This section describes the implementation of SNA to unravel the complexity of the emergency management interaction network. The methodology used for knowledge elicitation and structuring, and for mapping the network of interactions according to the metamatrix approach, is the same as discussed by [29].

Particularly, the integration of SA and PSM allowed reconstruction of the emergency management interaction network, according to the perception of both institutional and noninstitutional agents. Two main steps were performed: (a) semistructured individual interviews were performed to elicit individual knowledge and (b) participatory modeling exercises were designed and implemented, in two different moments, for collecting additional knowledge. The first participatory modeling exercise was focused on the retrospective analysis of the 2009 L'Aquila earthquake ("baseline" scenario). The second one oriented to the identification of the main criticalities of the system and on

Table 10: List of the agents, tasks, knowledge, and resources suggested by the stakeholders and included in the metamatrix approach.

Agent Description	ID	Task Description	ID	Knowledge Description	ID	Resources Description	ID
Local emergency manager	L.EM	Crisis coordination	T1	Local EM plan	IP1	Additional water resources	R1
Community	C	Health assistance	T2	National EM plan	IP2	Emergency water	R2
Community leaders	CL	Preparedness activities with the community	T3	Infrastructural conditions	IS1	Economic resources	R3
Local operational team 1	L.OP1	Activation and management of temporary shelters	T4	Damage entity monitoring	IS2	Human resources	R4
Local operational team 2	L.OP2	Evacuation of the citizens	T5	Location of damages	IS3	Machinery	R5
Local operational team 3	L.OP3	Rescue of missing people	T6	Location of casualties	IS4	Crisis management procedures	R6
Local technical support	L.TS	Structural/infrastructural assessment	T7	Structural damage assessment	IS5	Commitment	R7
Regional technical support	R.TS	Road functionality	T8	Warnings	IT1	Training	R8
National emergency managers	N.EM	Recovery of personal objects and goods.	T9	Seismic monitoring	IT2		
National operational team 1	N.OP1	Monitoring	T10	Temporary shelter location	IP3		
National operational team 2	N.OP2	Emergency management plan writing/updating	T11	Recovery information	IP4		
National operational team 3	N.OP3	Alerts, warnings, communication to citizens	T12				
National civil protection	NCP	Scheduling of the structural safety program	T13				
Water utility	WU						

potential changes/strategies. For the purpose of the SNA, participants described their role in emergency management and the tasks they have to carry out. They also identified the information and the resources needed to perform their activities and other actors providing/owning information and resources. They thus built the list of elements proposed in Table 10 and then suggested the connections represented in Figure 2, based on the understanding of roles, interdependencies, tasks, resources, and information flows. The participatory modeling exercises (Section 3) were used for validating the map in Figure 2 and the lists of Table 10, which reflects the metamatrix approach detailed in Section 3.2.

The result of the SNA was the map of interactions for emergency management proposed in Figure 2. This map was used for analyzing the actual role of two key important responders in the integrated resilience assessment framework, that is, the water utility and the local community.

5.3. Integrated Resilience Analysis. The GT measures described in Table 8 were implemented to assess the integrated resilience for the water distribution system in L'Aquila. The results obtained for both the hard and soft infrastructural systems are proposed in Table 11 and Figure 3.

The representation proposed in Figure 3 is highly relevant in order to have an overview of the specific role of single dimensions of resilience. This could help to identify weak points negatively contributing to the resilience of the whole system (e.g., lack of organizational skills/capabilities or physical limits for the CI) and, consequently, to select the most suitable and effective strategies to increase resilience. Such representation could be used with the aim of both assessing the current state of the system and quantifying the impact of the introduction of specific resilience-enhancing strategies or measures.

The results of this analysis allowed us to draw some hints concerning the main reasons of the infrastructure failures during the earthquake crisis. Although the network is quite robust, it is worth noticing that the density of bridges is high, and this may result in the possibility of easily isolating portions of the network. The redundancy is low, since the connectivity of the network is limited, the WDS being more similar to a tree-like system than a grid-like one. The network has a very low efficiency, which may result in the impossibility of rapidly adapting to new operating conditions. The resourcefulness is set to 0, since no effective monitoring or control systems were available at the time of the earthquake.

Figure 3 shows also the very limited contribution of the organizational and social dimensions to the integrated resilience of the water distribution network. This was mainly due to the limited capability of the water utility (organization) to have access to information needed to cope with the emergency. Although it demonstrated the capability to activate resources, it had only few short connections with the

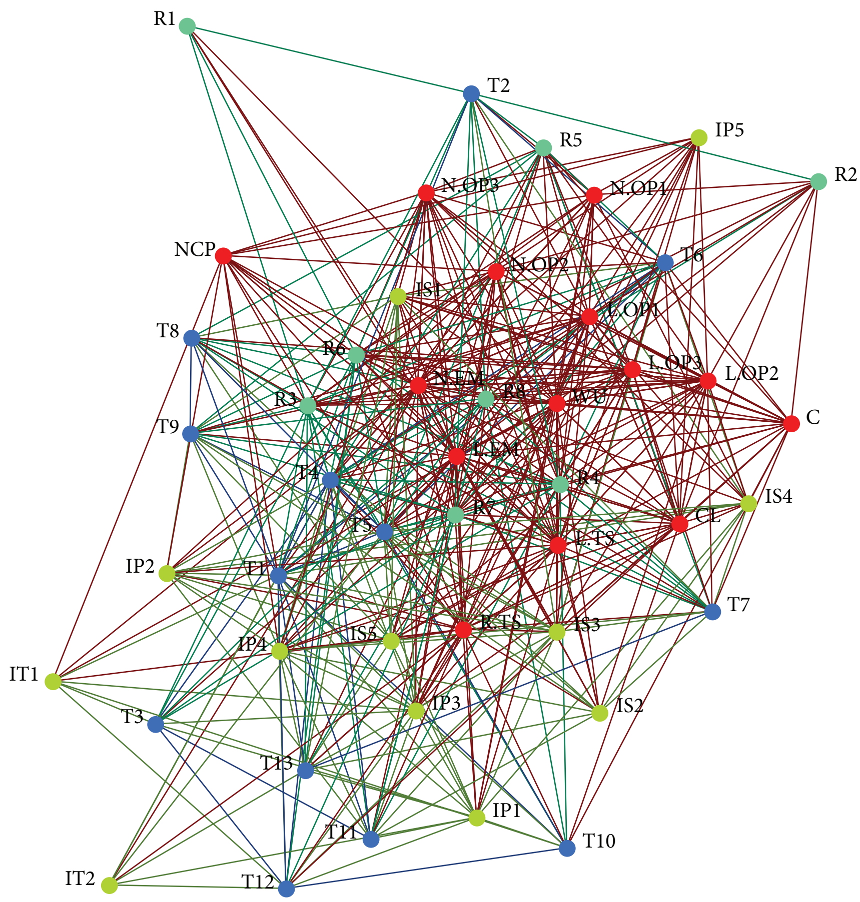


Figure 2: Representation of the emergency management network in L'Aquila. Agents are identified in red, information in green, tasks in blue, and resources in pale blue.

Table 11: Summary of the resilience measures in the L'Aquila case study.

	ROB	RED	RES	RAP
Technical dimension	0.69	0.037	0	0.034
Organizational dimension	0.183	0.064	0.324	0.245
Social dimension	0.388	0.125	0.244	0.228
Economic dimension	0.127	0.176	0.076	0.034

other responders, reducing the rapidity index. Moreover, the organization's robustness was low because of the lack of pieces of knowledge needed for dealing with the emergency. The lack of a geographical information system for systematizing the knowledge of the existing network negatively affected this index.

Similarly, the social components of the network—that is, local community—did not have a positive impact on the integrated resilience. As shown in Figure 3, the local community has a relatively high robustness degree, because of the dense network of interactions within the community and with the other agents. Nevertheless, the limited accessibility of important information kept low the values of the redundancy and robustness indexes. Finally, the low level of closeness centrality (long connection paths) had a negative impact on the rapidity of reaction.

Referring to the economic dimension, the low critical breakdown ratio suggests a limited robustness of the old WDS, due to the high amount of damages (and repairs required) and limitations to service. Economic resources to perform the tasks required in emergency management had limited availability, due to scarce preparedness of institutional agents and to other phenomena that conditioned the aftermath of the disaster (e.g., people not able to pay taxes and fees), limiting the economic resilience of the system.

5.4. Scenario Analysis. The developed methodology for integrated resilience assessment was implemented with a twofold objective: firstly, as detailed in Section 5.3, to estimate the resilience level with specific reference to the 2009 L'Aquila earthquake, accounting for both the hard and soft infrastructural components, and secondly, as described in the present section, to analyze the impact of specific resilience-enhancing strategies, selected taking into account both components and their multiple dimensions. Particularly, the scenario analysis aims at showing that, although the performances of hard infrastructures are crucial to cope with severe disruption and thus directly contributing to resilience, the role of soft infrastructures is relevant as well to deal with crisis. Enhancing resilience thus requires both improving the physical system (e.g., through maintenance,

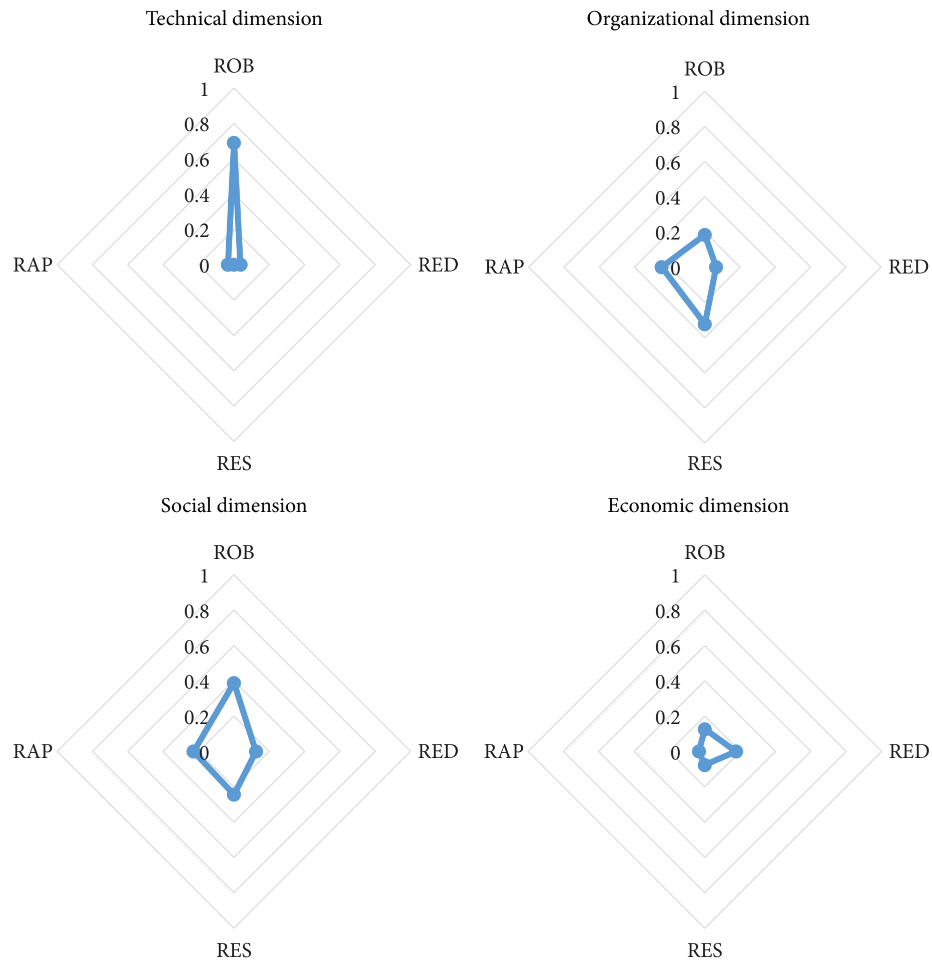


Figure 3: Spider graphs showing the values of specific components of resilience according to the metrics defined in Table 11.

Table 12: Summary of the resilience assessment model in the L'Aquila case study, referring to scenarios (1) and (2).

	ROB	RED	RES	RAP
Scenario (1)				
Technical dimension	0.95	0.25	1	0.21
Organizational dimension	0.183	0.064	0.324	0.245
Social dimension	0.388	0.125	0.244	0.228
Economic dimension	0.505	0.176	0.076	0.034
Scenario (2)				
Technical dimension	0.95	0.25	1	0.21
Organizational dimension	0.85	0.518	0.344	0.347
Social dimension	0.993	0.343	0.312	0.338
Economic dimension	0.505	0.385	0.966	0.257

adaptation, and reconstruction) and acting on soft infrastructures (e.g., on organizational culture, awareness raising, and preparedness/emergency planning), usefully comprising a portfolio of interventions [64, 65]. The integration of these options may suggest investments into systemic interventions, which may bring large benefits in building resilience, showing also a remarkably better cost/benefit ratio (despite some difficulties in correctly estimating economic efficiency of soft measures) [65].

More specifically, two scenarios are discussed for the L'Aquila case study:

(i) Scenario (1) considers a change in the hard infrastructural system, that is, the reconstruction of the water supply infrastructure with an improvement in its technical performances.

(ii) Scenario (2) analyzes a combined change in the hard and soft infrastructural system, that is, an improvement of system resilience acting both on the water supply system and on the effectiveness of the emergency management network.

Going further into details, scenario (1) is defined considering that the water supply system was redesigned (and is currently being built) after the earthquake. In fact, due to the high ratio of breaks in the urban WDS, to the dramatic changes in the distribution of population (and thus in demand pattern), and to the need of restoring/rebuilding several infrastructural systems at the same time, the hard infrastructure was completely restructured, based on innovative design criteria (e.g., the identification of districts for water

Figure 4: Spider graph showing the values of specific components of resilience according to the metrics defined in Table 12, referring to scenario (1).

supply and the improvement of the systems for network control). The metrics related to the hard infrastructural system were thus computed referring to the "new" WDS. Scenario (2) is built, instead, considering the joint impact of specific improvements in the emergency management network. The relevance of this scenario stems from the identification and analysis, during the participatory exercises, of some significant changes that occurred in the "soft" infrastructural system after the earthquake. Specifically, the connections between the community (C) and the water utility (WU) were significantly strengthened, as well as the connection between the WU and the other key agents involved in emergency management, due to an improved effectiveness of the emergency management plan and an increased experience in emergency management operations. From the SNA point of view, the main improvements of the emergency management network are (i) an increase in the number and strength of connections between agents, particularly referring to both incoming and outgoing connections between C and WU and the emergency managers (A × A matrix), (ii) an improved access to procedural information for both agents (A × K matrix, IP1, IP2, IP3, and IP4), and (iii) an improved access to resources to perform the required tasks, particularly for the WU (increased human and economic resources). The GT measures described in Table 8 allowed us to assess the benefits due to the changes in the interaction network. As expected, the robustness of both the organizational and social dimensions increased. This is mainly due to the increase in the number and strength of the connections. The results of this analysis have been used as basis for the debate aiming at improving the protocol for emergency management. The main institutional actors were involved in this ongoing process. Some important decisions were already taken—that is, involvement of the water utility in the protocol for intervention—but the process is still in its early phases.

Table 12 summarizes the results of scenarios (1) and (2), while Figures 4 and 5 include a comparison between both scenarios and the reference condition described in Figure 3. It can be easily argued that multiple actions may contribute to changes on different dimensions of resilience, globally concurring to an increase in resilience levels. The resilience-enhancing strategies merely oriented to improve the hard infrastructural system are definitely effective (scenario (1)), but it should be considered that acting on multiple dimensions of resilience of both hard and soft infrastructural systems might have a better effect (see, e.g., social and

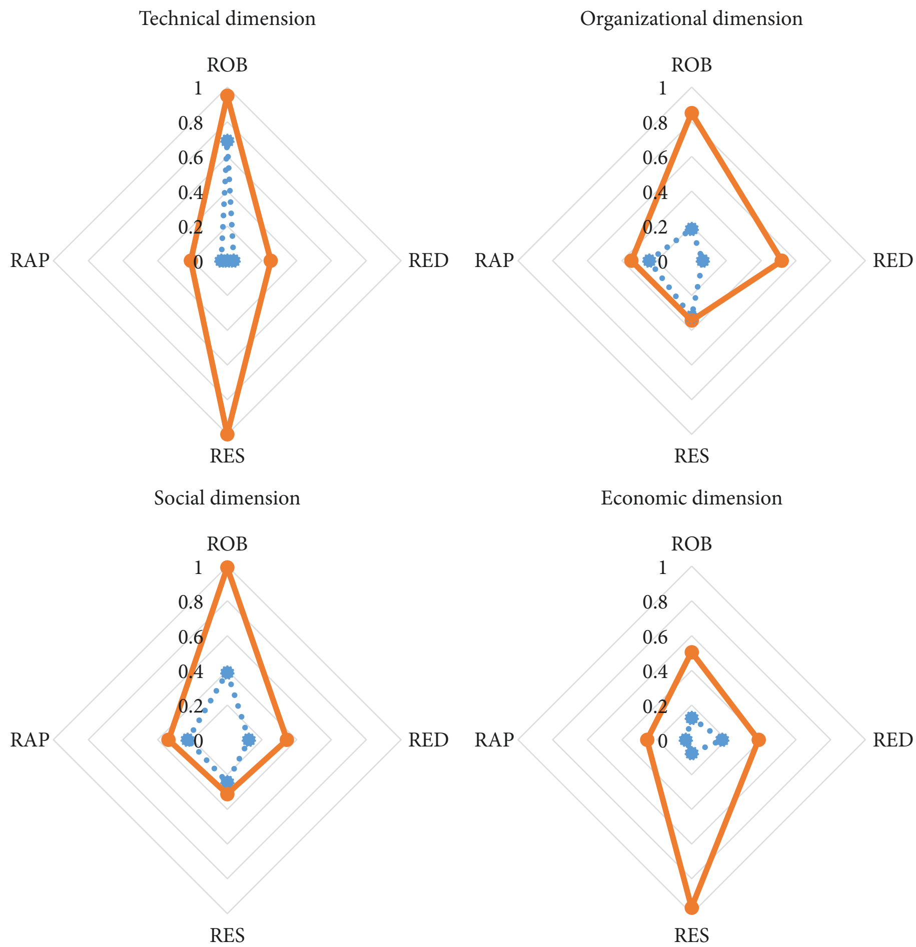


Figure 5: Spider graph showing the values of specific components of resilience according to the metrics defined in Table 12, referring to scenario (2).

economic dimensions) on system response to disasters (scenario (2)).

6. Conclusions

The present work aims at operationalizing the resilience concept for CIs. The results of the L'Aquila case study demonstrates that dealing with complexity—for example, managing emergency situation in complex systems—claims for integrated approaches based on the interaction between hard and soft infrastructural systems. The TOSE approach is used as a conceptual framework to model the multidimensionality of resilience, along with the 4Rs' set of attributes (*robustness*, *redundancy*, *resourcefulness*, and *rapidity*). Selected GT metrics are used to identify a set of properties which may be used to characterize the dimensions of CIs. The methodology was developed with specific reference to the well-known case of the L'Aquila earthquake. The hints from the case study allow us to state that the method described in this work, due to its capability to address the multidimensional nature of the system resilience, facilitates decision-makers in identifying the main criticalities in both soft and hard infrastructural systems and in suggesting effective resilience-enhancing strategies.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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