L´AQUILA MANUAL (AUTHORS: Giordano, R and Pagano, A. CNR-IRSA)

CS Manual
L'Aquila Case Study

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1. Introduction to this manual

The aim of this manual is to collect, structure and enable the transferability of the experiences carried out in the L'Aquila Case Study during the implementation of the EDUCEN project. In order to enhance the readability of the manual, the performed activities have been clustered in two main groups:

- The cluster for the **analysis of the network of interaction among different emergency responders**, which aimed at mapping and analysing the complex network of interactions taking place in case of emergency. To this aim, storyline approach, cognitive mapping and social network analysis methods were sequentially implemented.
- The cluster for the **analysis of soft and hard infrastructure resilience**, which aimed at better comprehend how soft and hard infrastructures interact in order to make the whole urban system more resilient in case of disaster. To this aim, system dynamic modelling and graph theory were adopted.

Both activities were developed and calibrated referring to the retrospective analysis of the earthquake in 2009.

1.1. L'Aquila CS: description and rationale

L'Aquila city had experienced multiple relevant earthquakes in the past. A disastrous earthquake occurred in 1461, with an estimated magnitude of 6.5 and approximately 150 victims. Another relevant earthquake occurred in 1703 (it was a part of a significant earthquake sequence), and killed approximately 6000 people in the city and its surroundings. Referring to the recent history, an event in January 1915 killed 32500 people, including almost the whole population of Avezzano, 50 km south of L'Aquila (Alexander 2014[1]).

The Case Study refers to the disastrous 6.3 earthquake which struck L'Aquila city and its province at 3.32 a.m. on 6 April 2009. As a consequence of the event, 308 people died and 1500 resulted injured.

Although the physical event was relatively moderate (moment magnitude 6.3), its impacts were particularly high, mainly due to the very high vulnerability of lives, livelihoods, building stock and institutions in the Apennine Mountains. The event got a great interest worldwide also due to a series of scandals and controversies that are still ongoing. Just to provide a well-known example, 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 information ("incomplete, imprecise and contradictory on the nature, causes, dangers and future development of seismic activity in the area in question" - Il Centro 2012) shared with the community. It resulted that some citizens had acted on that information and as a consequence had lost their lives.

This had a strong negative impact on the trust level of local community toward the emergency managers, with consequences on the acceptability of emergency management and recovery measures. After the earthquake, the local community was forced to abandon the city center. New towns were developed in safer places, disaggregating the original socio-cultural networks. New networks emerged after the disasters, showing different cultural aspects.

The role of hard infrastructures (e.g. water supply infrastructures) at urban level supported efforts of local communities during the EM, revealing as a key asset to cope with the disaster.

The analysis of the 2009 experiences allows to draw some preliminary conclusions concerning the main issues that need to be addressed in order to enhance the management of the different phases of the disaster risk reduction:

[1] Alexander, D. E. (2014). Communicating earthquake risk to the public: The trial of the L'Aquila Seven. Naturals Hazards, 72, 1159–1173.

- The main characteristics of the socio-cultural networks – i.e. trust, obligations, norms, etc. – affect the effectiveness of the risk information and warning dissemination strategies, and, thus, the capability of the different actors to react in time and properly to the emergency, reducing the disaster impacts;
- Formal and informal interaction networks co-exist during an emergency. The 2009 earthquake experiences demonstrate how the official information sharing strategies and interaction protocol could fail or, simply, have a limited effectiveness. Nevertheless, informal interaction mechanisms were activated by both institutional and non-institutional actors, allowing the flow of information and the cooperative emergency management;
- L'Aquila experience supports the understanding of the dynamic nature of the socio-cultural networks, and the impacts of stress – i.e. a disaster – on their characteristics. The social structure is created through cross-scale relationships between people and organizations and encompasses interactions with information/knowledge and social learning processing.
- A strong connection exists between soft and hard infrastructures: the reliability of physical infrastructures during the emergency management contributed to mobilize the social capital through the social network. Similarly, the resilience of the community conditioned the level of service provided by the infrastructure.

Starting from these preliminary evidences, the activities of the L'Aquila CS have been focused on enhancing the understanding of how cultural aspects, and specifically the organizational culture, affects the effectiveness of the interactions during an emergency among the different actors, institutional and non-institutional, and between these complex community of actors and the main hard infrastructures. As extensively demonstrated in the following sections, organizational culture strongly affects the way an actor (i.e. emergency responder, manager, member of the community, etc.) interact with the others (network of interactions) and with the built environment.

1.2. The objectives of the L'Aquila CS

Over the last few years, a number of natural disasters have demonstrated the need for quick and effective responses, to minimize the number of deaths and injuries, as well as the financial cost associated to damage and losses. Response needs to be provided under the severe stress of crisis conditions, and requires the coordinated involvement of experts and organizations from several fields.

Enhancing the coordination effectiveness in case of emergency requires to overcome the main organizational factors hindering the cooperation. Among these factors, the lack of distribution of information and the lack of situational awareness play a crucial role. During an emergence, it is crucial that the right agents receive the right information at the right time. Existing protocols and tools aiming at enabling the flow of information among the different actors during an emergency seem inadequate to cope with the dynamic nature of the emergency management process. Information management and sharing procedures within a responding organization and/or among different organizations might be jeopardized by the need to alter organization structure and roles, procedures and use of information in order to meet the demands of an exceptional event, such as an emergency situation. Moreover, interaction networks change dramatically during an emergency leading to the creation of temporary multi-organization. The role of the different agents in the interaction network and the tasks they have to perform could change during a crisis. Finally, the existing protocols and tools neglect the role played by local community. The institutional responders consider the community merely as a passive actor, whose main role is simply to receive the information provided through the official information channels. Members of the community are actually among the first and most effective responders during an emergency. Moreover, they role as information providers needs to be accounted for.

Starting from these premises, the activities carried out in L'Aquila aimed at:

- Better comprehend how differences in organizational culture affect the way different actors activate and/or reinforce connections with the others and with the surrounding environment during the different phases of the DRR. The way different actors perceive the information network to which they belong strongly affects the way they search and collect information during an emergency, and the level of trust. E.g. most of the first responders trust exclusively on information coming through a very hierarchical chain of information sharing, whereas members of the community have access to a multi-center network of information and will prefer information collected through a more "horizontal" network;
- Analyze the impacts of the topology of the interaction networks, accounting for the different perception of the involved actors, on the effectiveness of the sharing and dissemination of risk information and warnings. Despite the relevant role of "official" public information sharing strategies, transforming the risk information and warning into actions – i.e. how people hear, understand, believe, personalize and decide – highly depends on how the different actors perceive themselves within the social structures;
- Better comprehend the impacts of a disaster on the structure of the existing socio-cultural networks, including the institutional network of interaction. Social and cultural networks are not static systems. They change over time due to different reasons. Disasters often provoke changes in the authority relations, influencing who is perceived as the authority in this phase. Trust and reliance on information sources change as a result of stress.
- Modelling and analyzing the mutual interdependency between soft and hard infrastructures. Evidences demonstrate the tight connection between soft and hard infrastructure in case of emergency. On the one hand, the way local communities react to a disaster could have an impact on the resilience of the lifeline infrastructures. On the other hand, the accessibility to crucial services provided through the hard infrastructures – i.e. drinking water, transportations, communication, etc. – affects the recovery phase of the local community and its capability to keep alive the social capital.

The activities concerning culture and DRR carried out in L'Aquila allows to provide hints to emergency managers aiming at enhancing their capability to comprehend and account for the differences in problem perception and organizational and cultural differences when developing and implementing the emergency management plans. Specifically, the lessons learned from L'Aquila experiences could support emergency managers in overcoming the main barriers hampering the flow of information among institutional and non-institutional actors, and to enhance the cooperative emergency management process.

This Manual documents the activities undertaken with aim of producing the aforementioned improvements. The scope of this manual is twofold. On the one hand, it illustrates the main results obtained during the implementation of the EDUCEN activities. This part of the manual aims at enabling the scientific transferability in other CS of the methods and tools adopted in L'Aquila. The main audience of this part of the manual is the technical and scientific community involved in supporting the management of the different phases of the DRR. On the other hand, the manual aims at collecting and structuring the experiences and lessons learned from the main actors, both institutional and non-institutional, enabling the process of mutual learning, which is the main scope of the EDUCEN projects.

Therefore, besides the scientific scopes of the L'Aquila CS, it is crucial to emphasize the main objectives for the non-scientific audience, i.e. the emergency managers, the practitioners and the local population.

1.2.1. Objectives of the L'Aquila CS for the emergency managers

Most of the tools and methods implemented in L'Aquila CS cannot be implemented directly by decision makers and emergency managers. They require a high degree of competencies in network modelling and analysis. Nevertheless, the analysis of the activities carried out and of the obtained results allow to draw some crucial "lessons learned", that need to be shared within the community of the emergency managers. The specific objectives for the emergency managers in L'Aquila CS can be summarized as following:

- To develop and implement framework for the assessment of the effectiveness of the protocol of interactions in case of emergency;
- To better comprehend how different organizational cultures affect the process leading to the development of a common understanding among the different actors involved in the emergency management (situational awareness);
- To enhance the effectiveness of the collaborative emergency management and the coordination activities.
- To understand the complexity of connections between hard and soft infrastructures, in order to model how resilience at urban level can be affected in emergency conditions.
- To develop modeling techniques to quantitatively analyze the influence of cultural/behavioral issues in the whole DRR cycle, and to assess the potential impact of strategies implemented to deal with emergencies.
- To implement scenario analysis to support the predictive assessment of system evolution.

1.2.2. Objectives of the L'Aquila CS for the practitioners

In this section, we use the term "practitioners" to describe experts in the field of emergency management that can enable the process of revising and improving the emergency management protocols. These experts can make use of the tools referring to the training materials developed during EDUCEN. Specifically, the objectives for the practitioners can be summarized as following:

- To analyze the interaction network in case of emergency, and specifically, the flow of information within the institutional network, and between this network and the local community;
- To identify key vulnerability in the network, that is, those elements (i.e. agents, information or tasks) whose failure could lead to a dramatic reduction of the network effectiveness;
- Suggest potential improvement in the network, accounting for the actual role played by the different stakeholders in the network
- To identify 'soft' variables and strategies, which can be used as well, along with 'structural' measures in order to enhance the resilience of integrated hard/soft infrastructural systems.

1.2.3. Objectives of the L'Aquila CS for the local population

Finally, the third class of interested users of the EDUCEN results is composed by the local community. Classic institutional organizational structure tends to follow stable boundaries, established authority figures, and protocol driven actions which oftentimes are not suitable to integrate the community in emergency management operations. EDUCEN looks at the local community as one of the most active first responders in case of emergency. Therefore, the main objectives of the L'Aquila CS for the local population are:

- To better comprehend the mechanisms of interaction within the members of the local community, and between this community and the institutional system during the different phases of the emergency management;

- To identify key roles and responsibilities in the community interaction network – i.e. identify the key agents in the community, that is, those members of the community that can play a crucial role in facilitating the flow of information;
- To enable the integration process of the local community within the protocol of intervention in case of emergency;
- To overcome the main barriers hampering the wide diffusion of the emergency information.
- To better understand the impact that population dynamics and behaviors might have during emergency conditions on the availability and functionality of critical services.
- To analyze how reconstruction activities can be performed in order to match the needs of the served population, and to guarantee improved performances for engineering systems.

1.3. Key terms and definitions

- **Vulnerability** is an internal property of systems, depending on the factors that determine to what extent both people and assets are put at risk by events. Understanding the vulnerability level is crucial to select and implement the most suitable strategies for DRR.
- **Resilience** is based on the integration of the capacity to cope with and overcome all kinds of adversities, to the capacity to adapt, learning from past experiences, and to ability to transform institutions and assets pursuing welfare and sustainable societal robustness towards future crises.
- **Risk perception** is embedded in culture, and essential for the members of a society to evaluate situations and act in an appropriate manner. Understanding the ways risks are dealt with requires a thorough understanding of the cultural setting. Risk communication may significantly affect the way people are involved by the event and react to it.
- **Physical city Infrastructure**. Physical infrastructures represent key assets for the safety and the well-being of citizens both in ordinary conditions and during emergencies. Their operation is crucial to support the basic activities and the life of social infrastructures as well in case of devastating events.
- **Social capital and networks**. Social capital contributes to creating networks. The role of these networks strongly influences the capability to mobilize social capital in order to reduce disaster impacts. Informal networks emerge during emergency, as well as during recovery, thus emphasizing the role of community members as responder rather than just victims.

2. SELECTION OF METHODS: OPERATIONALISING CULTURE AS AN ASSET

Two main clusters of tools and methodology have been developed and implemented in L'Aquila CS:

- The integrated approach for exploring the role of cultural networks through Social Network Analysis as an asset in DRR for improving the dissemination of information;
- The integrated tool for the analysis of the interaction between the soft and hard infrastructures in case of disasters.

2.1. Exploring the role of cultural networks through Social Network Analysis as an asset in DRR for improving the dissemination of information

This tool aims at mapping the actual network of interactions taking place during an emergency, and to analyze this map in order to identify the key role and responsibilities, and to detect the main vulnerabilities in the network. In this work, we refer to vulnerabilities in the network as factor whose lack of effectiveness could lead to the failure of the whole emergency management network. This activity started from the assumption, supported by empirical evidences, according to which institutional protocols for information sharing during emergency describe only part of the actual flow of information.

In order to support the analysis of the interaction network in L'Aquila CS, three main tools were developed:

- Protocols of structured interviews in order to collect the individual perception of the emergency interaction network: in this phase a sequential implementation of storytelling approach (SA) and problem structuring method, specifically Fuzzy Cognitive Mapping (FCM), was implemented. The FCM allowed to translate the collected narratives into useful inputs for the SNA.
- Meta-network framework for structuring interaction network during an emergency: this tool allows to map and analyze the complexity of the interactions. The tool is based on the implementation of the Social Network Analysis (SNA) approach. The SNA was used to better comprehend the actual role played by the different actors – both institutional and non-institutional – in case of emergency, the tasks performed and the information each actor brings into the network. The SNA allowed to identify the potential vulnerabilities in the emergency interaction network.
- Analytical framework for investigating key elements and key vulnerabilities: this tool is based on the integrated implementation of different graph theory measures, aiming at assess the performance of the network according to its topology.

2.1.1. Perception of the emergency interaction network.

In order to develop the interaction network model, both experts' and local knowledge was collected in this phase, mainly concerning: i) the emergency management, ii) the role of information exchange, and iii) the interactions taking place during a crisis. The adopted approach for knowledge elicitation is based on the assumption that a particular section of knowledge, either deriving from experts or community members, is equally important. In this work, we use the term "experts" to indicate policy-makers and official responders involved in the emergency management. The experts' knowledge was elicited through a series of individual semi-structured interviews. A participatory modelling exercise was design for collecting community's knowledge. In both phases, a storyline approach (SA) was implemented. Referring to a specific episode, participants were required to describe the sequence of actions implemented in order to achieve their goals in the emergency management, the information used and the other agents with whom they interacted. Considering the scope of this work, the knowledge elicitation phase focused on the phase of emergency management. Preparedness and recovery were not investigated in this work. In the L'Aquila CS, the storyline approach focused on the disastrous earthquake happened in 2009.

The first issue to be addressed concerned the selection of the experts to be involved in this phase. A top-down stakeholder identification practice, which is referred as "snowballing" or "referral sampling", was implemented. The selection process started with the actors mentioned in the official protocols of intervention. The preliminary interviews carried out with these agents allowed us to widening the set of stakeholders to be involved.

The results of the interviews were structured in individual Cognitive Maps (CM) (Figure 1). The structuring phase allowed us to translate the narratives into useful inputs for the SNA phase.

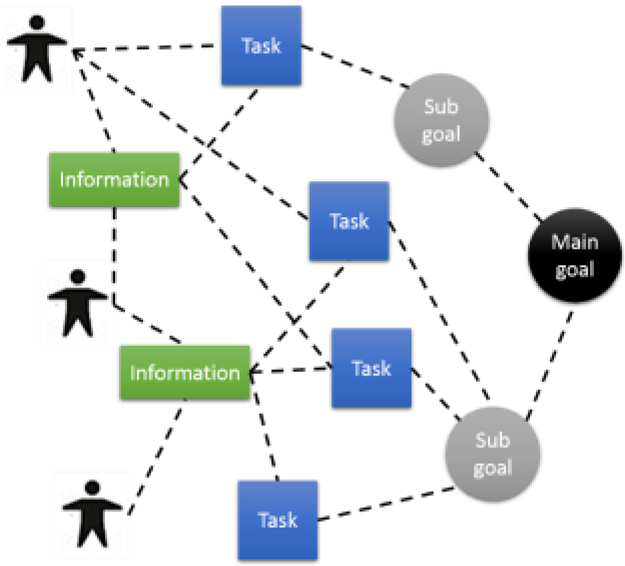


Fig. 1: Cognitive Map describing the individual's understanding of the connections between goal-task-information-agents

The interactions with the other agents can be activated through both the sharing of information and the cooperation to perform specific tasks. Each link in the CM is characterized by a weight, which describes the stakeholders' perception of the importance of that connection. The weight of the link agent-information describes the interviewee's perception about how crucial is the agent to obtain the needed information. Similarly, the weight of the link information-task represents the role played by the information in facilitating the implementation of that specific task. In order to facilitate the elicitation of the participants' opinions about the importance degree, linguistic judgements were used. Two semantic labels were used to describe the connection agent-information, i.e. "exclusive" and "limited". That is, the agent had exclusive/limited access to the information. Similarly, the information-task connection was assessed by the experts as "supporting", "crucial" and "indispensable".

Individual CM representing the experts' understandings of the complexity of the network of interactions were developed.

The knowledge elicitation phase was then completed with the involvement of members of the local communities in a participatory modelling exercise, aiming at eliciting and structuring the community's understanding of the emergency management process (Figure 2). During the first round of the modelling exercise, the participants were required to start providing their individual inputs concerning the other members of the community, institutional organizations and official responders with whom they interacted during the last emergency situation. To facilitate the interaction, a set of icons representing the main actors was created. In the second round, participants were required to describe the information collected during the emergency management and to link this information to the actors, both institutional and non, described in the previous phase. Participants were also required to assign a degree of importance to each interaction. A debate was carried out among participants in order to facilitate the synthesis among the different points of view. Finally, participants were required to describe how the collected information leaded to actions (tasks) carried out as emergency responses.

At the end of this phase, the CM representing the participants' understanding of the interaction network involving the community during an emergency was developed.

A detailed description of the implemented methodology can be found in the EDUCEN handbook. This manual focuses more on how the methods have been implemented in L'Aquila CS, the description of the obtained results and the lessons learned. Moreover, this manual describes the obstacles encountered during the process and the adopted approaches.

The implementation of the described methodology in the L'Aquila CS allowed to obtain two distinct results. On the one hand, suggestions about how to reduce the bottlenecks impeding the flow of information and, hence, the cooperation in case of emergency were obtained and discussed with local stakeholders. On the other hand, an effective methods aiming at supporting emergency managers to account for the complexity of the social and cultural networks and their impacts on DRR effectiveness was developed. This section is focused on the first results. The hints about how to support the replication of the method in other case studies are described in the section "lessons learned".
The following Table 1 shows the list of stakeholders involved in different phases of the methodology.

Table 1: List of stakeholders involved in EDUCEN activities

Name	**Role**	**Type**	**L'AQUILA**
L.EM	Local Emergency Manager	Individual	Mayor
N.EM	National emergency management	Organization	Di.Coma.C.
L.TS	Local Technical Support	Organization	Technical Municipal office
R.TS	Regional Technical Support	Organization	Regional Civil Protection agency
N.TS	National Technical support team	Organization	National Civil Protection agency
L.OP1	Local Operational Team #1 (Health assistance)	Organization	Local Red Cross team
N.OP1	National Operational Team #1 (Health assistance)	Organization	External Red Cross teams (coordinators and operators)
L.OP2	Local Operational Team #2 (Fire Brigade)	Organization	Local Fire Brigade team
N.OP2	National Operational Team #2 (Fire Brigade)	Organization	External Fire Brigade teams (coordinators and operators)
L.OP3	Local Operational Team #3 (Police Dept.)	Organization	Local Police team
N.OP3	National Operational Team #3 (Police Dept.)	Organization	External Police teams (coordinators and operators)
C	Community	Individual	Members of the community
CL	Community leaders	Individual	Representative of the community

The stakeholders' involvement started with the Mayor and the Municipal offices. The results of their interviews allowed us to widen the set of actors to be involved. The individual interviews were used to develop the cognitive maps representing the actors' understanding of interaction networks taken place during the 2009 earthquake.

Fig. 2: Interviews with the local institutions in order to develop the CM.

The protocol for the CM development was implemented. Figure 3 shows the CM developed for the municipal technical office:

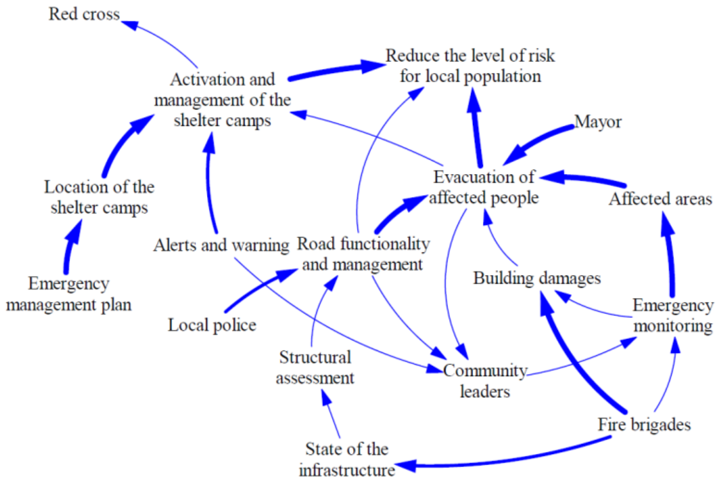


Fig. 3: CM developed referring to the municipal technical office of L'Aquila. The line thickness represents the importance of the link, according to the stakeholders' understanding

A workshop was organized in order to collect and structure the community's understanding of the interaction networks (Figure 4). The leaders of citizens' society associations were invited to this workshop. During the first round of the modelling exercise, the participants were required to start providing their individual inputs concerning the other members of the community, institutional organizations and official responders with whom they interacted during the last emergency situation. To facilitate the interaction, a set of icons representing the main actors was created. In the second round, participants were required to describe the information collected during the emergency management and to link this information to the actors, both institutional and non, described in the previous phase. Participants were also required to assign a degree of importance to each interaction. A debate was carried out among participants in order to facilitate the synthesis among the different points of view. Finally, participants were required to describe how the collected information leaded to actions (tasks) carried out as emergency responses.

Fig. 4: Workshop for the development of the community's CM.

At the end of this phase, the CM representing the participants' understanding of the interaction network involving the community during an emergency was developed.

The CM shows the main stakeholder's goal – i.e. to reduce the level of risk for the local population – and the actions implemented in order to achieve those objectives. Finally, the CM shows the interaction between this stakeholder and the other agents. The interaction concerns both the sharing of information (either received or distributed) and the cooperative implementation of some actions. Similarly, CM were developed for all the above mentioned decision actors.

The developed CMs had a twofold role in the analysis phase. On the one hand, they were used to detect and analyze the differences among the decision actors concerning the perception of the network for the emergency management – i.e. ambiguity analysis. On the other hand, it allowed to map and analyze the interaction network.

2.1.2. Mapping and analyzing the interaction network

The CM allowed us to translate the collected narrative – i.e. decision actors' experiences during the selected critical event – into useful inputs for the social network analysis. Specifically, the weight of the links in the CMs allowed to develop the matrixes for the network development. For a detailed description of the method implemented in this phase, a reader could refer to the Annex XXX.

The following Table 2 shows the *Agent x Agent* matrix:

Table 2: The Agent x Agent matrix obtained considering the CM inputs.

	L.EM	C	CL	L.OP1	L.OP2	L.OP3	L.TS	R.TS	N.EM	N.OP1	N.OP2	N.OP3	NCP
L.EM	0	2	8	4	0	10	10	6	10	0	0	0	5
C	0	0	10	2	4	4	0	0	0	0	0	0	0
CL	8	10	0	8	8	8	10	8	0	0	0	0	0
L.OP1	0	5	5	0	10	8	0	9	10	10	0	9	0
L.OP2	0	2	5	5	0	8	10	0	10	0	10	0	0
L.OP3	10	2	5	0	8	0	10	0	10	0	0	10	0
L.TS	10	0	8	0	8	8	0	10	10	0	5	5	0
R.TS	7	0	5	10	0	0	6	0	10	0	0	0	8
N.EM	10	0	0	10	10	10	10	10	0	10	10	10	10
N.OP1	0	0	0	10	0	0	0	0	10	0	0	0	0
N.OP2	0	0	0	0	10	0	0	0	10	0	0	0	0
N.OP3	5	0	0	0	0	8	0	0	10	0	0	0	0
NCP	8	0	0	0	0	0	0	0	10	5	5	5	0

The matrices were used as input for the development of the networks maps. The software ORA© was used to map the interactions. Figure 5 shows the *Agent x Agent* network.

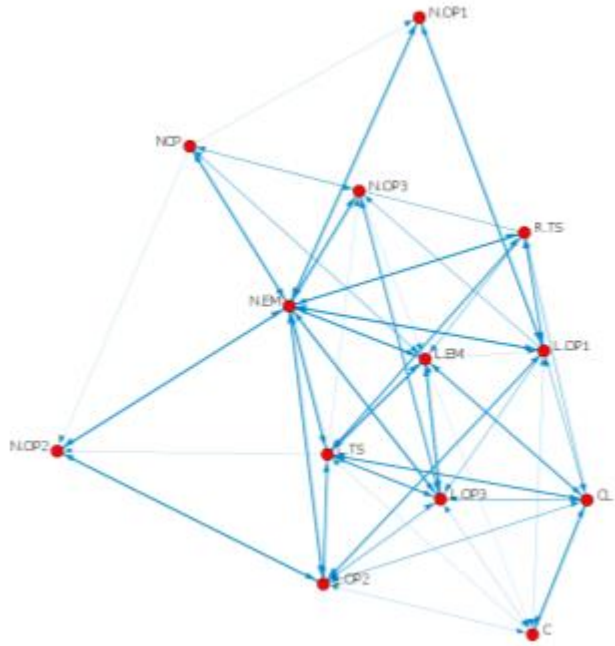


Fig. 5: Map of the Agent x Agent interaction.

The direction of the links indicate which agent mentioned the interaction. For instance, the link between L.EM2 and L.OP2 shows that L.EM2 perceived itself interacting with L.OP2, but not the vice-versa. The thickness of the links represent the weights assigned by the different actors during the knowledge elicitation phase. The comparison between this network and the one representing the official protocol of interactions in case of emergency (see figure 6) demonstrates the inadequacy of the protocols to fully describe the complexity of the interactions. The actual network is far less hierarchical and accounts for informal interactions taking place even among institutional actors. That is, during the knowledge elicitation phase we learned that, besides the official interactions, in case of emergency the institutional actors activated personal relationships to gather important information.

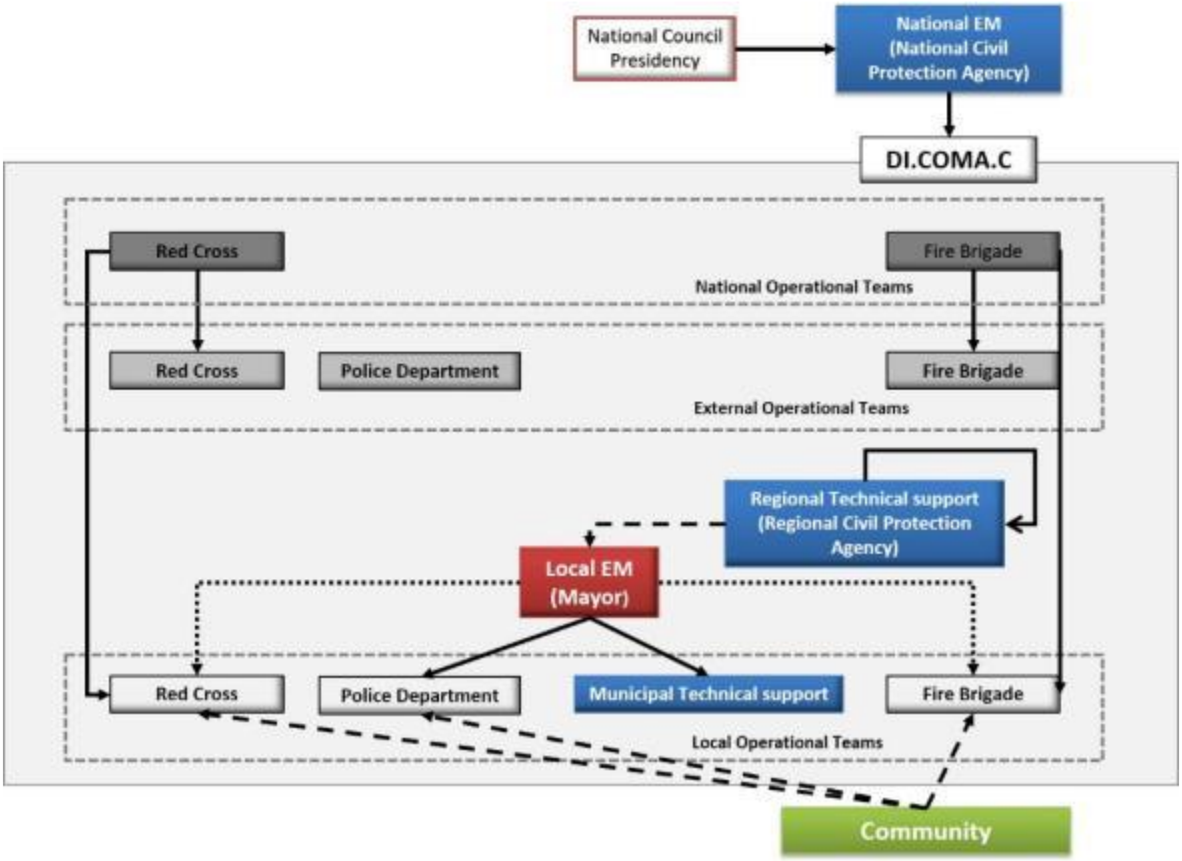


Fig. 6: Official protocol of intervention.

Figure 7 shows the Agent x Knowledge network. Table 3 shows the set of information used during the emergency, according to the institutional agents and the community leaders.

Table 3: List of information used by each agent when implementing their tasks

Information	Abbreviation
Local emergency management plan	IP1
National emergency management plan	IP2
State of the infrastructures	IS1
Earthquake damages monitoring	IS2
Affected areas	IS3
Location of wounded people	IS4
Assessment of building damages	IS5
Alerts and warnings	IT1
Earthquake monitoring	IT2
Location of the shelter camps	IP3
Recovery supporting information	IP4
Behaviours in case of emergency	IP5

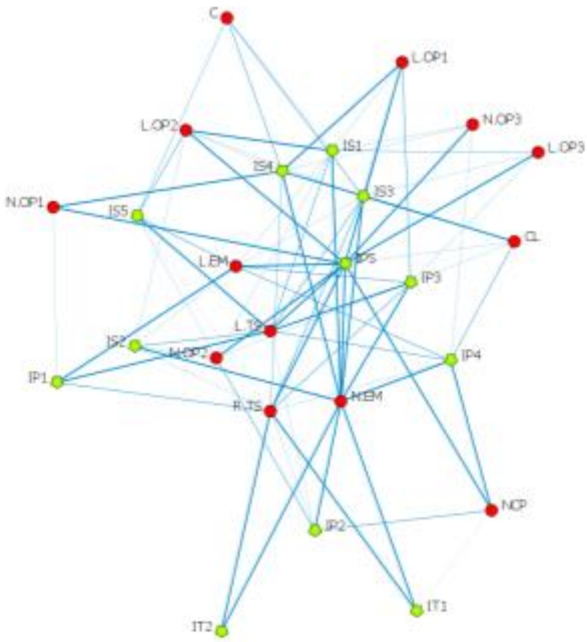


Fig. 7: Map of the Agent x Knowledge network

The map demonstrates that there is no exclusivity in the agent-knowledge interactions, namely there is no actor exclusively owning pieces of knowledge. Therefore, the cooperation among the different actors is crucial to overcome the fractured nature of the information system.
The combination of the different networks allowed to map the complex interactions among the main elements activated during the flood emergency, i.e. agents, knowledge and tasks (figure 8).

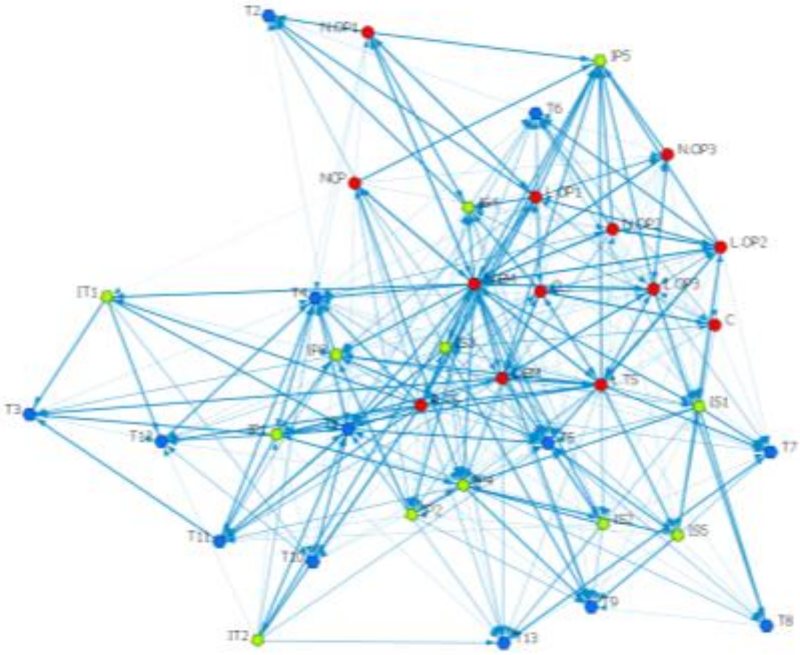


Fig. 8 Network of interaction among Agents, Knowledge and Task according to both experts and local knowledge.

The figure 12 shows the actual complexity of the interaction mechanisms supporting the emergency management. Failure in this network – i.e. lack of an information, missing cooperation for task implementation, etc. – could provoke uncontrollable cascading effects leading to the failure of the whole emergency management process. Therefore, it becomes crucial for the emergency managers to enhance their comprehension of this complexity, in order to implement actions aiming to increase the effectiveness of the emergency management network and to reduce its vulnerability.

2.1.3. Key elements and key vulnerabilities in the interaction network

The graph theory measures previously described were implemented in order to identify the key elements and the main vulnerabilities of the network. Table 4 shows the results of the analysis aiming at identifying the key agents in the network.

Table 4: Key agents in the L'Aquila emergency network

Measures	Key actor	Meaning
Total centrality degree	National civil protection Municipal civil protection Local emergency manager	These actors are characterized by a high number of connection (both in- and out-) with most of the other agents in the network.
Betweenness Centrality	National civil protection Community leaders Local red cross Municipal civil protection	These actors occur on many of the shortest paths between other agents. This means that these actors can easily move information from one part of the other of the network.
Hub centrality	National civil protection Municipal civil protection Community leaders Local red cross	Individuals or organizations that act as hubs are sending information to a wide range of others each of whom has many others reporting to them. Therefore, they act as hub of information within the network.
Most knowledge	National civil protection Municipal civil protection Regional civil protection	These actors have access to important pieces of information.
Most task	National civil protection Regional civil protection Local emergency manager Fire brigades	These actors are called to perform the most important tasks.

The analysis allowed us to identify the most crucial agents in the network accounting for the complexity of their relationships with the other agents, which affects their capability in moving information from one side of the network to the other. Moreover, the adopted approach assumed that an agent is crucial in the network performance if she/he brings important knowledge and if she/he cooperates in performing important tasks.

The results of analysis demonstrate the importance of the three most influential institutional actors at local, regional and national scales, i.e. the National Civil Protection, the Regional Civil Protection and the municipality (mayor and local civil protection). These actors had a dense network of interactions with the other agents (centrality measures), and had access to a wide set of crucial information allowing them to carry out crucial tasks. Beside these results, the analysis of the network emphasizes the actual role in the emergency management of the community leaders. These actors were not mentioned in the official protocol of intervention. Specifically, the community leaders could easily act as an interface between the institutional system and the local communities. Their high value of the betweenness centrality and hub centrality demonstrate that these actors could facilitate the sharing of the emergency information. The media were not mentioned by the participants. This is mainly because of the critical event selected for the discussion. During the 2009 earthquake, the social media were not still developed enough to actually support the emergency management.

The developed network was also analyzed in order to identify key vulnerabilities, i.e. those elements that could lead to failures of the emergency management operations and/or to decreasing effectiveness of the responding actions. The graph measures previously mentioned were implemented. The key vulnerabilities are described in the table 5.

Table 5: Key vulnerability in the network of Lorca flood emergency management

Type of elements	Key vulnerability	Meaning
Agent	Community leaders	This actor has a high degree of centrality but low degree of most knowledge. Therefore, she/he has access to limited knowledge impeding their role as information providers. They represents a barrier to information sharing rather than a bridge.
	Municipality	This actor has a high degree of most task and a low degree of most knowledge. This is mainly due to the limited capacity of the municipality to understand the technical information provided by the other actors. As result, the effectiveness of its action is limited.
	National Civil Protection	The analysis of the network shows the great importance of this actor. It represents the vertex of the network, because it tried to impose a strongly hierarchical structure. Due to this behavior, the capability of the local institutions to learn from this experience and to improve the emergency management procedures was negatively affected.
Knowledge	Locale emergency management plan	This information should play a crucial role since it has a high most task degree (it supports a large number of tasks), and a high centrality degree. Nevertheless, it is poorly shared among the different agents (low degree of most agent).
	Behaviour in case of emergency	This information represents a key vulnerability, because of its centrality among the community members, but very poor sharing with the institutions. This means that the institutions do not account for the capability of local community to react in case of emergency.
Task	Preparedness activity with community	This task is characterized by a high centrality degree in the *Task x Task* network. That is, it could facilitate the implementation of numerous other tasks. Nevertheless, only the municipality is responsible for the correct implementation of this task. An increased sharing of this task could increase its effectiveness.

2.2. Interaction between soft and hard infrastructures

Disasters are responsible for the occurrence of serious damages on structures and infrastructures, particularly in densely populated zones, such as urban areas. All the lifelines are significantly impacted by extreme events, and their functionality might be limited as a consequence of both physical damages and 'additional' occurrences (e.g. organizational issues, changes in population distribution, in service priorities in case of emergencies, …). Lifelines are thus highly vulnerable elements in emergency condition, but represent also a key resource to support a quick and effective recovery.

The impacts of disasters are devastating also from a socio-economic perspective. If a region is seriously impacted by a disaster, business closure may result in the prolonged inoperability of a community. How businesses deal with the impact of and recovery from disasters is fundamental for the whole community. The restoration of social networks in disaster impacted areas depends on obtaining goods and capitals, and on governmental policies; however, the characteristics of the community in which the business is located, may significantly condition recovery process and related strategies.

Disasters thus cause short- and long-term effects on social structures as well. Establishing causal relationships in social network formation and dynamics is difficult because of the complexity of engineering social relations in a controlled environment. The negative consequences people experience in any disaster are conditioned by their perceptions of risk and their vulnerability, and how these factors influence their ability to make and carry out decisions.
Among the emerging lessons in the immediate and long-term aftermath of disasters is the role that community organizations and community-based networks play in all stages of disaster preparedness and recovery. Community responses demonstrate the importance of local knowledge, resources, and cooperative strategies in determining their survival and recovery. Recovery processes are also closely coupled with preexisting conditions of community and social networks.

2.2.1. On the resilience of urban systems: the role of hard and soft infrastructures

The concept of resilience is strictly related to both static and dynamic components of disasters across pre and post event context. A static model of resilience identifies and organizes critical variables, whereas a dynamic model represents how and why such variables change across time and space. Resilient systems have a reduced probability of failure, lower consequences from failures and a reduced time for recovery. Referring specifically to urban environments, resilience is related to the capacity of cities to cope with and recover from external shocks. An urban system can be considered resilient if it is sustainable even during the hazard occurrence phase, the most critical period, in which the city suffers the impacts of an extreme event and tries to reconfigure both its physical and social aspects towards a new equilibrium.
The infrastructural system of a city has to be conceived as linked with social and institutional systems, but also with the economic and environmental ones that are all embedded within the urban context and dynamically interacting. Physical (hard) infrastructures involve amendments to the physical surroundings and landscape to serve a given purpose (e.g. transportation, power supply, water supply, management, and treatment). Social (soft) infrastructures refer to the networks and interactions among individuals, groups, and institutions within and outside the community. The link between them is crucial, since the resilience of a system is described by its level of functionality and assuming that it directly represents the level of satisfaction of citizen.
Enhancing resilience means improving the capacity of the whole system to anticipate threats, reduce vulnerability and allow a complete recovery from impacts. Several factors contribute to increase the resilience, which might not necessarily be related to the 'physical' characteristics of the system. They may depend on individual conditions (e.g. well-being and survival skills) and on community characteristics (community connectedness, community infrastructure, participation in disaster response and recovery, engagement in decision making). All these features are found to be highly influential before a disaster strikes, as well as in the event of a disaster and during recovery.
Several extreme events suggested that infrastructural systems play a fundamental role in keeping alive the social networks within a community in case of disasters by continuing to provide key services. The process of recovery after extreme events, is generally supported by the availability of critical services, which significantly contributes to increase the resilience of the whole community.

2.2.2. Knowledge collection and selection of methods

Following Tierney and Bruneau (2007)[2], the resilience of infrastructural systems derives from the integration of four dimensions: technical, organizational, social, and economic (*TOSE*). Going further into details, the technical domain refers primarily to the physical properties of systems, including the ability to resist damages, and the redundancy of the whole system. Organizational resilience is related to the organizations and institutions that manage the physical components of the systems,

[2] Tierney, K., & Bruneau, M. (2007). Conceptualizing and measuring resilience: A key to disaster loss Reduction.TR NEWS 250. pp. 14–18

and is thus significantly affected by 'culture': it encompasses measures of capacity, planning, training, leadership, experience, and information management that may improve (or hamper) disaster-related organizational performances and problem solving. Among the influential parameters, the ability to incorporate lessons learned from past disasters, the training and the experience of personnel should be considered. The social dimension includes population and community characteristics that render social groups either more vulnerable or more adaptable to hazards and disasters, and is strictly connected to 'cultural' issues as well: social indicators include for example, poverty, education, linguistic isolation, a lack of access to resources for protective action, such as evacuation. At last, economic resilience has been analyzed in terms of the inherent properties of local economies and in terms of their capacity for post-disaster improvisation, innovation, and resource substitution.
Culture thus represents a key asset in DRR and EM activities, even in engineering systems such as infrastructures. The interconnections between hard and soft infrastructures is particularly evident in the 'organizational' field (i.e. from the point of view of institutions and agents acting in emergency conditions) and in the 'social' field (i.e. in the way people deal with emergencies according to their personal beliefs, ideas and knowledge).

The Case Study of L'Aquila holds a key role in the history of disasters. The impacts of the earthquake over the whole province were wide and different, and related to both hard and soft infrastructural systems. On the one hand, the high vulnerability of buildings, structures and infrastructures caused severe impacts on the urban environment, and huge limitations to the basic services. On the other hand, the existing social networks were altered, also as a consequence of the physical damages on the built environment (e.g. citizens were moved to other places, either shelter camps or quasi-permanent settlements). L'Aquila earthquake thus highlighted how intertwined human and infrastructural systems can interact during and in the aftermath of an emergency, to support the whole phase of recovery from a disaster
The role of soft infrastructures was fundamental to support and drive the recovery phase, both in a 'passive' (e.g. the spatial distribution of the population drove the pattern of demand for specific services) and an 'active' way (e.g. culture, knowledge and relationships were key issues in overcoming the main limitations of the critical services). Particularly, the focus was set on the drinking water supply system for the following reasons: i) it resulted particularly vulnerable, from a structural point of view, to extreme events such as earthquakes and, specifically in L'Aquila, it was extensively damaged as a consequence of the sequence of seismic shocks; ii) it is a crucial service for the population, since drinking water must be provided to everyone even after disasters; iii) the service level depends on the spatial distribution of population, and changes dynamically with its evolution; iv) the repair/reconstruction of such infrastructural systems is a key aspect in the 'recovery' phase of the whole urban system, and is highly dependent on its topological features.

The identification of the most suitable methods for the analysis, and of their main potentialities/drawbacks, derived from both scientific literature and interaction with the experts. Similarly, the integration of the same sources of information allowed to develop a significant information base related to L'Aquila earthquake.
A literature review was performed mainly in order to:

- Have a comprehensive overview of the main hard infrastructural systems of the city, of their standard operating conditions and of their emergency operations.
- Characterize the dynamic evolution of the population after the event, in the short-medium-long term. The severity of impacts caused multiple changes to the population, with cascading impacts on the expected/required level of service for all the basic services. Just to provide an

example, the following Fig. 9 (from Contreras et al. 2014[3]) shows an overview of the spatial damage pattern after the earthquake in the urban area.

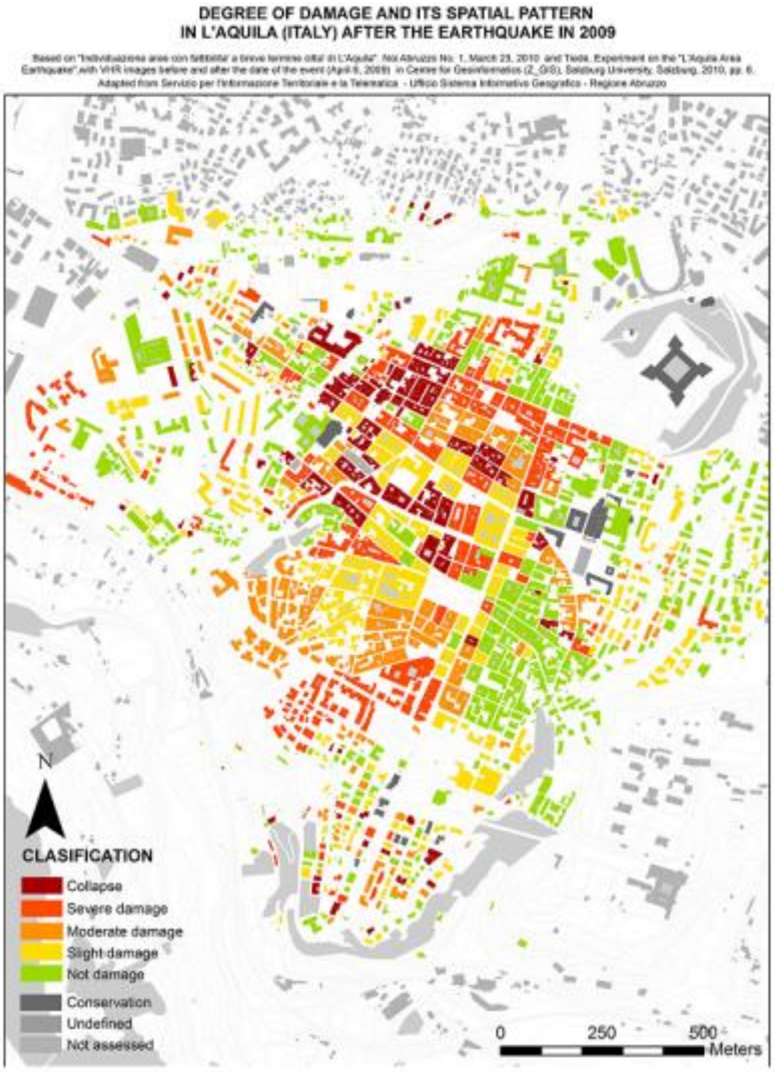


Fig. 9: Degree of damage and spatial pattern in L'Aquila after the earthquake in 2009

Semi structured interviews were performed as well with multiple local stakeholders in order to structure their expertise on the earthquake and its impacts, particularly focusing on drinking water supply systems. This supported in getting more information than those normally available in the scientific literature. The interviews mainly involved:

- Emergency managers, i.e. agents having different tasks in the aftermath of the event, whose main responsibility is guaranteeing the health, the safety and the well-being of a population after a disaster. Agents belonging to the Civil Protection authorities at different levels were mainly involved (i.e. Municipal, Regional, National)
- Other institutional agents 'interacting' in different ways with infrastructural systems in case of disasters (e.g. fire brigades, police, army, Red Cross, …)
- Utilities responsible for the functioning of critical infrastructures (i.e. Gran Sasso Acqua S.p.A. for water supply), both in normal and emergency operations. Their interviews were mainly

[3] Contreras D., Blaschke T., Kienberger S., Zeil P. (2014). Myths and realities about the recovery of L'Aquila after the earthquake. International Journal of Disaster Risk Reduction, 8:125–142

oriented at collecting basic information on: i) normal/emergency procedures for the management of infrastructural systems; ii) the key aspects and the most influential issues related to the four basic dimensions of resilience according to the TOSE approach; iii) a retrospective reconstruction of the emergency management and recovery phase referring to L'Aquila earthquake.
- Citizens/end users, mainly to collect information on the relationship they had with critical infrastructures during the earthquake in 2009, and to identify existing networks. The interviews were mainly oriented at: i) identifying the impacts of the disruption of infrastructures on their safety and well-being; ii) analyzing the evolution of service level for the key systems (mainly drinking water supply) in both EM and recovery; iii) investigating to what extent the culture and knowledge of people may support the EM procedures for hard infrastructures, and which are the main drivers influencing the 'social' dimension of resilience.

Starting also from the evidences available in the literature, and with the support of the involved stakeholders, two main modeling approaches were adopted: **SDM** was used to operationalize the TOSE approach to resilience, providing a tool to describe the dynamic evolution of a complex system; **Network Graph Theory** was used to propose a set of metrics to support the analysis of the key properties of a complex infrastructure, in the view also of the assessment of its connections with the network of users.

SDM

SDM consists of qualitative/conceptual and quantitative/numerical modelling methods. Qualitative modelling, e.g. based on causal loop diagrams, improves our conceptual system understanding. Quantitative modelling, e.g. stock-and-flow models, allows to investigate and visualize the effects of different strategies through simulation.
Causal loop diagrams and then, stock and flow diagrams, model relationships among variables which have the potential to change over time. Such models distinguish between different types of variables: there are stocks (or level or accumulation) and flows (or rate). A stock is a measurable accumulation of physical or non-physical resources, whereas a flow is the movement of something from one stock to another. Generally, stocks are graphically expressed as boxes, whereas flows are represented by arrows (Figure 10). It is interesting to consider that almost every business process, and its related components, can be expressed in terms of stocks and flows.

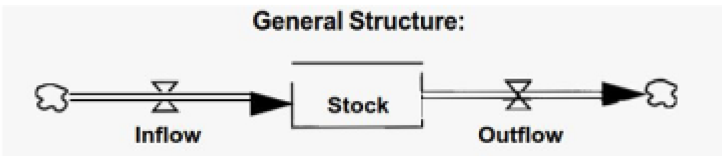


Fig. 10. Graphical representation of stock and flow notation

SDM is a particularly effective modeling solution if the system is complex and an analytical solution could be excessively time consuming or simply impossible. It shows significant capabilities for modeling decision-making processes and human behaviors, thus being particularly useful for analyzing organizational evolution. Such approach may reveal really useful in describing the way policies, delays, and structures are related, and how they influence the stability of the system. The strength of SDM also lies in its ability to account for nonlinearity in dynamics, feedbacks, and time delays.
The use of a SD model supported us to identify and analyze the main elements fostering or hampering resilience. The model had been used to evaluate the impact of actions and strategies for resilience improvement on the dynamic evolution of the system. Finally, it has been used to identify

critical feedbacks, and to evaluate their influence on the implementation of policies aiming to enhance LS resilience, assessing their evolution with time.
An SDM project typically consists of four main phases: problem definition, system conceptualization, model formulation, model evaluation/testing, policy analysis and implementation. The development of SD models is helpful for an improved system understanding, and the development of a tool to analyze and evaluate strategies and policies, and the testing of theories.
The following Figure 11 summarizes the main steps performed for model building and validation.

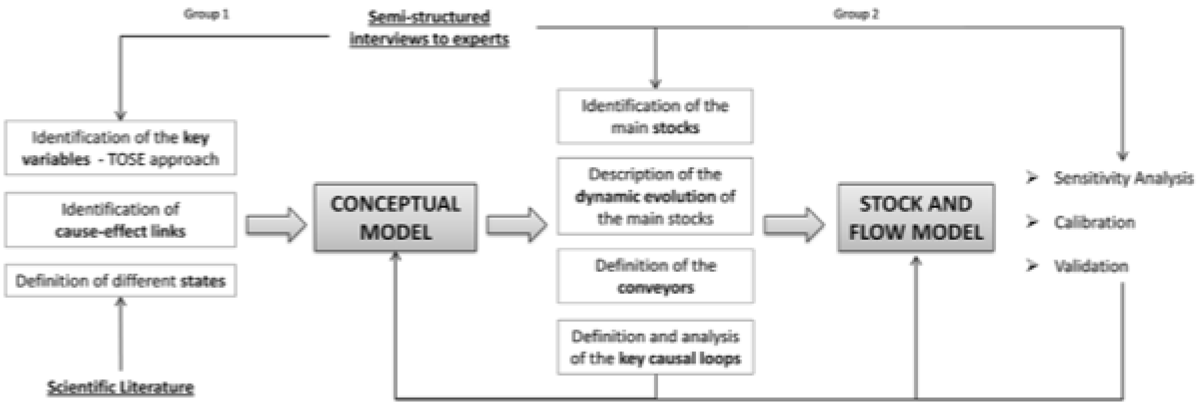


Fig. 11. Steps for information collection, model building and validation.

The key phases were:

a. Knowledge elicitation

Modeling activities required a careful integration of the scientific knowledge available in literature with expert knowledge, which was elicited through semi-structured interviews, according to participatory work principles. Literature evidences were used to develop the first version of the conceptual model identifying the main cause-effect relationships. The domain experts, both institutional actors and citizens directly involved in emergency activities, cooperated in the knowledge elicitation and preliminary modelling phases.

b. Conceptual modeling

The experts involved in modeling activities (institutional actors, researchers and citizens) were clustered in two different groups in order to support on one hand the phase of conceptual model building and on the other the definition of the stock and flow model, with its consequential calibration and validation.
The process of group model building started from the conceptual model definition, representing the sum of cause-effect chains influencing the stock and flow model. In order to gather the fundamental individual and collective knowledge, the domain experts integrated the conceptual model, adding or deleting variables and modifying links. The modelling process ended when no new concepts and/or relationships emerged after a number of interviews and researchers supported the global model design. The interviews were carried out limiting bias in expert knowledge collection: particular attention was made on problem framing (to reduce subjectivity and ambiguity), availability issues (the tendency to overestimate the magnitude of recent/familiar events) and anchoring (systematic underestimation of uncertainty/variability).
Specifically, the experts were asked to describe the main variables and to properly connect them according to the expected influences. They were also asked to provide a quantitative interpretation of all the considered variables (even non-physical ones, such as knowledge level) and of their potential states. Finally, they were asked to describe the dynamic evolution of the variables, the main causes of these changes and the potential effects.

c. SDM model building

The conceptual model was then used as a basis for the development of the stock-and-flow model. A first subset of variables was defined referring to the conceptual model, i.e. level of knowledge, available economic resources, water demand (from both population on site and population in shelter camps), level of service/loss of service. Such variables were modeled as stocks, according to the SDM methodology, since they describe the accumulation or depletion of both physical and non-physical resources. Another subset of variables was defined and modeled as 'conveyors' using the collected knowledge. Those variables are related to either externally specified conditions (e.g. 'intensity of the hazard'), or to actions/policies that can be implemented and may have an influence on resilience levels (e.g. increasing the training level of employees, implement monitoring activities, availability of GIS and database).

The general structure of the model was then discussed with a sub-group of experts, who reviewed the variables and their relationships. Additionally, a quantitative calibration was performed referring to L'Aquila earthquake case study. A few key stocks were selected for calibration (e.g. 'water deficit'), and their dynamic evolution was simulated. Experts were asked to identify for each variable a scatter plot to build an expected trend. The comparison between the expected and the predicted trend allowed the calibration of the key equations used in the model. Small deviations were attributed to the difficulties in collecting reliable data. Nevertheless, the experts considered these deviations as minor. The conceptual structure of the model is proposed in the following Fig. 12.

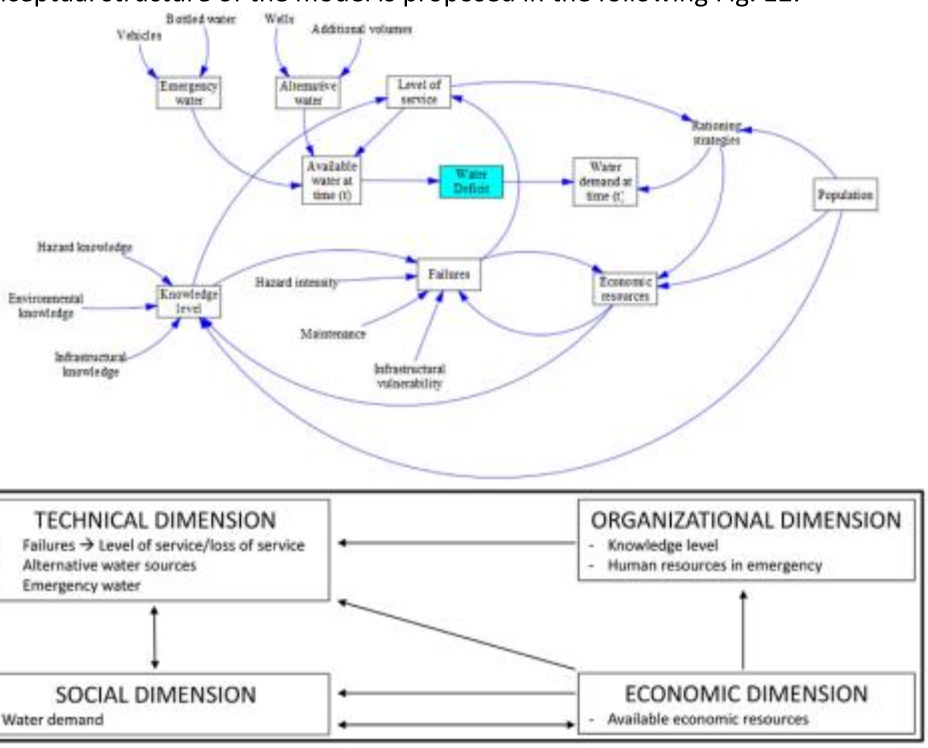


Fig. 12. Conceptual scheme of the resilience assessment model based on TOSE approach

Referring to the above Figure, the dimensions of resilience were defined adapting the general framework, adapting it to a drinking water supply system. The scheme was built in order to deal separately with the four basic dimensions of resilience. Then the reciprocal influences among variables were identified. For instance, some capabilities reflecting organizational culture (e.g. the availability of human resources, the availability of a good knowledge concerning the infrastructure and the environment) which may have a direct influence on system resilience (i.e. they support a quick and effective response to technical issues) are explicitly included. The role of the social dimension was identified as a key element contributing to resilience, particularly focusing on the characterization of how behaviors, attitudes and awareness of the served population may either help or hamper resilience. The model mainly aims at providing information on the water deficit during

emergency and in the immediate aftermath, performing a comparison between water inflow and water demand.
The global model of resilience is plotted in the following Fig. 13 (full details are in Pagano et al. 2017[4]).

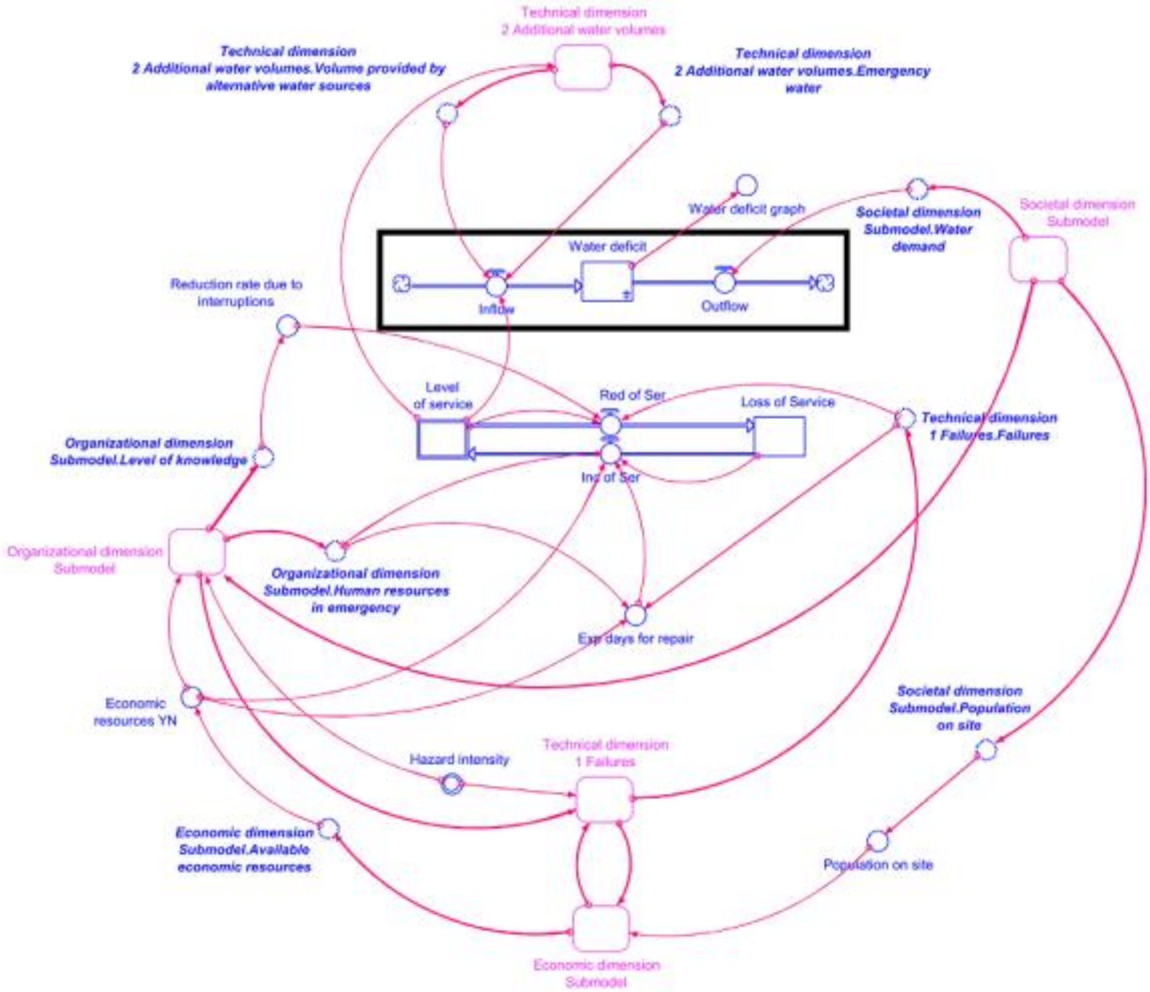


Fig. 13: SD based resilience assessment model

Specific sub-models are identified by purple boxes and defined in order to deal with key issues contributing to resilience according to the TOSE conceptualization. Most of the sub-models are mutually interconnected, and can be run and analyzed independently
Just to provide an overview of the whole model, the 'inflow' volume is primarily conditioned by the water that can be conveyed using the existing infrastructure. This depends on the expected 'failures' (sub-model 'Technical dimension 1–Failures'), which are to a set of variables derive by other sub-models, and related to economic 'Organizational dimension', 'Societal dimension' and 'Economic dimension'. During emergencies, the inflow volume is also integrated using alternative sources ('volume provided by alternative water sources'), such as wells or 'other available volumes' (e.g. tanks). 'Emergency water' sources are activated as well ('emergency vehicles' or "bottled water") to compensate the reduction of available water volumes (sub-model 'Technical dimension – 2 Additional water volumes'). Each of the sub-models considered provides a quantitative insight into the main dynamics of the specific dimensions of the TOSE approach.

[4] Pagano A., Pluchinotta I., Giordano R., Vurro M. (2017). Drinking water supply in resilient cities: Notes from L'Aquila earthquake case study. Sustainable Cities and Society 28: 435–449

Particularly focusing on the 'Organizational dimension', the model describes the impacts on the system resilience due to the development of a full understanding (a *culture*) of the infrastructural system, the surrounding environment and the hazard (e.g. 'infrastructural knowledge', 'environmental knowledge' and 'hazard or event knowledge'). This goal is achieved through the enhancement of information acquisition (e.g. 'field surveys', 'monitoring and forecasting', 'infrastructure monitoring') and sharing capabilities (e.g. 'availability of GIS and database', 'cooperation with other institutions'). Moreover, the model displays how the timeliness and the effectiveness of the involvement of 'human resources in emergency' is of utmost importance. To this aim, 'training level' plays also a crucial role as well as 'concern and cooperation' attitude. The model shows also (sub-model 'Economic dimension') the role of the interdependencies between the 'available economic resources' and the capability of the infrastructure to cope with 'failures'. It displays that the reduction of the population using the water services (due to delocalization either in other cities or in the shelter camps) results in a decrease of the available economic resources ('incomes'). Internal economic resourcefulness and 'emergency economic resources' than can be activated after the occurrence of a disaster are included. From the social point of view (sub-model 'Societal dimension'), the model is able to simulate the spatial/temporal dynamic of the local population ('Population on site', 'population delocalized', 'population in the shelter camps') as a function of the expected damage on buildings ('total buildings', 'collapsed' and 'damaged'); consequently, the required level of service ('Water demand') is changed, also considering the potential 'reduction ratio' strategies and the 'community awareness'.

Graph Network Theory

The interconnectedness between hard and soft infrastructural systems was further investigated using techniques based on Graph Theory. A complete overview of the adoption of Graph Network Theory for the analysis of infrastructures such as water supply systems was proposed by several authors (e.g. Yazdani et al. 2011[5]).
The topology of critical infrastructures, such as water distribution systems, can be easily described through the definition of a network of nodes connected by links. The structure of the network itself reflects the characteristics of the underlying network of users of the service, both in terms of spatial pattern and in terms of service requirements and expected performances (e.g. the nodes reflect the water demand). The topology and the functionality are thus two strictly intertwined aspects of the operation of the whole system. It is worth to consider that this underlying pattern of users, and their specific needs, evolves with time during the whole emergency, and thus the network should be flexible enough to provide a sufficient level of service, although somehow limited, even in case of dramatic changes in some conditions (e.g. extensive damages in the network).
Such a network is typically governed by complex structures and dynamical processes, due to the large number of interconnected and interacting components. A quite simple way to model such networks is to represent the structure of the system through a mathematical graph, collecting nodes to represent specific elements and links to represent the pipes between nodes.
The study of complex networks by using graph theory helps with the classification of different networks and with the analysis of the influence of their shape and connectedness on the vulnerability, robustness and tolerance.
Structural measurements may quantify the connectivity patterns among the network components. These metrics become trivial in WDNs which exhibit low redundancy and sparseness at transmission or subsystem level. The structural network measurements can be classified in several ways, but mainly into statistical and spectral forms. All the topological metrics can be used to assess the

[5] Yazdani A., Appiah Otoo R., Jeffrey P. (2011) Resilience enhancing expansion strategies for water distribution systems: A network theory approach, Environmental Modelling & Software 26 : 1574-1582

reliability of complex networks, describing the influence of the underlying structure and connectivity constrains on network behavior.

The selection of a set of indicators/metrics allows identifying the key elements to support proper network operation, to prioritize actions to deal with emergency and to check whether a sub-network of users (e.g. the "critical" ones, such as the system of hospitals, shelter camps, …) can be supplied by the hard infrastructural system in variable operating scenarios.

L'Aquila case study is pretty unique and relevant also because it allows the comparative analysis of two different networks operating within almost the same urban pattern. The urban water distribution system was completely redesigned after the disaster and is currently being built (further details are in the box "Reconstructing urban infrastructures after extreme events: the case of L'Aquila drinking water distribution network"). The same methodology was implemented to assess both infrastructural configurations, and selected metrics used to compare systems. In the following Figures 14 and 15 the two systems are depicted ('OLD' and 'NEW' networks), along with their representation according to network theory formalization.

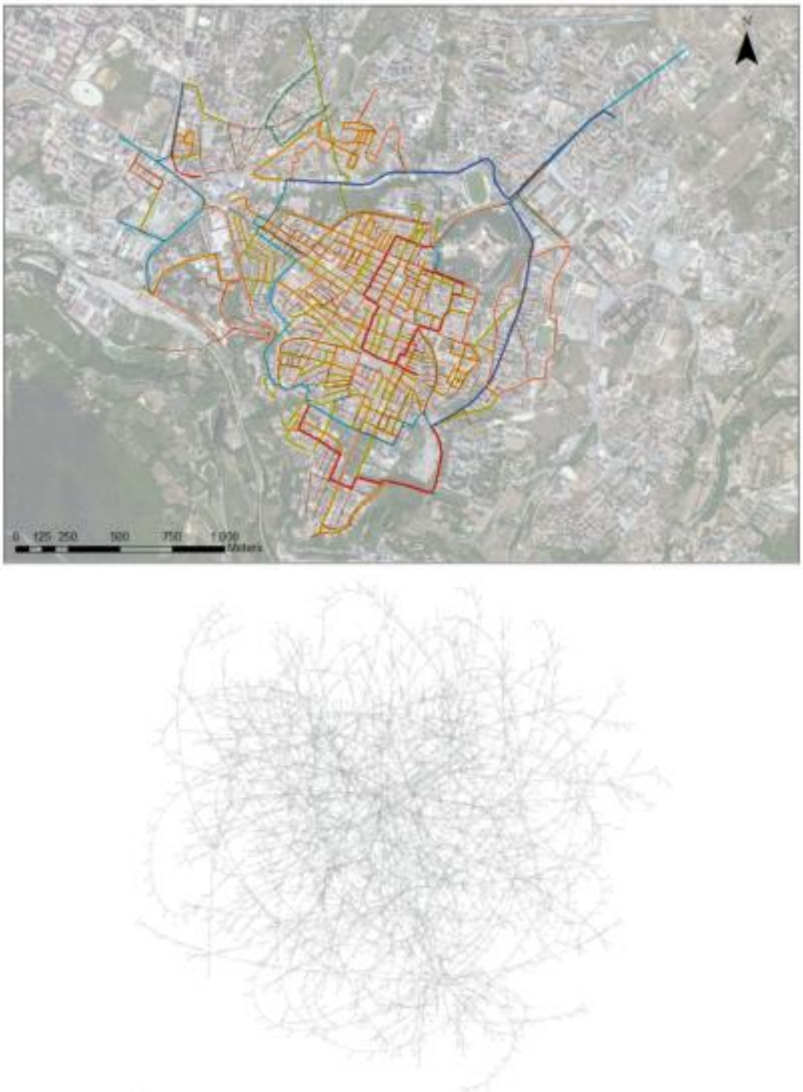


Fig. 14. Urban water distribution network before the earthquake ('OLD' network).

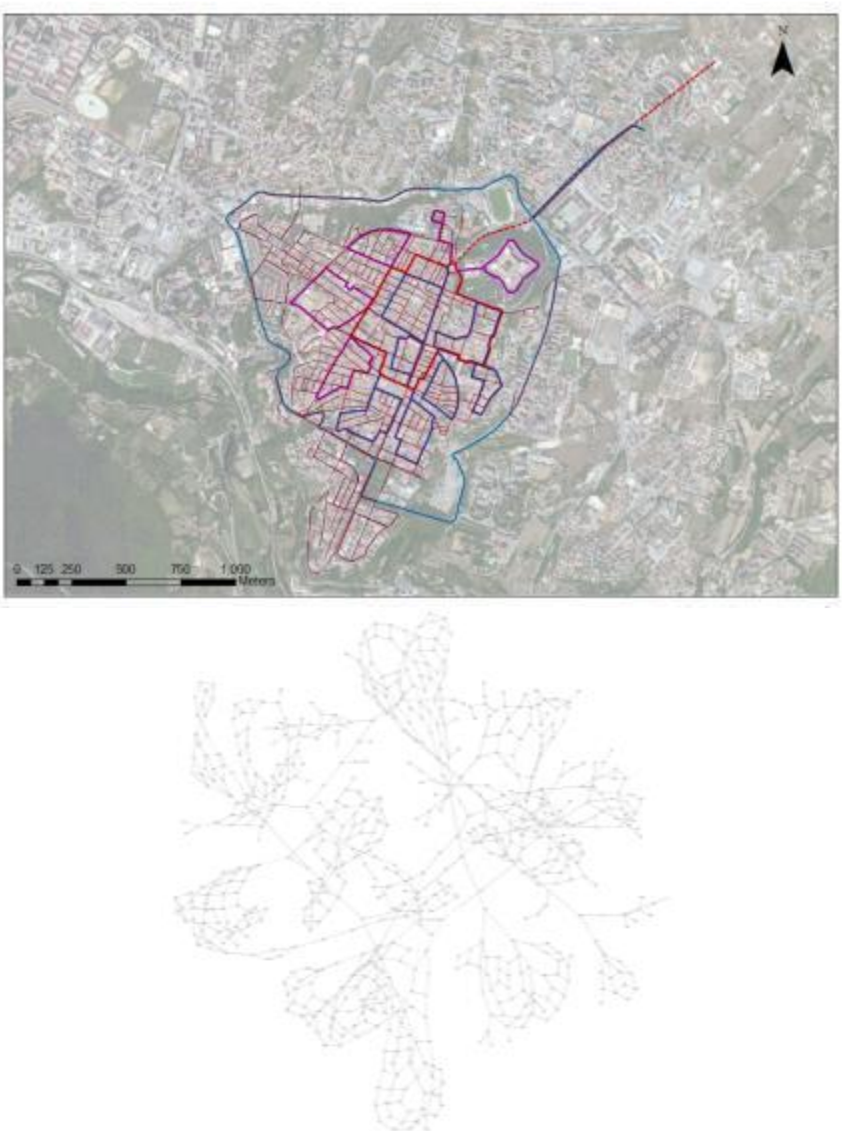


Fig. 15. Urban water distribution network after the earthquake ('NEW' network).

Following the available literature, a few metrics were used to describe the key aspects of the networks in terms of reliability in case of extreme events. Most of metrics reflect either the robustness or the flexibility of the system. The adopted measures are summarized in the following:

- **Link density *q*** (Network density) is the most basic indicator of the linkedness or sparseness of the structure of a network.
- **Average node degree *k*** is a basic measure of node connectivity. It reflects the overall topological similarity of the network to perfect grids or lattice-like structures.
- **Network diameter**: captures the maximum eccentricity of nodes in the network.
- **Average path-length l_T**: estimates the average number of links that need to be traversed in order to reach from one point to another, representing network reachability and efficiency.
- **Clustering coefficient C_c**, is used to measure the redundancy by quantifying the density of triangular loops and the degree to which junctions in a graph tend to be linked.
- **Meshed-ness coefficient R_m** provides an estimation of topological redundancy by finding the number of independent loops as a percentage of the maximum possible loops.
- **Central-point dominance C_B** measures the concentration of the network topology around a central location. It quantifies network vulnerability against failures.

- **Density of articulation points D_{ap}** estimates the percentage of the nodes/junctions whose failure may potentially disrupt water delivery by isolating a part of the network.
- **Density of bridges D_{br}** estimates the percentage of the links/pipes whose failure may potentially disrupt water delivery by isolating a part of the.
- **Spectral gap $\Delta\lambda$** is computed as the difference between the first and second eigenvalues of the adjacency matrix. Small spectral gap would probably indicate the presence of articulation points or bridges.
- **Algebraic connectivity $\lambda 2$:** higher values suggest better network's structural robustness and fault tolerance.
- **Critical ratio of defragmentation f_c** provides a theoretical value for the critical fraction of the nodes which need to be removed for a network to lose its large scale connectivity.

The measures, computed in an undirected and unweighted version, are summarized in the following Table 6. It is worth mentioning that the 'NEW' network is made of two independent subnetworks ('CS' – Centro Storico and 'ZM' – Zona Media), and thus the metrics were computed for both independently.

Table 6. Results of the computed metrics in the 'OLD' and 'NEW' networks.

NETWORK	q	k		l_T	C_c	R_m	C_B	D_{ap}	D_{br}	λ_2	$\Delta\lambda$	f_c
NEW – CS	0.006	3.00	26	13.43	0.041	0.252	0.412	0.1	0.11	0.0027	0.3869	0.500
NEW – ZM	0.013	2.63	23	10.74	0.02	0.162	0.584	0.285	0.51	0.004	0.3798	0.387
OLD	0.0006	2.15	97	32.76	0.004	037	0.455	0.391		0.00041	1.1247	0.127

Reconstructing urban infrastructures after extreme events: the case of L'Aquila drinking water distribution network

As a consequence of the earthquake and of its impacts on the built environment, L'Aquila is still undergoing a complex process of reconstruction. Particularly, on the one hand the extent of damages in the whole urban area limited the functionality of infrastructures and the accessibility for community; on the other hand, the changes in the population localization due to both temporary sheltering strategies and to the evolution of new permanent areas, forced a radical change of the performances required to the infrastructures.

Figure. One of the main damages in 2009: Gran Sasso Aqueduct

The experience and the knowledge developed during the Earthquake in 2009 and in the aftermath of the disaster, provided crucial information to support the reconstruction. Learning from past errors and from the key criticalities encountered was a fundamental step for an innovative, sustainable, effective, safe, 'resilient' design. Just to provide an example, the high uncertainty of the available information and the poor accessibility of some infrastructures often limited the possibility to operate promptly during the emergency; similarly, the need to adapt the whole network to both changes in the urban pattern and specific local needs (e.g. the need to provide some buildings with water using a network with a huge number of breaks) during the reconstruction phase, caused significant stress levels for the system. The urban critical infrastructural systems were thus deeply rethought, and redesigned according to the new needs of the city, and to the experience.

The design of the 'SMART TUNNEL' reflects a basic principle: electricity, gas, water and communication systems are key services supporting daily activities and the well-being of a community. The basic idea behind the smart tunnel is simply to collect and integrate all the critical services in an 'invisible' shell, i.e. an underground concrete gallery, in order to protect them from external threats and make them easily accessible and repairable, both in case of disasters and in ordinary operation.

Providing safe drinking water to a community in case of disasters is one of the main commitments of emergency managers and local authorities. Particularly, GSA S.p.A. was directly involved in the aftermath of the event, in the operations to recover the functionality of infrastructural systems. The urban water distribution network of L'Aquila city, particularly, is being currently rebuilt according to innovative criteria, such as the distrectualization. The basic idea is to split the whole network into a number of subsystems characterized by spatial and functionality homogeneity in order to facilitate maintenance and management procedures. Distrectualization allows: a) controlling leakages and water losses; b) isolating single subsections of the whole network; c) implementing more effective measurements of hydraulic parameters. The distrectualization supports flexibility and adaptation capability to the evolution of the urban pattern, and thus is strongly connected to the evolution of the whole city.

Ing. Stefano PACITTI – Gran Sasso Acqua S.p.A.

Full details can be found at the following website: http://www.sottoserviziaq.it/it/home.html

3. SYNTHESIS AND LESSONS LEARNED

This section describes the main outcomes of the L'Aquila Case Study in terms of lessons learned. Similarly to the structure of the CS objectives, the discussion about the main outcomes is structured according three main line of reasoning, i.e.:

- main outcomes for the emergency managers,
- main outcomes for the practitioners, and
- main outcomes for the community.

3.1. Main outcomes for the emergency managers

3.1.1. Social Network analysis

A workshop was organized in the CS, aiming at discussing the results of the analysis and to start the debate about the potential improvements of the current emergency management procedures. The main institutional actors involved in the previous EDUCEN activities were invited. The analysis of the results and the consequent debate allowed the participant to become aware of the oversimplification of the interactional structure at the basis of the development of formal protocols of intervention. This protocol is characterized by a strongly hierarchical and inflexible structure, and represented a barrier to the enabling of an actual collaborative emergency management process involving the different actors. This was mainly because of its incapability to account for the actual role played by the different actors and for the resources required for supporting the cooperation among them. The official protocol described only a small part of the complex network, that is, the institutional and formal interactions. The collected knowledge demonstrated that, during an emergency, informal interactions were activated even among institutional actors, based on personal and already established relationships. Moreover, the set of information exchanged within this informal networks is often broader than the one defined by the official protocols of information exchange.

The methodology allowed the CS to map the complexity of the interactions and, through the selection of a set of graph theory measures, to better comprehend the interaction mechanisms influencing the effectiveness of the cooperative emergency response. That is, what information needs to be shared, what task needs to be cooperatively implemented. Moreover, the analysis allowed the CS to define the actual role played by each actor, according to the information they bring in the network, and their role in performing the emergency management tasks. The results of the analysis were used by the local stakeholders to inform the debate and to identify potential improvements of the protocol of intervention and cooperation. Therefore, the results demonstrated that improving the cooperation in emergency management claims for a better understanding of the interdependence principle, that is, a collaborative emergency management claims for tools and methodologies capable to create a decision-making environment in which parties are fully aware of their role and the roles of the others in the interaction space.

Moreover, the obtained results demonstrated that the methodology was capable to account for the differences in organizational culture and to analyze how those differences could lead to different management of emergency information. On the one hand, some institutional actors – e.g. the Municipality – considered the multi-central structure as the most effective structure in allowing the rapid exchange of information within each level of the organizational structure and between different levels. These actors seemed capable to adapt their information collection strategy to the different conditions, showing resilience to failures of the official protocols of information sharing. Institutional actors with a dense network of interactions – i.e. the Municipality – seemed to be capable to shift from the formal to the informal network in order to gather the needed information. On the other hand, the official responders – e.g. the national civil protection – assumed a strongly hierarchical structure of the information exchange process. These actors trusted exclusively information flowing from the vertex through intermediary, and easily recognizable, levels. This is because they needed to reduce the "noises" in information collection. Neglecting these differences could lead to the development of ineffective strategies for information sharing for emergency management. Integrating the Municipality in a hierarchically structured network could negatively affect its role as response coordinator. Contrarily, increasing the number of information centres in the responders' networks could lead to the paralysis of their activities. The experiences carried out in L'Aquila suggested that developing effective emergency management strategies requires a clear understating of the differences among agents' understanding of the interaction network.

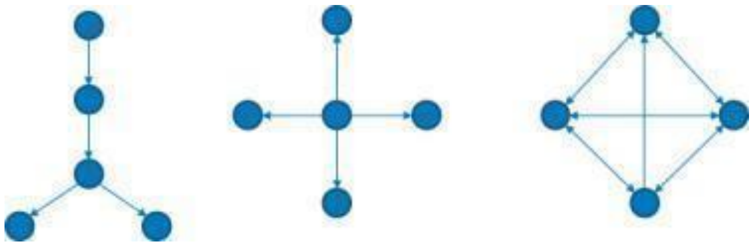


Fig. 16: Ambiguity in the perception of the topology of the interaction network

Finally, the adopted methodology allowed the CS to emphasize the role of the community in the emergency management phases, and to make the institutional actors aware of the need to account for the community's understanding of the emergency situation. Specifically, the analysis of the community's CM and the related network allowed us to better comprehend the reasons of the low level of trust toward the institutional information. The community's network has a strong multi-centred structure, allowing community's members to select the more suitable information sources and activate informal networks of information sharing. This is mainly due to the limited comprehensibility of the information provided through the institutional channels. The analysis of the network allowed to define the central role played by the community leaders in facilitating the flow of information. They represent the actual information centres for the community. This result was considered as crucial for the definition of potential improvements of the emergency management procedure

Lessons learned for the local civil protection agency

The involvement of the Municipal branch of the Civil Protection Agency in the EDUCEN project allowed to establish a fruitful debate with the other institutions involved in the emergency management at urban level. The bilateral meetings and the workshops organized during the implementation of the CS activities allowed us to better comprehend the diversity of the intervention procedures for the different institutional actors. The EDUCEN activities shed a light on the complexity of the coordination activities in case of emergency, when different actors need to collaborate in order to develop a common ground of information for the implementation of the different emergency actions.

Another crucial lesson learned during the implementation of the EDUCEN project concerns the difficulties in transferring important information to the community during the different phases of the emergency. Specifically, the meetings organized in L'Aquila CS allowed us to questioning the institutional information flow channels. The narratives collected during the CS implementation demonstrated that coupling the formal information flow channels with the existing informal networks could lead to an increase of the rapidity and effectiveness of the information sharing process.

3.1.2. Interaction between soft and hard infrastructure

Several meetings were held, also with a direct involvement of emergency managers, in order to get feedbacks on the activities performed and to summarize the most important outcomes of the Case Study.

From a **methodological point of view**, the main advantage connected to the modeling was related to the operationalization of the TOSE paradigm for resilience, accounting for its dynamic and complex nature. The model revealed suitable for LS resilience assessment and management, not necessarily limiting to water supply systems.

The cooperation of emergency managers in the activity was particularly positive both in the phase of model building and in the phase of model implementation and validation. The involvement of experts was required at multiple levels and with several purposes:

- understanding the system and its boundaries
- identifying the key variables
- describing the processes that affect variables through mathematical relationships
- mapping the structure of the model
- simulating scenarios for understanding model behavior.

The involvement of emergency managers helped developing the awareness on the need for an innovative approach to infrastructural resilience, moving beyond the traditional technical one. The approach based on SDM was thus highly useful to provide a formalization of the interconnections among such different dimensions concurring to resilience, and to integrate a complex set of variables.

Similarly, the approach based on graph theory was discussed as well, being particularly significant mainly because of the similarities with the approach that has been used to perform the SNA to analyze the network of relationships among actors involved in emergency management activities. Thus, from both a conceptual and a practical point of view, the methodology is common, and the same tools and comparable metrics can be used (with specifications depending on the focus of the analysis).

From a **theoretical point of view**, the main conclusions drawn by emergency managers are summarized in the following:

- Physical infrastructures provide a vital support to communities during emergency and recovery phases after a disaster. On the one hand, the uninterrupted availability of critical services is a requirement to guarantee the safety and the well-being of a population when a disaster occurs and speeds up the recovery: in this direction, the technical performances of the whole infrastructural system are a key asset to deal effectively with emergencies and contribute to community resilience. On the other hand, the resilience of a community affects the level of service provided by the hard infrastructural system as well: the behaviors of the users (e.g. good practices, flexibility, …), their level of knowledge along with the skills of the authorities managing the emergency and driving decision-making – in a word, their *culture* - have a direct influence on the response of the hard infrastructural system.

- Infrastructural systems must directly match the needs of a community, and thus should firstly reflect the spatial distribution of the served population. Secondly, the performances of infrastructural systems should be flexible enough to evolve with time, in the aftermath of a disaster and in the recovery phase as well, since the needs of the whole system change according to the specific path of recovery determined by the specific strategies implemented.

- Complex systems exposed to extreme events significantly change their state and conditions over time. Dynamic approaches are therefore needed to analyze their evolution, since they allow describing the change of system conditions through the different phases, taking explicitly into account the impact of strategies and decisions to cope with emergency conditions (through scenario analysis).

Starting from the above considerations, meetings were also held in order to discuss the applicability of the model in order to perform scenario analysis: this may support decision-makers to understand the impact of different strategies, conditions, assumptions on the response of the system.
The results of scenario analysis are summarized in the following Fig. 17. The key outcome is the evolution of water deficit with time, according to the specific contribution of all the aspects and variables considered in the TOSE approach to resilience. The comparative analysis of multiple scenarios helps describing the impact of different states of specific variables on the model outcomes. Starting from the Scenario 0, which reconstructs the 'real' evolution of the events after the earthquake, the others are built for the purpose of comparison as follows: 'Scenario 1' shows how a decrease in organizational skills may have a dramatic influence on system response; 'Scenario 2' simulates a decrease of 'infrastructure physical vulnerability' which, although expensive has a definitely positive impact; 'Scenario 3' describes instead an integrated strategy where infrastructural improvement actions are supported by also by a better 'knowledge of critical points', 'training level' of the personnel and enhancement of 'community awareness'.

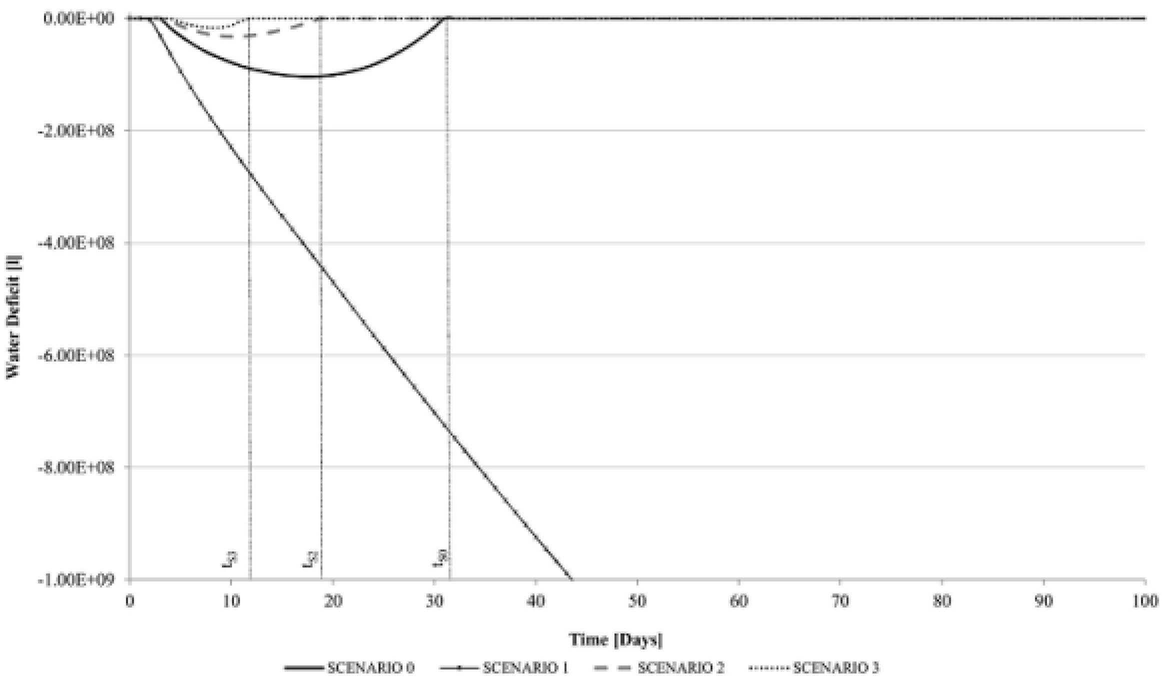


Fig. 17. Results of the resilience assessment in terms of 'Water deficit' for the modeled scenarios.

The results were discussed in details with the experts, and clearly underlined that the role of 'non-structural' measures on soft infrastructural system might be important as well as structural ones to increase resilience. Particularly, acting on several 'cultural' issues related to both individual (e.g. people awareness) and organizational features (e.g. cooperation, training level, knowledge) may have a benefit comparable with the one associated to the implementation of structural measures.

3.2. Main outcomes for the practitioners

3.2.1. Social Network analysis

One of the main results of the L'Aquila CS concerns the replicability of the methodologies and tools developed and/or implemented in the CS. During the implementation of EDUCEN project, two

"follower" case studies were interested in implementing the methodologies for the analysis of the complexity of emergency interaction networks, i.e. Lorca (Spain – flash flood) and Valladolid (Spain – flood). Specifically, the Lorca CS allowed us to start the structuring of the training materials, whose main scope is to enable the transferability of the methodologies and tools to other contexts. The Valladolid case allowed us to test the effectiveness of the transferability protocol.
At the end of this process, the following training material (Table 7) were developed and make available for being used in other case studies:

Table 7: current status of the training materials.

Training materials	Available	In preparation
Protocols for the interviews	X	
Guidelines for the CM development	X	
Guidelines for the meta-matrix development		X
Guidelines for the network analysis		X

The training materials are meant to facilitate the replication of the developed methodology in other potential case studies. The objectives is to enable the creation of a community of practice, composed by experts in emergency management capable to support emergency managers in better comprehending the complexity of the interaction networks. The training materials will be disseminated as annexes to this manual, and will concern the different methods and tools described in this manual.

3.2.2. Interaction between soft and hard infrastructure

Referring specifically to the theme of hard/soft infrastructures interconnections, the replicability of tools and methodologies was not directly tested in other cases. Nevertheless, the proposed methodologies are based on a solid scientific basis, with several previous applications, and have been deeply tested as well, in order to limit potential 'case specific' issues.
The main outcomes discussed with practitioners are summarized in the following:

- Classical approaches to infrastructural reliability or performance level may be limited in describing the complexity of real systems. The resilience assessment of engineering systems, such as infrastructures requires a comprehensive approach moving beyond the merely technical dimension. The 'culture' (of both organizations and communities) is a key asset to describe resilience. The CS allowed to broaden the perspective with specific reference to more traditional approaches to resilience, going beyond the mere analysis of the structural (or 'technical') dimension. The operational dimension takes into account the preparedness of the authorities to cope with emergency situation, their resourcefulness, their rapidity, the internal skills and flexibility. The social dimension is strictly connected with the capability that the community (and its sub-groups) show in dealing with emergency conditions. The economic dimension of resilience is a key driver too, either accelerating or stopping the processes related to emergency management and recovery.

- The SDM model allows the definition of scenarios, which can be used to perform a 'what-if' analysis. The 'what-if' analysis support measuring how changes in a set of independent variables might influence dependent variables in a simulation model, to anticipate the potential evolutions of the system. This analysis is highly relevant to identify the impacts of the implementation (or absence) of specific strategies to enhance system's resilience in all its dimensions.

The analysis based on Network Theory principles was performed, with the direct support of the local water utility, on the whole drinking water supply system in L'Aquila. Besides being useful to describe ordinary operation, it is worth considering that techniques based on graph theory can be adopted to analyze and compare different systems operating in both normal and extreme conditions. Particularly, the analysis supports the description of infrastructural systems capability to either resist stresses induced by extreme events or to adapt to changes in specific operating conditions (e.g. the spatial distribution of population, the location of emergency areas, the reconstruction phase, …).
The 'unique' potentiality connected with the case study was also related to the opportunity to compare two water supply systems located in the same area: the existing network, before the earthquake, and the new one (redesigned after the disaster). This helped in analyzing the differences in design criteria, and the capability to match the specific needs of a complex urban pattern. The discussion of the results clearly showed that, according to the analyzed metrics, the re-design of the urban WDS provided a positive impact on the whole urban system. The resilience of the new network, designed according to the criteria of 'distrectualization' was significantly higher. The new network has a definitely higher flexibility and capability to absorb stresses and changes in operating conditions. This is also a key requisite to adapt to the network of users and to the spatial and temporal evolution of the population patterns in the urban area.

3.3. Main outcomes for the local community

Finally, the analysis of the activities carried out in the L'Aquila CS allowed to identify important outcomes for the community. The discussion that took place during the participatory exercise, and the debate supported by the results of the EDUCEN analysis, make the local community aware of their role as emergency responders. Specifically, they become aware of the importance of the dense connection among different actors at local level to be used as an alternative channel to make the emergency information flowing as fast as possible. Moreover, the role of the community leaders (i.e. representative of the citizens' associations, etc.) as crucial interface between the institutional system and the other members of the community. That is, they could facilitate the flow of information and support the local authorities in translating technical information into understandable and actionable information for the community.

Citizens are generally the first responders when a disaster strikes, and thus represent a key 'backup' resource in emergency conditions with respect to official ones, supporting the operation of critical services. The existing connections within a community, and the main features of the community itself, represent a fundamental asset to deal with disasters. Referring to infrastructural systems, the behaviors of people and users of critical services are highly influential on the performance path of an infrastructural systems, either hampering or fostering the processes of recovery, and contributing to determine the entity of impacts. The available knowledge, particularly related to the memory of previous disasters, is a key issue as well, since support the citizens in developing a better awareness and in the implementation of the most suitable behaviors.

4. THE WAY FORWARD

This section of the manual describes how the experiences in the L'Aquila CS can be transferred in other case studies, supporting the dissemination phase.

4.1. Preparing for the next time

The transferability of the L'Aquila CS experiences to other CS was already partially tested during the EDUCEN implementation. Two other cities demonstrated interest in implementing the L'Aquila integrated approach for the assessment of the effectiveness of the interaction network in case of emergency. This section describes the lessons learned during the "experiences transfer" process.
The transferability of the methodology was, roughly speaking, successful. Specifically, the first transfer process involving Lorca CS required a more direct involvement of the EDUCEN team in the implementation of the methodology. The Lorca experiences allowed us to revise and adapt the protocol for the implementation of the methodology, accounting for the difficulties encountered during the first replication attempts.
The following sections describe the main hints for the replication

4.1.1. The technical audience (i.e. emergency managers and experts)

One of the key issue to be accounted for when replicating the L'Aquila experiences in other case studies concerns the capabilities of the analyst involved in the collection and structuring of the local knowledge to clearly discern between the actual emergency managers' experiences and the official protocol of interaction. The experiences carried out in L'Aquila and in the two replicating cases – i.e. Lorca and Valladolid – demonstrate that emergency managers are so deeply grounded in their procedures that they tend to mix up experiences and procedures. This represents a critical bias for the analysis, because it impedes the modelling of the informal network activated during an emergency. In order to reduce this bias, the analysis should be focused on a specific emergency management episode. The implementation of the Critical Event Analysis, as described in the EDUCEN deliverable on methods and tools, could be useful at this stage of the knowledge elicitation phase. Moreover, the analysis should be focused on a relatively recent episode. The more distant in the time is the emergency episode, and the more influent is the above mentioned bias.
As far as the issue of hard/soft infrastructures interconnections is concerned, the developed methodologies were tested in the case study only, but no significant criticalities emerged in model building and development, which may condition its replicability in other case studies. Referring to the approach based on graph theory, it is well-established, and with multiple applications in several cases, including also multiple infrastructural systems. As far as the SD resilience assessment model is concerned, its structure is flexible enough to allow the modeler to adapt the model to either new or updated information/knowledge possibly available. The key issue to consider, as in general in any kind of model, is that the quality and the availability of input data significantly affects the quality of the outcomes. A basic requirement to guarantee an effective replication of the methodology is for sure connected to the collection and proper structuring of the input information needed for the model, which must be subjected to a 'pre-processing'. The availability of reliable information is a key resource to deal effectively with emergency conditions and, generally, it should be guaranteed well before the occurrence of a disaster.

4.1.2. The general public

The main issue that need to be addressed when involving the general public in the analysis of the emergency management network concerns the need to clearly map the flow of interactions within the community. As demonstrated by the experiences carried out in L'Aquila, the analysis of the interactions among the different members of the community allows to better define the roles played in case of emergency. This analysis is specifically useful to identify the main leaders of the

community, i.e. those actors that can enhance the effectiveness of the interaction mechanisms within the community and between the community and the institutional system.
The selection of the sample for the knowledge elicitation phase is crucial at this stage.

Annex 1 – Framework for the knowledge elicitation

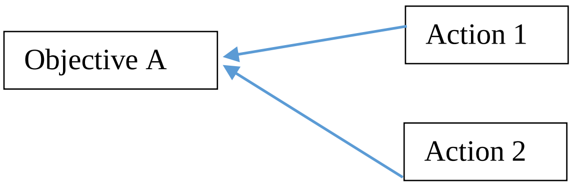
The interviews should be carried out keeping in mind that the results will be used to develop the model for the SNA. The interviews should allow to collect the following basic information related to the emergency management:

- Who interacted with whom;
- What information was exchange;
- What task was performed using what information;
- Who performed which task.

The collection of this information should be based on the Critical Event storytelling approach. That is, participants should be required to describe the different phases of the emergency management concerning one specific critical event. Therefore, once defined the kind of disaster (e.g. flood), participants should focus on specific flood event – i.e. the last evet or the most dramatic one. It is crucial that all the participants refer to the same event.

The interviews need to be have a hierarchical structure, as for the cognitive elicitation approach. The *goal-action* approach is suggested. According to this approach, the first question is: 1) what is your role (goal) during an emergency (e.g. rescue of missing people; keeping the road open, etc.)?

At this point, for each of the goals, the participants should describe the actions carried out during the selected critical event. It is important to specify that the interview aims at collecting their actual experience (story), not the description of the official protocol of intervention. (According to our experience, a typical bias is the mix between experience and protocol. This is particularly true for official responders/institutions). The links between action and goal need to be defined. Therefore, participants will be required to specify which action allowed to achieve which goal. If possible, this phase could be carried out by drawing the links, as in the following figure:



The links need to be weighted according to the perceived degree of importance. Therefore, participants will be required to specify how important implementing action 1 was in order to achieve objective A, etc. The weight could be described using linguistic assessment (e.g. very important, important, not really important).

Then, we need to move to the phase Action-information. For each of the above mentioned actions, participants will be required to specify what information was used to support its implementation (e.g. in order to control the traffic in the road I needed to know the condition of the infrastructure). Once more, the links between information and action have to be weighted. Therefore, participants will be required to specify how important that specific information was in order to perform that specific action.

Finally, the agent-agent connections need to be identified. To this aim, participants will be required to name the other actors (both institutional and non-institutional) with whom they interacted during the selected episode. Once more, participants should be leaded to described the actual situation, and not how the official protocol is supposed to work. Once they named them, you should start asking what kind of interactions they had. According to the methodology implemented in L'Aquila and Lorca, we mainly focused on two types of interactions, i.e. information sharing, and task cooperation. Therefore, for each of the actors mentioned, the participants will be asked:

- Did you receive information from this actor? Which one (among those already discussed)?
- Did you provide information to this actor? Which one)
- Did this actor cooperate with you in carrying out a specific action? Which one (among those already discussed)?

Even for this phase, each link should be weighted according to the degree of importance.
At the end of the interview, a scheme similar to the one in the following figure should be developed: