Emergency Management Capabilities of Interdependent Systems: Framework for Analysis

Mariachiara Piraina (corresponding author), mariachiara.piraina@polimi.it
Paolo Trucco, paolo.trucco@polimi.it
Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano

Abstract
The management of emergencies affecting interdependent critical infrastructure (CI) systems is a complex issue of increasing concern. The existence of multiple cascading effects, limited situational awareness, and the need for coordination between several actors are factors that justify the conceptualization of CI as a complex adaptive system (CAS). Although the capability concept has been extensively adopted in emergency management (EM) literature, proper classification and modeling of CI systems is lacking. This study aims to adopt a capability-based approach for EM to improve the adaptability to the prevailing and unpredictable circumstances, based on a combination of literature review and field research. It proposes a classification and modeling framework for the analysis of the intra- and interorganizational capabilities using a pilot application involving the Italy-Switzerland cross-border transport infrastructure. This framework is suitable for modeling the EM capabilities under different operational contexts and emergency scenarios. Moreover, it enables the representation and description of a CI system through elementary components that capture the main features of a CAS. The obtained results indicate that the proposed framework can foster public-private collaboration (PPC) in the development of CI protection and resilience (CIP-R) programs.

Keywords: Critical Infrastructure, Emergency Management, Capability, Complex Adaptive Systems, Interdependencies, Framework.

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1. Introduction

Our society is frequently affected by either natural or manmade accidents, which represent a threat to people and economic activities. This is particularly relevant when critical infrastructure (CI) systems are involved because people's lives and economic activities depend on their service continuity (Turoff et al. 2016). As CI systems are interdependent (Rinaldi et al. 2001) and may expand beyond geographical borders, long and wide domino effects may be generated, where the hazard affecting a system may cause other hazardous conditions to occur in the other systems with potentially serious consequences (Kadri et al. 2014; Hickford et al. 2018; Cantelmi et al. 2021). In addition, CI systems are being increasingly institutionally fragmented because of the privatization, liberalization, and deregulation in many advanced countries in the recent decades (De Bruijne and Van Eeten, 2007). Consequently, emergencies affecting CI systems can be particularly severe and difficult to manage.

Undoubtedly, cross-border issues in emergency management (EM), which may arise from the physical and operational interconnection between the CI systems of different countries, represent one of the most relevant complexity drivers, and are a challenge for policymakers, CI operators, and first responders. As it is impossible for a single organization to offer all the competences, information, and resources for managing a cross-border emergency involving CI systems (Petrenj et al. 2013), cooperation between various actors (Kapucu, 2009; Bhandari et al., 2014), ranging from public institutions to private business organizations (DHS, 2009), is required. The involvement of several organizations with different roles and responsibilities renders communication, information sharing, and coordination fundamental to the implementation of an effective emergency response (Nunavath et al. 2015; Cedergren et al. 2018). However, because of the high uncertainty, dynamism, and complexity of the environment, a hierarchical approach of governance is not the most appropriate, and flatter structures are recommended (Trucco and Petrenj 2017). This is also due to the presence of both public and private organizations that interact through horizontal organizational structures based on voluntary collaboration.

All these factors are frequently repeated in literature to justify the conceptualization of CI systems as sociotechnical systems (Comfort and Kapucu 2006) and, in particular, complex adaptive systems (CASs). A CAS can be defined as a "collection of individual agents with freedom to act in ways that are not always totally predictable and whose actions are interconnected so that one agent's actions changes the context for other agents" (Plsek and Greenhalgh 2001; Holden 2005).

Because of the role and characteristics of CI systems, their ability to reduce, absorb, and recover from a disruption is critical, along with their adaptability to unpredictable circumstances. This is reflected in the CI resilience view, which in recent years has become a prevalent approach in both literature (Pant et al. 2014; Alsubaie et al. 2015) and policies (Pursiainen and Gattinesi 2014), overcoming an earlier purely protective strategy (Moteff et al. 2003).

In EM literature, the resilience perspective is directly linked with a focus on capability building (Kozine and Andersen 2015), rather than on procedures and plans (Penadés et al. 2017). However, the concept of EM capability is still under development and is not univocally defined in literature, as indicated in the review by Lindbom et al. (2015). Moreover, a coherent framework for the classification and analysis of EM capabilities is lacking. Prior studies are limited to case-specific applications; some of them are too expansive (Granåsen et al. 2018; FEMA 2020), whereas the others are sector-specific and therefore, not applicable to different operational contexts (Chen et al. 2009; Davis et al. 2013; Wu and Ren 2017). The identification of all the capabilities required in a CI system for improving EM under different accident scenarios is not a simple task.

There are different features that describe EM capabilities, and the importance of integrating technological, human, and organizational components has been mainly discussed in literature (Woltjer and Hollnagel 2007; Patriarca et al. 2017).

Hence, it is crucial to understand the behavior of organizations, their organization, and the collective performance when an emergency occurs. Thus, not only the roles and responsibilities within organizations or the resources that can be mobilized need analysis, but also the internal and external information flows and the other means of coordination.

The aim of this study is to contribute to solving the above-mentioned issues by fostering a capability-based approach to EM when interconnected CI systems are involved. In the context of this study, capability can be generally defined as the "description of an [organization's] ability to do something" (NATO, 2018), and can be considered as an appropriate task that an organization can execute when a disruptive event occurs in order to minimize the resulting negative consequences for the stakeholders. The overarching goal is to develop an integrated approach that is robust from a theoretical standpoint, and practically usable by institutional and business actors.

The previously mentioned high degree of interdependence of CI systems and their fragmented management emphasizes the role of both intra- and inter-organizational capabilities, where the latter are built on the proper management of the relationships between different organizations throughout the entire EM cycle. Based on these considerations, the following research questions (RQs) are set:

RQ1: What are the core intra- and inter-organizational capabilities for implementing effective emergency management in complex interdependent systems?

RQ2: How can the intra- and inter-organizational emergency management capabilities of complex interdependent systems be modeled?

These RQs are answered by developing a framework that includes the following: i) A generalized classification scheme of the EM capabilities, and ii) a method for EM capability modeling and analysis in a multi-actor context. This framework is intended to support EM related activities in different operational environments by providing a common reference language for defining EM capabilities and a set of standardized modeling tools. The framework can be used by single organisations for developing emergency and business continuity plans that better integrate external dependencies; within Public-Private Collaboration programmes for CI resilience, at national or international level, the framework can be taken as a reference for modelling inter-organisational capabilities and dependencies, or for developing collaborative plans to cope with specific emergencies. Finally, the coordinated set of modelling tools included in the framework are also suitable for the development and documentation of use cases or the specification of functional requirements of technical solutions for EM, such as information sharing platforms or communication systems. More in general, the analyses supported by the framework are deemed as propaedeutic to further quantitative capability assessment studies. A pilot application of the framework is presented in this paper to demonstrate its benefits in the context of a realistic application case talking CI disruption events with cross-border effects, for which multi-actor collaborative response plans are developed.

The newly proposed classification is based on the FEMA taxonomy of the EM capabilities (FEMA, 2020); however, it offers a more comprehensive specification that is sufficiently general for application to various actors, including not only first responders, and different operational contexts. The modeling component of the framework is intended to provide a univocal and structured method for the description and representation of a CI system through standardized elementary components. It can be used for analyzing the EM processes of an organization, its resources, and information flow at the intra- as well as interorganizational levels. The term modeling is not common in EM literature; mapping is used at times, but only with reference to a map or GIS representation of the resources (Abdalla and Niall 2009; Gagnon et al. 2012; Assilzadeh et al. 2012). However, in CAS literature (e.g., Holland 1992; Oughton et al. 2018; Chen et al. 2020), the terms model or modeling are commonly used to denote methods for the high-level description of the system or specific analytical implementations of the CAS features.

The remainder of this paper is organized as follows. Section 2 describes the theoretical background and methodological approach of the study. Section 3 presents the state-of-the-art definitions and classification of the EM capabilities and their modeling. Section 4 describes the developed framework; the first part details the newly proposed classification of the EM capabilities, whereas the second introduces the tools for the representation and description of the EM capabilities. Section 5 describes the implementation procedure of the framework. Section 6 presents an illustrative case to demonstrate the application of the framework. The novel elements are discussed in Section 7, with respect to the main features of a CAS. Finally, the contributions of this study, its limitations, and future developments are presented in the Conclusions section.

2. Theoretical background and methodological approach

2.1. Relevant Theories on Emergency Management and Interdependent Systems

Theories are useful tools for addressing problems coherently, even though different theories can be deemed suitable for tackling the same problem (Reeves et al. 2008). Likewise, in the EM management domain, several theoretical perspectives, such as the traditional theory of disaster phases (Coetzee and Van Niekerk 2012), social construction perspective (Hewitt 2005), and chaos or system theories (Koehler et al. 2001) have been adopted by researchers. Some of them are explicitly based on the capability concept, whereas the others focus on the system characteristics or behavioral factors.

In some studies, the resource-based view (RBV) (Barney, 1991) and resource orchestration theory (ROT) (Wowak et al., 2013) have been applied as the theoretical background for the definition and operationalization of the capabilities (Chen et al. 2010; Tatham et al. 2012; Jeble et al. 2019). In operations management literature, the ROT is used to investigate the resources (tangible and intangible assets) that should be orchestrated to gain a competitive advantage, which is generated not only by owning these resources but also through the capability of orchestrating them (Helfat et al., 2009; Hitt et al., 2011; Sirmon et al., 2011, 2007; Hansen et al., 2004). Based on this line of thought, this study adopts a capability-based approach for effective EM.

An extensively applied theoretical perspective in interdependent systems is the CAS theory (Chen et al. 2020) originating from the peculiar characteristics of a CAS (Table 1), which is a system composed of multiple interrelated elements that are adaptable, i.e., “they can change based on emerging abilities and experiences” (Chen et al. 2020). The adaptability concept refers to the ability of organizations to reallocate their resources and actions (Kapucu 2009), and reorganize themselves to better respond to the changes in the surrounding environment (Holland 1992). Each organization has specific knowledge that is then shared with the other organizations to form collaborative networks (Chen et al. 2020). Consequently, it is obvious that coordination and collaboration between different organizations are important orchestration capabilities in CASs (Kapucu 2009). As stated by Pumpuni-Lenss et al. (2017), “strong central control is not required for a CAS to function, and instituting any type of restriction may hinder its function.”

The CAS theory can be leveraged for diagnostic purposes because it provides the general principles for investigating the possible performance degradation mechanisms in a CAS (e.g., irreversibility and time-dependent decisions), and for assessing the cascading consequences of specific actions (e.g., due to the nonlinearity feature, a small change can have significant effect on the entire system) as well. Considering infrastructure networks, for example, this theoretical perspective focuses on a combination of technical and social components that interact nonlinearly, determining the evolution, aggregate behavior, and anticipation of these systems (Holland 1992). In summary, the CAS theory reflects all the main characteristics of interdependent sociotechnical systems composed of a large variety of organizations and can facilitate better EM when CI systems are involved.

Table 1 lists the main features of a CAS, distinguishing between the *structural* (i.e., the manner in which different components are connected to each another to form a CAS) and *managerial features* (related to the way in which a CAS is managed at the single component as well as relationship levels). These features are used to evaluate whether and to what extent the proposed framework enables adequate modeling of the core CAS characteristics (Section 6), in this study.

Table 1 Main features of a CAS

CAS feature	Description	Reference
Structural features		
Nonlinearity	Autonomous but interconnected organizations are characterized by nonlinear and unpredictable interactions (Pumpuni-Lenss et al. 2017). Due to the uncertainty of the environment and the increasing interdependency of the systems, the relationships between these systems are nonlinear and indeterminate (Oughton et al. 2018; Chen et al. 2020); i.e., a small change in a single element can have significant effect on the entire system (Reiman et al. 2015).	(Holden 2005; Comfort and Kapucu 2006; Reiman et al. 2015; Pumpuni-Lenss et al. 2017; Oughton et al. 2018; Chen et al. 2020)
Emergence	The interdependence between system parts can result in the emergence of different actions and behaviors. However, it is not simple to decompose the system into individual stable parts (Oughton et al. 2018). As stated by Reiman et al. (2015) "emergence is a result of the pattern of connections among diverse agents" where the emergent properties arise from the interactions among agents and are different from those of the parts. As a consequence, unpredictable outcomes and different possible future states could occur (Oughton et al. 2018). Emergence is also defined as the "appearance of a phenomenon at an aggregate level that cannot be described in terms of the particulate actions" (Johnson et al. 2011; Pumpuni-Lenss et al. 2017).	(Holland 1992; Holden 2005; Johnson et al. 2011; Reiman et al. 2015; Pumpuni-Lenss et al. 2017; Oughton et al. 2018)
Agent diversity	In CASs, there are different components and agents that are interconnected but diverse from each other (Oughton et al. 2018). Due to this diversity between agents, a single agent cannot understand the entire system; hence, relationships among them are essential (Reiman et al. 2015).	(Holden 2005; Reiman et al. 2015; Oughton et al. 2018)
Dynamics and evolution	CASs are characterized by dynamic changes that generate incremental development and evolution (Oughton et al. 2018). Moreover, due to this dynamic evolution, there is no optimal equilibrium state but continual change (Holden 2005; Oughton et al. 2018); i.e., "the system is in a continuous process of flux and change" (Reiman et al. 2015).	(Holland 1992; Holden 2005; Reiman et al. 2015; Oughton et al. 2018)
Irreversibility	The irreversibility of CASs is related to the scarcity of time-independent decisions that generate a "lock-in" effect (Oughton et al. 2018). Reiman et al. (2015) refer to it as "history dependence" where the actions are irreversible because it is impossible to go back in time. However, the knowledge acquired from the past be beneficial in future.	(Reiman et al. 2015; Oughton et al. 2018)
Managerial features		
Self-organization	In CASs, the organizations can self-organize themselves; i.e., control in these systems is distributed and not centralized (Reiman et al. 2015). When there is a change in behavior, it is determined by a single actor and there are no imposing external forces, commands, or controls (Comfort and Kapucu 2006; Pumpuni-Lenss et al. 2017). Moreover, the "self-organizing behavior among a set of organizations leads to mutual adaptation and reciprocity that represent coordination in practice" (Comfort et al., 2004). This concept entails "the ability to reallocate resources and action to meet changing demands from the environment" (Kauffman 1993; Comfort and Kapucu 2006).	(Kauffman 1993; Comfort et al. 2004; Comfort and Kapucu 2006; Reiman et al. 2015; Pumpuni-Lenss et al. 2017; Oughton et al. 2018; Chen et al. 2020)

Adaptability	The multiple interrelated elements comprising a system are adaptable because “they can change based on the emerging abilities and experiences” (Chen et al. 2020). Considering the adaptability concept, even if the environment changes, organizations can reallocate their resources and actions (Kapucu 2009); i.e., the system can adapt itself to the changes in the surrounding environment.	(Holland 1992; Comfort et al. 2004; Comfort and Kapucu 2006; Kapucu 2009; Pumpuni-Lenss et al. 2017; Oughton et al. 2018; Chen et al. 2020)
Simple rules	Each part of the system has its own rules that according to Holland (1992) are simple in most cases because a condition is followed by an action. These simple rules are represented by “protocols that define the nature, path, and format of the movement and information exchange among individual independent elements”(Pumpuni-Lenss et al. 2017). Moreover, this is related to the adaptive behavior because the simple rules favor interaction between the parts of the system even if a single part is unknown (Ashmos et al. 2002; Pumpuni-Lenss et al. 2017).	(Holland 1992; Ashmos et al. 2002; Pumpuni-Lenss et al. 2017)

2.2. Study methodology

A mixed method approach, consisting of state-of-the-at review, conceptual reasoning and pilot application, was adopted to carry out the study.

Literature on EM capability classification was critically reviewed, followed by conceptual reasoning to develop a comprehensive classification of the EM capabilities of interdependent CI systems. For RQ2, another literature review was performed focusing on the methods and techniques for modeling the capabilities for mission-critical operations. A framework for EM capability modeling was developed based on NATO Architecture Framework 4.0 (NATO, 2018). Finally, in the last phase, the proposed framework was tested through a pilot application and assessed against the CAS features (Table 1). The overall research methodology implemented in this study is graphically represented in Fig. 1.

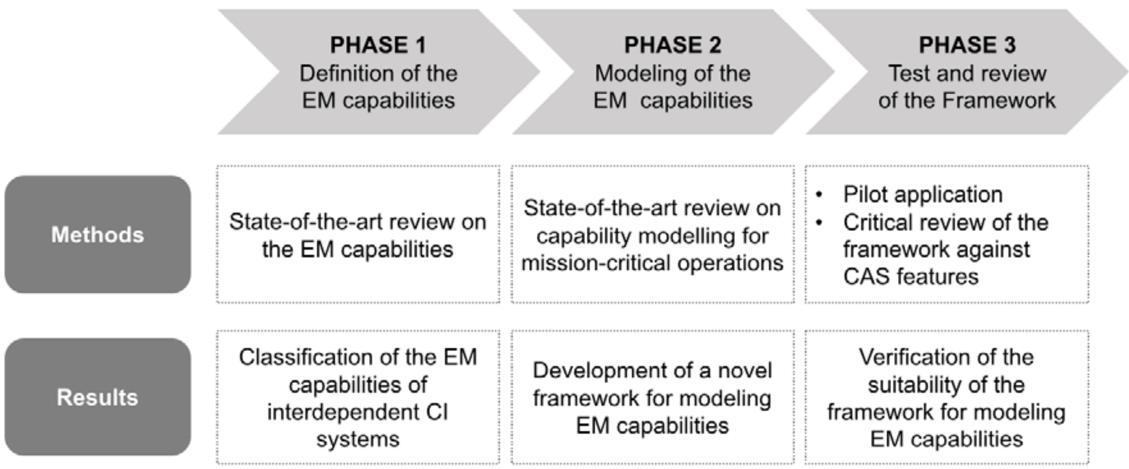

Fig. 1 Study methodology

3. Review of the State-of-the-art Emergency Management capabilities

To answer the two research questions, a review of the state-of-the-art EM capabilities was performed, which included two parts: the first dealt with the definition and classification of the EM capabilities, whereas the second focused on the EM capability modeling methods.

3.1. Definition and classification of the EM capabilities

The specific objective was to identify and select the core intra- and interorganizational capabilities reported in literature on the EM of complex interdependent systems. This could be retrieved from two literature streams: classification or taxonomic studies (e.g., literature reviews) and capability assessment methods. For this purpose, systematic search of the titles, abstracts, and keywords was performed in November 2020 by adopting multiple combinations (AND sequences) of keywords: “Capabilit* assessment”, “capacit* assessment”, “capabilit* evaluation”, “capacit* evaluation”, “emergency management”, “disaster management”, “disaster planning”, resilience.

The search first targeted scientific literature; the Scopus database was used because it is the most comprehensive database in the engineering and management domain. The search was limited to the English sources published between 2009 and 2020 excluding the documents that do not address the key elements of RQ1, that do not include capability classification and that are sector specific, such as the EM capabilities for the power industry (Song et al. 2020), or address a single actor, such as the EM capabilities of local governments (Grefalda et al. 2020). The final set included in the literature analysis comprised 21 scientific documents. In addition, relevant or authoritative technical literature was searched on Google, resulting in the inclusion of three other documents in the final sample (i.e., CDC, 2018; FEMA, 2020; ISO 22325, 2016).

The documents were analyzed focusing on the classification of the EM capabilities. All the documents in the selected sample classify the capabilities into categories with one or more hierarchical levels. Most of them include at least two levels; in some cases, the first level corresponds to the EM cycle phase, considered as a classification dimension rather than a dimension related to deployment (Wang et al. 2009; Yong et al. 2012; Li and Wang 2015; Wu and Ren 2017; Qi et al. 2018; Yu et al. 2019; Zhifeng 2020).

Table 2 summarizes the main characteristics of the revised classifications; 23 different proposals are indicated because Kozine et al. (2018) and Trucco et al. (2018) are part of the same work. Most of the studies propose *systematic categorization of the capabilities* and include a taxonomy for their classification in the framework. Only 12 of these documents propose a set of capabilities that are *adaptable to different scenarios*, i.e., to various operational contexts and accident types. Many contributions provide a first-level classification of the capabilities, which is general, and a second-level, which is highly specific and therefore, not adaptable to different scenarios. For instance, Ma et al. (2019) focus on a fire emergency system, Yang and Xu (2011) refers to the emergency capacity of urban subways, and Yong et al. (2012) and Zhang et al. (2018) limit the analysis to the maritime context. Only six documents provide *comprehensive classification of the capabilities*, where all the main operations and the needs of EM operations are addressed. However, as Wang et al. (2009) and Yong et al. (2012) refer to specific scenarios, they are not fully aligned with the purpose of this study.

On the other hand, some of the studies propose *very general types of capabilities*; i.e., they are not clearly defined and detailed, rendering comparison against alternative classifications and practical application difficult; for example, Chen et al. (2009) consider the responding, monitoring, and communication capabilities. In other cases, a broad list with *similar capabilities* is provided, and there is overlap or ambiguity in the definition in certain cases. For instance, FEMA (2020) refers to 32 capabilities in which some of them appear similar in scope, and Qi et al. (2018) propose an emergency forecasting capability divided into four similar subcapabilities. However, the FEMA classification appears to be the most complete among the reviewed contributions; therefore, it is considered as the landmark in this study.

The importance of an *interorganizational perspective* when defining EM capabilities is widely recognized: 15 among the 23 contributions list coordination, collaboration, and information sharing as the core EM capabilities.

In summary, most of the classifications reported in literature are either sector-specific or general; a broad list of capabilities are provided, which in some cases are similar, overlapping, or ill-defined and ambiguous. To address this lacuna, this study introduces a new classification framework along with a new list of capabilities (subsection 4.1). The aim is to develop an EM capability classification scheme that can be used under different EM contexts and accident scenarios.

Table 2 Main characteristics of the selected literature on EM capability classification
(“x” = the characteristic is covered; “-” = the characteristic is not covered)

Reference	**Systematic categorization of the capabilities**	**Comprehensive classification of the capabilities (main operations and needs)**	**Adaptation of the capabilities to different scenarios (e. g., contexts and hazardous conditions)**	**Very general types of capabilities**	**Similar and ill-defined capabilities**	**EM cycle phases as a classification dimension**	**Interorganizational perspective (coordination, collaboration, information sharing)**
CDC (2018)	x	-	-	-	-	-	x
Chen et al. (2009)	x	-	-	x	-	-	-
Davis et al. (2013)	x	-	-	-	-	-	-
FEMA (2020)	x	x	x	-	x	-	x
Granåsen et al. (2018)	x	x	x	x	x	-	x
ISO 22325 (2016)	x	-	x	-	-	-	x
Ju et al. (2012)	x	-	x	-	-	-	x
Kozine et al. (2018) Trucco et al. (2018)	x	x	x	-	x	-	x
Li and Jiang (2012)	x	-	-	-	-	-	-
Li and Wang (2015)	x	-	x	-	-	x	x
Lindbom et al. (2015)	x	-	x	-	-	-	x
Ma et al. (2019)	x	-	-	-	-	-	x
Qi et al. (2018)	x	-	x	-	x	x	x
Tan and Ren (2010)	x	-	x	x	-	-	-
Wang et al. (2009)	x	x	-	-	x	x	-
Wang et al. (2018)	x	-	x	-	-	-	x
Wu and Ren (2017)	x	-	x	-	-	x	-
Yang and Xu (2011)	x	-	-	-	-	-	-
Yong et al. (2012)	x	x	-	-	x	x	x
Yu et al. (2019)	x	-	-	-	-	x	x
Zhang et al. (2018)	x	-	-	-	x	-	-
Zhang et al. (2019)	x	-	-	-	-	-	x
Zhifeng (2020)	x	x	x	-	-	x	x

3.2. Models and methods for EM capability modeling

EM capability modeling as a method for planning EM operations and the related information flows is crucial when dealing with multi-actor, multi-sectoral, or even cross-border relationships. The absence of common terminology and a standardized method for representing organizational information hinders information sharing and communication processes, affecting EM operations (Norri-Sederholm et al. 2017). Moreover, the limited visibility of the capabilities owned by other organizations results in poor allocation of the responsibilities and limits the possibility of asking for the right help when needed.

To select the most relevant contributions to the problem of modeling coordinated EM operations, systematic literature search on the titles, abstracts, and keywords was performed on the Scopus in November 2020 by adopting multiple combinations (AND sequences) of keywords: “emergency management”, “capabilit* analys*”, “capabilit* specification”, “capabilit* building”, capabilit*, model*ing.

Literature on disaster management was considered irrelevant because this study does not investigate the modeling of disaster scenarios and the related humanitarian operations. Moreover, the term “capacity” (or capacit*) was not included in the list of keywords in order to explicitly exclude contributions on the technical capacity. Again, the results were limited to English sources published between 2009 and 2020. The final set included in the literature analysis comprised 48 scientific documents (Table 3). Additional relevant sources were found in the technical literature based on Google search, including research project SALUS (Müller and Reinert 2014) and the NATO Architecture Framework (NAF; NATO 2018).

As highlighted in Table 3, the selected literature was examined and compared against different methodological approaches (i.e., simulation, analytical, and descriptive modeling) and study objectives. Most studies adopted simulation models as in Ganji and Miles (2018), who investigated the benefits of integrating simulation modeling and human-centered design to support and simplify collaborative planning for CI recovery. Li et al. (2019) developed a framework to model and simulate the network dynamics of inter- and intraorganizational coordination in the infrastructure domain. In contrast, other studies proposed an analytical model for the assessment of specific capabilities, such as Zhang et al. (2019), who referred to indicators for assessing the maritime search and rescue response capability. The remaining studies referred to descriptive models.

As for the study objective, the reviewed contributions mainly addressed risk assessment (Lv et al. 2013; Albano et al. 2016), resilience assessment (Crawford et al. 2018; Bristow 2019), specific capability assessment (Xu 2018; Zhang et al. 2018; Ma et al. 2019), or models based on GIS applications (Abdalla and Niall 2009; Gagnon et al. 2012; Assilzadeh et al. 2012). Another stream of literature focused on system development (e.g., technological tools and IT platforms for EM) as in the case of Gagnon et al. (2012), who referred to a human-centered emergency response tool (SYnRGY) for measuring and simulating the capabilities. Lauras et al. (2015) proposed an approach to model business processes for orchestration and execution in crisis response, using an event cloud platform. In particular, the platform was developed to connect and orchestrate people, devices, and services, ensuring timely and accurate information to the actors.

Table 3 Main characteristics of the selected literature on EM capability modeling

		Methodological approach		
		Simulation modeling	**Analytical modeling**	**Descriptive modeling**
Study objective	**Risk assessment**	(Assilzadeh et al. 2012)	(Bouwsema 2012; Lv et al. 2013)	(Albano et al. 2016; Crawford et al. 2018; Rogers et al. 2018)

	Resilience assessment	(Trnka and Johansson 2011; Ganji and Miles 2018; Ganji et al. 2019; Li et al. 2019)	(Romanowski et al. 2016)	(Zukowski 2014; Kozine and Andersen 2015; Masys et al. 2016; Kozine et al. 2018; Son et al. 2018; Bristow 2019)
	System development	(Scheulen et al. 2009; Friedman-Hill et al. 2010; Gagnon et al. 2012)		(Müller and Reinert 2014; Lauras et al. 2015; NATO 2018; Bristow 2019)
	GIS application	(Abdalla and Niall 2009; Gagnon et al. 2012; Assilzadeh et al. 2012)		
	Assessment of specific capabilities	(Pasetto et al. 2017; Leung et al. 2018; Loftis et al. 2018)	(Yang and Zhang 2014; Xu 2018; Zhang et al. 2018, 2019; Sienkiewicz-Małyjurek 2019; Zhifeng 2020; Song et al. 2020)	(Yang and Zhang 2014; Dohan et al. 2015; Ma et al. 2019; Alvanchi and Seyrfar 2020)
	Others	(Henson et al. 2009; An et al. 2012; Capote et al. 2013; Lee and Pietz 2013; Kaveh et al. 2014; Wojtalewicz et al. 2014)	(El-Anwar et al. 2010; Altay 2013; Ding et al. 2013; Lv et al. 2013; El-Anwar and Chen 2016)	(Shen et al. 2012; Banks et al. 2014)

Among the system development studies that adopt a descriptive modeling approach, Müller and Reinert (2014) provide “a framework and approach to coordinate the perspectives of different types of stakeholders within a public safety and security organization” (Müller and Reinert 2014). They refer to the open safety and security architecture framework (OSSAF) based on an enterprise architecture for describing an organization and the interactions among its different parts. In particular, this framework adopts NAF Version 4. The NAF aims “to provide a standard for developing and describing architectures for both military and business use” (NATO 2018), where an architecture describes “the fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution” (ISO/IEC/IEEE 40210 2011). The architecture is based on the adoption of viewpoints (i.e., tools) that “are a means to focus on particular subjects and aspects of stakeholder concerns” (NATO 2018). According to NATO (2018), it is possible to adopt viewpoints that belong to five different categories (Fig. 2): ***concept*** viewpoints (to analyze high-level capabilities), ***service specification*** viewpoints (to describe the services), ***logical specification*** viewpoints (to analyze the nodes, their behavior, and interaction), ***physical resource specification*** viewpoints (to analyze human and material resources), and ***architecture metadata*** viewpoints (to analyze the architecture’s administrative aspects). The wide variety of tools presented in the NAF facilitates the representation and description of different aspects of the same organization. The NAF is sufficiently general for application to different contexts and for modeling different capabilities.

In summary, in scientific literature, contributions on the models and methods for EM capability modeling are limited, and other than the work of Müller and Reinert (2014), none of them offer a comprehensive framework, method, or tool for modeling the EM capabilities. Moreover, none of the scientific and technical works is explicitly based on a comprehensive classification of the EM capabilities. Thus, in this study, NAF viewpoints suitable for the objective of modeling the EM capabilities of interdependent CI systems were selected for coherent integration into a wider framework comprising a generalized classification of the EM capabilities.

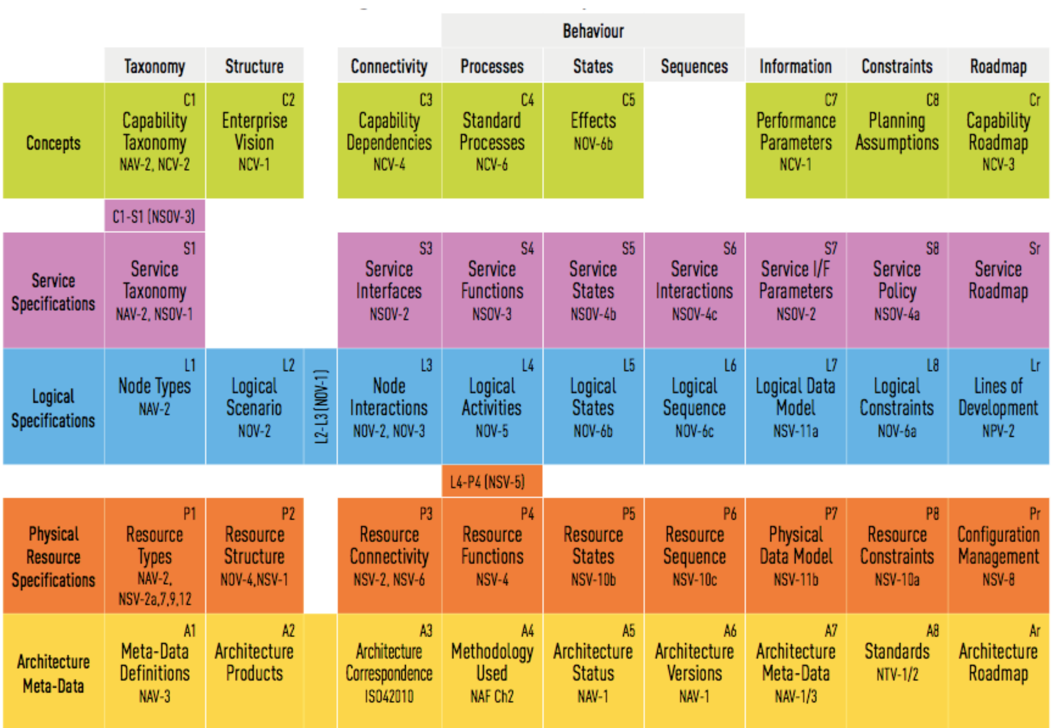

Fig. 2 NAF viewpoints (NATO 2018)

4. Framework for the classification and modeling of the EM capabilities of interdependent systems

With the aim of overcoming the existing knowledge gaps in EM capability classification, a novel framework was developed, as described in the following. The first section shows the comprehensive classification of EM capabilities that can be adopted by different actors thanks to its generalized and standardized features. Then the modeling part of the framework is presented in section 4.2., where the capabilities modeled are those identified in the classification section.

4.1. Comprehensive classification of the EM capabilities

Considering the need for simplifying the mutual understanding and information sharing among the organizations involved in the EM cycle, a multilevel classification of the EM capabilities was developed, as depicted in Fig. 3. Five main clusters were identified with reference to the classification proposed by the ISO 22325 (2016) standard:

- *Resource management* “is the efficient and effective allocation and deployment of resources when and where they are needed” (ISO 22325, 2016). Hence, it includes the capabilities related to the adoption of the resources (tangible and intangible) owned by the organizations under analysis.
- *Risk management* represents the “coordinated activities to direct and control an organization with regard to risk” (ISO Guide 73, 2009).
- *Communication and coordination* includes the interorganizational capabilities used for favoring information exchange outside the boundaries of a single organization and for integrating emergency responder operations. This cluster is a combination of two dimensions (i.e., information and communication, and coordination and cooperation), as identified by ISO 22325 (2016).
- The *emergency management planning* cluster is introduced to account for the activities related to planning and need assessment.

- *Surge management* includes activities aimed at providing support to humans and protecting the environment (CDC, 2018).

The main categories are described and documented below in more detail. In particular, the EM capabilities were allocated to each cluster by the authors taking into consideration the main aim and scope of each EM capability and its best fit with the categories introduced by the ISO 22325 (2016) standard.

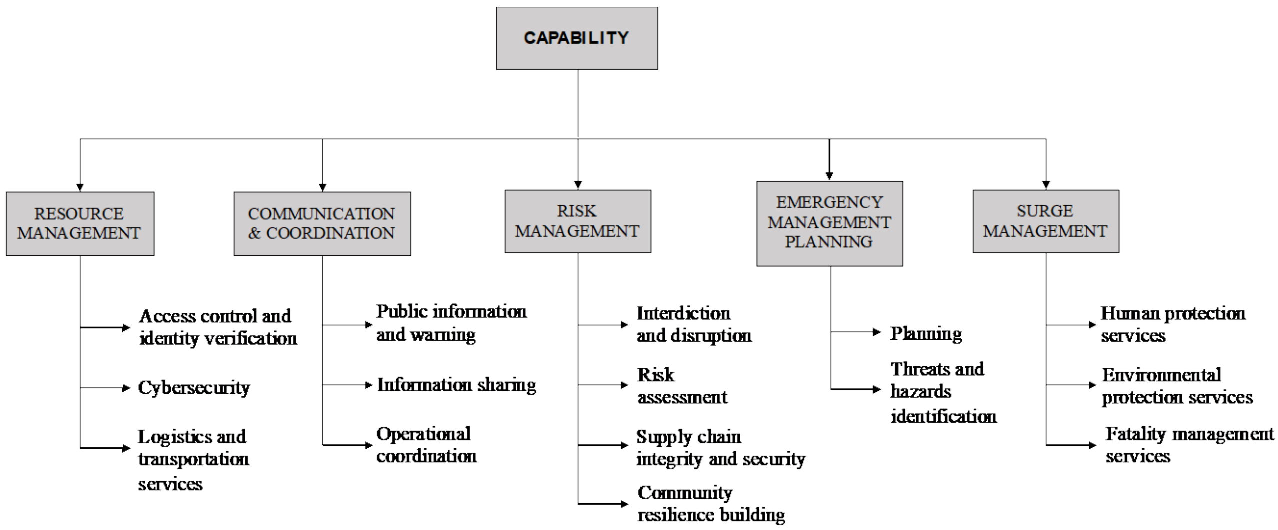

Fig. 3 Classification of the Emergency Management capabilities

4.1.1. Resource Management

Access control and identity verification

It includes the adoption of physical, technological, and cyber measures to verify the access to critical locations, systems, and information (FEMA 2020). In particular, it considers the verification of user identity to authorize or deny access to systems (physical or cyber) and to manage the access of authorized individuals (FEMA 2019).

Cybersecurity

It pertains to the adoption of measures for protecting (or restoring) “electronic communication systems, information, and services from damage, unauthorized use, and exploitation” (FEMA 2019, 2020). It is a protection measure that may include the implementation of guidelines to secure critical information and communication systems, guaranteeing their reliability, integrity, and availability (FEMA 2019). Moreover, it may include the detection and analysis of malicious activities in order to implement countermeasures and mitigation activities for protecting the system against malicious actors.

Logistics and transportation services

It is defined as the provision of logistics and transportation services in the affected areas to deliver the necessary items and services, and evacuate people and animals (FEMA 2020). This may include, for instance, the delivery of essential commodities, equipment, services, and personnel for supporting the impacted communities (FEMA 2019). Moreover, it includes the activities performed to make a route accessible by removing debris. Many authors refer to this capability; Li and Wang (2015) mention logistic support, whereas Li and Jiang (2012) and Wang et al. (2009) mention the transportation capacity.

4.1.2. Communication and Coordination

Public information and warning

It refers to the delivery of information regarding threats or hazards to the entire community, the implemented actions, and the available assistance (FEMA 2020). It considers all the phases of the EM cycle and aims to deliver different types of information and communication, adopting methods that are "clear, consistent, accessible, and culturally and linguistically appropriate" to effectively reach most of the population (FEMA 2019). Moreover, the CDC (2018) considers the emergency public information and warning capability as "the ability to develop, coordinate, and disseminate information, alerts, warnings, and notifications to the public and incident management personnel." Other authors also refer to the capabilities related to public information and warning: Davis et al. (2013) refer to communication and information dissemination, including activities such as drafting emergency communication plans and using a health alert network; Zhang et al. (2019) specify the coverage rate of communication and media promotion by measuring the portion of the community effectively reached by the conveyed messages; Wang et al. (2009) mention public awareness on disaster prevention and public understanding of the disaster plans; Yong et al. (2012) refer to propaganda, education, and the dissemination of information.

Information sharing

It refers to the exchange of timely and accurate information and data among governments or other organizations to better respond to disruptive events (FEMA 2020). Information sharing, and the collaboration enabled by it, is recognized as a key pillar for the development of effective EM. As stated by Petrenj et al. (2013), a single organization cannot provide all the information, resources, and competencies needed to manage an emergency. The CDC (2018) recognizes the importance of this capability in the preparation and response to events for exchanging information, data, and knowledge among various actors such as governments and the private sector. Other authors have also highlighted this capability: Yu et al. (2019) and Wu and Ren (2017) refer to communication information support; Qi et al. (2018) mention the information transmission capability; Granåsen et al. (2018) refer to it in relation to the interaction capabilities; Li and Wang (2015) specify three different activities related to information sharing (information platform construction, information monitoring, and information analysis for early warning).

Operational coordination

It refers to the presence of a coordinated operational structure and process for integrating emergency responder operations and fostering the execution of all the other capabilities (FEMA 2020). It is fundamental in all the phases of the EM cycle and includes various activities such as the development and maintenance of an incident response strategy, collaboration with all the relevant protection partners, determination of jurisdictional priorities, objectives, strategies, and resource allocation, as well as the coordination of search and rescue (CDC, 2018; FEMA, 2020; Zhang et al., 2019). With respect to information sharing, this capability is mentioned by various authors: Li and Wang (2015) state that the emergency coordination capability comprises information communication, departmental coordination, and staff coordination; Yu et al. (2019) mention onsite command coordination and relevant departmental cooperation to stress the need for a "fast, efficient, and uniform onsite command and coordination," and the importance of all-level collaboration in the EM context.

Moreover, several other authors have considered the capabilities related to operational coordination (Granåsen et al. 2018; Wang et al. 2018; Ma et al. 2019; Zhang et al. 2019).

4.1.3. Risk Management

Interdiction and disruption

It comprises the ability to "delay, divert, intercept, halt, apprehend, or secure threats and/or hazards" (FEMA 2019, 2020). In the context of protection and prevention, this capability includes activities that may be undertaken to cope with specific hazards and threats in order to secure an area. For instance, as stated by FEMA (2020, 2019), it may refer to the activities performed to anticipate and block terrorist operations, secure and dispose chemical, biological, radiological, nuclear, and explosive devices, and the implementation of measures aimed at mitigating the spread of disease threats.

Risk assessment

It refers to the identification, assessment, and prioritization of risks in order to implement adequate measures (Trucco et al. 2018; FEMA 2020). Thereby, more informed actions are performed to reduce the risks and consequences generated by a given hazard and/or threat. This capability, generally developed in the mitigation phase, may be performed during different phases; for instance, to validate or update the previous evaluations needed to cope with the changes in the surrounding environment. Other authors refer to capabilities linked with risk assessment: Wang et al. (2018) discuss risk identification and Wu and Ren (2017) generally refer to risk management.

Supply chain integrity and security

It refers to the strengthening of the security and resilience of the supply chain by acting on the key nodes and on the physical flows between them (FEMA 2019, 2020). For example, considering nodes as portions of rails and roads, this capability is related to all the activities performed to render materials in transit - such as medicines, food, toxic, or polluting materials - safe and traceable.

Community resilience building

Starting from the identification, communication, and planning for risks, it is the ability of organizations to empower communities to withstand and recover from short- and long-term incidents (FEMA 2020). Thereby, individuals and communities can make informed decisions that are more resilient to future incidents. The CDC (2018) refers to community preparedness and community recovery. Community preparedness is related to activities such as the development of human services, awareness training for the community, and the creation of plans and procedures aimed at preventing and responding to emergencies. The last point is related to community recovery, which includes activities aimed at prioritizing, monitoring, and implementing recovery operations in order to restore normal conditions. Examples of the activities related to this capability are provided by Wang et al. (2009), who refer to the capability of urban construction against disasters, community defensive measures, public participation in disaster preparedness exercises, self-help capability of the residents, and the improvement of contingency plans.

4.1.4. Emergency Management Planning

Planning

It involves "a systematic process engaging the whole community as appropriate in the development of executable strategic, operational, and/or tactical-level approaches to meet defined objectives" (FEMA 2019, 2020). The activities related to planning performed in different phases of the EM cycle can involve the development and implementation of plans, programs, training, and exercises to ensure the continuity of operations (FEMA 2019). For instance, it includes all the activities aimed at protecting CI systems. Many authors refer to the capabilities and activities related to the development and execution of emergency plans (Wang et al. 2009; Ju et al. 2012; Li and Jiang 2012; Yong et al. 2012; Li and Wang 2015) or to plans and procedures in general (Tan and Ren 2010; Davis et al. 2013; Granåsen et al. 2018), recognizing the importance of this capability.

Threat and Hazard identification

It refers to the identification of threats and hazards in a given area (including frequency and magnitude determination), and their incorporation in the planning and analysis processes with the aim of understanding the needs on the ground (FEMA 2019, 2020). It involves the identification of the risk sources, followed by the determination of the frequency and severity of each hazard and threat. However, this capability is strictly related to risk assessment because it represents the first step in the risk assessment process.

4.1.5. Surge Management

Human protection services

It includes all the services (e.g., mass care, emergency medical services, mass search, and rescue operations) aimed at providing support to the affected populations. For instance, it aims to protect the public by delivering emergency supplies as soon as possible (i.e., mass care services) or save the maximum number of people in danger using trained people and includes animal rescue (i.e., mass search and rescue operations). Various authors refer to mass care services (CDC, 2018; FEMA, 2020; Qi et al., 2018), search and rescue services (Qi et al. 2018; Yu et al. 2019; Zhang et al. 2019), and human protection services, in general (Wang et al. 2009; Ju et al. 2012; Li and Jiang 2012; Yong et al. 2012), recognizing the importance of this capability.

Environmental protection services

It includes all the services aimed at protecting and restoring the surrounding environment (e.g., natural and cultural resource protection) from hazards. For instance, it includes the activities for monitoring the state of waste disposal or for protecting animals and resources affected by a disruptive event. More specifically, FEMA (2020, 2019) refers to physical protective measures, and natural and cultural resources. Other authors also recognize the importance of environmental preservation (Qi et al. 2018).

Fatality management services

It includes the activities aimed at providing fatality management services, such as the recovery, transport, and identification of the victims, in collaboration with the other actors (FEMA 2020). The CDC (2018) details activities such as the determination of the cause and manner of death, management of personal effects, and analysis of the incident location. Wang et al. (2009) mention fatality management, which refers to the capacity of treating victims as part of the recovery and support capability after a disaster.

The proposed classification of the EM capabilities is a prerequisite for their modeling through the second part of the framework presented below.

4.2. EM capability modeling for interdependent systems

The second part of the framework provides guidelines and conceptual tools for modeling the EM capabilities. In particular, it provides a univocal structured approach, organized into three levels for the description and representation of a sociotechnical system through standardized elementary components. The three levels of analysis are as follows:

A) General modeling of the EM operations and information flows.
B) Emergency scenario-based modeling of the operations and information flows.
C) Inventory of the inter- and intraorganizational capabilities.

To address the specific needs of each level of analysis, certain NAF 4.0 viewpoints were selected.

4.2.1. General overview

The unit of analysis assumed in the framework is a single organization or a network of interdependent organizations collectively involved in EM operations within a given geographic area. Setting the scope of the analysis is the first step in adopting this framework. This involves identifying the geographical boundaries and thereby, the CI systems and organizations involved.

Table 4 summarizes the goals addressed by the three levels of analysis, which can be performed independently according to the specific aim and scope of the analysis. In some cases, one of the levels may be required. However, in cases where all the three levels of analysis are needed, it is recommended to start from level-A because it provides a general overview of the organizations under analysis. In the second step, it is possible to implement level-B, focusing on specific scenarios, and eventually level-C, to investigate EM capabilities and their relationships.

For gathering the relevant data and information to develop all the levels of analysis, different sources and methods were considered, such as official reports, internal documents, interviews with experts, as well as the organization of workshops and focus groups. In some cases, the territorial competences and agreements related to the country in which the study is conducted offer useful insights into the interactions between organizations and the capabilities provided. For levels B and C, because of the level of detail and the sensitivity of the information, public documents and data are generally insufficient. Here, the use of interviews to collect information related to a specific organization (e.g., the resources that can be mobilized) and the organization of workshops or focus groups for investigating the interactions between multiple organizations are suggested as good practices. As reported in Table 5, three specific symbols (circle, square, rhombus) are used to specify the method through which information is collected.

Table 4 EM capability modelling: Levels of analysis, corresponding goals, and modeled information.

GOALS	**A) General modeling of the EM operations and information flows**	**B) Emergency scenario-based modeling of the operations and information flows**	**C) Inventory of the inter- and intraorganizational capabilities**
Overview of the organizational structure of the EM actors: key roles and responsibilities	• Organizational chart		

Interactions between different organizations	• Communication channels • Exchanged information	• Communication channels • Exchanged information	
Identification of the information flows for each EM phase		• Chronological sequence of activities	
Identification of the resources owned by the EM actors (e.g., materials, people)	• Resources by means of know-how, personnel, physical infrastructure, TLC infrastructure, vehicles, and other assets	• Resources by means of know-how, personnel, physical infrastructure, TLC infrastructure, vehicles, and other assets	• Resources by means of know-how, personnel, physical infrastructure, TLC infrastructure, vehicles, and other assets
Identification of EM capabilities	• EM capabilities classification	• EM capabilities classification	• EM capabilities classification
Identification of relationships between capabilities			• EM capability dependencies

Table 5 Methods used for collecting relevant data and information.

Symbol	Meaning
○	The required information can be collected from internal *documentation* directly provided by the organization being examined (e.g., organizational charts, emergency plans, reports of past events).
□	The *documents* provided may not be sufficient to collect all the information; hence, *interviews* with key informants (e.g., risk and security managers) are recommended.
◇	Some of the information is detailed and difficult to collect. In these cases, *interviews* with key informants and/or the organization of *workshops or focus groups* are recommended.

4.2.2. General modeling of the EM operations and information flows

The first level of analysis (i.e., level-A) is intended to represent and document the EM operations and the active information flows independently from the prevailing emergency conditions. Analysis is performed using the tools for either a single organization or the interaction among multiple organizations. In particular, the selected tools provide the possibility to analyze the following:

- the roles of the EM actors
- the information exchanged and the corresponding communication channels
- the type and quantity of resources that each organization can mobilize in an emergency.

Level-A of the analysis renders it possible to identify the criticalities in the misalignment of organizational structures, in the type, sequence, and redundancy of communication channels, or finally, in the variety and quantity of resources that the organizations can mobilize during an emergency.

As shown in Fig. 4, six NAF 4.0 viewpoints are suggested for this level of analysis; the acronyms are the same as those specified in the original NAF documentation depicted in Table 6. Some of the tools can be implemented in parallel (i.e., *P4 – resource functions*, *L3 – node interactions*, *C7 – performance parameters*, *P2 – resource structure*), whereas others need to be adopted following a logical sequence. This is the case of *L3* and *L2 (logical scenario)* because modeling the exchanged information and communication channels (done through L3) enables us to build a model of the interaction among organizations (i.e., L2). Similarly, *C7* and *C1 (Capability Taxonomy)* should be developed in a logical sequence because identification of the available resources (C7) facilitates the identification of the corresponding capabilities (C1).

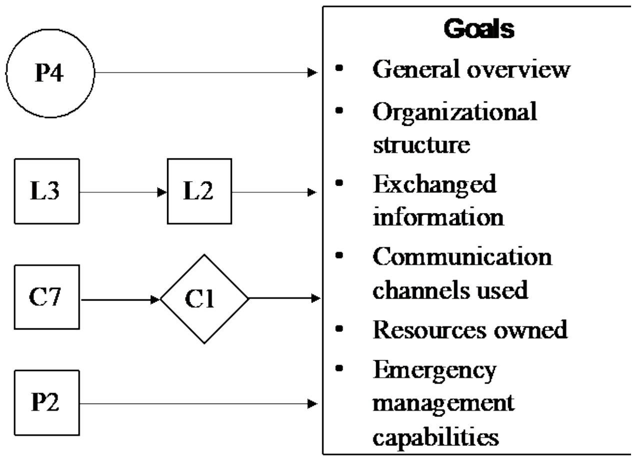

Fig. 4 Level-A: General modeling of the EM operations and information flows.

Table 6 Selected NAF tools and their application within the proposed framework.

Tools	Use
C1 – Capability Taxonomy	To represent the emergency management capabilities of organizations.
C3 – Capability Dependencies	To highlight the dependencies among the capabilities.
C4 – Standard Processes	To show the emergency management phase in which the capabilities are required.
C7 – Performance Parameters	To represent the resources possessed by the emergency actors (e.g., materials, people, physical infrastructure systems, competences).
L2 – Logical Scenario	To represent the interactions between different organizations (e.g., exchanged information, communication channels used), highlighting the presence of unidirectional or bidirectional communication.
L3 – Node Interactions	To represent the sender and recipient of the information, the typology of the exchanged information, or the communication channels used.
L6 – Logical Sequence	To show the chronological sequence of activities, highlighting the emergency management phase when the information is exchanged.
P2 – Resource Structure	To show the interactions between different organizations and the resources owned. It is a summary of the main information collected through the other tools.
P4 – Resource Functions	To represent the key roles within each single organization in order to understand the responsibilities of different actors.

4.2.3. Emergency scenario-based modeling of the operations and information flows

The second level of analysis (i.e., level-B) is aimed at analyzing specific events or operational scenarios; thus, it covers the same scope as level-A but provides a higher level of detail with contextualization. It should be used for analyzing interorganizational capabilities and information flows, rather than for investigating the operations of a single organization. More specifically, the selected modeling tools are intended to

- describe the emergency scenario (i.e., the sequence of elementary events and response activities)
- analyze the interactions (i.e., communication channels and exchanged information) that are established when a specific event or emergency scenario occurs
- analyze the resources available for managing a specific emergency scenario and define a list of EM capabilities in line with the proposed classification (first part of the framework).

Level-B can be implemented independently from level-A; however, when both levels are required, it is recommended to implement level-A first. For instance, the two levels may be implemented in different stages: level A-at the beginning of a study to understand how organizations normally interact and level-B at a later stage to investigate how organizations interact and operate during a specific emergency. As shown in Fig. 5, six NAF 4.0 viewpoints were selected to accomplish this level of analysis. This set is similar to that identified for level-A, except for *P4,* which is substituted by *L6 (logical sequence)* in level-B to better the depict the information flows during different EM phases.

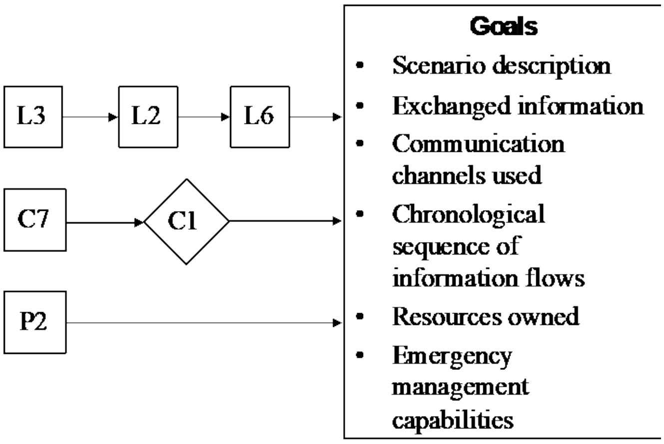

Fig. 5 Level- B: Emergency scenario-based modeling of the operations and information flows.

4.2.4. Inventory of the inter- and intra-organizational capabilities

The third level of analysis (i.e., level-C) provides a detailed inventory of the inter- and intra-organizational capabilities. The unit of analysis is a single organization or a sociotechnical system comprising different organizations and CI systems. Fig. 6 shows the four selected NAF 4.0 viewpoints and their logical relationships. *C7 (performance parameters)* is used to analyze the resources owned by each organization and identify the related EM capabilities (i.e., *C1– Capability Taxonomy*), and to show the dependencies between different capabilities (i.e., *C3 – Capability Dependencies*) and/or the EM phase (i.e., *C4 – standard processes*) where the capability is primarily deployed. Thereby, all the organizations involved are granted full visibility of the capabilities provided by the other organizations, enabling better orchestration and achieving higher effectiveness and efficiency.

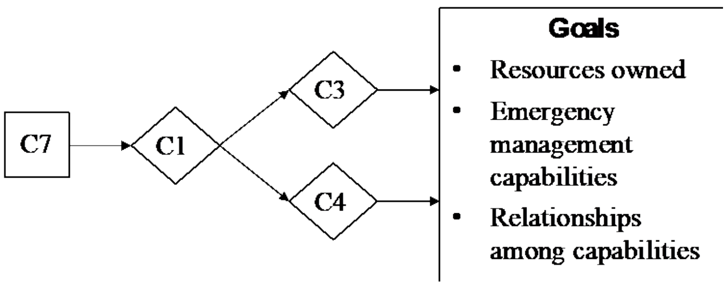

Fig. 6 Level-C: Inventory of the inter-and intraorganizational capabilities.

5. The implementation procedure

The proposed framework can be consistently implemented by following the step-wise procedure depicted in Fig. 7. The first part of the procedure is aimed at clarifying the aim of the study and the boundaries of the system under investigation, so as to take coherent choices for the subsequent configuration and implementation of the framework. The execution phase includes the collection, analysis and interpretation of all the relevant data.

In detail, the analyst should reflect on the aim and scope of the study thus also defining the functional and geographical boundaries of the systems under analysis. This requires the identification of the CI systems to be included (e.g., the transport infrastructure system), the geographical area of reference (e.g., Italy and Switzerland) and the key actors (e.g., CI operators, first responders, public administration). The aim and scope of the analysis is the main driver of the decisions to be taken in the following steps, such as the selection of a specific classification of EM capabilities. A comprehensive taxonomy is presented in Section 4.1, however, the framework can also be applied by making use of different EM capability classifications. .The next step is the identification of the most appropriate level of analysis (Cfr. Section 4.2), which practically translates into the selection of the most appropriate modeling tools, among those offered by the framework (Cfr. Section 4.2.), and the data acquisition methods. In particular, three main methods are suggested:

- Document analysis: it refers to the collection and content analysis of the internal documentation directly provided by the organizations being examined (e.g., organizational charts, emergency plans, reports of past events);
- Interviews: when documents are not sufficient to collect all the required information for modelling EM capabilities, interviews with key informants (e.g., risk and security managers, line managers in first responder organisations) are recommended;
- Workshops and focus groups: it refers to structured methods which might be added to interviews to collect reliable information on inter-organisational capabilities mainly.

However, there are tools that require more than one data collection method. In these cases, it is suggested to start with document analysis and to proceed with direct single interviews, and finally organise multi-actor workshops in case a triangulation of information on inter-organisational interactions is needed.

The next step is the coding of the acquired data where the EM capabilities of the selected organizations are identified starting from the tangible and intangible resources they have (e.g., competences). In that case, the EM capabilities are classified according to the selected taxonomy, such as the one presented in section 4.1.Ddata are then analysed in more detail to extract information for modelling the identified EM capabilities by making use of the selected tools. Finally, results are critically interpreted to draw insights and recommendations for the adoption effective EM capability building measures(e.g. collaborative EM plans, functional requirements of information sharing platforms).

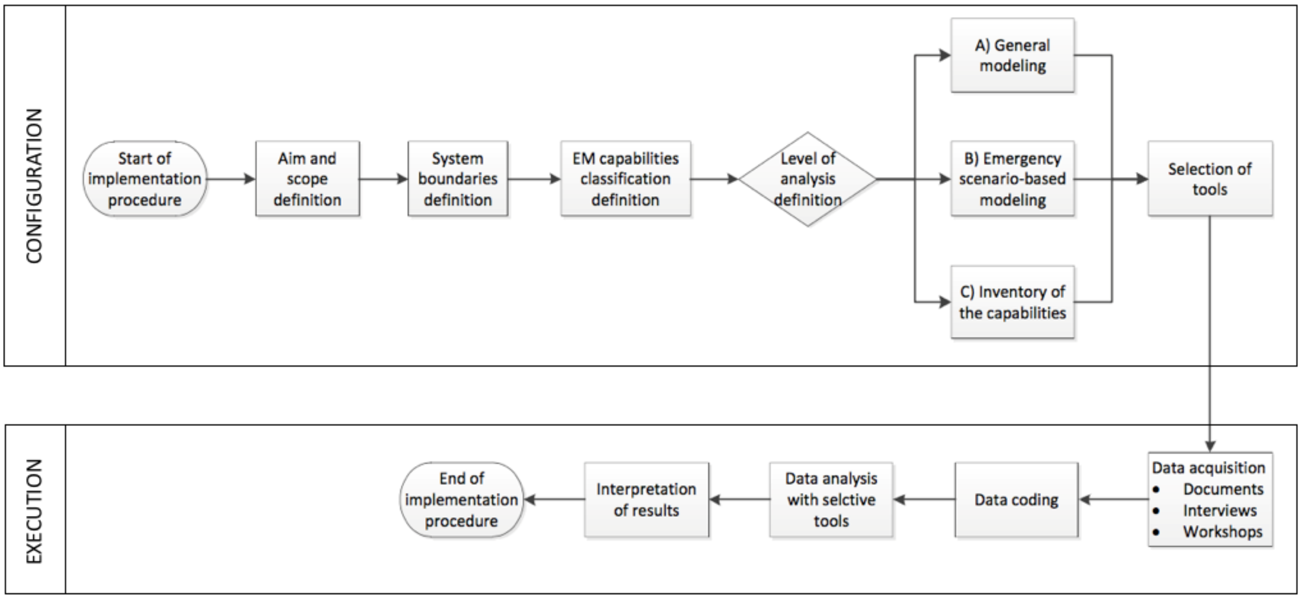

Fig. 7 Implementation procedure

6. Pilot application

The SICt project (resilience of cross-border critical infrastructure or Sicurezza Infrastrutture Critiche transfrontaliere in Italian; www.sict-project.eu) offered the authors an opportunity to develop a pilot application for the proposed framework, illustrate its practical implementation, and demonstrate its value addition. SICt is an Interreg project between Italy (Lombardy Region) and Switzerland (Canton Ticino), which involves CI operators, first responders, and public institutions (Fig. 8). It "aims to strengthen the joint risk management [capabilities] linked to events that may partially or totally disrupt the continuity of critical transport infrastructure service with cross-border relevance" (SICt 2021). The project includes different types of transport infrastructure, such as roads, motorways, railways, and various public and private organizations from both regions (Fig. 9). As an illustrative case, only a subset of organizations was included, guaranteeing adequate diversity (Table 7).

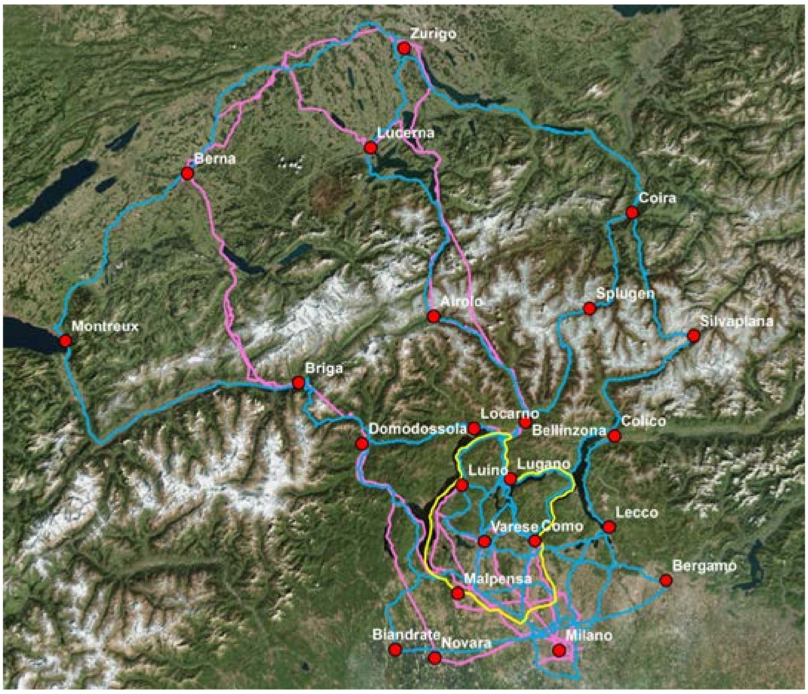

Fig. 8 Study area of the SICt project.

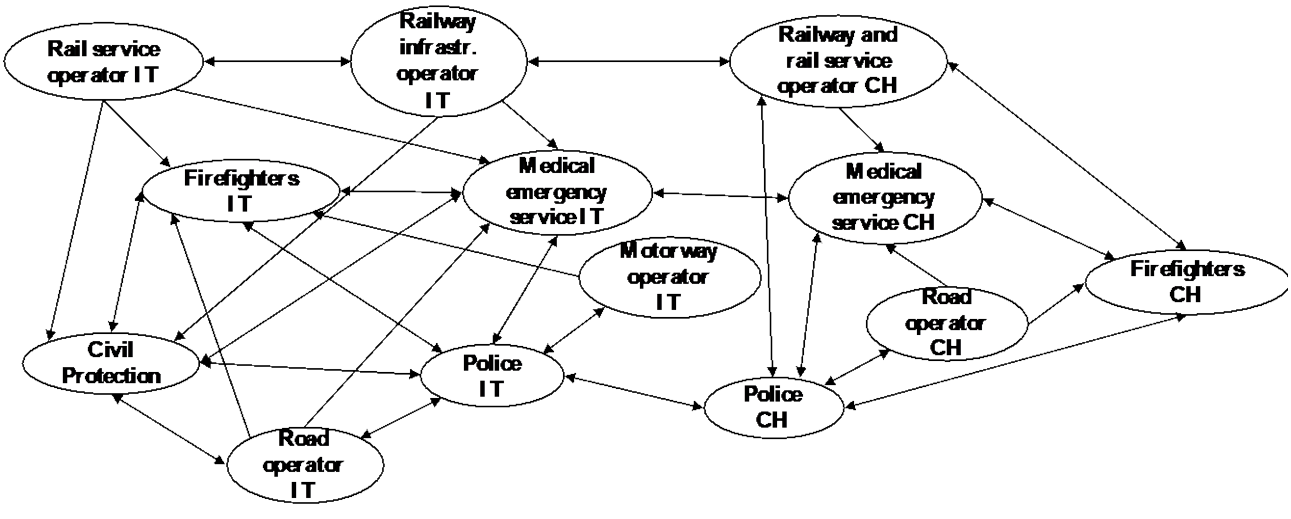

Fig. 9 L2 - Logical scenario: CI operators and first responders involved in the SICt project.

Table 7 Role and nature of the organizations involved in the SICt project.

Country	Organization	Role	Nature
IT	Civil protection	It deals with the mobilization and coordination of the national resources useful for assisting society.	Public
	Firefighters	It deals with the rescue of people, civil defense, protection of assets and the environment.	Public
	Medical emergency service	It deals with medical emergency services within the Italian territory.	Public
	Motorway operator	It deals with the management of the motorway system within the Lombardy region focusing on traffic and maintenance.	Private
	Police	It deals with the control and regulation of mobility on Italian roads with respect to the prevention and detection of incidents.	Public
	Railway infrastructure operator	It deals with the management of railway infrastructure, ensuring traffic safety, and maintaining the infrastructure efficiency.	Public
	Rail service operator	It deals with the rail transport of people and freight.	Public
	Road operator	It deals with the planning, construction, and maintenance of roads in the Italian territory.	Public
CH	Firefighters	It is responsible for intervening in the event of fires, natural hazards, or other events in order to protect people, animals, assets, and the environment.	Private
	Medical emergency service	It deals with the medical emergency services within the Swiss territory.	Public
	Police	It is responsible for ensuring safety and maintaining legally established order. In Switzerland, the police are the actors who coordinate the activities during emergencies.	Public
	Railway and rail service operator	It deals with the management of railway infrastructure and the rail transport of people and freight.	Public
	Road operator	It deals with all the activities related to roads such as maintenance and traffic.	Public

For level-A of the analysis, documents on the organizational structure, the available resources, and emergency plans were collected from some of the organizations (15 documents were studied). As it was not possible to collect sufficient material for all the operators, interviews were conducted with each organization separately. The interviews were primarily aimed at collecting information for completing level-A of the analysis; however, materials useful for levels B and C were gathered as well. The interviews included three parts: the first was aimed at investigating the organizational structure (e.g., roles and responsibilities), the second one was for analyzing the interactions and possible dependencies between organizations, and the final part was to address the EM capabilities. Globally, 15 interviews of approximately 1.5 h each were conducted by the researchers, for a total of 23 h. In addition, other information was collected by attending project workshops and roundtables where more operators and first responders were involved (approximately 16 registered hours of workshops and roundtables).

In the following subsections, the tools related to the three levels of analysis are presented in detail along with some of the implementation and practical insights.

6.1. Level-A

The *P4 (Resource Functions)* tool is used to highlight the resources of interest (human and/or technological) and their relationships. Fig. 10 depicts the EM organizational structure of a motorway operator in Italy.

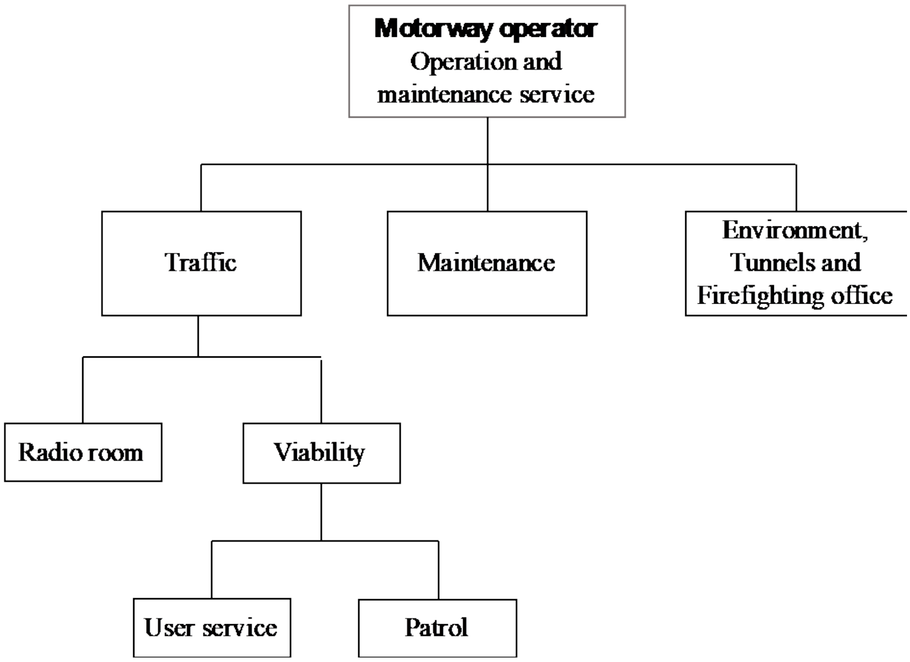

Fig. 10 P4 - Resource functions: EM organizational structure of a motorway operator

Tool *L3 (node interactions)* is used to represent the interactions and dependencies between organizations, primarily, the communication channels and/or the types of information exchanged. As shown in Table 8, the senders of the information are represented in the rows, whereas the recipients are represented in the columns; only the officially established communication channels are represented. However, the presence of active informal communication channels clearly emerged during the interviews (e.g., WhatsApp), which exist because of the personal relationships between professionals belonging to different organizations. Hence, thorough analysis of all the communication channels may highlight the presence of noncertified communication that lead to unpredictable and nonlinear interactions between organizations (e.g., there may be cases where informal channels produce information overload or inconsistency). For instance, Table 8 indicates that the telephone is by far the primary means of communication and that there is no digital platform supporting multi-actor orchestration of the information-sharing process. Moreover, a formal communication channel between Italian and Swiss firefighters is lacking. In similar cases, mapping of the more informal communication channels is recommended. Frequently, in operational contexts, inter-institutional communication is performed through WhatsApp in which peers share messages or files. Finally, as anticipated, the *L3* tool can also be used to model the types (i.e., main content) of information exchanged between organizations.

Table 8 *L3* – Node interactions: communication channels used.

SENDER \ COMMUNICATION CHANNEL	RECIPIENT: Road operator IT	Motorway operator IT	Medical emergency service IT	Civil Protection IT	Police IT	Railway infrastr. operator IT	Rail service operator IT	Firefighters IT	Road operator CH	Medical emergency service CH	Railway and rail service operator CH	Police CH	Firefighters CH
Road operator IT			Tel	Tel	Tel			Tel					
Motorway operator IT					Tel Email			Tel Email					
Medical emergency service IT				Tel Fax	Tel			Tel		Tel			
Civil Protection IT	Tel		Tel		Tel			Tel					
Police IT	Tel	Tel Email	Tel Email	Tel				Tel				Tel	
Railway infrastructure operator IT			Tel Email	Tel Email			Tel Email				Tel Mail		
Rail service operator IT			Tel	Tel		Tel		Tel					
Firefighters IT			Tel	Tel	Tel								
Road operator CH										Tel Email Radio		Tel Email Radio	Tel Email Radio
Medical emergency service CH			Tel Email Fax									Tel Radio	Tel Radio
Rail operator CH						Tel				Tel		Tel	Tel
Police CH					Tel				Tel Radio	Tel Radio	Tel		Tel Radio
Firefighters CH										Tel Radio	Tel	Tel Radio	

Moreover, the L3 tool is necessary to build *L2 (Logical Scenario)*, which graphically shows the interactions among organizations (represented as nodes), favoring the analysis of the strengths and weaknesses of the current arrangements (Fig. 9). *L2* can be used to highlight unidirectional (arrow with one tip) or bidirectional (arrow with two tips) communication. As shown in Fig. 9, most of the interactions between Italy and Switzerland appear to be centrally managed by the first responders, particularly the Swiss Police, who interact with the Italian Police, with the exception of medical emergency services and railway operators. However, this does not imply a vertical governance mechanism between the public and private organizations in the two regions.

The fourth tool is *C7 (performance parameters)* aimed at creating an inventory and analysing the resources owned by different organizations in order to identify the corresponding capabilities (the classification used for the capabilities is introduced in subsection 4.1). As depicted in Table 9, six resource categories were identified (i.e., know-how, personnel, physical infrastructure, TLC infrastructure, vehicles, and other assets). In addition, the type of resource and the general description are provided for each category. The *C7* tool is flexible, and different attributes can be associated with a resource (e.g., quantity, application area) as well as the owner organization. The example presented in Table 9 shows the resources and corresponding capabilities of a motorway operator in Italy.

Table 9 *C7* – Performance parameters: Resources and related EM capabilities of an Italian motorway operator.

Resource category	Resource type	Description/Usage	Capability	Capability Cluster
Know-how	Operational sector activities	Special transport	Logistics and transportation services	Resource management
	Operational sector activities	Snow event management	Risk assessment	Risk management
			Planning	EM planning
	Maintenance sector activities	Daily roads checks	Threat and Hazards identification	EM planning
	Artwork monitoring	Periodic checks of artwork	Environmental protection services	Surge management

Personnel	Patrol	On the field to send alarm signal	Community resilience building	Risk management
	Maintenance team	Perform maintenance activities	Interdiction and disruption	Risk management
	Team for monitoring the state of waste disposal	Waste disposal	Environmental protection services	Surge management
Physical Infrastructure	Radio room	Receive and communicate information	Operational coordination	Communication and coordination
			Information sharing	Communication and coordination
TLC Infrastructure	Video Camera	Monitoring	Threat and Hazards identification	EM planning
			Access control and identity verification	Resource management
Vehicles	Truck for chloride spreading service	Protect roads from snow	Interdiction and disruption	Risk management
Other Assets	Reduction signage	Inform passengers	Public information and warning	Communication and coordination
	Animal cages	Transport animals safely	Supply chain integrity and security	Risk management

Based on the preliminary analysis developed using *C7* at the resource level, *C1 (capability taxonomy tool)* can be used to define and document the EM capabilities provided by a given organization or collectively by a network of organizations. The example in Fig. 11 shows the EM capabilities of an Italian motorway operator, which includes 13 among the 15 categories in the adopted classification (subsection 4.1).

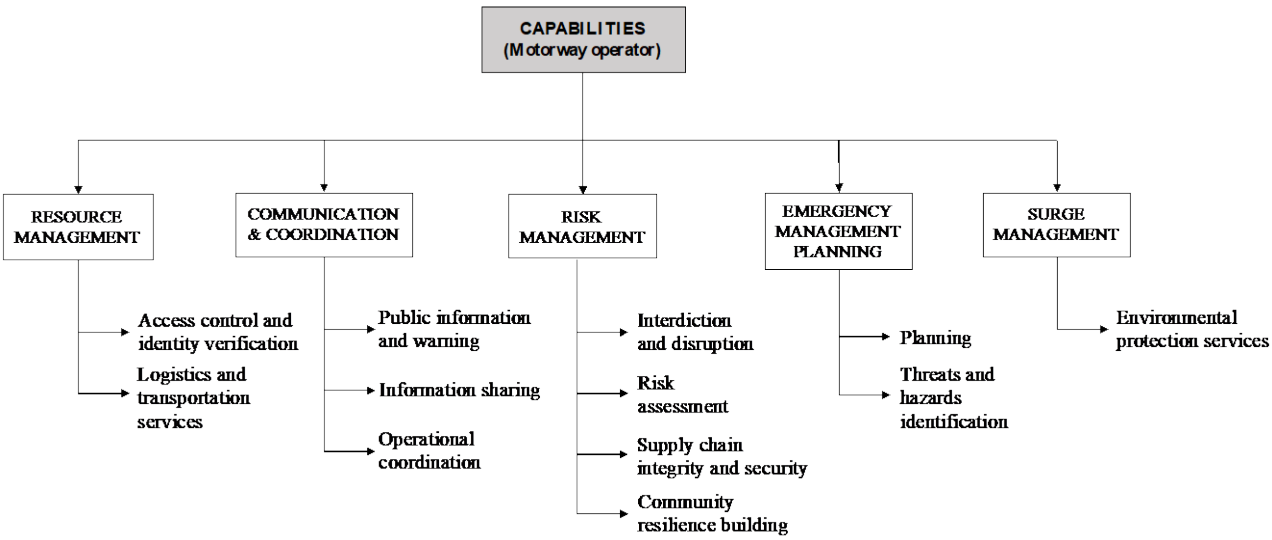

Fig. 11 *C1* – Capability taxonomy: EM capabilities of an Italian motorway operator.

Finally, the last tool, which is part of level-A, is *P2 (resource structure)*. It is used to represent the possible dependencies (functional or logical) between resources that belong to the same organization; moreover, it can be used to model the operational flow between different organizations, as depicted in Fig. 12. Although this tool can be used to analyze a general emergency, it is even more useful for investigating the interactions that arise when a specific event occurs (level-B in the framework).

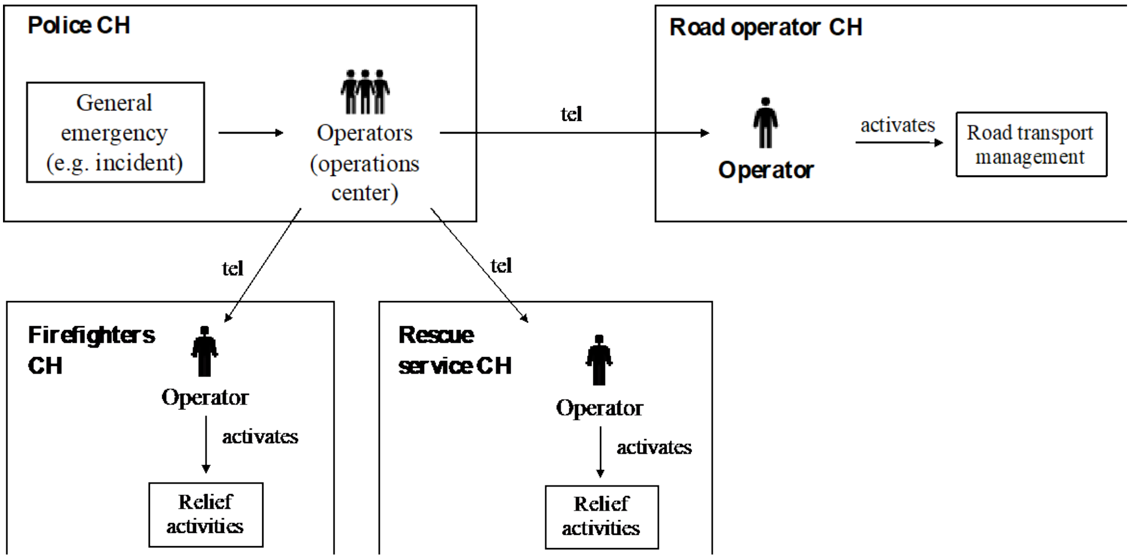

Fig. 12 *P2* – Resource structure: Interactions between resources.

6.2. Level-B

Most of the tools related to level-B are the same as those used in level-A of the analysis (i.e., *L3, L2, C7, C1, P2*). The difference between the two levels is in the context of the analysis. In level-B, the analysis considers the interactions, resources, and capabilities deployed under a specific emergency scenario. For this purpose, *L6 (Logical Sequence tool*) is used to set the chronological sequence of the activities performed by different organizations. Fig. 13 shows an example of the information exchanged in different phases of the EM cycle between the organizations involved in the management of an event (e.g., fire with injured people).

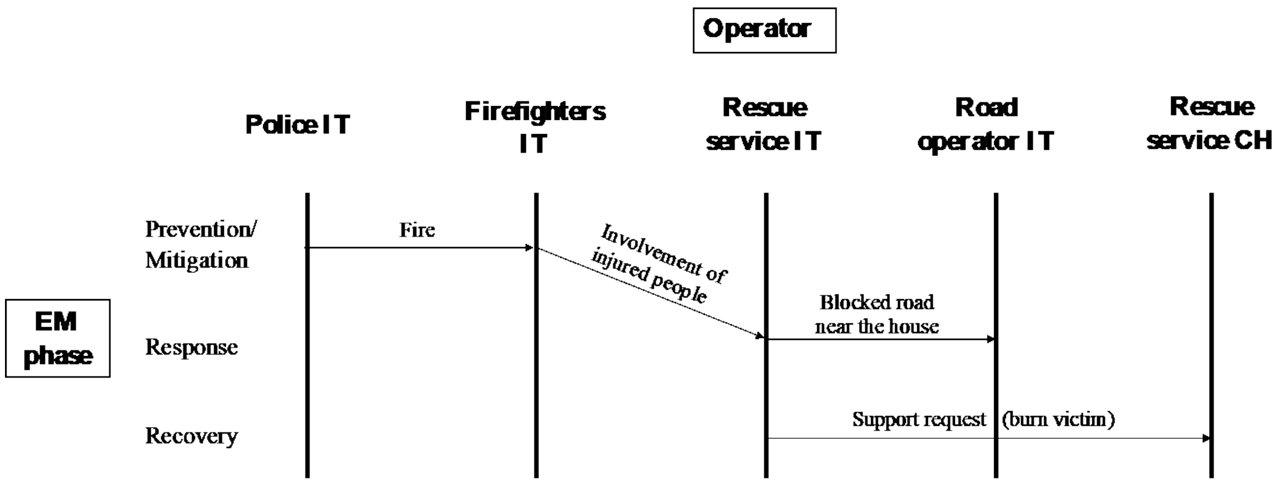

Fig. 13 *L6* – Logical sequence: Chronological sequence of the activities.

6.3. Level-C

Finally, the third level of analysis (level-C) results in a fully documented and specified list of EM capabilities linked to the CI operators and first responders. Tools *C7 (Performance Parameters)* and *C1 (Capability Taxonomy)* have already been presented in subsection 5.1. The other two tools adopted in level-C are *C3 (Capability Dependencies)* and *C4 (Standard Processes).*

The *C3* tool is used to detail the interdependencies between the EM capabilities. It is an extension of *C1*, where the connection between the capabilities of different organizations is highlighted. Fig. 14 displays an example of the existing dependencies between the capabilities of the Swiss actors. In this illustrative case, the dependencies were determined considering the method in which the resources are used, and highlight the influence of an organization's capability on those of the other organizations (i.e., the output of a capability is the input of another capability).

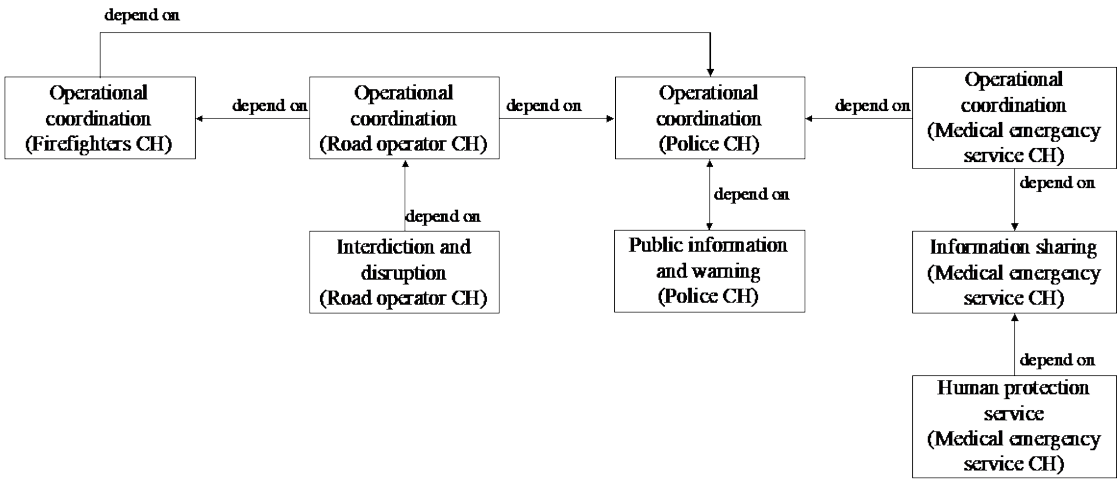

Fig. 14 *C1* – Capability dependencies: EM capabilities of Swiss actors.

Finally, the *C4 (Standard Processes)* tool details the relevance of each capability in different EM phases and can be used for modeling the capabilities of a single organization or a network of organizations. In Table 10 the EM capabilities of the Swiss Police (already identified through the tool *C7 – performance parameters*) are classified against the EM phase of deployment.

Table 10 *C4* – Standard Processes: EM capabilities and phases.

Cluster	**Capability (Police CH)**	**Emergency Management phase**			
		Prevention Mitigation	**Preparedness**	**Response**	**Recovery**
Resource Management	Access control and identity verification	x			
	Logistics and transportation services			x	
Risk Management	Community resilience building	x		x	x
	Interdiction and disruption	x		x	
	Risk assessment	x	x		
	Supply chain integrity and security			x	
Communication and Coordination	Information sharing	x	x	x	x
	Operational coordination	x	x	x	x
EM planning	Threat and Hazard identification	x	x		

7. Discussion

The proposed integrated framework contributes to the advancement of the state-of-the-art with respect to two main aspects. First, it provides the general definition and classification of EM capabilities, which are sufficiently general and applicable to different operational contexts and emergency scenarios. Therefore, the study contributes to overcoming the existing lacuna in literature, which focus on application-specific and context-specific classifications of the EM capabilities (Yang and Xu 2011; Yong et al. 2012; Zhang et al. 2018; Ma et al. 2019). Next, it provides analysts with a structured set of tools and guidelines for modeling and analyzing the EM capabilities, which is suitable for multi-actor, multi-sectoral, and cross-border contexts. Therefore, this study addresses the lack of a generalized methodology for EM capability modeling in the existing literature, where application-specific methods alone have been documented (Banks et al. 2014; Crawford et al. 2018; Bristow 2019; Sienkiewicz-Małyjurek 2019).

Furthermore, the aim of the study was to develop a framework that is robust from a theoretical perspective. The CAS theory was selected among the most relevant theories in the EM domain because it captures the features of systems characterized by multiple inter-related elements that can change over time. In particular, these features draw attention to the possible instability and disruptions that may affect the systems and the consequences of the actions.

For transparent evaluation of the theoretical robustness of the proposed framework, its characteristics were compared against the CAS features (Table 1). Table 11 summarizes the results in terms of the types and extent to which the CAS features are addressed by one or more characteristics of the framework. It can be noted that the eight identified CAS features are captured by the framework with different levels of detail. To grade the levels, the following scale and symbols were used:

(++): The framework can directly model the CAS features, indicating that the CAS feature is intrinsically reflected in the framework.

(+): The framework can indirectly model the CAS features. Hence, the framework enables analysis of the factors connected to the CAS feature.

(-): The framework cannot capture the CAS feature.

The results reported in Table 11 show that the developed framework can directly model agent diversity, self-organization, adaptability, and the simple rules that characterize the functioning and behaviour of the system (e.g. information flows and interactions). This is because the framework enables the collective analysis of different organizations (agent diversity), which have their own governance mechanisms and decide the level of inter-organisational coordination and collaboration on a voluntary basis (self-organization). Moreover, when implemented in the planning/preparedness phase, the framework directly supports analysis of the adaptability characteristics of the system and the key operating rules.

However, the nonlinearity and emergence features are indirectly captured by the framework mainly through the modelling of certain mechanisms that generate these characteristics (e.g., formal vs. informal communication channels, redundancies in the resources and capabilities), whereas the dynamics and evolution as well as the irreversibility features cannot be captured by any of the elements of the framework due to the lack of dynamic modelling tools.

Overall, by comparing the proposed framework with the EM capability classifications and models and methods used for their modeling, the main advantages can be summarized as follows:

- *Generalization*: It can be applied to model and can analyze a wide and comprehensive spectrum of EM capabilities under different operational and emergency contexts. Indeed, most of the available classifications of capabilities are not adaptable to different scenarios (Yang and Xu 2011; Yong et al. 2012; Zhang et al. 2018; Ma et al. 2019) while different models and methods for EM capability modeling can only be used for the assessment of specific capabilities

(Yang and Zhang 2014; Dohan et al. 2015; Ma et al. 2019; Alvanchi and Seyrfar 2020). Moreover, it can be used to model highly heterogeneous multi-actor environments, as illustrated by the pilot application.

- *Standardization*: On the one hand, the classification scheme for the EM capabilities offers a common reference applicable to organizations operating in different countries; on the other hand, the adoption of a selected subset of NAF 4.0 viewpoints offers standardized ways of collecting and reporting organizational information even in situations with a high heterogeneity of actors (e.g., multisectoral or cross-border systems).
- *Flexibility*: It allows the customization of the scope and levels of analysis according to specific needs and the system characteristics. Indeed, the NAF viewpoints that are normally applied for military and business use (NATO, 2018), are now introduced in a scientific environment favoring its application to different interdependent systems.

Table 11 Mapping of the framework characteristics against the CAS features.

("++" = the framework can directly model the CAS feature; "+" = the framework can indirectly model the CAS feature; "-" = the framework cannot capture the CAS feature)

CAS feature	Matching with the Framework characteristics	
Structural features		
Nonlinearity	The application of the framework may highlight some of the mechanisms that generate nonlinear interactions between different parts of the system. Thus, it does not quantitatively assess the nonlinear effects in the system, but offers evidence of the mechanisms that lead to nonlinearities. For instance, this emerges through the adoption of tools related to the interactions between organizations and the analysis of information flows.	+
Emergence	The presence of capabilities that are redundant in the system (e.g., different organizations could have the same capabilities) can favor the management of emergent situations. Thus, the capability view taken by the framework can help in addressing the emergence of multiple related behaviors of the system. The framework also enables the modeling of the formal and informal means of interaction between different actors that helps in capturing emergent behaviors.	+
Agent diversity	The framework owns the key conceptual elements for modeling organizations with different roles, responsibilities, processes, and capabilities; thus, it is can fully capture the agent diversity at different levels.	++
Dynamics and evolution	Even if the framework can be easily updated when the system changes or evolves, it can return static analyses only. However, this CAS feature is not one of the most relevant in the context of EM of interdependent CI systems because the main objective is to rapidly bounce back to the prior stable operating conditions, and long-term CI system evolution is not within the scope of EM operations.	-
Irreversibility	Even if this feature is important for a full understanding of the challenges in the EM of interdependent CI systems, it is not within the framework's aim and scope. The framework is intended to support the analysis of EM capabilities in the planning and preparedness phase, but it does not directly provide any support to the tactical decision making process during emergency response.	-
Managerial features		
Self-organization	The framework has been conceived to model a system characterized by both horizontal governance mechanisms, typical of a PPC context, and the vertical hierarchies of a traditional command and control model, which is typically adopted among first responders. Moreover, by applying the framework, each organization is first analyzed autonomously and then with the multifaceted connections with the entire sociotechnical system (communication channels, information sharing, capabilities) under different governance models.	++
Adaptability	The capability-based view shapes all the elements of the framework and was explicitly sought to support resilient EM planning, enabling the coordination of multiple assets and resources in a more flexible and agile manner.	++
Simple rules	The framework favors the mapping and understanding of the information flows and interactions between different parts of the system using tools that represent information	++

	exchange and the sequence of activities. Thereby, management of the interactions and the coordination required between parts of the system during a specific emergency event are better supported.	

8. Conclusions

As the management of emergency events in interdependent CI systems is becoming increasingly challenging, a capability-based approach to emergency planning and response for fostering CI resilience is required. In this study, a framework for the classification and analysis of the intra- and inter-organizational EM capabilities was developed.

This study contributes to the EM discipline by providing a coherent and theoretically robust methodology for capability analysis. The classification of the EM capabilities can be applied in different contexts and hazardous conditions. A new classification framework was introduced along with a new list of capabilities that can be adapted to different scenarios, covering the main operations and needs characterizing the EM context. Furthermore, the framework enables comprehensive representation and description of the system and its elementary components. In particular, the EM capability analysis methodology was developed and reviewed based on the features of a CAS, resulting in a framework capable of modeling the structural and managerial features of such systems.

Moreover, the study contributes to theory by demonstrating the suitability of the CASs theory for addressing relevant issues in the EM domain. Although the illustrative case is specifically related to transport infrastructure systems, the framework can be used to analyse different interdependent systems and can model both intra- and inter-organisational capabilities.

In addition, this study has clear relevance for practical application. The generalized classification of the EM capabilities simplifies the mutual understanding between the different actors and organizations involved in the EM assessment and planning phases. The expected benefits cover all the phases of the EM cycle, from prevention and preparedness (which is the primary area of application of the framework; therefore, direct impact is expected) to response and recovery (which is the area of indirect impact due to more effective planning). A common reference language is offered to practitioners for defining and documenting the EM capabilities. Furthermore, analysts are provided with a set of tools for the modelling of EM capabilities based on the organizational and operational arrangements of all the involved actors, from first responders to CI operators. Overall, the framework can be regarded as an effective means for fostering inter-institutional collaboration (e.g., public-private collaborations) in order to improve the resilience of interdependent CI systems. In addition, general guidance for the implementation of the framework under different contexts (e.g., general or emergency scenario-based modeling) is provided.

However, some of the elements of the framework require analytical or methodological improvements, such as the analysis of the interdependencies between capabilities, and a set of metrics and methods are needed for the quantitative assessment of the capabilities. This study is part of a broader research endeavor that also addresses the assessment and orchestration of the EM capabilities of interdependent systems.

In general, foundational and applied research on capability-based EM is still in its infancy, particularly when interdependent CI systems are at stake. A growing research effort is needed on the conceptual as well as methodological aspects, along with the documentation and assessment of full-scale implementation in real-life environment.

Declarations

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Conflicts of interest/Competing interests. None.

Availability of data and material. The authors make materials available upon request.

Code availability. Not applicable.

Authors' contributions. Not applicable.

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