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Improving resilience in Critical Infrastructures through learning from past events

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Rome, 28th Apr 2023

Raffaele Cantelmi

ABSTRACT

Modern societies are increasingly dependent on the proper functioning of Critical Infrastructures (CIs). CIs produce and distribute essential goods or services, as for power transmission systems, water treatment and distribution infrastructures, transportation systems, communication networks, nuclear power plants, and information technologies. Being resilient, where resilience denotes the capacity of a system to recover from challenges or disruptive events, becomes a key property for CIs, which are constantly exposed to threats that can undermine safety, security, and business continuity.

Nowadays, a variety of approaches exists in the context of CIs' resilience research. This dissertation starts with a systematic review based on PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) on the approaches that have a complete qualitative dimension, or that can be used as entry points for semi-quantitative analyses. The review identifies four principal dimensions of resilience referred to CIs (i.e., techno-centric, organizational, community, and urban) and discusses the related qualitative or semi-quantitative methods.

The scope of the thesis emphasizes the organizational dimension, as a socio-technical construct. Accordingly, the following research question has been posed: *how can learning improve resilience in an organization*?

Firstly, the benefits of learning in a particular CI, i.e. the supply chain in reverse logistics related to the small arms utilized by Italian Armed Forces, have been studied. Following the theory of Learning From Incidents, the theoretical model helped to elaborate a centralized information management system for the Supply Chain Management of small arms within a Business

Intelligence (BI) framework, which can be the basis for an effective decision-making process, capable of increasing the systemic resilience of the supply chain itself.

Secondly, the research question has been extended to another extremely topical context, i.e. the Emergency Management (EM), exploring the crisis induced learning where single-loop and double-loop learning cycles can be established regarding the behavioral perspective. Specifically, the former refers to the correction of practices within organizational plans without changing core beliefs and fundamental rules of the organization, while the latter aims at resolving incompatible organizational behavior by restructuring the norms themselves together with the associated practices or assumptions. Consequently, with the aim of ensuring high EM systems resilience, and effective single-loop and double-loop crisis induced learning at organizational level, the study examined learning opportunities that emerge through the exploration of adaptive practices necessary to face the complexity of a socio-technical work domain as the EM of Covid-19 outbreaks on Oil & Gas platforms. Both qualitative and quantitative approaches have been adopted to analyze the resilience of this specific socio-technical system.
On this consciousness, with the intention to explore systems theoretic possibilities to model the EM system, the Functional Resonance Analysis Method (FRAM) has been proposed as a qualitative method for developing a systematic understanding of adaptive practices, modelling planning and resilient behaviors and ultimately supporting crisis induced learning.

After the FRAM analysis, the same EM system has also been studied adopting a Bayesian Network (BN) to quantify resilience potentials of an EM procedure resulting from the adaptive practices and lessons learned by an EM organization.

While the study of CIs is still an open and challenging topic, this dissertation provides methodologies and running examples on how systemic approaches may support data-driven learning to ultimately improve organizational resilience. These results, possibly extended with future research drivers, are expected to support decision-makers in their tactical and operational endeavors.

Disclaimer

This publication-based dissertation relies on three previously published manuscripts:

– sections 2.2, 2.3, 2.4, 2.5, 2.6, 2.7 are based on the content of the paper *"R. Cantelmi, G. Di Gravio, R. Patriarca, Reviewing qualitative research approaches in the context of critical infrastructure resilience, Environ. Syst. Decis. (2021). https://doi.org/10.1007/s10669-020-09795-8*";

– sections 3.3, 3.4, 3.5, 3.6, 3.7 introduce the work discussed in the paper *"R. Cantelmi, G. Di Gravio, R. Patriarca, Learning from incidents: A supply chain management perspective in military environments, Sustain. 12 (2020). https://doi.org/10.3390/su12145750*";

– sections 4.3, 4.4, 4.5, 4.6 rely on the study presented in the paper *"R. Cantelmi, R. Steen, G. Di Gravio, R. Patriarca, Resilience in emergency management: Learning from Covid-19 in oil and gas platforms, Int. J. Disaster Risk Reduct. 76 (2022) 103026 https://doi.org/10.1016/j.ijdrr.2022.103026*".

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To Marianna, Sveva and Daria,

sparkling lights of my life

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CHAPTER 1

1.INTRODUCTION

1.1. Background

Nowadays, due to the frequent occurrence of catastrophic events related to human activities or natural disasters, the awareness of the strategic importance of Critical Infrastructures (CIs) has grown worldwide: assuring safety, security, and business continuity of CIs, despite several hazards and threats, emerges as a new paradigm to avoid heavy repercussions for modern societies. Specifically, CIs are large-scale, man-made systems that function interdependently to produce and distribute essential goods (such as energy, water, and data) and services (such as transportation, banking, and healthcare). An infrastructure is defined as critical if its incapacity or destruction has a significant impact on health, safety, security, economics, and social well-being of a state (Council Directive 2008/114/EC of 8 December 2008).

CIs are various by nature, e.g., physical-engineered, cybernetic or organizational, by environment (geographical, natural) and operational context (political/legal/institutional, economic, etc.). Examples are those providing services of: energy (including generation, transmission, distribution and storage, in regard with electricity, oil and gas supply); transportation (including rail, roads, aviation and waterways); information and telecommunication (including information systems, industrial control systems (SCADA), Internet, fixed and mobile communications and broadcasting) [1].

Consequently, CIs represent a vital element for modern societies and studying their resilience has become strategic for decision makers. Specifically, the concept of resilience, deeply explained in Chapter 2, denotes the capacity of a system to recover from challenges or disruptive events [1].

Because of the high level of interconnections, a failure in a CI can produce additional cascading failures [2], sending ripple effects throughout regional, national or international scales with potential catastrophic consequences. Operationalising the concept of resilience can become puzzling for CIs' management, especially considering their interdependent nature which recalls the systems-of-systems treats. Managing resilience calls for a reconsideration of available risk management methods and models in order not to fall within the trap of reductionism and over-simplified linear modelling techniques. New frameworks are needed for the integration of methods capable of viewing the problem from different perspectives (topological and functional, static and dynamic), suitable for coping with the high complexity of the system and the related uncertainties [3]. Through a systematic review of the available literature, Chapter 2 shows that such complexity is addressed by frameworks based on different approaches classified by [4] in qualitative - Tier I, quantitative - Tier III, or a combination of the two - Tier II.

Among Critical Infrastructures, supply chains play today a role of strategic importance for our global and interconnected world and their proper management has become essential for the business continuity of the organization at hand. Generally, supply chain network includes manufacturers, logistics firms, distributors, and many other indirect agents (banks, brokers, insurance companies, etc.) [5] and its main target is supplying goods or services to the customer. Until the 1950s, in military field like any other production domain, business leaders thought of logistics as a

combination of procurement, maintenance, transportation of facilities, material, and personnel [6]. From the early 1980s, such perspective incorporated the concept of Supply Chain Management (SCM), extending the idea of logistics to the management of suppliers and customers interactions, in order to improve the efficiency and resilience of the supply chain itself.
SCM has become one of the most popular concepts in the management area since the 1980s [7], with a number of journals in manufacturing, procurement, and transportation, information pushing forward the development of the SCM idea in a global competitive environment [8–10]. Specifically, in the military context, the annual industrial capabilities report, compiled by the Pentagon's Office of Manufacturing and Industrial Base Policy, recognizes that the industrial base of the armament sector is particularly strained, due to the irregular flow of procurement and the lack of new designs developed internally [11]. These observations confirm the critical relevance of measuring and managing information on key operational and performance parameters [12].

In a systemic perspective, it is important to underline that the delivery of a good or a service does not terminate the supply chain. A systemic SCM shall rather include the so-called reverse logistics, which ensure that used, defective and discarded products are properly managed in order to increase the effectiveness and efficiency of the network [5]. In the domain of repairable items, reverse logistics is usually regulated by performance-based contracting, i.e., after-sales services aimed at cutting fixed-price costs by ad-hoc interventions [13], following its introduction in the early 1990s [14]. In military contexts, reverse logistics ensures that the material lifecycle is sustainable, facilitating the recycling or reusing of equipment which can be repaired and utilized [15]. Therefore, with the aim of increasing the efficiency, the effectiveness and the resilience of the SCM, it has become necessary to adopt structured and effective frameworks for managing reverse streams of the supply chain, both in terms of operations and information management [16]. Good decisions are based on timely, accurate and relevant information, which represents the link between activities and operations [17]. Despite recent significant advances and dramatic improvements in information technology, the discipline of SCM can be further enhanced to address modern practical real-world challenges [18], even more specifically in military supply chains. Available research mostly focuses on the quantitative analysis of detailed aspects of the supply chain. For example, some scholars propose a game model of military reverse logistics based on the Nash equilibrium [19]. Similarly, another work focuses on an optimal model of principal–agent relationships for waste military air materials, stressing the need for provider-specific incentive mechanisms [20]. More recently, a hybrid machine learning model has been developed to improve and predict spare parts reverse flow [21]. A large set of research is also focused on routing problems for reverse logistics or end of life vehicles, exploring multiple facility location problems, e.g., single-facility [22], grouped location problem [23], k-location routing [24], multi-period location routing problems [25]. While these studies contribute widely on the progress of reverse logistics, they do not present a deep analysis on the management of the reverse flow, especially within military supply chains.

On this side, our research complements the wide literature relying on mathematical formulation for reverse logistics via a framework to be used for dealing with technical inconveniences from an organizational perspective. The outcome of the framework allows for an understanding of the strengths and weakness of both the product at hand and the agents involved in its management process. Based on these premises, data on reverse logistics have

been related to the theory of Learning From Incident (LFI), to take maximum advantage from reporting actions. LFI (or more generally from past events) as explained more deeply in Chapter 3, can be defined as a change in the repertoire of behaviors of an organization [26], i.e., a shared understanding of the need for new actions to minimize or prevent negative events [27]. The academic field of LFI is partly fragmented [28], but it is widely acknowledged its potential for both safety and productivity [29,30].
To reap its rewards, learning has to be set in an organizational environment including the identification of events to be investigated, the application of the most suitable analysis techniques, an in-depth reflection on the results for the development of meaningful repertoires, the sharing of the latter, and the structure of the most advantageous conditions for their applicability [27]. LFI is thus aligned with the idea of a more efficient and resilient supply chain, where the application of a systematic learning system may provide savings on input costs such as time, labor and energy, and thus enable profitable outputs and increase customer satisfaction, also in light of environmental dimensions [31]. The relevance of such a proactive learning system has been widely acknowledged in military technical publications, as detailed in the NATO lessons learned handbook [32].

Learning from past events is also essential in other contexts, such as that of Emergency Management (EM). Emergencies create challenges for organizations by putting them in settings where they stretch operational boundaries and manifest adaptive capacities [33,34]. However, they also represent a chance for changes in policy reforms, institutional overhaul, and even leadership revival [35,36]. The adaptive capacity and willingness to change are key elements for embracing such learning opportunities [37–39]. Understanding what worked well during the emergency, which aspects of emergency plans were successful, which ones were not put in place, or not even practicable, etc., enhances organizational resilience for future Emergency Response (ER) operations [40].

Learning from emergencies is at the heart of the recovery and mitigation stages in any Emergency Management System (EMS), even though it is not a linear and straightforward process. The actors involved in ER operations might have different priorities, goals, opinions, strategies, and political agendas on situation management and system improvements [41].

1.2. Research Question

Despite the unique face of any emergency, universal elements reflect underlying common treats of emergency situations. These elements include hazards that pose an immediate threat to health, safety, security, property, or environment, time pressure and a high level of uncertainties.

Additionally, especially over the execution of this research project, Covid-19 has imposed ground-breaking unexpected challenges in everyday life, as well as in industrial operations. EM operations also need to be reconsidered, in order to ensure an effective and safe management of new and reshaped threats in dynamic scenarios [42]. Such dynamicity demands for systemic approaches to deal with operational practices in a way that emphasizes the study of actual variability, explores adaptive practices and looks for systems-wide rather than localized solutions [43]. This idea refers to the notion of Resilience Engineering (RE), i.e. the discipline focused on engineering the ability of acting resiliently in face of both expected and unexpected situations. The topic has been highly debated both in EM context [44], and in modern safety management [45].

Accordingly, the following research question clarifies the scope of this thesis: *how can learning improve resilience in an organization*?

To answer this research question, research activities have been conducted at different levels, according to two different aims, as discussed in the following section 1.3.

1.3. Aims

1.3.1. Aim 1 – To review literature about resilience management in Critical Infrastructures

Considering the scope of this work to be centered in the management of Critical Infrastructures' resilience, reviewing the corresponding literature was deemed as a main priority. The topic has been already debated in literature, as documented by reviews restricted to specific CIs (e.g. energy systems [46], cyber CIs [47], remote sensing [48], supply chain [49]), or with an explicit focus only on quantification aspects (see e.g. [50–53]). However, to the best of our knowledge, there was no explicit up-to-date literature review related to qualitative (or semi-quantitative) methodologies as developed for managing resilience of CIs. Therefore, a systematic literature review, focused on the qualitative and semi-quantitative approaches to the CIs' resilience analysis, was considered necessary to start our research.

During this review, four principal dimensions of resilience referred to CIs (i.e., techno-centric, organizational, community, and urban) have been identified and the related qualitative or semi-quantitative methods have been discussed. The scope of the thesis emphasizes the organizational dimension, as a socio-technical construct.

1.3.2. *Aim 2 – To develop approaches to manage resilience in Critical Infrastructures and apply them in operational use cases*

The second aim of our research was to develop models and methods aligned with, and capable of extending, approaches already available in literature.

Specifically, the benefits of learning in CIs' management started to be investigated through formal models, firstly relying on Learning From Incident (LFI) theory [54,55].

After exploring the improvement of the resilience of a supply chain through a LFI system, this second aim was extended to another extremely topical context, i.e. the EM. In this case, the socio-technical nature of the system at hand has been investigated through the Functional Resonance Analysis Method (FRAM) [56], firstly used in qualitative terms (Tier I), and then extended via a Bayesian Network (BN) representation (Tier III).

For the research on improving the resilience of a supply chain via LFI, a use case has been developed linked to the CI of the reverse logistics related to the small arms utilized by Italian Armed Forces. Comparing the results of the theoretical model with the current reality, shortcomings have been noticed and a centralized information management system, for the SCM of small arms, has been elaborated. More specifically, the analysis has been conducted on reporting issues related to a specific weapon, supplied to three different Armed Forces. Data and analysis refer to a 6-year interval, manipulated in order not to violate the intellectual property of the agents involved and without disclosing any sensitive information.

By exemplary statistics and dashboards to support decision-making, our research aimed at proving the benefits of a systematic LFI information management system. The purpose was two-fold: (i) the definition of concepts and roles for implementing an LFI in military environments; (ii) the development of a database structure for ensuring the implementation of previously mentioned roles and concepts, in line with NATO guidelines.

The basic of LFI has been then used to capture socio-technical interactions at organizational level through the FRAM in order to understand how crisis induced learning could improve the organizational resilience. The study has examined learning opportunities that emerge through the exploration of adaptive practices necessary to face the complexity of a socio-technical work domain as the EM of Covid-19 outbreaks on Oil & Gas platforms, in collaboration with the OFFB (Norwegian Operator's Association for ER) company. OFFB represents a perfect use case, being the organization in charge of providing EM solutions also exposed to unexpected challenges (at the time of the event): the management of Covid-19 contagion episodes on offshore O&G platforms. The aim of the case was to document the validity of the proposed approach in studying learning opportunities emerging through the exploration of adaptive practices as being performed in practice. The research, conducted in collaboration with the staff of OFFB company and staff from the Norwegian Business School of Stavanger (NOR), has been contextualized into real operations happened in 2020-2021 and performed by the company which was responsible for second line EM in O&G platforms. Operations, during the three different episodes occurred, have been modelled using the FRAM, the systems-theoretic approach grounded in RE and described in section 4.2. The analysis went beyond documental knowledge, rather incorporating qualitative descriptions of work practices as informed by front-line operators. After the FRAM analysis, the same EMS has also been studied following a Tier III approach. Specifically, a BN has been adopted to quantify resilience potentials of an EM procedure resulting from the adaptive practices and lessons learned by an EM organization.

1.4. Structure of the thesis

Figure 1 shows the workflow of the topics addressed in the dissertation. The dissertation body is divided into two main areas referred to Learning From Incidents and crisis induced learning, both answering the research question.

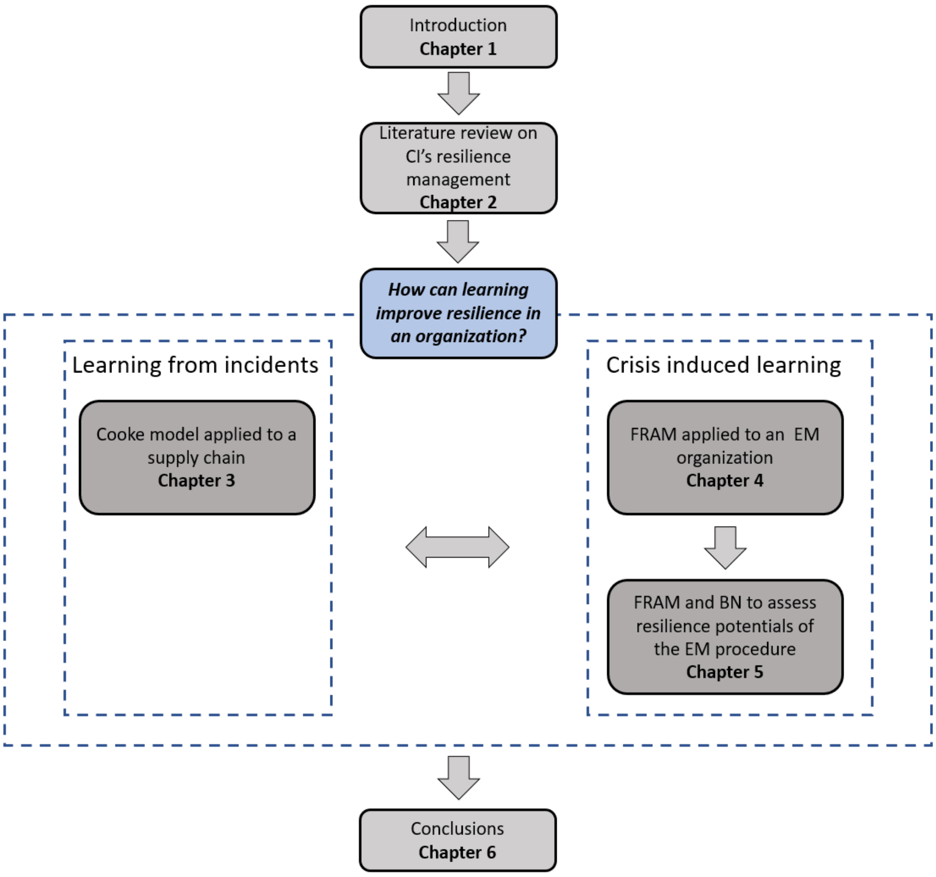

Figure 1 - flowchart of the dissertation logical connections between the topics addressed

The remainder of the thesis is organized as follows.

Firstly, in **Chapter 2**, a systematic review literature on CIs' resilience management is introduced. Then, within the Learning From Incidents theory **Chapter 3** presents the LFI Cooke model and applies this model to the real case of a reverse logistics supply chain of armament material, within a Business Intelligence framework.

Chapter 4 introduces the benefits of crisis induced learning to improve socio-technical systems and proposes the FRAM as a core method to qualitative assess the adaptive capacity and resilience of an EM company during real operations regarding Covid-19 outbreaks on O&G offshore platforms. **Chapter 5** extends the FRAM findings, adding a numeric dimension through the application of Bayesian Networks. Specifically, the resilience potentials of a newly EM procedure, introduced as a learning opportunity after the handling of the three Covid-19 cases, have been assessed recurring to a combination of FRAM and BN.

The last chapter (**Chapter 6**) presents the summary and conclusions of the dissertation, laying out major research contributions and future research directions.

CHAPTER 2

2. EXPLORING RESILIENCE IN CRITICAL INFRASTRUCTURES

The content of this chapter partly relies on a previously published manuscript: R. Cantelmi, G. Di Gravio, R. Patriarca, Reviewing qualitative research approaches in the context of critical infrastructure resilience, Environ. Syst. Decis. (2021). https://doi.org/10.1007/s10669-020-09795-8.

2.1. General definitions

Nowadays CIs are a vital element for modern societies and studying their resilience acquires a strategic role for the decision-making process. In scientific literature, the term resilience firstly appeared in materials engineering to describe the capacity of a material to return to the initial shape after deformation (Trautwine, 1907). Then, this term was used in seminal ecology research, highlighting the concept of robustness and adaptation [57]. Later, this word has been used in psychological, economic, social, organizational, and social-ecological domains. In the engineering domain, such as infrastructure engineering, transportation management, water management and process industries, resilience has been utilized to denote the intrinsic property of the system to respond and adjust the functioning before or after a disaster or disturbance, in order to sustain the normal system's operational performance. For example, according to Hollnagel et al. (2007), a resilient system should: (1) provide a secure or flexible response to instant or continuous disturbances; (2) conduct self-monitoring of its performance; (3)

predict risks and risk development opportunities; and (4) learn from past events.

Starting from its Latin etymological root on the word *resilio* (i.e. to leap back), resilience denotes the capacity of a system to recover from challenges or disruptive events [1]. Among the several definitions of resilience, [58] give a wide perspective for CIs' management: "the ability of the system to reduce the chances of shock, to absorb a shock if it occurs and to recover quickly after a shock (re-establish normal performance)". This ability is recognised to result from four properties (i.e. robustness, redundancy, resourcefulness, rapidity), which are inter-related through technical, organizational, and social aspects. These abilities encompass slightly different perspectives which jointly offer the opportunity to deal with micro-meso-macro level CIs' management [59]: from pure technical artefacts, towards social structures made up by small groups [60], or large organisations [61].

Resilience is relevant for management because it focuses on performance levels, as well as time and cost required to reach them [62]. For example, within CIs, resilience is defined as "the capacity of a civil infrastructure system to minimise performance loss due to disruption, and to recover a specified performance level within acceptable predefined time and cost limits" [63].

Generally, capacity is the property of a system to achieve its objectives. Resilience capacity enhances the capability of a system to absorb, adapt, and recover from any shock or disruption. The resilience paradigm can therefore be described by using a set of resilience capacities, namely, absorptive capacity, adaptive capacity, and restorative capacity based on the different stages before, during, and after a disruption.

Absorptive capacity, endogenous in a system, is its ability to automatically absorb the impact of a disruption in order to minimize sensitivity or exposure to the shock. Considered as the first line of defence to withstand the shock, the absorptive capacity of a system implies the developing of preventive measures and courses of actions before a disruptive event occurs, in order to avoid or minimize permanent undesirable consequences. Adaptive capacity, the second line of defence, is defined as the system's capability to adapt itself and attempt to cope with the adverse consequences or moderate potential damage without any recovery activity. By regulating the perturbations due to the shock after a disruption, it is considered to be part of a post-disaster strategy, also known as capacity of response. Last line of defence, restorative capacity is the degree of ease for a system to recover permanently from a disruption. Restorative capacity depends to a large extent on restoring budget and technical resources: therefore, it might not be fully achieved if stakeholders do not provide adequate financial and technical support.

The consequences of disruptions often lead to unanticipated system behaviour and reduced overall system resilience. Several research studies have been conducted to reduce the likelihood of the occurrence of the catastrophic event by applying security management tools, known as pre-disaster or contingency strategy. Beyond the contingency strategy, a fast response, a high level of preparedness, and a quick recover are of paramount importance in minimizing the disruption caused by the event. The combined approach of response and recovery are often referred to as post-disaster strategy or mitigation strategy.

2.2. CIs' resilience analysis approaches

Due to their interdependent nature, CIs recalls system-of-systems treats, which have to be approached not recurring to reductionism and over-simplified linear modelling techniques.

Because of the high level of interconnections, a failure in a CI can produce cascading failures, sending ripple effects throughout regional, national or international scales with potential catastrophic consequences. Consequently, CIs' resilience management has been representing a demanding challenge which requires new frameworks for the integration of methods able to view the problem from different perspectives (topological and functional, static and dynamic), suitable for coping with the high complexity of the systems and the related uncertainties.

Available literature shows that such complexity is addressed by frameworks based on either qualitative or quantitative approaches, or a combination of the two. Quantitative data usually refer to historical data, laboratory experiments, climate models, or design specifications, whereas qualitative assessments come from surveyed experts or operators, i.e. public decision makers, technical operators, community leaders, managers, [64,65]. A comparison on the features of such approaches has been discussed widely. For example, [66] prepared a workshop where military commanders and civilian decision makers were brought together to explore how they make resilience-driven choices on a daily and long term basis. According to the results of the study, a quali-quantitative approach allows for greater overall flexibility in applications ranging from well-known hazards to highly uncertain ones, thanks to the subject matter experts' (SMEs) judgments [67]. These latter can overcome those frequent cases where retrieving reliable quantitative data is challenging [68]. Thereafter, qualitative information might be integrated into dedicated models to define representative and synthetic indexes.

This concept can be explored more systematically via a tiered framework to resilience assessment (Figure 2), intended to ease policy development and favour the adoption of resilience practices [4].

This framework consists of three different tiers at which a complex problem such as CIs' resilience can be progressively analysed.

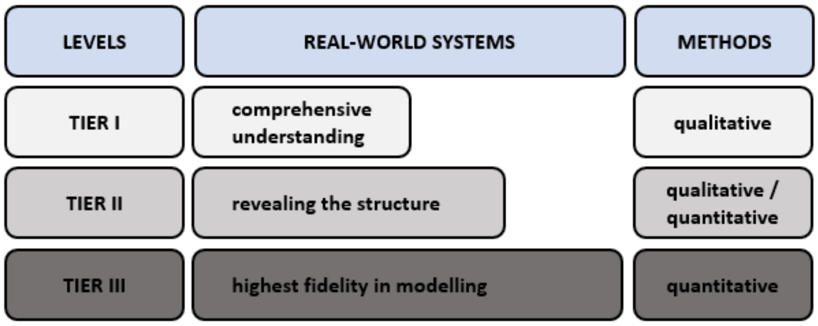

Figure 2 - tiered framework to resilience assessment

Each tier has its own specific objectives, methods, and tools. Tier I involves the use of existing data, experts' judgement, and conceptual models, in order to provide a comprehensive understanding of system's functioning. At Tier II, decision analysis methods (such as Multicriteria Decision Analysis) are utilised, e.g. the Resilience Matrix [69] or the Analytic Hierarchy Process (AHP) [70]. Tier II encompass methods intended to reveal the structure of the system, to check scenarios, or to compare alternatives, that later on in Tier III can be further specified. The last tier seeks to provide the highest fidelity in modelling real-world systems, through, for example, system dynamics models, graph theory, Bayesian networks, or agent-based models that allow dedicated simulations. In summary, [4] help to classify resilience analytics: according to those authors, Tier I uses qualitative methods, Tier II can utilise both qualitative and quantitative ones, while Tier III analysis is mainly based on a quantitative approach. Under current challenging times, where some CIs have become even more critical for our society, the study of resilience acquires a strategical role for decision-making, at any modelling tier. Research on each tier progressed widely over recent years, thanks to many scholars who offered multiple opportunities for improving the CIs' management, embracing a resilience-oriented research dimension.

2.3. Review methodology

The systematic approach followed by [71], on which this chapter is based, relies on PRISMA ([72]) and consists of 5 phases, as sketched in Figure 3, conducted through the usage of MS Excel and Mendeley.

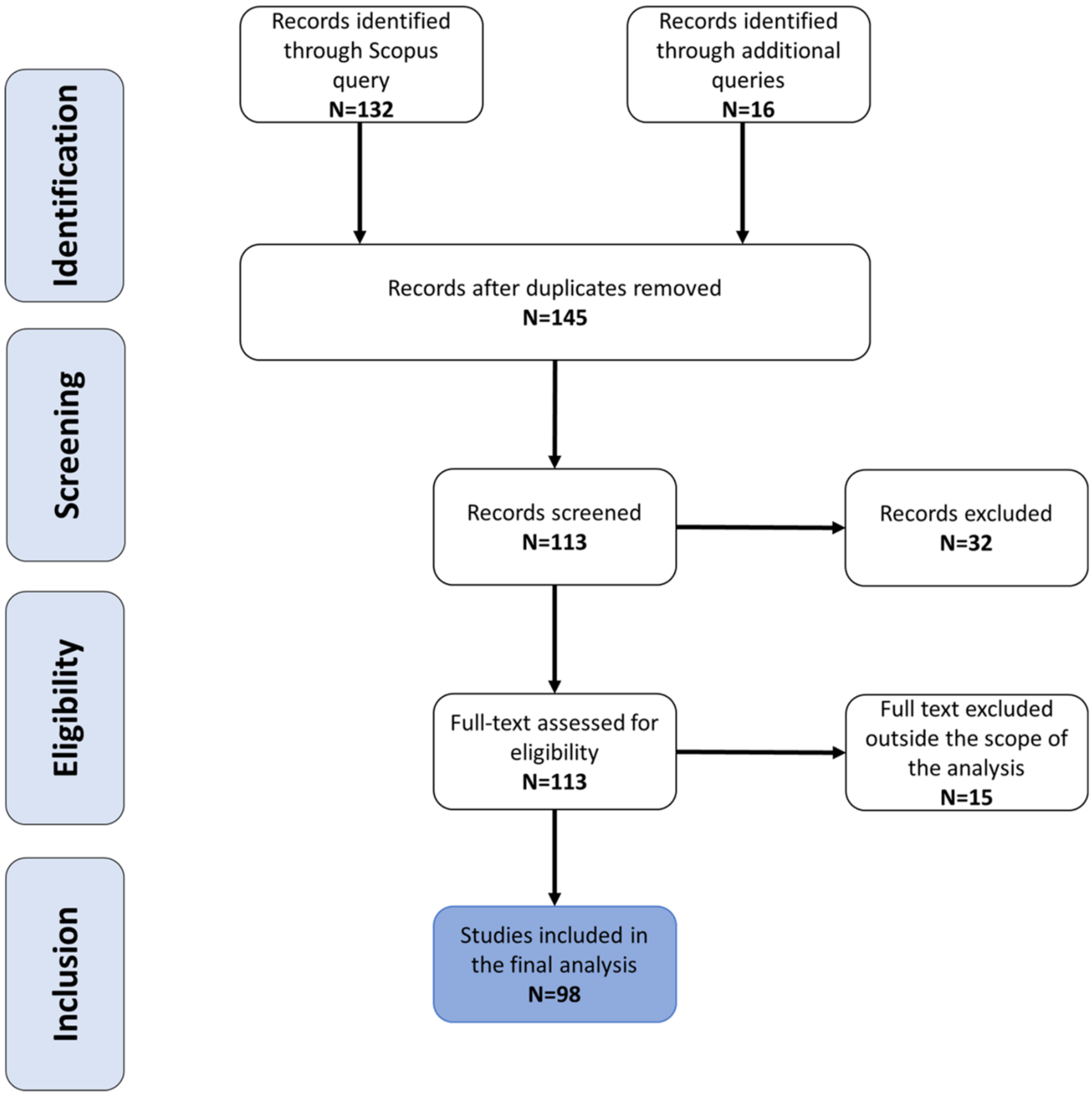

Figure 3 - literature search strategy

2.3.1. STEP 1: setting the search query

The review first step was the definition of the search query scope. The query has been progressively refined to include the largest set of contributions potentially related to qualitative approaches for CIs' resilience. The final search query, implemented in Scopus query system, regarded every paper, indexed up to March 2020, making use in title, abstract, or keywords of the expression ‘resilience AND “critical infrastructure”’, as well as any of the following terms: qualitative, questionnaire, workshop, focus group, interview, surveys. The selection of terms was inspired by [73].

The query has been limited to the Scopus database, since it is recognised as the biggest repository of peer-reviewed literature with over 5.000 publishers and over 71 million records fairly balanced among technical and social aspects of science [74].

Following an inductive process on abstract reading, the dataset has been widened to include other documents as referred to EU/US-funded projects mentioned in the full text of papers as assessed for eligibility, running an additional query with for title, abstract, or keywords including ‘resilience AND “critical infrastructure”’ AND the name of the project (e.g. CIRMin, DARWIN, IMPROVER, NEXUS, Resilience Shift, SMART Measure Resilience) [75]. The two queries return, respectively, 132 and 16 documents.

2.3.2. STEP 2: refinement of dataset

Overall, a dataset of 148 papers matching the search criteria was found. As a preliminary step, a data refinement on the titles analysis has been performed in order to eliminate duplicates: 3 duplicates have been identified and deleted, meaning that 145 documents progressed to the next phases.

2.3.3. STEP 3: screening

In the third step, documents relevant for the scope of the review were selected. Each abstract was carefully analysed, leading to the exclusion of several documents which were just mentioning the word “survey” as a synonymous for "study" or "review", not implying the actual use of any qualitative research method for managing resilience of CIs.

The analysis was conducted by two researchers independently, leading to an agreement ratio of over 95%. Ambiguous situations have been solved conservatively, keeping those papers for full-text reading.

After this screening phase, 32 papers were left out, meaning that 113 documents required a full-text assessment for eligibility.

2.3.4. STEP 4: eligibility assessment

In this step an eligibility assessment for the following full-text reading of the remaining documents was performed. The analysis was conducted by two researchers independently (over 95% agreement). The few incoherencies was solved via a group discussion, involving also a third researcher. Through this step, 15 documents have been excluded, being considered outside the scope of the analysis, and a dataset of 98 documents was determined to progress to the final step.

2.3.5. STEP 5: analysis of papers included in the final dataset

In the last step an analysis of the full text of the remaining 98 papers was conducted, aiming at refining the meta-data on the papers, in order to ensure meaningful bibliometric analyses, and to follow an ad hoc protocol for systematic knowledge elicitation. The protocol included aim of the paper; domain being investigated; type of qualitative approach; causes and threats; method or model used; metrics/indexes used or defined. The dataset was split between the researchers and cross-checks was defined to guarantee a higher consistency. The analysis followed a deductive perspective with an unconstrained categorisation: iteratively adding different categories was considered possible within the bounds of the protocols, in line with inductive content analysis [76].

On the results of this categorisation, documents were presented following different dimensions of resilience for CIs to facilitate the narrative dimension of the document (cf. section 2.5). In summary, the adopted logic resulted in identifying four resilience dimensions, namely "techno-centric", "organizational", "community", and "urban" within which different qualitative approaches were utilised, several threats or hazards were identified, and many issues were discussed in order to improve resilience.

2.4. Bibliometric findings

In this section, some bibliometric findings are shown.

Figure 4 illustrates the evolution of the analysed documents across years, comparing as well subscription-access papers vs open-access. In this context, open-access documents increase significantly in recent years, even if it remains below 40%.

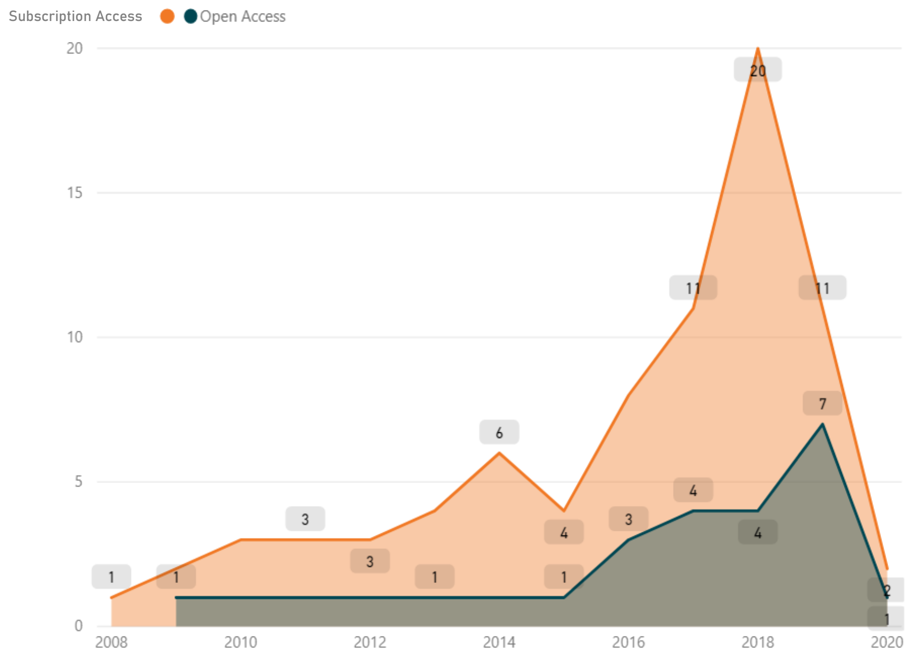

Figure 4 - evolution and access type of documents over years

Figure 5 is about the paper's typology among the dataset and shows a balanced proportion between journal articles and conference proceedings. This indicates that when approaching to CIs' resilience from a qualitative point of view, both conferences and journals seem to be relevant publication fora. It is also worth mentioning that many of the proceedings are related to research conducted under various stages of funded projects, demonstrating that conferences represent a preferred way to disseminate intermediate results.

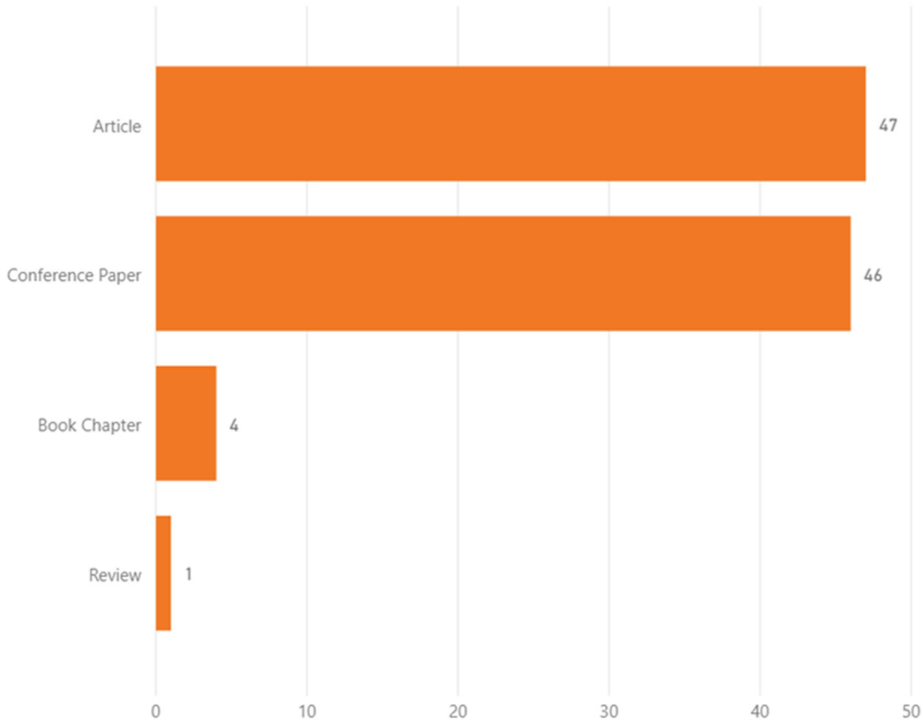

Figure 5 - document types in the dataset

In detail, the documents are spread across different conferences and journals, with few sources including more than three papers, i.e., on International Journal of Disaster Risk Reduction (4 documents), International Journal of Critical Infrastructure Protection (4 documents), Reliability Engineering and System Safety (3 documents), International Journal of Critical Infrastructures (3 documents), Sustainability (3 documents). On the other hand, the most frequent conferences are European Safety and Reliability—ESREL Conferences (8 documents), Information Systems for Crisis Response and Management—ISCRAM Conferences (7 documents), and International Development Research Centre— IDRC Conferences (3 documents).

Specifically, Figure 6 conducts to additional reflections about the content of the papers in the dataset. In the pie chart more than half of the documents regards interviews (about 30%) and questionnaires (about 28%). It is also worth noticing the percentage of approaches consisting of workshops (15%) or focus groups (10%), methods where experts or stakeholders can share their ideas, opinions, and visions (focus group) or can find solutions and draw conclusions (workshops).

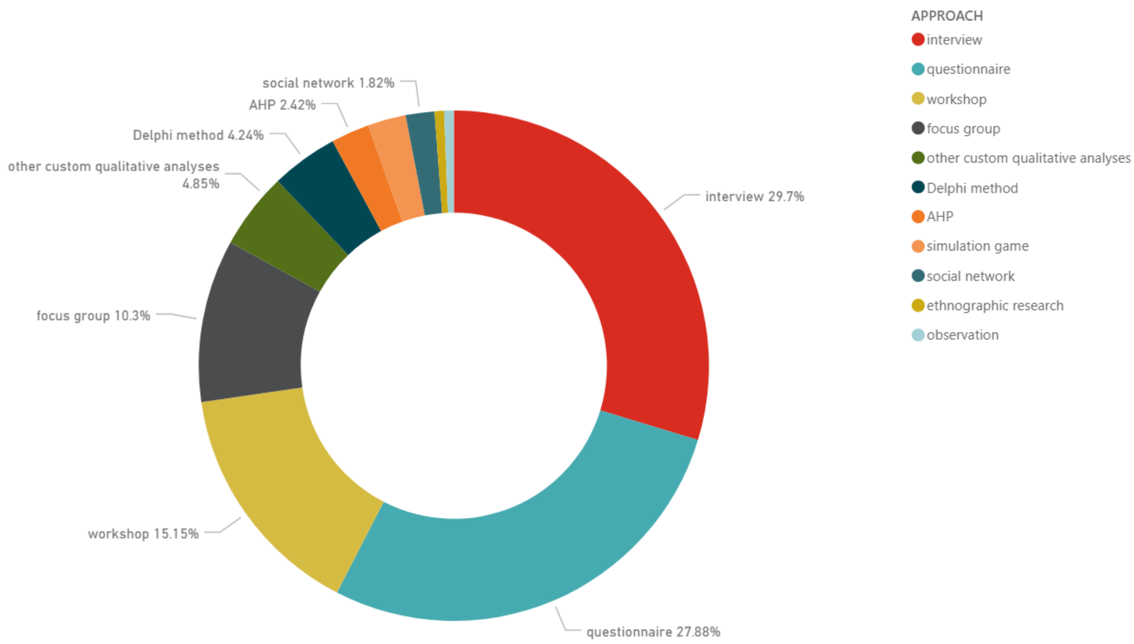

Figure 6 - percentage of used qualitative approach

In addition, specific knowledge elicitation methods such as the Delphi method [77] or the Analytic Hierarchy Process (AHP) have been utilised for prioritising ideas, concepts, guidelines, attributes, etc. These approaches remain of interest for qualitative research because of their knowledge elicitation process, which is at Tier I, qualitative by nature. Furthermore, simulation games have been discussed about their potential in understanding human behaviours and arousing people's interest. Other sources are related to social networking, or some type of observation (naturalistic), or ethnographic research.

Besides the overall percentages of Figure 6, Figure 7 points out how many different qualitative approaches were utilised by each paper. Although most of the documents (55%) adopts a single approach, it is worth mentioning that the other half of papers utilises more than one approach, with about 20% of the documents using 3, 4, or even 5 techniques jointly.

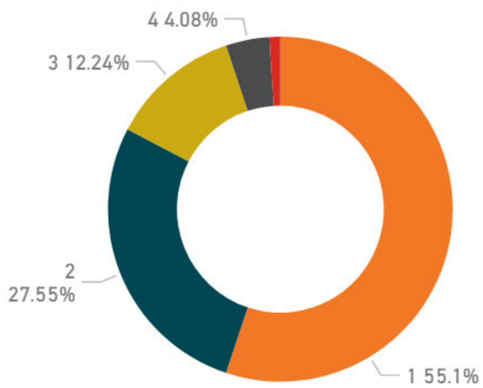

Figure 7 - number of different qualitative approaches utilised by each paper

This observation seems to reveal the benefit of mixed method research, and the need of triangulation [78].

Moreover, Figure 8 histograms show the different domains covered by the papers, in conjunction with the typology of utilised qualitative approaches. The most frequent domain is related to energy systems (frequently ascribed to power grids), followed by transportation systems (e.g. roads, motorways, railroads, or ports). The non-negligible number of "not specified" documents depends on many papers that are not referred to a particular domain or CI and do not contextualise their work, which therefore remains applicable to multiple domains.

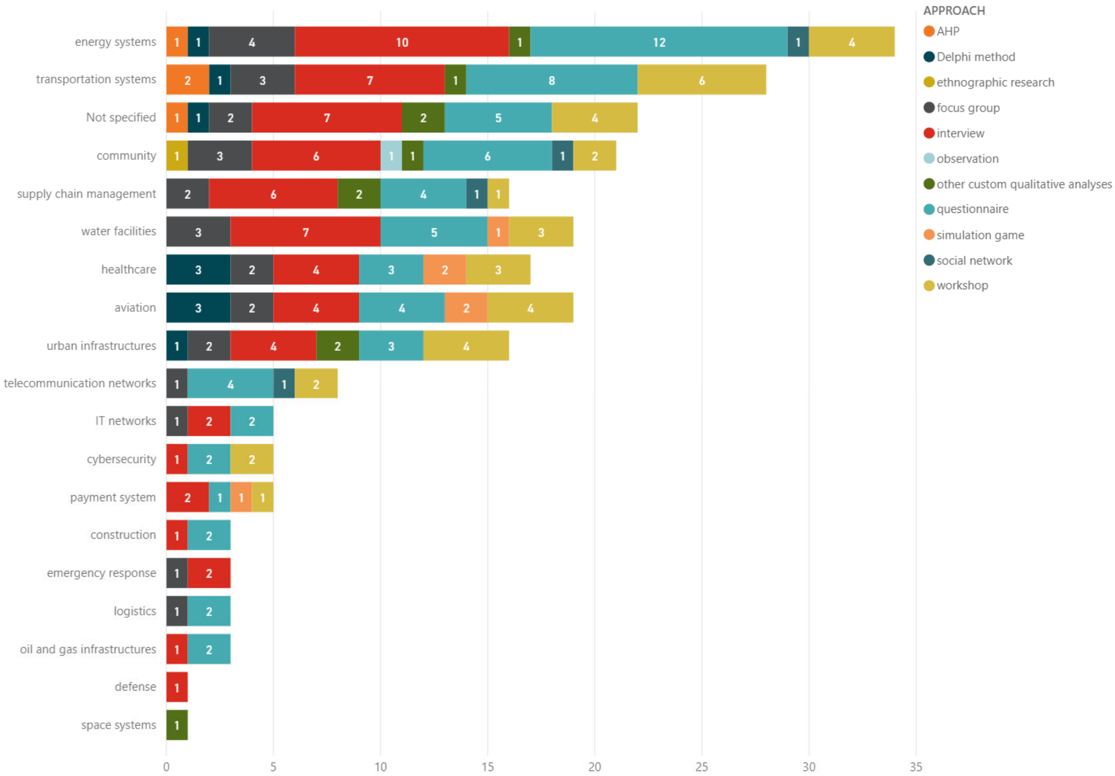

Figure 8 - different domains combined with different qualitative approaches utilised

Other relevant domains are linked to communities and urban infrastructures and among CIs, supply chain management and water facilities also appear in the dataset.

Lastly, a combined view on the results, which summarizes the previous findings, is proposed in Table 1: by rows, the figures represent the total papers per domain, whereas, by columns, the total papers per approach.

Table 1 - overview of results

DOMAIN	AHP	Delphi method	ethnographic research	focus group	interview	observation	other custom qualitative analyses	questionnaire	simulation game	social network	workshop	Total
energy systems	1	1		4	10		1	12		1	4	**24**
transportation systems	2	1		3	7		1	8			6	**16**
Not specified	1	1		2	7		2	5			4	**14**
community			1	3	6	1	1	6		1	2	**13**
supply chain management				2	6		2	4		1	1	**11**
water facilities				3	7			5	1		3	**11**
healthcare		3		2	4			3	2		3	**9**
aviation		3		2	4			4	2		4	**8**
urban infrastructures		1		2	4		2	3			4	**8**
telecommunication networks				1				4		1	2	**6**
IT networks				1	2			2				**4**
cybersecurity					1			2			2	**3**
payment system					2			1	1		1	**3**
construction					1			2				**2**
emergency response				1	2							**2**
logistics				1				2				**2**
oil and gas infrastructures					1			2				**2**
defense					1							**1**
space systems							1					**1**
Total	**4**	**7**	**1**	**17**	**49**	**1**	**8**	**46**	**4**	**3**	**25**	**98**

2.5. Descriptive findings

In line with recent research ([79]), this section proposes four different dimensions relevant for qualitative research applied to CIs. These dimensions include different, sometimes complementary, resilience aspects, i.e. techno-centric, organizational, community, and urban.

The following subsections (cf. subsections 2.5.1, 2.5.2, 2.5.3, and 2.5.4) are intended to provide a synthesis of reviewed studies, highlighting methodological steps, and obtained results. Although these dimensions can sometimes overlap, they are considered helpful to support the narrative understanding of the reviewed approaches, as further detailed in the Appendix.

2.5.1. Techno-centric resilience

In this subsection, papers encompassing a research dimension that follows primarily the resilience technical aspects have been included. These documents analyse several complex systems from civil infrastructures towards supply chains.

Among the wide range of CIs, e.g. power grids, telecommunications networks, transportation infrastructure, water supply systems, and sewerage, [80] focus on UK energy and transport infrastructures, via a set of scenario episodes, by supporting key stakeholders in their resilience assessment. After an analysis conducted through the Political, Economic, Social, Technological, Environmental, Legal (PESTEL) lenses, tailored crisis episodes were added to stress test the scenarios and to operate in a not "business as usual" situation and a first set of key stakeholders from academia, UK Government departments, engineering firms, local resilience forums, was interviewed to elaborate two tailored episodes related to flooding and terrorist attack, and other stakeholders were then invited to participate in focus groups, in order to consider weaknesses and strengths of the "2050 world", guided by the three generations of resilience.

When considering strengths and weaknesses of a region, CIs' spatial planning at different administrative levels becomes a crucial element to be focused on, as done by a research conducted in Germany ([81]). Spatial planning considers and integrates the multiple stakeholders' needs, through the "mutual feedback" principle, which is an iterative top-down/bottom-up process to develop spatial development's principles and visions, to evaluate the compatibility of the proposals for plans and projects, and to monitor the impacts of the realised developments on natural resources. A survey among all 111 German regional planning authorities studied the current perception of the CIs' protection, in order to increase their resilience. Although the issue was generally known among the respondents, the survey showed how regions were not prepared to apply a systematic CIs' protection strategy as claimed by national security authorities or by European institutions.

In Canada, [82] aim at assessing the main tendencies of the different dimensions of resilience within three major CI networks, i.e. energy, telecommunication, and transportation through a survey among hundreds of CIs managers from governmental, community, and private-sector organisations who were identified screening official government information, annual reports, and official websites. The survey examined various aspects of emergency preparedness, internal and external resilience adaptive management, and post-crisis organizational learning. Resilience was evaluated through a wide range of indicators using a Likert scale[1] and the general attributes were analysed to seek statistically significant differences between groups of organisations by sector, type, and size (using Chi-square and Kruskal–Wallis). The empirical study provides insights into the main challenges and barriers to resilience: decision-making abilities, risk monitoring, crisis management informational designs, projective intelligence, strategic positioning.

These challenges imply adopting human resource-based, procedure-based, technology-based strategies to increase infrastructure resilience. The selection of the most adequate strategy becomes a multi-dimensional problem, as investigated through multi-criteria decision-making techniques such as the AHP. At a higher abstraction level, the results obtained by a pool of experts from the Romanian Land Forces Academy suggest that the best strategy to improve CIs resilience refers to human resources, relying on an intensive training system of employees, in order to empower them within the system ([83]). Similarly, another research applied the analytic network process (ANP),

[1] A Likert scale is a psychometric scale commonly used to scaling responses in a survey research. When responding to a Likert item, respondents specify their level of agreement or disagreement on a symmetric agree–disagree scale for a series of statements. Thus, the range captures the intensity of their feelings for a given item.

a variant of AHP, to prioritise factors affecting port resilience, involving 11 experts including government scholars, officials, and planners.

The consistency of ANP answers was ensured using the Delphi method, resulting in three major factors, i.e. shipping route density, travel time, ground access system ([84]).

[85] aim at building community resilience by introducing a spatial–temporal vulnerability assessment, which enables decision makers (i.e. CI providers, management authorities, crisis management groups) to enhance their initial understanding of a power outage impacts. In this paper, the Delphi has been also utilized to give a consistent definition of a power outage indicator, namely the Relevance Criticality Weight, as assessed by decision makers from different cities and disaster management authorities. This indicator has been combined with the Coping Capacity Resource (CCR), estimating CI capacities to continue the activities during a power outage for a short time, and finally integrated into a vulnerability model based on Monte Carlo simulation.

Other papers usually refer to Critical Infrastructures Key Resources (CIKRs) to describe infrastructure systems. In [86], the U.S. Sandia National Laboratories propose a unifying framework which can be applied to all the CIKR systems identified by the U.S. Department of Homeland Security to study their resilience, explicitly considering the cost of recovery efforts. Specifically, the discussed framework consists of an approach for quantitative measurement of resilience costs, and a qualitative method to assess features that determine systems resilience. The quantitative measurement includes two factors: the Systemic Impact (SI), defined as the difference between a targeted system performance level and an actual system performance after the disrupting event, and the Total Recovery Effect (TRE) i.e. the amount of the resources expended during recovery process following the disruption. The framework also introduces a qualitative analysis, which can be performed to explain the quantitative measurement or can take the place of quantitative results when data are not available.

This analysis utilises three system capacities to explain how inherent properties of a system can determine systems resilience, by reducing SI and TRE. These capacities are absorptive, adaptive, and restorative. Better resilience systems can then be designed by developing resilience enhancement features, that improve one or more of these capacities: for example, storage is an enhancement feature for absorptive capacity; emergency generators enhance the adaptive capacity; break detection monitoring systems increase restorative capacity in power grids.

In [62], the authors utilise a previous framework elaborated in [86], to analyse the resilience of a particular CIKR like the U.S. petrochemical supply chain during hurricane disruptions. Specifically, the Sandia centre performed a comparative analysis by simulating disruptions with the National Infrastructure and Simulation Analysis Center (NISAC) Petrochemical Supply Chain Model. This latter consists of two primary components: the chemical data model (CDM), a database of domestic and foreign chemical plants, chemical infrastructures, chemical productions, and commodity flows, and the NISAC Agent-Based Laboratory for Economics (N-ABLE) microeconomics simulation tool that performs supply chain analysis.

Within the N-ABLE, each agent-based enterprise firm is composed by supervisors, strategic planners, production workers, buyers, and sellers. When applied to CDM, the N-ABLE can predict loss estimates and economic impacts to be used for measuring the systemic impact of a petrochemical supply chain, affected by a hurricane. In addition, N-ABLE can help to estimate the costs associated with the recovery and adaptation processes, which are crucial for calculating the TRE in a resilience analysis. The framework allows to determine resilient costs, starting from the calculated values of SI and TRE, but it also allows qualitative assessments of attributes that enhance the supply chain's absorptive, adaptive, and restorative capacities.

In [87], a Resilience Index (RI), useful for assessing CIKR facilities, has been developed. The RI can assist owners/operators to compare their facilities to similar sectors sites and can help them to take better risk-based decisions. The data were collected through a questionnaire of more than 1.500 data points per facility (i.e. transportation assets, electrical substations, commercial buildings, and dams). After a Quality Assurance review process, the RI was developed through an aggregation of data collected into four levels of information, by using multi-attribute theory, an approach that helped to decompose resilience into its individual attributes and then organised them into an organizational tree.

[88] study the propagation mechanism and consequent dependencies of another CIKR, the Fast-Moving Consumer Goods supply chain of perishable goods in Italy. Fuzzy Cognitive Maps (FCMs) were utilised defining 13 concepts that reflected qualities, characteristics, attributes, and paths of the modelled system, and tracing edges that represented the interconnections between concepts. Three independent FCMs, related to different temporal frames (i.e. after one day, four days, and three weeks), were implemented recurring to expert elicitation. Therefore, a specific questionnaire was distributed at least one week before, conducting a single face-to-face interview to define concepts and to weight the relationships in the adjacency matrices of the FCM approach. Regarding the case study, the results show that the most crucial concepts are the electricity supply, the data network, and the staff availability.

Also [89] focus on the Infrastructure Failure Interdependencies (IFIs) by developing a qualitative method, based on experts' knowledge, for identifying and describing the potential sector-specific and cross-sector IFIs of CIs. The method, consisting of four phases (i.e. preparation, material collection, analysis, results), was developed and applied with the Finnish regional preparedness committees. In the first phase, the planning group defined the threat scenario. Then, company representatives from the studied CIs (i.e. IT infrastructures, electricity distribution, and telecommunications) were invited, together with representatives from other CI fields (healthcare and government agencies), to identify the broader interdependencies and to elaborate a scenario with a severe storm and a pandemic influenza. The second and third phase, respectively, material collection, and analysis, were conducted in iterative manner, performing a cycle which continued through several workshops with up to fifty experts, until the collected and structured material was satisfactory. In this case, the difference between the discussed method and the Delphi method is related to the anonymity of the experts: in the Delphi method it guarantees freedom of opinions and minimises the effect of dominant characters, whereas the facilitated face-to-face approach of the discussed method promotes the cooperation among the actors, who would cooperate in the crisis situation. The discussions were recorded, and the collected information was first structured in mind maps and then the resulting documentation was used in the creation of an ISFI matrix that describes the causal intra-sector and inter-sector interconnections. Finally, the results were presented in system diagrams, a form that makes it easier to understand the failure interfaces between the CIs and the chains of dependencies.

As regards IFIs, [90] introduce a methodology called Preliminary Interdependence Analysis (PIA), useful for building, refining, and analysing models of interdependent complex CIs. This method starts with a qualitative phase during which the scenario must be accurately defined, and subject matter experts are asked to provide data and information which will be utilised to parametrise the selected model. Then, via a set of focused refinements, PIA may evolve into a quantitative method for assessing the risk due to interdependencies between CIs.

In order to analyse IFIs of specific supply chains and demand nodes, [91] present a Grassroots Infrastructure Dependency Model (GRID-M). This model helps public safety officials to make better approximations about disruptions, by using pre-incident survey data. GRID-M can also help the officials to gain near-real-time situational awareness on the physical state of a node, by using the damage assessment application. GRID-M displays all outputs within a Geographic Information Systems environment with additional prepopulated layers such as real-time traffic and demographic information of the affected communities. This information can support the prioritisation of infrastructures in planning, exercise simulations, real-word situations, and restoration activities.

[92] use information extracted from geodatabase, applying the concept of network resilience to the motor-fuel supply chain (FSC) management in New York City, affected by hurricanes. The authors use a stochastic bi-stage optimisation model to analyse practical strategies for the allocation of resources, called Resilience-Enhancing Strategies (RES). In order to model the transportation network, an application program interface (API) implemented in Visual Basic was used to extract data from the ESRI geodatabase and translate them to a graph network consisting of nodes and arcs; then the impact of hurricanes were modelled by considering three characteristics: type and frequency; vulnerable locations; expected flooding intensity. The authors

defined a context-specific resilience index referred to the average demand met across the gas stations, along with a variable representing the Unmet Demand Rate (UDR), which allowed the authors to solve the model for the minimum expected value of the UDR, minimising the FSC's overall inoperability and fuel distribution costs. Several experiments were conducted, varying policy scenarios, physical improvements, and budget limitations. The results showed how the three pillars (absorption, adaptation, and restoration) of the mentioned RES are interlinked and how different combinations of investment scenarios may provide different levels of resilience.

As discussed earlier, several threats can undermine systems included in the techno-centric dimension of resilience. [93], for example, deal with seismic risk. During the 2014 Cascadia Earthquake Readiness Workshop in Washington, the attendees were coordinated by facilitators in order to identify the most important infrastructure, related to three thematic areas (emergency management, critical energy infrastructures, and ports and waterways) exposed to the risk of an earthquake or tsunami and to brainstorm potential solutions. The participants produced a list of recommendations, observations, takeaways, and highest priority infrastructure improvements, to cope with possible earthquakes or tsunami and to increase infrastructure resilience.

[94] present a case study involving three different States (New York, Massachusetts, and Vermont) of the U.S. subjected to the Sandy storm of 2012. This study aims at comparing how climate and energy are being linked in smart grid planning and development. Discussions from 22 focus groups including 3–8 representatives of a single organisation were recorded, professionally transcribed, and coded with NVivo 10.0 software to characterise discursive patterns and linkages between climate change and energy by analysing text, focused on both climate mitigation and climate

adaptation. Data analysis was based on the principles of grounded theory, which offers an internally logical set of techniques for collecting and analysing qualitative data. The triangulation of knowledge, via clarification questions and informant validations, supported a high level of accuracy, through a continual movement between data collection and analysis. Comparatively, the study found that the balance between the conversations about adaptation versus mitigation was associated with the severity of the storm's impact in each of the three states. Differences between stakeholders were also examined, revealing that energy system operation experts (i.e. utilities) preferred adaptation measures to mitigation ones, while the opposite was for other energy system actors (i.e. authorities, researchers).

[95] introduce terrorism, as a man-made threat, requiring the development of risk assessment specifications for the RAMPART (Risk AssessMent toolbox for the Prevention and reduction of terrorist Attacks on metRo and light-rail criTical infrastructures) project. The paper focuses on the incorporating resilience in the risk assessment techniques. During a workshop with experts, six risk/resilience assessment methodologies used in Canada, EU, and USA were selected for detailed analysis and six key factors that constitute a robust Risk Assessment Methodology (RAM) were identified. About one of these factors, "qualitative vs. quantitative approach", the paper argues that a risk assessment in the public transport security should be done firstly in a qualitative way, because of the lack of statistics (especially concerning terrorist incidents), necessary to perform a quantitative assessment based on mathematical formulas and calculations.

[96] aim at demonstrating the effectiveness of simulation gaming to develop systems-thinking skills, which are critical to understand the infrastructure management complex nature. By using Vensim software, the authors

implemented a system dynamic model to represent, through a simulation game called LA Water Game, the problem of maintaining the Los Angeles water distribution infrastructure quality of over a 75-year period. The game was performed in 16 workshops of over 200 participants consisting of undergraduate and graduate students, faculty, and active-duty military personnel. Data collection, through debriefing interviews and participant observations, showed the success of this particular teaching method: the players, with cognitive and effective engagement and intrinsic motivation, were able to identify the interdependencies between game variables, the non-linear nature of infrastructure deterioration, the stochastic emergency breaks, and the reinforcing loops within the game. Consequently, simulation gaming can be considered successful for training resilience skills.

Among techno-centric resilience, specific attention has been paid to those systems with a large Information Technology dimension ([97]). For example, [98] aim at assessing the safety, security, and resilience of Information and Communication Technology (ICT) and Supervisory Control And Data Acquisition (SCADA) systems used in the Norwegian oil and gas industry, through surveying 46 Norwegian offshore oil and gas installations. In the survey, Yes/No answers were possible, but respondents could also provide free-form comments. The survey and the subsequent discussions provided some important key results: poor risk awareness; poor scenario training and emergency preparedness; lack of systems certification; lack of network barriers; inadequate deployment of patches; lack of consistent safety/security guidelines; absence of systematic knowledge sharing.

In [99], a research is conducted to investigate at which extent a simulation-based approach can be applied to large socio-technical IT networks. These networks (i.e. a municipal IT network and the SCADA system of a wastewater network) are modelled, by using Monte Carlo simulation, to study their recovery times. The utilised model is hybrid and considers the technical network, represented with graph theory, as well as the repair system, represented with a queuing model with four types of entities: jobs, queues, stock, and repairers. Data were collected through interviews and focus groups and through document analysis to gather information about fault modes, their relative probabilities, resources needed for repair, and repair times. The results were evaluated through interviews to check trustworthiness, usefulness, ability to increase system resilience, improvement, and generalisation possibilities. The authors conclude that this approach can be extended also including software and dependency failures to hardware and operator failures and considering investments, price of network, and repair resources as suggested by system experts' feedbacks.

Dealing with Industrial Control Systems (ICS), [100] provide a review and an analysis of available cybersecurity Self-Assessment tools, which can be utilised by ICT owners and CI operators. In order to identify weaknesses and cyber vulnerabilities and to establish targets for continuing improvement, these tools consent an evaluation for many purposes: (1) they can be utilised by management teams to gain a security assurance general understanding and to make informed decisions; (2) they can be used as a guide to assess the security status of a system; (3) they can enhance and support employees' security awareness; (4) they may be used to fulfil reporting requirements, to prepare for audits or to identify resource needs.

Again on cyber vulnerabilities, [101] present the work in progress in developing cybersecurity and training in healthcare facilities. Specifically, they introduce the Proactive Resilience Educational Framework (Prosilience EF), which aims at reducing cybersecurity vulnerabilities and exposure in hospitals. The paper claims to make hospitals more resilient for cyber-attacks: by identifying potential cybersecurity vulnerabilities and cyber threats; by describing best practices and training for targeted and untargeted attacks; by raising healthcare staff awareness about privacy and security; by developing training schemes on cybersecurity in hospitals for staff different categories. The framework launches an iterative process of awareness and training development with relevant stakeholders (healthcare authorities, end users-hospitals, industry members, cybersecurity training providers), assessing the framework itself through workshops and joint exercises.

[102] aim at developing and testing a framework that holistically measures the quality of Information Security Management (ISM) in the context of cybersecurity and allows for comparative assessments of organisations in CI sectors, starting from the Balanced Scorecards (BSC) measurement system. Following a design science approach, workshops, cyclic refinements of the instrument, pre-tests, and framework evaluation within 30 CI organisations were conducted, involving subject experts and Chief Security Information Officers (CISOs) as the main stakeholders from the information security domain. The quantitative assessment served to benchmark, but to complement this evaluation by explaining and interpreting scores, open qualitative questions were necessary to capture the special context situations. The authors argue that the scorecards, used as quantitative estimators, alone do not portray the complete security status.

[103] present an indirect measurement method to improve preventative maintenance and increase resilience of CIs as communication networks or electrical transmission infrastructure. The authors start from considering that many instances of failed infrastructures are not immediately discovered by CI operators or owners, but rather, by the public who report the problems with

relative and qualitative descriptions. The idea of the paper is to enhance these qualitative descriptions by using a human-in-the loop algorithm, derived from the concept of Agile IoT, providing quantitative measurements (through actionable intelligence from the general public, who utilises own devices, or by using already deployed sensors, like traffic cameras) which could help prioritising repairs to reduce failures likelihood and to better allocate time and crew resources.

In order to assess resilience of a networked system that depends from ICT, like the Internet, [104] introduce a hardware-based emulation (emulation testbed). The authors study the emulation fidelity by comparing experimental results between two different emulation configurations against the reference real configuration. While confirming the emulation testbed efficiency and similitude, the authors recommend that the interpretation of experimental results should not be based on absolute numbers, which are hardware dependent, but rather on system behaviour and trends. This means that emulations are representative of real systems from a qualitative point of view, in terms of emerging behaviour, rather than a quantitative perspective, in terms of absolute performance.

[105] explore how CI resilience can be enhanced through the information-sharing practices of its operators during each stage of an incident (mitigation, preparedness, response, recovery). Effective crisis communication should manage information through the collection and dissemination of crisis-related information, while also managing its meaning to persuade the public in the hope that they will plan for and respond appropriately to risks and threats. Interviews, focus groups, and consultations were conducted with 31 relevant stakeholders across Europe. CI and emergency management professionals were asked about: current communication strategies; whether digital media

had been incorporated; how traditional and digital media were used together; what audience they hope to reach using different platforms. Interviews with journalists focused on their social media experiences in detecting and verifying incidents, and whether they addressed ethical and legal challenges, by using social media in relation to emergencies.

The public indeed expects CIs operators to keep them informed about progresses on CIs restoration and answer rapidly to queries, as proven by a large questionnaire based study (N = 403) and several semi-structured interviews with multiple stakeholders ([106]).

Finally, [107] deal with the resilience of particular ICT systems, which are subject and object of crisis and emergency management: Critical Space Infrastructure (CSI), like satellites orbiting the Earth, may compromise, with their failures, the competent actors' capacity to manage the crisis. Regarding the space governance, authors argue that space actors must agree on key resilience measures, implement them and enforce them unilaterally on third parties, such as other states or corporations, despite the lack of jurisdiction due to the international character of the space environment. Moreover, they foster the cooperation among space actors and the systems interoperability, to ensure timely access to various resources or to substitute one space system for another, in terms of short-term provisioning of critical space services.

2.5.2. Organizational resilience

When dealing with CIs, there are usually non-negligible organizational components to be considered in the analysis, i.e. components which embrace a social dimension complementary to the more technical aspects of a system. This subsection points out the contributions which make an explicit effort to understand, model, and measure the organizational resilience for CIs ([108]).

Referring to construction organisations, [109] identify strategic resilience indicators through a triangulation analysis of literature review, questionnaire survey, and in-depth interviews. Firstly, an extended literature review revealed 72 indicators related to organizational resilience, among which 27 indicators were selected according to their frequencies, by means of Nvivo software. Secondly, an electronic questionnaire was undertaken to elicit the views of construction practitioners and resilience experts in New Zealand.

The questionnaire was composed by closed-ended and open-ended questions and aimed at identifying the profile of respondents and organisations, at getting an overall view of their organizational resilience practice, and at finding out respondents' opinions on key resilience indicators and ranking the latter ones. Thirdly, semi-structured interviews were conducted with 23 construction practitioners from construction client and contractor organisations (i.e. mainly project senior executives). The transcript interviews were qualitative analysed by using Nvivo software, searching for key themes. Data triangulation improved reliability, by reducing judgmental bias, and by supporting most significant indicators validation through interviews. Most experts agreed that the top five indicators for assessing resilience of the construction industry, in rank order are: leadership, planning strategies, internal resources, decision-making, and staff engagement.

Again in New Zealand, [110] present a method to benchmark the organizational resilience of CIs' providers, i.e. the Benchmark Resilience Tool, based on 13 resilience indicators. Respondents were asked to use a Likert scale to rate how much they agreed with each statement and had to answer other demographic and preparedness questions (age, gender, organisation, emergency plan use, etc.). The study assesses relative resilience strengths and weaknesses of CI organisations, finding the "effective partnership" as the strongest indicator whereas "breaking silos" (i.e. breaking barriers to the sharing of ideas and skills) and "stress testing plans" (i.e. the capacity to actively practice emergency, crises, or business continuity plans) as the weakest ones. Findings also show that senior managers have much more positive perceptions of their organisations' resilience compared with other staff workers.

Conducted by a private company, the study described in [111] provides a critique of standardised factors for organizational resilience, analysing the electric power restoration process in Manhattan after 11 September 2001. Qualitative and quantitative data were collected to support triangulation of observations. Internal reports from the company and articles in the popular press provided also contextual information on the company's response, while data regarding the timing, cues, and key decisions were provided through the Critical Decision Method (CDM). Data on participants were collected by questionnaires and data on the performance of technological systems (i.e. timing and location of restoration activities) were collected through logs of the performed work. The Woods factors (i.e. buffering capacity, flexibility/stiffness, margin, tolerance, cross-scale interactions) were analysed and the study proposed another factor—boundary-spanning capability—which may help to understand how cross-organizational linkages can help to determine organizational resilience.

[75] present a work which is part of the European research project DARWIN, whose aim is improving responses to crises affecting CIs or social structures, by developing resilience management guidelines ([112]). The first phase of DARWIN Project was to identify concepts, practices, and approaches of resilience management through a Systematic Literature Review and interviews with relevant stakeholders involved in crisis management. A final

list of 56 concepts, practices, and approaches was compiled, phrased in a uniform mode, and incorporated into a computerised survey tool, using Survey Monkey. A 2-cycle modified Delphi process was conducted to decide which items of the list should have been included in the resilience management guidelines. Reviewing the items that reached the highest scores reveals that they comprise at least one of the three common elements frequently found in definitions of resilience: the need of flexibility, adjustability, and adaptability; the need for sharing and understanding for the actors involved; the focusing on CIs, considered vital for organisations and communities.

[113] introduce another ongoing work within the scope of the DARWIN project: the resilience management guidelines. These latter, applied to the Air Traffic Management (ATM) and the healthcare domain, are intended to support organisations in critical situations and evaluate their effectiveness by attribute- and performance based approaches, in line with, respectively, engineering resilience and resilience engineering (i.e. resilience in technical systems and resilience in complex socio-technical systems).

Simulation trials, performed by operational experts in the form of gaming sessions, assessed the effectiveness of the adopted operational procedures. Additional scenarios were developed to emphasise the organizational interdependencies between ATM and healthcare CIs. Finally, a debriefing was conducted to assess the system performance, indicating possible bottlenecks and identifying brittleness.

[114] aim at assessing organisations' resilience performance, providing a framework based on a value model, against which each type of CI was comparatively assessed. A set of interviews was conducted to 50 industry experts from a variety of CIs' sectors with direct responsibility for the risk and

resilience assessment. Each infrastructure type was reviewed in terms of value expectations from its various stakeholders' groups (i.e. end user/customer to investors, suppliers, and constituent organisations). The evidence for these assessments was based on the results of the interviews in addition to performance metrics published by government authorities, regulators, consumer organisations. Key findings were the focus on response and recovery instead of proactive mitigation measures; the lack of incentives to work proactively with other providers; the non-measurement of the impacts of disruption on UK society.

Based on the INTACT project co-founded by the European Union, [115] focus on Risk Management Measures (RMM). Specifically, the study contributes to the value creation of RMM, which is crucial for decision-making and for the development of strategies in order to prevent or reduce the extreme weather events' impacts. A case study, regarding the electricity distribution network in Finland, was presented to validate the proposed approach.

The stakeholder value of RMM during the entire life cycle of CI was assessed, by applying AHP to the considerations and evaluations made by 18 experts from the DSO (Distribution System Operator), the regional rescue service, the city of Tampere, the Finnish Red Cross, and an ICT company. The AHP method ranked the following value criteria for comparing the RMMs: benefits of the RMMs in economic, environmental, and social terms; impact of the RMMs on reliability, availability, and maintainability of electricity distribution network; life-cycle cost (investment and operating costs) of the RMMs. Then, the involved stakeholders were divided into three groups and they identified alternative RMMs which were categorised according to the phases of the disaster management cycle (i.e. mitigation & prevention; preparedness; response; recovery). The assessment findings ranked the following RMMs in order of relevance: mutual planning and training, underground cabling, ICT systems, and forming and disseminating situational awareness.

Another paper deals with climate change (CC) and its related natural hazards for CIs. Airports are CIs particularly at risk from the potential consequences of CC with impacts like sea-level rise, increased temperature, changes in precipitations or in wind patterns. The work presented in [116] starts from the studies carried out by EUROCONTROL, the European Organisation for the Safety of Air Navigation, to demonstrate that, although awareness is growing, there are still significant barriers to take actions (e.g. lack of reliable information, missing guidance). Therefore, EUROCONTROL, together with Manchester Metropolitan University, organised a workshop, attended by 30 participants representing industry, regulators, and academia, which led to identify four key priorities to overcome these barriers: better understanding of the problem; assessing the problem; initiating actions to adapt both operations and infrastructure; collaboration in research and information sharing and communication of best practices both within Europe and globally.

Taking into account the international framework to promote disaster risk reduction throughout the education sector, [117] focus on assessing the school resilience, from an organizational point of view. A survey, made by 7 different types of questionnaires for different ages (from 3 to 19 years) and respondents (students, headmasters, professors, auxiliary personnel), was conducted in 27 schools in Tuscany (Italy), located in areas of high geo-hydrological and seismic hazards. The questions were inspired by the Naylor examples of assessment techniques and were structured in different ways to identify criticalities in the community management process: closed question, open-ended question, completing table, matching exercise, cartoon strip sequence, graphic organiser, sequencing, graphic open-ended question, and graphic closed question. Shared results have been obtained from a resilience analysis on US campus emergency management units, by means of a survey, and then investigated in statistical terms ([118]).

Shifting towards civil response management, [119] examines the Swedish Emergency Response planning process, trying to identify and characterise the sources of uncertainty related to power shortages. This planning is a multi-agency activity that requires decomposition and coordination of goals and means throughout a multilevel approach. It involves local actors as municipalities and power grid operators, regional actors like county administrations, and national actors as agencies. The author conducts a literature and document review by analysing guidelines, national laws, and reports regarding the Swedish description of the planning approach. Thereby, sources of uncertainty, stemming from lack of knowledge, emerged and guided the meetings with planners at municipalities and County Administrative Boards (CABs). Semi-structured interviews were then conducted, registered, and transcribed: a questionnaire with open-ended questions, based on the sources of uncertainty, was utilised to guarantee a similar structure for the interviews and to allow participants to report on individual experiences and perceptions. Follow-up questions were asked for more richness of detail and clarity. This study revealed three sources of uncertainty: the planning reference process in general, the decision-making process, and the direction and guidance alongside these processes.

In the same national context, [120] deals with the resilience in the case of power shortage, focusing on the Swedish STYREL policy. STYREL (a Swedish acronym for "Steering of electricity to prioritised users during short term electricity shortages") is a planning and prioritisation process, involving national authorities, CABs, and municipalities. The aim of this process is to identify and prioritise the vital societal functions that must be carried out during a situation of power shortage, to foster sustainability and to increase resilience for power supply. A survey including 21 coordinators at the regional level and semi-structures interviews at three different CABs were conducted to provide a broad picture on the importance of the process, its usefulness, and the trust within the networks. However, according to the frank discussion outlined by the author, there are no guarantees that STYREL process, such as it has been carried out, will make the electrical energy supply more resilient and sustainable; nor does it seem that STYREL has created any formal or established type of collaboration between private and public sectors actors in practice.

Also [121] analyse the possible impacts of a power outage, focusing on the German healthcare. As effects and measures are strongly determined by the power outage duration, three scenarios are developed reflecting three different outage durations: below 8 h, between 8 and 24 h, more than 24 h. Discussions on these scenarios were fostered among the participants and three sub-groups were formed for the impact analysis. In a second step, Preparation, Mitigation and Recovery (PMR) measures were collected and discussed, and results were sent to experts for commenting. Finally, semi-structured interviews with additional experts were conducted to have a more balanced view. The impact analysis represents an important starting point for the identification of crisis and continuity management measures referred to the three different phases of the crisis management process: prevention, crisis management, and recovery. Another workshop important result was that good cooperation between administrative authorities and healthcare providers as well as power suppliers may reduce negative impacts significantly. Cooperation includes information sharing, for example on the expected outage duration, on the patients needing power-dependent medical devices, and on respective resources.

[122] focuses on power industry and examines how distribution system operators (DSOs) align their policies to the principles of resilience within information security. The author performs a case study of incident management, conducting 19 semi-structured interviews to survey current practices and to identify the improvements needed to enhance smart grids. The ISO/IEC 27,035:2011 incident management process scheme, composed by five phases (plan and prepare; detection and reporting; assessment and decision; responses; lesson learnt), is used to investigate findings from the interviews to ICT and power automation systems managers of six large Norwegian DSOs. The investigation reveals that DSOs have quite some steps to go in the direction of being resilient organisations with respect to information security: plans for responding to information security incidents do not exist in all DSOs, training is an under prioritised activity, noticing and evaluating minor incidents are not common in practice.

The energy sector represents a societal economic driver whose vulnerabilities, barriers, and resilience are required to be studied ([123]). Among the personnel of three different power plant facilities (Abu Dhabi, Dubai, Sharjah), 42 questionnaires based on "yes/no" options, close-ended questions, and few open-ended questions were answered by professionals aged between 30 and 40 and semi-structured face-to-face interviews were conducted with top management. Questionnaire results were shown to respondents, who were asked to comment their own perspective, and then interpreted via a resilience management lens. Data were elaborated through MS Excel and SPSS, generating descriptive statistics. Findings indicate terrorism, atmospheric, and tectonic hazards as the main risks of vulnerability, while the lack or absence of awareness, education, and national government legislation revealed as the main barriers.

[124] aims at creating a picture of the strengths and weaknesses of the state of Georgia and Savanah area, based on a review of existing resilience initiatives and interviews with CIs' representatives. About 30 individuals among facility managers, safety specialists and other representatives of Georgia-based CIs' sites (i.e. state, local, military, and private facilities) were interviewed. Questions included current practices that enhance and detract from resilience, barriers to resilience, development of contingency plans, typologies of exercises conducted, identifications of less or more prepared sectors, identification of interdependencies and cascading effects between sectors, command structures, leadership, public outreach, how to allocate resources to best improve resilience.

With a similar focus, the framework introduced by [79] provides a set of policies to be implemented in order to increase CIs' resilience level. These policies were obtained through several research methods: Group Model Building workshops; examination of multiple case studies of different past major industrial accidents; a Delphi method where 15 multidisciplinary experts from different sectors (academic, transport, energy, and first responders) took part answering two different questionnaires with different aims and contents. The policies were classified based on the four resilience dimensions (technical, organizational, economic, and social) and on the two identified resilience types (internal resilience referred to a specific CI and external resilience associated to involved external agents such as government, first responders, and society). Finally, 25 experts were asked to provide the temporal order in which the policies should have been implemented, to achieve a high efficiency and effectiveness in their implementation.

Some papers start from disruptions in the payment systems and investigate the organizational aspects to increase their resilience. [125] come back on gaming simulation and aim at creating a game for participants from food, fuel, and financial industry sectors, who could benefit from major training to understand the challenges posed by interdependencies like a major disruption in the payment systems. Specifically, the authors focus on the design choices for developing a mixed-methods approach in order to assess teams' resilient capability. The authors suggest that team resilience can only be captured by a holistic mixed-method that considers both "soft" aspects like team workload, collaboration, trust, shared awareness, collected through verbal questions or queries, as well as "hard" measures of team qualities and performances, considering some indicators like payment options, good flows, trust, and security.

Also [126] identify and discuss challenges faced in case of disruptions in the payment system. The method is based on inductive qualitative research. Data sources included documents of previous incidents, interviews with key representatives of each relevant sector and two workshops with local and national actors. Results from document study and interviews were utilised for building two scenarios discussed during the following workshops, whose outputs were analysed to identify seven challenges for CIs' resilience. The analysis proves resilience to be not only a matter of technical measures (i.e. alternative payment solutions, rationing fuel or food, and offering services to the vulnerable part of society), rather it involves several communicative challenges (i.e. maintaining trust, preventing hoarding, avoiding panic).

Another paper deals explicitly with the organizational aspects of the payment system: [127] aim at understanding how local businesses in the sectors of banking, food, and fuel distribution are prepared to manage any disruptions.

Six semi-structured interviews were recorded and transcribed, and a thematic analysis was then applied to the transcribed material. The results show that food, fuel, and bank sectors are not prepared for a long-period disruption in the payment system. The respondents trust others (mainly IT Support) to solve the problems and they assume that disruptions last few minutes or hours. There is no plan, so the respondents are likely to close their business if the payment system is not working for a longer period. These concerns may be also emphasised in the current pandemic era.

2.5.3. Community resilience

Following an even broader perspective, this subsection illustrates those papers that deal with CI resilience at a community level. Resilience is interpreted here as the ability of a community to handle surprises, avoid disasters/accidents, and to be able to recover to a satisfactory state, i.e. normal societal operations ([128]), and it is now discussed in terms of its respective qualitative research methods.

When dealing with a community dimension of resilience, it is necessary to take into consideration the role of public perception and public tolerance levels for minimum level of service and rapidity of service restoration, as widely demonstrated by IMPROVER project ([129–132]). This latter indeed, by adopting a wide variety of qualitative research techniques (e.g. workshops, interviews, and questionnaires), provided evidence of the crucial role played by public engagement in the CIs resilience management ([133]). Among the experiments, the case studies on the transportation system related to the Oresund crossing between Denmark and Sweden ([134]) and the Hungarian highways ([135]) are noteworthy.

[136] focus on the resilience of a rural community of central Appalachia, a U.S. remote mountainous region prone to flooding. An inter-professional team of nursing, architecture, and engineering students conducted a comprehensive assessment of health and environmental living conditions via an ethnographic data collection approach, using both quantitative and qualitative sources of data: interviews, surveying, open-ended questions, observations, measurement, and photography. Qualitative interview data were organised and securely managed using NVivo software, while quantitative data were organised into a database and descriptive statistical analysis using SPSS 22. A model of resilience for the rural Appalachian community was developed, depicting the cycle of facing hardships, rebounding, supporting one another, and building community.

Also [137] deals with building community resilience in the Muzarabani district of Zimbabwe, often subjected to drought and flood-related disasters. The study applies systems-thinking approaches to examine how rural livelihoods address such living difficulties. 40 interviews were conducted among local authorities, traditional leaders, villagers, and health officials, focusing on the five livelihoods pillars: Natural, Economic, Human, Physical, Social. Then, three separate focus groups were held on the same macro-areas, including people who experienced the highest magnitude floods in 2008. Finally, a survey involving 700 households was conducted through questionnaires self-administered with the research assistants' help. The results were analysed by using thematic analysis and descriptive frequencies in Vensim software. In the study, resilience emerges as sharing resources among flood and drought victims and shows existing absorptive and adaptive capacities that smallholder farmers put in place to cope with natural hazards. Ethno-based flood and drought warnings, temporal migration to highest zones, particular social net (Zunde raMamb) and scheme (*nhimbe*) to share resources: these are the constituents of absorptive capacities. Adaptive capacities like practice of flood recession agriculture *(mudzedze*), dual cropping system, traditional flood proofing structures (*dura* and *dara*) suggest that the community has also the ability to store and recall flood experience, to learn and reorganise resources to address flood threats.

[138] focus on CIs' measurements, using recovery curves, after the impact of the hurricane Katrina in 2005 over two coastal communities of the Mississippi region. Data were collected by interviewing key informants as government officials, public works administrators, and emergency personnel. Public documents, Geographic Information Systems (GIS) data, and Photographic evidence were also used to integrate interviews. Press releases and media reports completed the missing data, although these releases and reports represent, according to the authors, inherently suboptimal sources: press releases are issued from corporate sources and tend to put organisations in good light by minimising failures, while media reports look for the emotional and interesting issues. Consequently, the research underlines the importance of data collection in emergency, establishing recovery curves and standardised measurement technologies for infrastructure, as helping tools to understand the effects and assist community to prepare for next events.

Still on hurricane Katrina, [139] presents the vicissitudes of the city of New Orleans. The author visits the region six times after the disaster and conducted naturalistic observations and interviews with planners, academics, and other people involved in the reconstruction efforts. The research, conducted with qualitative methods, allowed developing a conceptual framework to define principles for guiding actions related to building more sustainable and hazard-resilient communities. In this framework, the task of the governance institutions is to mediate human access to natural resources and prevent human beings' impacts from exceeding certain thresholds. Then, the authors provide a list of principles aimed at involving local communities in the decision-making processes and in the ecological sustainability prioritisation.

A similar focus on the reconstruction process has been documented in [140], but in Tacloban city (Philippines), after the typhoon Haiyan in 2013. The authorities decided to implement a No-Dwelling Zone (NDZ) along the coastline. Housing reconstruction and people relocation programs were started in order to move households to other safer areas. Among these people, the authors conducted paper-based questionnaire surveys to investigate: disaster experiences; assistance received; reconstruction or relocation experience; household and community decision-making; demographic profile. The responses were triangulated with focus groups with beneficiary households and key informant interviews were conducted with government and non-government organisations. Finally, the collected data were examined by using Wilcoxon–Mann–Whitney test for categorical variables, Spearman's Rank Correlation for ordinal variables, and One-way Analysis of Variance for comparisons of groups. The questionnaire survey was conducted at three different sites that used three different approaches: owner-driven onsite reconstruction; community-driven off-site relocation; contractor-driven off-site relocation. Household respondents were asked to indicate their satisfaction level regarding the programs, based on a five-point Likert scale. In terms of resilience management, results showed that on-site reconstruction was delayed due to insufficient assistance schemes like materials and skill training, while off-site relocation was delayed by prolonged land acquisition and subcontracting issues. Satisfaction levels of respondents were affected by CIs' disruption, such as water and utility services, lack of livelihood opportunities as markets or business establishments, and proximity to learning facilities.

[141] deal with the Chilean response after the severe tsunami of February 2010. After examination of the Chilean law framework for coastal planning, the study analysed tsunami mitigation measures and policies developed at local level in recent reconstruction plans. Then, a total of 50 semi-structured interviews and questionnaires with key local and regional actors of public and private sectors, as well as community leaders, were conducted to analyse tsunami impact mitigation measures. The collected data processing was conducted through a simple content analysis and a frequencies analysis of each response category. This study found that mitigation measures in Chilean coastal urban planning after 2010 have been focused at the local level on anti-tsunami engineering solutions, whereas other policies like key infrastructures restriction in tsunami flood zones or relocation of housing and key equipment were not adopted, due to the fact that reconstruction plans were non-binding master plans and citizens scarcely participated in their development.

The research by [142] deals with coastal communities and describe NASA's efforts on applying remote sensing and modelling in areas exposed to high potential risks. In particular, the NASA Disaster Program held a workshop in Spring 2017 with participants from academic institutions, local and regional which gave birth to the Mid-Atlantic Community and Area at Intensive Risk (CAIR) team that demonstrated the ability to integrate satellite earth observations and physical models into trusted and actionable knowledge for tactical and strategic decision-making.

Regarding a different threat, [143] analyse the emergence of new networks, agents, and institutions after the 2016 earthquake, for the small coastal settlement of Kaikōura in New Zealand. The paper utilises a qualitative method based on 12 semi-structured interviews and two focus groups, supported by literature review and document analysis. The first interviewees were selected among existing research collaborations with emergency management staff and local council. Then, a snow-ball strategy was implemented to identify further participants representative of the range of affected interests, in order to have a convenient sample (e.g. local government, regional economic development staff, food producers). Themes were identified and emerged through the process of data analysis using deductive and inductive methods, validated by inter-reliability analysis. The paper introduces two case studies that show the transformation of the rural community after the earthquake. In the first one, the shock induced by this event raised the awareness of the rural community of how important it was to strengthen local food networks, to build local capabilities, to promote local agricultural products as one of the reasons for tourism, the major economic driver of the district. The second case study regards the activity of a team that was formed after the earthquake to provide isolated rural households with life essentials and a readily accessible line of communication, responding to immediate personal needs.

On the importance of CIs for local communities, [132] focuses on regional airports in Sweden, clarifying their role for communities, in terms of regional development and civil protection. Four semi-structured interviews, based on a questionnaire with open-ended questions, were conducted, and recorded among a selection of stakeholders. The data collection was extended with a workshop of 14 delegates from public and private organisations, which aimed at giving suggestions to develop a conceptual model for assessing risks, the criticality of infrastructure in the context of civil protection and the economic value of airports. In this case, the participants emphasised the importance of

several transports by air for the society: ambulance flights, transportation of criminals, flights for crisis management such as fighting wildfires.
Another paper deals with the economic impacts on a community: [144] investigate the adverse impacts of hurricanes to interdependent workforce sectors in Virginia, using the dynamic inoperability input–output model (DIIM), a risk-based transformation of the Leontief's classic input–output model (i.e. a system of linear equations). To study the ripple effects which lead to serious economic repercussions and to identify the most critical workforce sectors and prioritise them, two significant metrics were considered: inoperability level and economic loss to industry sectors. Although this research is based on quantitative method, qualitative sources, as published surveys of workforce absenteeism in the aftermath of hurricanes, constituted the core of the data analysis, being the source for the formulation of the workforce perturbation models. The results provide guidance in disaster policy-making, particularly in systems-based resource allocation, enhancing preparedness to better manage the consequences of hurricanes to workforce sectors.

2.5.4. Urban resilience

This subsection is dedicated to the analysis of the papers where resilience is addressed explicitly as referred to cities and urban development. In this context, resilience could have a dual interpretation: an umbrella term for everything to be addressed within a city, related to sustainability aspects, climate change adaptation, or disaster risk reduction, and an ability required within a stable risk assessment process ([145,146]). This second dimension is the one considering of interest in this review, since it is nested in the recovery phase after a hazard impact, representing the "bouncing back" process phase which is the literal translation of the term resilience discussed in previous sections ([147]).

On this research stream, both [147] and [148] are chapters included in the book entitled: "Urban disaster resilience and security". In the former, the authors point out the relevance of urban areas, which are laboratories for observing and conceptualising resilience, because of the concentration and overlay of human beings, values, ideas with structural and non-structural objects, giving rise to socio-environmental or socio-ecological systems. In this environment, CIs inefficiency could even worsen a disaster situation for society, but CIs are also key components for recovering, since they are a core part of the resilience of an urban habitat. Again [148] emphasise the central role of urban dimension where urban environment and resilient cities are flagships of recent research to investigate not only worst case impacts of natural or man-made hazards but also to test the effectiveness of measures. Urban areas are selected for research and funding, since density of people and human values are concentrated here and this is both an asset and a risk factor. Finally, the authors show how existing indicators for resilience assessment can be improved or new indicators can be created: by adjusting old indicators, by involving experts or by using data sources or big data.

[149] report first-year findings of the European Union's Horizon 2020 project called Smart Mature Resilience (SMR) ([150,151]). This project aims to develop a maturity model (a tool to assess current effectiveness of a group, supporting figuring out what needs to be improved) for society's resilience, focusing on the progress towards resilience of seven cities, assimilated to the vertebrae of the strong European resilience backbone. Specifically, the model consists of four maturity stages: Starting, Moderate, Robust, and verTebrate (SMART) corresponding to increasing the capabilities of the cities towards higher

resilience maturity levels. The model was enhanced through a literature review on resilience, followed by an expert assessment by using Delphi method, and a series of workshops with experts on CIs, climate change, social dynamics (i.e. immigration, poverty, population ageing) and city representatives. Through Group Model Building, policies at strategic level were associated to each stage of the maturity model and classified along four resilience dimensions: Robustness of infrastructure & Resources, Preparedness, Leadership & Governance, Cooperation and Learning. The paper also introduces an interactive questionnaire for risk assessment programmed in Excel (i.e. Systemic Risk Assessment Questionnaire), whose questions are dependent each other, capturing the interdependence between risks, and whose output is a risk score which helps in assessing a particular project or initiative and in prioritising those areas which require more attention. Finally, by using a Group Explorer decision support system, different views regarding the risks associated to CIs, climate change and social problems, were collected during the workshops.

[152] shed light on the key role of the urban governance in the German approach to the CIs' protection. The study is based on literature and documentary analyses, interviews with 48 experts and workshops with practitioners from local utility companies and crisis management teams. The qualitative research pointed out some critical issues for the urban governance level: the German federal system (the Lander delegate the key operational tasks to the municipalities), the European regulatory market reforms (many public utilities have been privatised and many networked infrastructures have been unbundled into disintegrated companies), and the budget reduction (the companies are more likely to accept temporary revenue losses through supply disruptions during crises than to invest in the prevention of such events).

These issues result in a lack of coordination and cooperation among the main stakeholders; scarce information sharing and awareness of other infrastructure locations and their potential vulnerability; different vision about intervention priorities, mitigation strategies, staff training, and crisis exercises.

[153] explores the awareness of cascading risk, the possible mitigation measures, and the current levels of training among stakeholders of the city of London, all intended as measures for increasing resilience in crisis management. The research started from a workshop whose participants came from emergency response organisations, public utilities, businesses, and academia. The workshop included questions with multiple items to be evaluated through a standard Likert scale. To record the bottom-up stakeholders' perspective, each survey section also included open questions for the answerers, asking suggestions for mitigation measures, training strategies, general comments on the workshop. The answers were analysed with SPSS software, considering respondents' experience, affiliation, and gender; possible correlations between answers within sections and across sections were also searched. The findings confirm that the current crisis management approach to cascading risk is inadequate. London stakeholders are aware and concerned about cascading events and interdependencies, but they recognise that these issues are not sufficiently incorporated in the current policies, practices, and emergency management at large.

From a terrorist point of view, urban environment is a perfect target, since cities can be seen as nodes where people, ideas, value streams, and information meet. In this context, [154] aim at better understanding the operational environment when a CI becomes a target of a terrorist attack. Therefore, two scenarios, which reflected the model for comprehensive security defined in the

Finnish Security Strategy for Society, were elaborated during a workshop: water contamination and electricity disruption. The workshop, organised at the Police University College in Tampere, was facilitated by a modified Open Space method. Unlike the original method, participants did not suggest topics for discussion, but they were invited to discuss about formation of situation awareness, competencies, and resources in crisis management, crisis communication, and development of a new tool in terms of continuity management. The sixteen participants represented the key actors who would be involved in the workshop scenarios in real life. In order to enhance system resilience, the findings reaffirm the importance of a multi-agency situational awareness, shared among key actors, as an essential element in decision-making and the need for a more networked defence to face threats as organised crime, hybrid action, and terrorism.

The study in [155] is based on the research conducted in the INTACT and HARMONISE projects, both co-funded by the European Union ([156]). The first project addresses CIs' resilience to the challenges posed by extreme weather events, while the second one presents resilience enhancement methods for large-scale urban built infrastructures. The aim of the paper is to establish a systematic approach for conducting urban CIs' risk assessment for calculating and comparing benefits of the measures and costs. The proposed approach is flexible, encompassing not only a rigorous quantitative evaluation, but also allowing for a semi-quantitative or qualitative assessment. For example, for CI and system modelling, since the technical information on CI core functions and processes is specific for each CI and system, cooperation with experts, who have the knowledge and the data access, is needed. Moreover, for risk estimation and evaluation, there are three different types of calculations: qualitative, semi-quantitative, and quantitative. Some methods aim at general mapping and understanding of potential consequences and impacts, others are based on very detailed analysis in the form of indexing and strict quantitative modelling; a mixture of this approaches is used in some cases.

Finally, [157] propose a guide to help cities to become more resilient by considering urban CIs as key elements to cope with Climate Change (CC) -related crises and maintain citizens' welfare. The research consisted of two phases: the conceptualisation and the development phases. In the first phase, a literature review was carried out, analysing scientific and grey literature articles and reports. In the second phase, a co-creation approach was adopted, through focus group method, to elicit information from experts in two cities in the Basque country (Spain). Specifically, two workshops in each city were organised with 30 multidisciplinary experts to identify resilience building policies for improving urban CIs' resilience level and to carry out a detailed analysis for classifying the CIs against CC impacts and for studying the interrelationships among CIs. Then, two pilot tests, one in each city, were carried out to review the guide and use it in a real context. Moreover, additional interviews with the heads of the environmental departments of eight towns which had not participated in the development phase were carried out to provide relevant feedbacks. The research main result is a guide to help cities to analyse their current situation and understand challenges and opportunities supporting the development of resilience-strengthening strategies.

2.6. Discussion

This section summarises and discusses the outcomes of current works on qualitative research on CIs' resilience as emerged from full-text analysis of reviewed documents. These papers have explored macro-themes that resilience research on CIs should take into account, mainly in case of Tier I (or Tier II) approaches. Nevertheless, many of these discussion points remain valid even for more quantitative investigations, as for Tier III approaches ([4]).

2.6.1. *Qualitative and quantitative, or qualitative alone?*

Adopting a qualitative rather than a quantitative approach to study complex issues is not an easy decision: both approaches have their pros and cons. As mentioned in the introduction, this is a debated topic, which also emerges from the reviewed papers. This choice should be driven by the needs and desires of the decision makers, who usually prefer having numbers on which base their determinations. For some type of analyses, e.g. cost–benefit, quantitative assessment is expected to be done ([95]), while for others, there could be much more flexibility. Concerning quantitative sources, often considered lacking in data, it has been proposed to elicit knowledge from press releases and media, which are however deemed sub-optimal sources. Press releases are issued from corporate documents and tend to put organisations in good light by minimising failures, while media reports look for the emotional and interesting issues of stories ([138]). This means it is a viable option, but there should be a conscious use of the respective storytelling. A possible option here, at least for some type of outages and events, could be related to the usage of social media ([158]) (e.g. Twitter) as a social sensors and obtain information on this direction. Some early results on power grids demonstrate the potential benefits to further research on the topic ([159,160]).

Quantitative data offer an inherent benchmarking dimension, which anyway requires to be complemented by qualitative assessment in order to ask the right questions for understanding the context, and provide meaningful answers to interpret the scores ([102]). Nonetheless, qualitative assessment needs also careful and thorough planning to avoid unmanageable results. In retrospect, it is worth mentioning how [102] admit that questionnaire and terminology could have been more precise in their study if workshops and interviews had been conducted first. Then, the original questionnaire should have been revised taking into account respondents' comments, allowing for a more precise questionnaire to be distributed. Understanding the right sample size for preliminary interviews and workshops is always based on a trade-off, which might rely on the so-called knowledge saturation principle ([161]). Future research may thus investigate this principle explicitly in the context of CIs, to demonstrate its feasibility and define guidelines to support analysts in conducting their research.

A certain scepticism about resilience measurability in quantitative terms has been documented, due to CIs' complexity which cannot be simply analysed by larger data availability ([148]). The same authors warn about the shortcomings of exemplary social science qualitative assessments, backed from their experience on the field. By using participative social science methods such as workshops, focus group discussions, and expert interviews, [148] realise that the same experts might offer contradicting arguments in assessments which are repeated only few weeks after the first one.

Quantitative scoring reliability has to be treated as cautiously as individual qualitative results reliability. Nevertheless, combining the two dimensions appears a promising choice to build bridges between users, social and natural scientists. Such mixed methods and approaches are often balancing demands by different end users, and even if they could partly disappoint some of them, they generally allow for a bigger picture.

2.6.2. *Stakeholders' involvement*

Another relevant point of discussion is the involvement of all stakeholders, both in urban realities, in complex infrastructure systems, and in organizational settings, characterised by close interdependencies and hybridity between the social, natural, and technological worlds ([152]).

For example, the importance of preparedness and contingency thinking emerges explicitly in urban settings, along with the need for a networked defence strategy among stakeholders to face threats which lurk within the increased diverse and sophisticate operating environment (e.g. organised crime, hybrid action, and terrorism) ([154]). Resilience requires different strategies for urban realities ([162]): while bigger cities usually have centralised resources to face crises, smaller ones depend even more strictly on the collective use of resources and, consequently, emphasise cooperation and coordination, including citizens' participation ([157]).

Further examples of the need for stakeholders' involvement relate to community resilience, where methods such as the Resilience Matrix ([4,69]) or its variant Population Resilience Matrix ([163]) have been used to organise community goals in a context of population displacement and infrastructure reconstruction. Concerning the Population Resilience Matrix, the authors explicitly state community engagement to establish legitimacy around acceptable performance limits as fundamental.

A similar need for stakeholders' involvement has been documented at intra- and inter-organizational levels to support stakeholders' common knowledge and resilience to cascading failures ([89]). A noteworthy result in this case is the cooperation benefits between administrative authorities, healthcare providers, and power suppliers to plan for the negative impacts of a disruption ([121]). At the extremes of this concept there lies the push for the inclusion of mitigation measures into legislation ([153]), and local level engagement, where private citizens can voluntarily self-arrange into groups to define a resilience strategy ([164]).

Nonetheless, such type of coordination is a rather complicate and delicate task, and should be treated taking care of the potential privatisation of some companies, as well as the organizational cultures. A critical reflection in this sense comes from the STYREL project, where the public–private cooperation envisaged in the process revealed lack of trust between actors, concerning both lack of resources and feedbacks ([120]). Most reviewed papers shed light on the importance of data availability and information sharing. Few studies focus on extracting the failure dependencies on experts' knowledge because detailed information about the CI failure interdependencies is considered highly sensitive and private CI operators are reluctant to share information with academic communities ([89,92]).

Involvement means cooperation, information sharing, transparency, and discussion to enrich one other perspective. Communication is crucial at all level of CIs' management ([165]). Future research should explore the contributing success factors to cooperation as well as evidence of those scenarios where cooperation drove to positive outcomes should be given, separating the strategies that foster success from the ones that may create detrimental effects.

A promising research stream in this sense could refer to the usage of methods built in the context of Resilience Engineering used for socio-technical system safety, as for the Functional Resonance Analysis Method, early applied for CI resilience in the urban context ([146]). At societal, or even organizational level, this may imply the push for development of dedicated app to inform about vulnerabilities and response strategies, as for the early results in the disaster management domain ([166]).

2.6.3. *Guidelines, but for whom?*

Several papers show the need of guidelines and criteria for helping authorities at different scales to develop crisis management, to analyse vulnerabilities, and to improve CIs' resilience ([167,168]). Of course, the societal scale at which guidelines are proposed shapes the details and operating strategies suggested ([169]).

At international scale, focusing on transportation infrastructure, it is worth mentioning how the European Surface Transport Operator (EUSTO) built common guidelines for developing security plans for surface transport with an EU dimension, involving National Contact Points of EU members and surface transport stakeholders ([170]). Still in EU, the AESOP (Association of European Schools of Planning) guidelines offer details on identifying target population, and emphasise the need for CI operators to give evidence via news media of their positive working relationships with their counterparts, always in light of the regulatory context ([105]).

At national scale, CIs require more regulatory efforts by national policies and highlight the need for identifying place-based vulnerabilities, locally differentiated preparedness strategies, and the training of local utility companies as well as crisis management teams ([152]). Furthermore, some public–private partnerships, leadership, trusted and secured information sharing, and exercises for social vulnerability assessment should also be fostered ([124]).

At regional scale, guidelines should support authorities to integrate CIs protection and reconstruction into the spatial planning process. This target can be achieved via indicators (e.g. population equivalents) for a systematic analysis of vulnerabilities, interdependencies, and criticalities of infrastructures and customers ([81]). This is a viable research stream, as demonstrated by the interventions defined at a local level to increase community resilience in light of a multilevel integrated management approach, particularly careful to respect and empower local cultures and capabilities ([139]) or by modelling population displacement as a function of infrastructure reconstruction decisions, in order to implement best strategies for infrastructure recovery ([171]). The local level also includes the urban resilience management and the treats a stakeholder profile should respect to be involved in a resilience research ([157]).

In summary, the reviewed papers reveal the need of guidelines, and the benefits arising from them at different scales ([172]), with no specific inter-level research available yet. Future research should thus start from these results and propose different staging areas to harmonise the priorities, and the constraints imposed by different competent authorities acting at different scales (international, nation, regional, local).

2.6.4. Continuous trusted learning

A continuous trusted learning process is crucial for both organisations and communities. In this context, a poor risk awareness is frequently reported, as well as the absence of systematic knowledge sharing, and poor scenario training and emergency preparedness ([98]).

Available solutions about organisations in literature refer to the preparation of inter-teams' meetings, where diverse personnel are involved (technicians, operators, managers, etc.) to reinforce mutual understanding and foster participation, by complementing top-down decision-making with some bottom-up evidences. Owning solutions is expected to support a learning-oriented healthy environment ([123]). Similar evidence emerges in school emergency management: school staff do not fully know the actions and the post-evacuation procedures, and both staff and students do not share the right perception of natural hazards. At a management level, this result calls for a reconsideration of the connection between schools' evacuation plans and cities' civil protection plans ([117]). Risk awareness and learning oriented approach are essential for communities who face natural hazards continuously, and have to deal with improvised means ([137,143]).

As an example, the above mentioned research on the Appalachian community has demonstrated their resilience based on faith and spirituality, cultural values and heritage, and social support despite stressors like poverty, rural isolation, low educational attainment ([136]). Similar results have been achieved by this type of research conducted in Zimbabwe where the results pinpoint to lemmas used by the community to identify inherent capacities and strategies ([137]).

These observations show how helpful could be a qualitative approach, designed for ethnographic research to unravel local absorptive and adaptive capacities. Understanding humans in their real-life environment becomes a central point for incorporating anthropocentric assessment and transferring it to other communities. In addition to validate the idea in many communities, future research could extend the concept to organizational ethnography ([173]).

2.6.5. From cybersecurity to cyber resilience

With the exception of some papers such as [174] where the Risk Matrix is adopted to develop metrics useful for evaluating the cyber systems' resilience, as demonstrated by the bibliometric findings in section 2.4, cybersecurity has been studied less than others through qualitative research methods.

Literature review shows a focus on identifying cyber vulnerabilities and preventing cyber-attacks, but much less on mitigating their effects by improving cyber resilience. For example, [100] found that the majority of the available questions, among the distributed qualitative surveys, focus on technical safeguards and protection measures rather than examining response and recovery strategies. Available Self-Assessment tools are only one—limited—component to assess cybersecurity: they should be reviewed to ensure the full resilience capabilities and customised based on the organisation profile ([100]).

Cybersecurity requires an evolution of traditional risk management process, requiring a greater emphasis on shared responsibility, leadership, and human resources ([101]). The same observations could apply to cyber resilience in space missions ([175]).

These early observations indicate that cyber resilience among modern CIs is an under-developed domain, which requires a modern view on resilience inspired by other more traditional CIs. Qualitative research here plays a central role to prioritise activities and identify threats through dedicated surveys that can increase the level and quality of information security to next maturity levels.

2.7. Concluding remarks

Continuing failures and disasters remind us the need to further advance available scientific understanding, and policy-making of CIs' resilience. Resilience management in modern CIs requires an understanding of CIs' functioning, as well as the needs and the determinant features of all the involved stakeholders. Indeed, modern CIs require methodologies able to capture diversity, heterogeneity, and inter-relatedness, providing meaningful and interpretable representations also in light of cyber-physical systems interdependencies ([176]). Qualitative research has a high potential in such contexts, as shown by the results of the systematic review presented in [71]. Through qualitative research, CIs analysis can more explicitly reflect the complex and tight coupled factors of individual, group, societal behaviours, as they act in conjunction with technological artefacts.

While the empirical findings discussed in the present Chapter demonstrate the usability and usefulness of qualitative research to address CIs' resilience management, several research areas have still to be developed, related to the notion of knowledge integration: (i) from a methodological perspective, integration with quantitative methods that still adopt a systemic perspective; (ii) from a management perspective, integration across different micro-meso-macro scales; (iii) from a strategical perspective, integration among data from different stakeholders, ensuring trust and cooperation; (iv) from a tactical perspective, integration and dissemination of knowledge to support a continuous trusted learning.

In our uncertain and turbulent modern world, future research on CIs' resilience should prioritise integration to support the survival and development of future organisations, communities, cities, and societies towards the next staging areas of evolution and adaptations.

CHAPTER 3

3. LEARNING FROM INCIDENTS TO IMPROVE ORGANIZATIONAL RESILIENCE

The content of this chapter partly relies on a previously published manuscript: R. Cantelmi, G. Di Gravio, R. Patriarca, Learning from incidents: A supply chain management perspective in military environments, Sustain. 12 (2020). https://doi.org/10.3390/su12145750

Acronyms

AAD	Aeronautic Armaments Directorate
AF	Armed Force
GAS	Gas recovery system failure
HDL	Handle failure
ILE-LM ILE	Material Management (ILE-NL-2100-0006-12-00B01)
ILE-MM ILE	Logistic Management (ILE-NL-1110-0001-12-00B01)
INV	To be Investigated
LAD	Land Armaments Directorate
LFI	Learning from Incident
MEC	Mechanical failure
NCD	Non-Conformity to Drawing
NUC	Unique Codification Number
NUL	Null
SAMP	Small Arms Maintenance Pole
SLD	Rail slide failure
SPR	Spring failure

THM	Thermo-fusion failure
USC	Partial Unscrewing failure

3.1. Learning from incidents: a theoretical overview

Regarding incidents or accidents, there are two prominent schools of thought that attempt to explain their occurrence in high-risk complex organizations: the Normal Accident Theory (NAT) and the High Reliability Organization Theory (HROT). The theory of Incident Learning can be considered a link between these two theories [54].

Disasters have long incubation periods, during which warning signs (or incidents) are not detected or recorded [177,178]. This suggests that a system for learning from incidents (LFI) could be the "sensor" that the organization needs to detect these warning signs early and to implement preventive measures. Therefore, while it is plausible to believe that the occurrence of incidents may be normal, on the other hand an organization with an effective Incident Learning System (ILS) can respond to these incidents to prevent accidents or disasters from occurring in the future. Through this continuous improvement process, the organization can evolve over time into an HRO.

To understand why accidents happen, it may be useful to imagine the existence of a risk system, or a system that generates accidents [54]. It cannot be separated from the business system which instead produces the useful outputs of the organization, however it is possible to obtain valuable information by observing the two systems as if they were distinct. Although incidents are actually undesirable results of the business system, it is instructive to see them as an output of the risk system, hidden from view but unfortunately with real results.

In the same way that quality management principles are applied to control the quality of business system products and services, similar principles must be applied to control the "quality" of risk system incidents. Indeed, it would be equally valid to consider accidents as "quality defects" or to consider quality defects as "incidents": in this way the same principles of monitoring and control will be applied.

Organizations should use an ILS to identify incidents and analyze them in order to correct defects in the risk management system, in the same way they employ a quality management system to address quality problems and improve the business system. Figure 9 shows how feedback from quality management and incident learning systems improve organization performance.

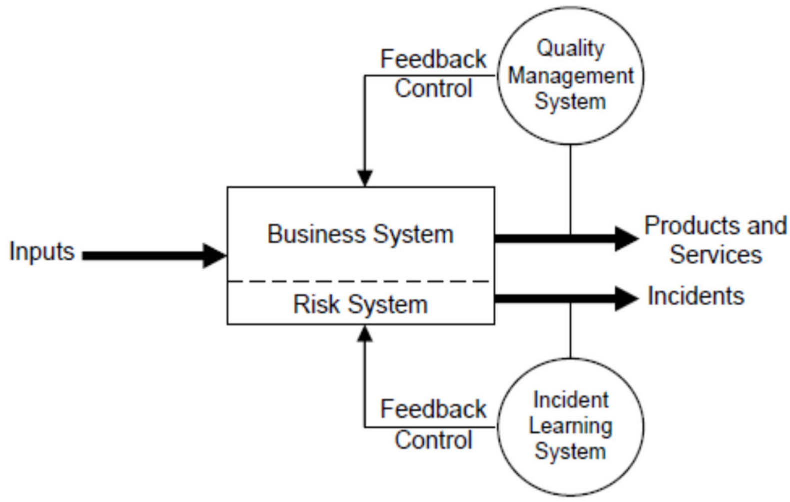

Figure 9 - continuous improvement of business performance [54]

Ideally, the two systems should be integrated within the framework of Total Quality Management (TQM). The integration of safety management and quality management has been proposed by several authors [179–183]. Integrating an ILS with quality management is one way to make TQM operational. This integrated view of TQM, illustrated in Figure 10, also includes safety, where the quality management system focuses on accident prevention and the ILS contributes to the improvement of the business system through the analysis of accidents that occur.

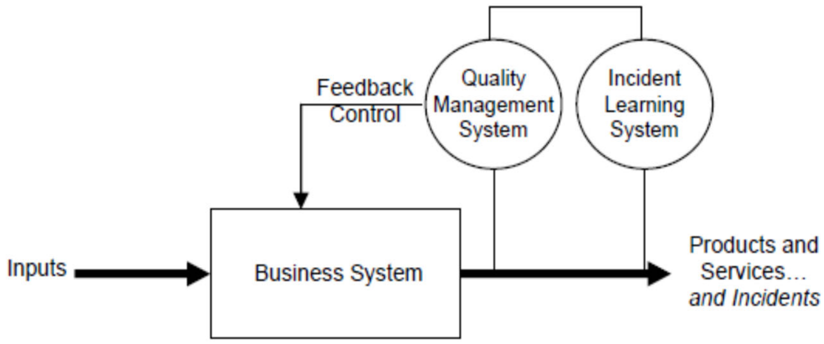

Figure 10 - an integrated vision of TQM also includes safety [54]

With good reason, therefore, the ILS provides a risk control process for the organization.

Given the importance of disaster prevention for the survival of a socio-technical organization, an ILS should be as central to the organization's mission as the production or service delivery system that is the principal focus of the organization. This is reinforced by the fact that, in the medium and long term, the adoption of an ILS will bring the following benefits [54]:

- with the same degree of complexity of the interactions of a socio-technical nature and level of coupling, the organizations that have the most effective incident learning systems will have better performance from the point of view of safety, quality, respect for the environment and economic performance;
- all socio-technical organizations will experience normal accidents or incidents, but the presence of an effective learning system from incidents will mitigate the risk of disaster and allow a level of performance comparable to "high reliability";

- in an organization with an effective incident learning system, the number of reported incidents may initially increase, but the average severity of reported incidents will decrease over time.

In short, the adoption of an ILS will enhance the resilience of the adopting organization.

3.2. The LFI Cooke model

A theoretical model of an ILS can be found in [54] as anticipated in the introduction.

The first component of a learning system from incidents is the identification and response, without which no learning is possible [184]. Unless the organization is already made aware of learning from accidents, deviations from normal behaviour will usually not be noticed or will be accepted as "normal deviations". Actually, it is important to carefully evaluate at what level the detection threshold should be set, otherwise the organization will be submerged by an avalanche of incidents that could exceed its ability to investigate and respond adequately, since even in the case of a near-miss, for example, an immediate response would be required to correct any unsafe conditions resulting from the event.

Therefore, it is necessary to define a criterion for the consequent response in order to determine if an emergency intervention is required immediately or if it is necessary to implement the corrections that will stabilize the situation. For example, a small fire requires an immediate response because it could escalate into a major accident, if immediate action is not taken to extinguish it. Only when the accident is properly controlled and the situation is stable, data on the accident should be collected.

The second component of an ILS is reporting. It is a fundamental phase since no incident can be investigated if it is never reported. The fraction of reported incidents depends on the sensitivity of employees, who observe or are involved in the accidents, to the safety issue. In this regard, taking into account that management is responsible for spreading the culture of safety within the organization, it is clear that the sensitivity of employees to safety is strongly influenced by the management commitment to this topic. Management can show its commitment to safety by creating a climate in which incident reporting is rewarded rather than punished. Part of the "reward" could be to make the reporting process as simple as possible and to involve in the investigative process the person who made the report, if desired.

The incident investigation is the best known component of an ILS. It involves examining the site and interviewing witnesses, collects and evaluates the available data to establish the sequence of events and determine what exactly happened. Usually, an investigative team turns out to be more effective than a single investigator.

Many sources state that the purpose of incident investigations is to determine the root cause of the accident. However, since there cannot be a single "root cause", it would be better to direct efforts towards identifying the causal structure. This should be viewed as a separate step in the process, which should reduce the temptation for the investigative team to come to a conclusion before all relevant data have been collected and evaluated. Most safety textbooks refer to the determination of one or two main or fundamental causes of the accident; a widely used approach reduces all possible causes to an all-encompassing look-up table [185]. However, this linear reductionist approach cannot work for complex system incidents where there can be a multiplicity of "root causes".

The desire to find a single root cause has been defined in the literature as "the seduction of the root cause" [186]. For incidents that occur in complex systems, one possible approach is to integrate root cause analysis techniques with systems thinking. Causal loop diagrams, which capture the causal structure of the accident in a network of interconnected causes and effects, would be an appropriate way to represent a complex causality. Incident investigation teams could be trained to be able to model the causal relationship system.

The investigative team's work is usually complemented by the preparation of an incident report which includes findings and recommendations. The distribution of this report within the organization is a way to communicate the lessons learned from incidents (communicate incident learnings). Another way is to summarize the important lessons in a document that can be digitally distributed within the organization and, if deemed appropriate, externally to the members of the sector associations. The recipients list may also vary depending on the severity of the accident.

Another phase of the learning process is to reconsider the previous incidents (recall previous incidents) and hypothesize possible failure modes that have not yet occurred, but which previous incidents suggest to be possible. The reconsideration of previous incidents and the formulation of hypotheses can be carried out individually, through an interview process or better in working groups that often prove to be particularly suitable for stimulating ideas and strengthening learning.

Of course, it is important to implement corrective actions and follow up on all recommendations made by the investigative team. An effective action and the follow-up of all pending recommendations will challenge management planning and control. This is particularly true for the actions of systematic elimination of the causes of incidents, which can extend to the entire organization and involve many people in different geographic locations. In the modern information age, computer databases can be used effectively to keep track of recommendations and to follow them to completion. Processes outside the ILS, such as audits and inspections, are also useful for checking that corrective actions have been successfully implemented. The improvement in safety can also be rewarded through the employee and management remuneration system.

Figure 11 summarizes the above, showing how the components of an ILS complete the continuous improvement cycle for the organizational system. The diagram also shows the important connection with the outside, through which learning at the local level is shared with other offices and units belonging to the same organization and with other organizations through sector associations.

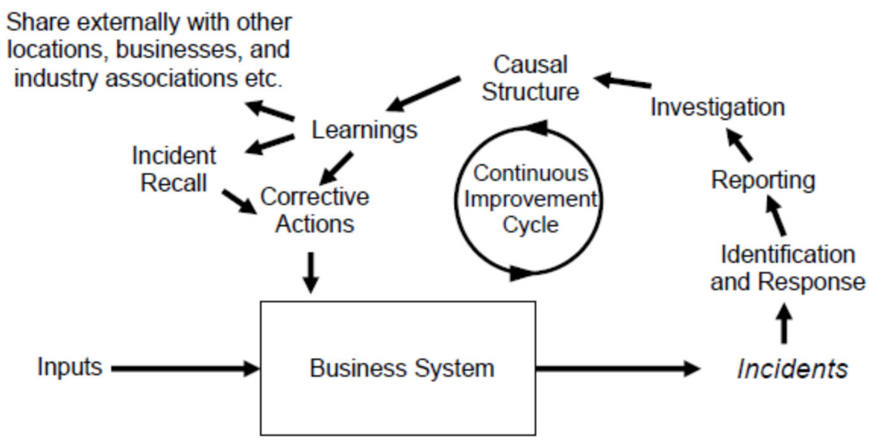

Figure 11 - Incident Learning System closes the feedback loop [54]

Figure 11 shows that if even a single arrow is missing, the feedback loop is interrupted and learning from that incident does not occur. It may happen that the quality of the information that passes from one phase of the process to the next is poor or decreasing. Considering this effect on hundreds of incidents, an aggregate model could be obtained in which each "arrow" has a weight equal to the number of information that returns to the company system; this weight can be considered as the efficiency of each phase of the cycle.

It can be assumed that if the cycle shown in Figure 11 does not continue to run, the organization may run into self-satisfaction, placing excessive trust in the management of safety and its activities. To ensure that the cycle runs smoothly, there also must be a balance between the number of reported incidents and the organization's ability to investigate and learn from incidents. These considerations suggest that it is important to establish an appropriate threshold for incident reporting and to allocate appropriate resources for incident investigation.

The external cycle for shared learning shown in Figure 11 should be closed by the benchmarking process that analyses best practices and adapts them to improve the business system. This concept is shown in Figure 12. Sharing lessons learned outside the organization encourages others not only to learn from the incident itself but also to share what they have previously learned with the organization where the incident occurred. Other organizations can contact the organization where the incident occurred in order to report that they had to face a particular problem and to share their solution.

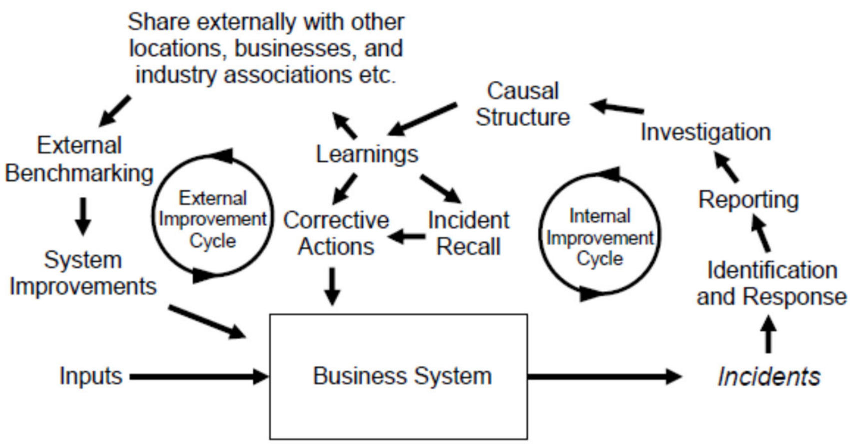

Figure 12 - external benchmarking closes another feedback loop [54]

Organizations should track quantified losses from incidents and include this metric in their Key Performance Indicators. The reduction in losses provides the economic justification for investing in the ILS.

3.3. The case study of a supply chain in reverse logistics

This section describes how the theoretical foundation for the LFI system has been adapted for information management (subsection 3.3.1), subsequently describing (subsection 3.3.2) the regulatory reporting framework of (ILE-NL-1110-0001-12-00B01, ILE-NL-2100-0006-12-00B01), as developed by the entity for logistics (called ILE). Lastly, the section details the as-is reporting framework (subsection 3.3.3).

3.3.1. Adapting the theoretical model

The theoretical model shown in section 3.2, inspired by literature regarding incident learning originating from reliability and safety management [54,55], has been applied to the case study regarding the supply chain in reverse logistics.

Figure 13 depicts this adaptation of the theoretical model to the particular case study. In the adapted model, the eight main phases of the Incident Learning System are performed by different actors related to the small arms reverse logistics supply chain. The Units are responsible for the efficiency of the small arms and are required to report any inconvenience to the competent Authority, i.e. the Land Armaments Directorate (LAD). The latter assesses the drawbacks and, if necessary, appoints the Small Armament Maintenance Pole (SAMP-PMAL) to investigate them in order to find the causal structure. The technical investigation findings are reviewed by LAD, who takes corrective actions and shares the lessons learned, in order to prevent similar incidents from happening again in the future.

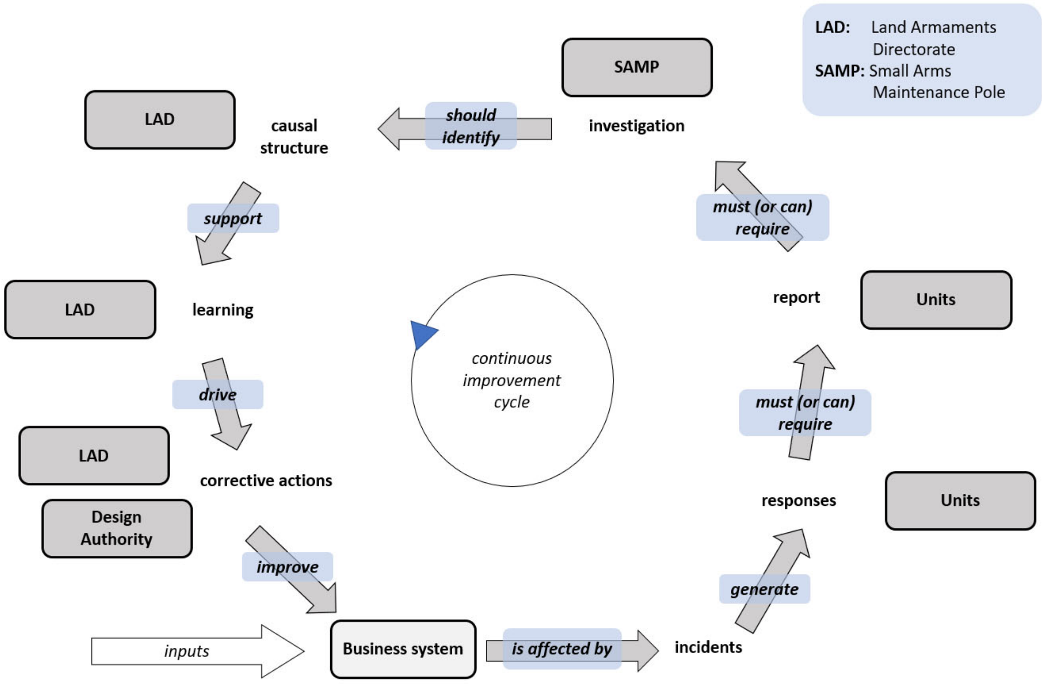

Figure 13 - the theoretical learning from incidents (LFI) model applied to the case study

3.3.2. *The regulatory framework*

NATO stresses the importance of a LFI model, as established by the Joint Analysis and Lessons Learned Center (JALLC), whose mission is to carry out an inter-force analysis of everyday operations, training, and exercises, including the implementation and management of a single database for all NATO countries regarding lessons learned. The NATO learning doctrine applies to any military activity, even though in real practices it faces the challenges imposed by the lack of a healthy reporting culture. For this purpose, each member Nation adjusts the NATO doctrine on LFI by a set of customized inter-organizations and intra-organization directives, issued by national bodies.

On this basis, [187] focused on the regulatory framework implemented in Italy for small arms, as described by two logistics publications which are of interest for sustainable Supply Chain Management (SCM):

- ILE-NL-1110-0001-12-00B01 (cf. subsection 3.3.2.1), which deals with the management of the different materials supplied to the Italian Army, for the sake of clarity called ILE-MM (ILE - Material Management)
- ILE-NL-2100-0006-12-00B01 (cf. subsection 3.3.2.2), which derives from the previous one and regulates the management activities and the logistic device related to the armament material, for the sake of clarity called ILE-LM (ILE - Logistics Management).

The regulatory framework is completed by the technical directive TER-50-1000-0007-12-00B000 (cf. subsection 3.3.2.3), repeatedly recalled by the ILE-NL-2100-0006-12-00B01, which defines the control procedures to ensure the usability of a weapon in safe conditions for the operator and the reliability for operational purposes.

3.3.2.1. ILE-NL-1110-0001-12-00B01

This publication was issued to maintain the availability of means, materials and weapon systems at the levels set by the Army General Staff, for the effective use of Units in operations and training activities. The ILE-MM defines the correct procedures of technical-logistical management so that maintenance interventions and supply activities take place in a harmonious and balanced functional framework, following a cost-effective target. The purpose of the publication is therefore to establish the rules governing the management of the material parks supplied to the Italian Army, for operational, training and logistical needs.

The publication consists of a “general section” and the “park material section”. The former provides the main features of the logistic support in all its aspects, and a series of dossiers related to the detailed management rules for homogeneous sets of materials. This section further defines the procedures relating to the main elements of the logistic support, i.e., procurement, supplies, maintenance, transport.

Procurement is at the origin of the material management process and it aims at acquiring the means and materials necessary to achieve or maintain the expected operational capacity.

The Supplies are intended to make the material resources available to the Units, in scheduled times, places and quantities to ensure the operational capabilities necessary for operations. This activity also includes the reverse material handling about replacement of inefficient vehicles and materials.

Maintenance is the activity which seeks to ensure the reliability of the means and materials through checks, revisions, reconfigurations and various types of processing. Furthermore, the ILE-MM specifies the tasks of the Second Level of Maintenance (FLS) institutions, i.e., the Maintenance Poles, which are entrusted with all the corrective actions that fall outside the competence of the First Level of Maintenance (FLA) and the general revision interventions related to the peculiarity of the materials, means and weapon systems. Moreover, the publication establishes, among a series of other activities, that the so-called Maintenance Poles are accountable of carrying out technical investigations on incidents and accidents related to the material of its own competence. For the case under exam, the publication assigns to the Small Arms Maintenance Pole (SAMP - PMAL) the competence on small arms and light weapons.

The publication defines Transport as an operational activity aimed at transferring personnel, vehicles and materials from a place of origin to a destination, using land, sea and air carriers, through the related infrastructure. In the second section, the ILE-MM defines the Park Materials as the union of all weapons, artillery, technical means for shooting, rotated and tracked vehicles, machines for earthworks, and aircraft supplied to the Army. It identifies five Park Areas and respective sub-areas, including homogeneous sets of several species of materials, means or weapon systems, having similar technical and employment characteristics, unitarily considered for the purpose of facilitating the material management. "E Area" concerning armament materials is the one of interest for our research.

3.3.2.2. ILE-NL-2100-0006-12-00B01

The publication ILE-LM is one of the dossiers of the ILE-MM described in subsection 3.3.2.1 and concerns the materials relating to the "E Area" Park, for which it defines the management activities and the related logistic device. For each material, a specific technical life is indicated in order to allow a correct management of the potentials as well as the planning of maintenance operations. At the end of this life, the material is submitted to general revision by the Maintenance Poles and, whereas possible, the resetting of the technical life is carried out. The publication then reports a series of tables, for each type of weapon, which detail the preventive interventions, the competent Logistics Area (FLA or FLS), the periodicity of these interventions, the necessary time.

3.3.2.3. TER-50-1000-0007-12-00B000

This document details the technical inspection procedures aimed at ascertaining, at all levels, the usability of the arms allowing both safety for the users and reliability for operational purposes. These procedures utilize gauges or verifying instruments, which are a set of artefacts that allow for the checking of significant dimensions for the most important parts of the weapon from the point of view of safety and operation in a simple and rapid manner, as designed by the weapon manufacturer.

3.3.3. Focus of the research: reporting

Following the previous mentioned regulations, the inconveniences constituting technical problems must be reported according to the form in the Annex O of the publication ILE-LM, which defines the roles and the action for each supply chain agent. The reporting form has to be sent to different agents: (i) the Land Armaments Directorate (LAD), which is responsible for technical-administrative issues related to armament, (ii) the Command of Transport and Materials of the Army Logistic Command, (iii) the Logistic Department of the Army General Staff, and (iv) the Commands on which the Unit producing the report depends.

The report is structured in five sections, which are described following a supply chain information management perspective.

The first section deals with the description of the material and the parts affected by the problem, as well as the applicable technical documentation and the data related to the various types of maintenance interventions carried out. From an information management perspective, it is relevant to prioritize some of the fields included in the technical report.

For the material, relevant fields are the Unique Codification Number (NUC), the name and type of the weapon, the Manufacturer, the number plate/frame/serial number (or other identifying element), the date of introduction into service; for the system: the name, the serial number, the subgroup or the figure number, while for the parts involved in the incident: the name, the catalogue number and the NUC. Additional fields are the relevant Publication or Technical Ordinance; dates and number of hours of operation, and number of shots fired before the last specialized maintenance, the last reliability check, the last technical check, as well as the most recent general revision.

The second section illustrates the purpose of the reporting, highlighting whether: it concerns the personnel's safety; it regards the functionality of the material; or it is for information purposes only.

The third section deals with the description of the problem, including shots/hours of usage when the incident happened; narrative of the incident; possible causes (if any); taken measures (if any); number of detected cases (if any); previous reports (if any); proposals (if any); any other note.

The fourth section expresses the reporting priority (from high to low): emergency; urgent; normal. The fifth section (not mandatory) contains a field to report any other data considered to be of interest, and some photos of relevant parts are usually attached, as shown in (e.g.,) Figure 14 and Figure 15.

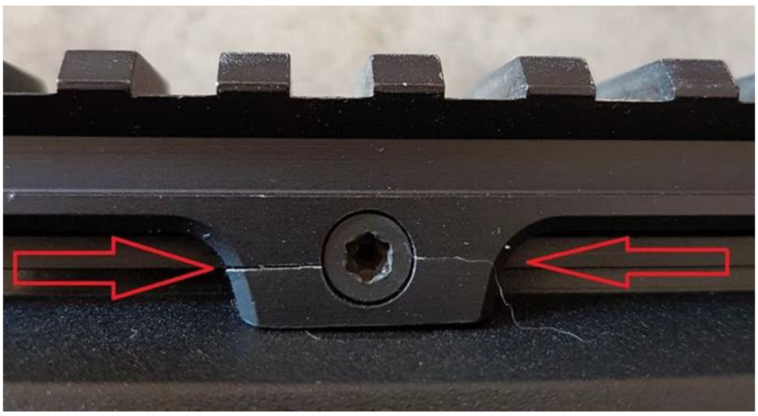

Figure 14 - example of technical inconvenience: mechanical damage in the rail of automatic rifle.

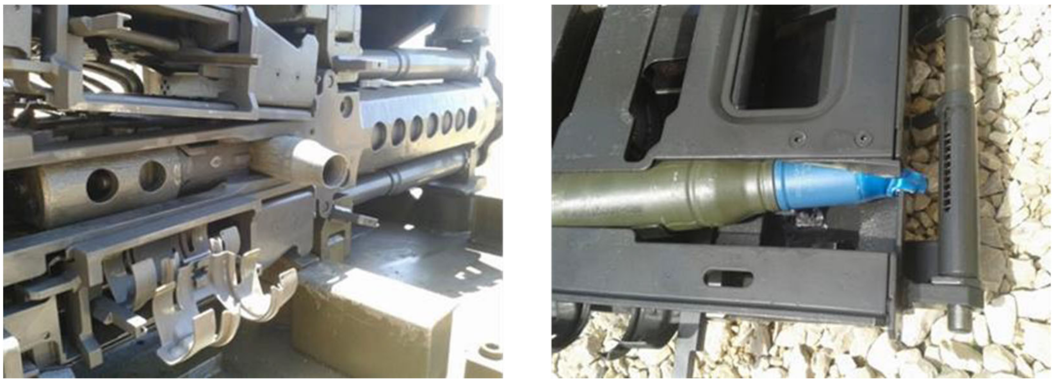

Figure 15 - example of a technical inconvenience for cal. 25 mm machine gun: jammed munitions

Nevertheless, the information management from these reporting activities does not prescribe any systemic data structure and data collection, lacking prerequisites for a completely effective LFI system.

Starting from this situation, section 3.4 presents a centralized SCM approach in order to maximize the potential of the LFI system, whose results are presented in section 3.5.

3.4. Methodology

The centralized information management system was developed for the SCM of small arms, and it is here described in terms of data collection (subsection 3.4.1), and database structure (subsection 3.4.2). Then, analyses on the dataset are presented in the context of a specific weapon (section 3.5), which is supplied to three different Armed Forces. Data and analyses refer to a 6-year interval span, which were manipulated in order not to break the intellectual property of the agents involved, without disclosing any sensitive information.

3.4.1. Centralized supply chain information management: data collection

The first phase of the work was the data collection from the submitted forms by different Units, creating an IT data repository. The report proposed by the

ILE-LM should be rigidly structured with well-defined fields to facilitate data entry and allow a simplified information management. Nevertheless, the acquisition, collection, and management of the reports for the weapon of the case study were a long and laborious activity, which lasted for about six weeks. This was related to the fact that the messages and the related forms had been transmitted over years in paper format and it was necessary to consult the historical archive and manually enter the data in the various fields of the database. For this reason, a centralized digital repository became necessary and fostered the development of a Business Intelligence (BI) solution to facilitate dynamic data extraction and data analyses.

3.4.2. *Database structure*

Once the reports were gathered, it was necessary to structure the received data in a relational database. Such a database was built to allow an immediate data consultation and support holistic analyses in a multi-variate perspective. This database, whose architecture is shown in Figure 16, is made up of five tables: Reports, Weapons, Units, Contracts, Geographical coordinates.

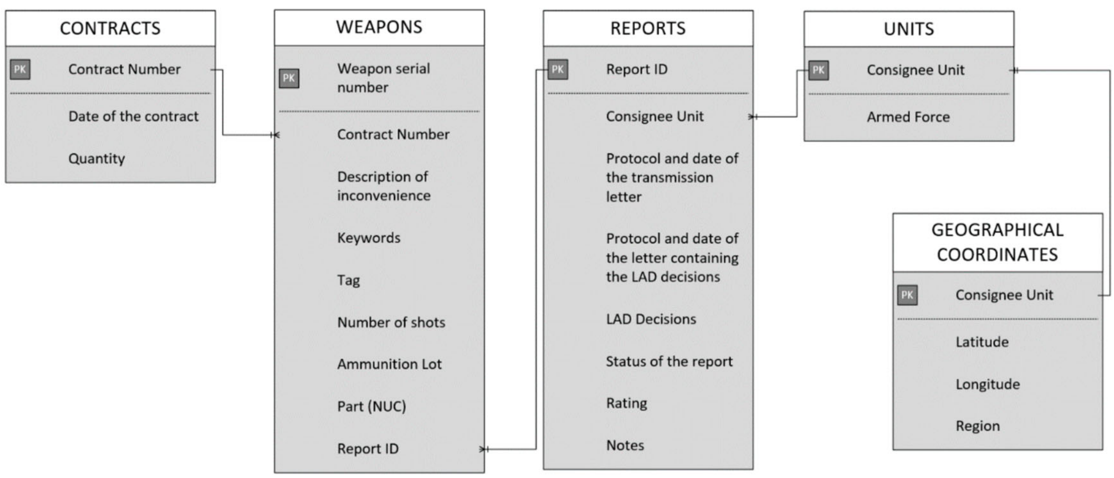

Figure 16 - database architecture using the Crow's foot notation (PK = Primary Key)

Figure 16 aims to put emphasis on data organizations in tables, and relationships among tables for the subsequent analyses. Note that the presented structure is intended as a general data architecture to be used for BI. The "Reports" table contains all the reports received over a period of six years, theoretically, by Units belonging to three different Armed Forces. The key of the table is the couple protocol and date of the reporting message. Other fields of the table are: report identification number (primary key); consignee Unit (or originator of the report); protocol and date of the LAD technical inquiry format letter; protocol and date of the transmission letter of the SAMP technical investigation; protocol and date of the letter containing the LAD determinations; LAD decisions; status of the report; Rating (a score calculated following the rules in subsection 3.5.2); and a free text for notes. The "LAD decisions" field contains the decisions taken by the LAD. In case no investigation is considered necessary, the motivations are reported or, once the investigative process was completed, the corrective actions identified or undertaken are described. The "status of the report" field can be: "in process" - if LAD has still to decide; "in progress" - if the technical investigation is being carried out at the SAMP; "closed" - when the SAMP closed the investigation and LAD has provided its determinations or the technical investigation is not necessary since the inconvenience is already known or because it is due to the normal use of the weapon.

A "Weapons" table, which shows the data recorded on the forms for each weapon, was also implemented. This table is linked to the previous one using the same key, i.e., the couple protocol-data. Besides the key, its fields are: weapon serial number (primary key); number of the contract; description of the inconvenience; keywords; tag (label used to categorize the incident/accident); number of fired shots; ammunition lot; and part. Note that the ammunition lot is critical information, particularly relevant in cases where an explosion of the weapon has occurred. Unfortunately, the standard reporting form does not provide a dedicated field, thus this information is not always reported (requiring a successive dedicated information request).

The "Units" table concerns the originators of the reports and includes the following fields: Consignee Unit (primary key); AF (indicating the Unit's Armed Force).

The "Geographical Coordinates" table details the latitude and longitude of the Unit, to support a graphical representation of the reports in relation to Units. This table comes as a separate table from Unit since it includes data already in place before the development of the LFI system.

The "Contracts" table contains details on the contracts signed for the supply of the analysed weapon during the years. Relevant fields are: contract number; date of the contract (the date of the contract's approval); quantity (the number of weapons procured with a specific contract).

3.4.3. Business Intelligence framework

Once the data were organized according to the structure described in subsection 3.4.2, statistical analyses were performed to support a holistic and effective supply chain information management.

These analyses rely on Business Intelligence (BI), intended as a set of techniques, technologies, systems, practices, methodologies, and applications that transform raw data into meaningful and useful information. BI was adopted in several domains, with recent research developments in aviation safety LFI at European level [188,189]. Similarly, BI becomes relevant for modern supply chains, since it supports a deeper understanding of the business values of an organization [190]. To this extent, the proposed LFI system, implemented via a BI architecture, supports a large number of analytical analyses and a dynamic investigation of the variables included in the dataset, filling a gap in available literature on reverse supply chain in military environments.

3.5. Results

This section describes the main results obtained from the application of the BI approach based on the LFI perspective to a case study.

3.5.1. Preliminary observations on reporting activity

As a preliminary observation, the reports of technical incidents/accidents related to the case study have been originated by Units belonging to only two different Armed Forces. Since the weapon at hand is supplied—albeit in minor quantities—even to a third Armed Force, it is questionable that no reports were sent by the latter one.

Another consideration that can be made on reporting activity with reference to the case study, is related to the number of Units that have reported technical problems. This number represents about a third of the Units that actually utilize the weapon at hand. It would be appropriate to investigate whether the absence of reporting by approximately sixty percent of Units is justified (e.g., particular precautions taken during training or maintenance procedures that allowed to prevent incidents), or is due to under-reporting (i.e., in case of an incident, the weapon is sent for repair or replacement, if under warranty, directly to the manufacturer, without reporting the incident in accordance with relevant regulations).

3.5.2. Systematic analysis of the reports

Firstly, the analysis showed that just less than 10% of the reports were correctly compiled in each section. More specifically, 35% did not include the shots number; and 90% did not report any indication about the ammunition lot number. It is worthy pointing out that this latter information was always reported in cases that presented a weapon explosion, or was successively acquired upon explicit request by the LAD. Additionally, 15% of the reports did not include either the name of the item affected by the incident, nor the NUC. Finally, the same serial number was reported in six cases, which indicates an error in the reporting form (same weapon is used multiple times). Starting from these observations, a rating system was calculated for each form to support holistic information management and assess the quality of reports. This type of analysis aims at identifying the most virtuous reporting Units and taking them as reference examples (best in class, see Figure 17) for the other Units, to stimulate the latter to produce more accurate reporting forms. The rating includes three families (number of shots reported, ammunition lot reported, NUC reported) with maximum assigned scores respectively (30, 30, 40).

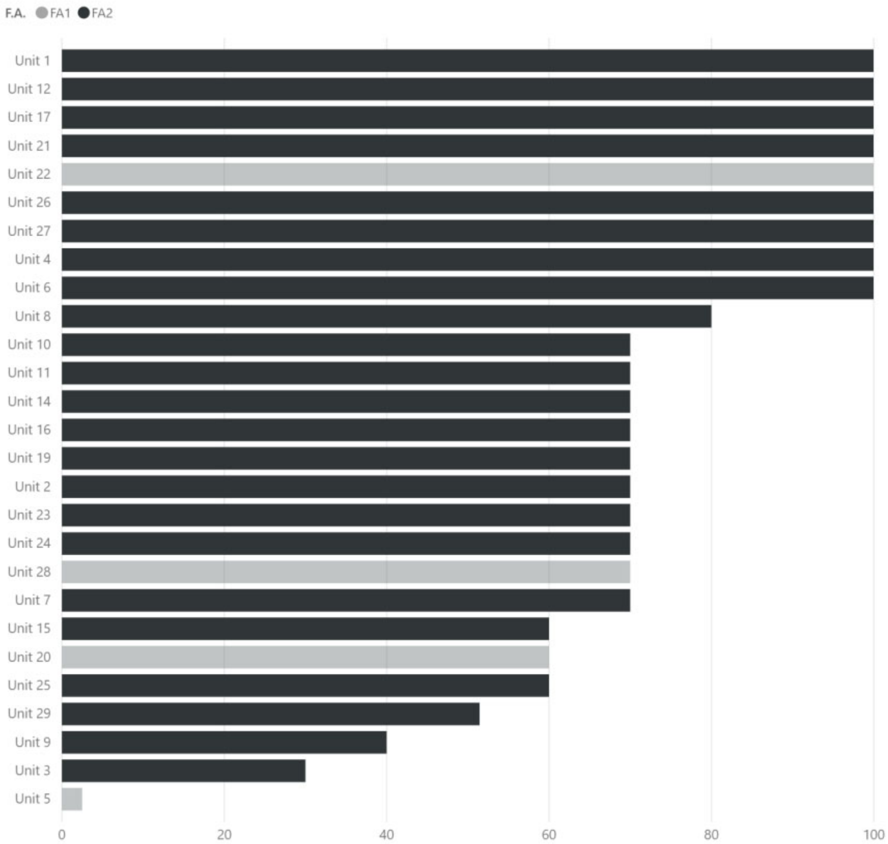

Figure 17 - scores distribution of reports quality per unit

3.5.3. *Relationships between contracts and incidents*

Consequently, the six procurement contracts were analysed in relation to the number of reports in order to map the contractual supply performance. The relationships were discussed in relative terms, i.e., number of reports vs. number of weapons supplied through the contract. The contract presenting the highest report/quantity ratio is the first contract in chronological order (Contract 1) with a decreasing report/quantity ratio in accordance with the time span (see Figure 18). Such contract refers to a product which was undergoing consolidation, i.e., the first phase of its usage with multiple problems emerging.

Over the years, the adoption of mitigating actions defined through the reporting process has motivated some changes to the weapon configuration, in order to improve its technical maturity (Contract 8 and 9).

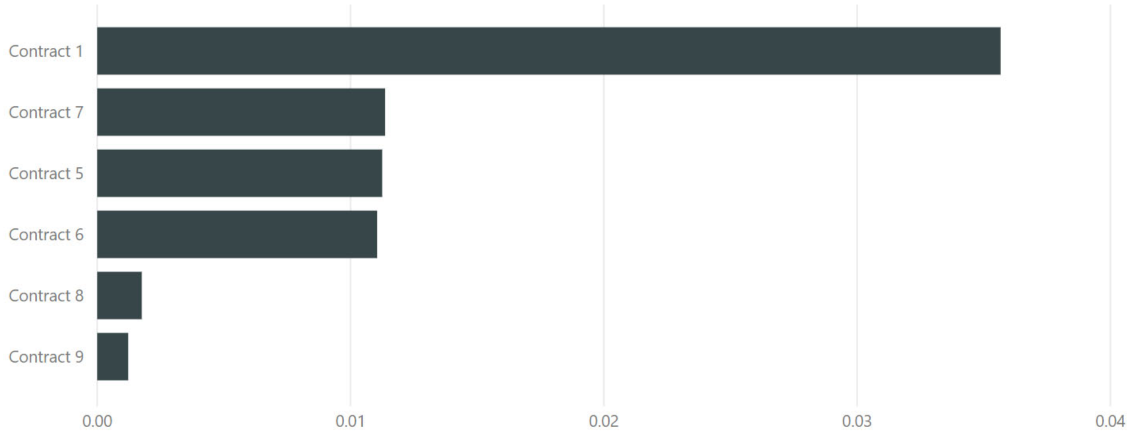

Figure 18 - reported cases over quantities per contract

3.5.4. Pareto analysis

A Pareto analysis has been used as a tool to prioritize some aspects of the phenomenon being investigated, out of multiple causes. More specifically, each category of incidents/accidents occurred was firstly tagged: a "tag" was added to each report, containing a three-letter code in order to link the incidents belonging to the same type (see Table 2).

Table 2 - tag codification for main failure modes

TAG	DESCRIPTION
GAS (Gas recovery system failure)	The label identifies cases where it was found or there is a suspicion that the inconveniences occurred on the weapons are due to the non-compliant diameter of the hole in the gas outlet that regulates the recovery system to subtract gas.
HDL (Handle failure)	Tag used to identify all cases that have a defect in the front handle.
INV (To Be Investigated)	Tag used for those cases to be investigated, whose reasons have not been clearly identified yet, but have in common the occurrence of the explosion of a part of the weapon.
MEC (Mechanical failure)	Tag used to identify mechanical failure of a component, not related to an explosion phenomenon.

NCD (Non-Conformity to Drawing)	Tag used to define the cases in which a non-conformity issue is found with respect to the constructive drawings on some details of the weapon.
NUL (Null)	Tag used to identify cases of minor interest that do not constitute a serious inconvenience.
SLD (Rail slide failure)	Tag used to identify all cases that have a defect in the upper guide of the slide.
SPR (Spring failure)	Tag used to identify all cases where there is a defect in the springs of the ejector assembly.
THM (Thermo-fusion failure)	Tag used for cases in which a principle of thermo-fusion of the polymer constituting the carcass has occurred.
USC (Partial Unscrewing failure)	Tag used to identify cases of partial unscrewing.

The Pareto diagram in Figure 19, points out that three categories (i.e., SPR, SLD, GAS) out of ten cover more than 75% of the identified technical inconveniences. This type of analysis allows thus to isolate the technical inconveniences where priority interventions is required. It can also be utilized for an immediate ex-post verification of the implemented interventions effectiveness: by comparing two representations of the same phenomenon, before and after the intervention, a clear overview of the progress made and a measure of the overall improvement can be achieved.

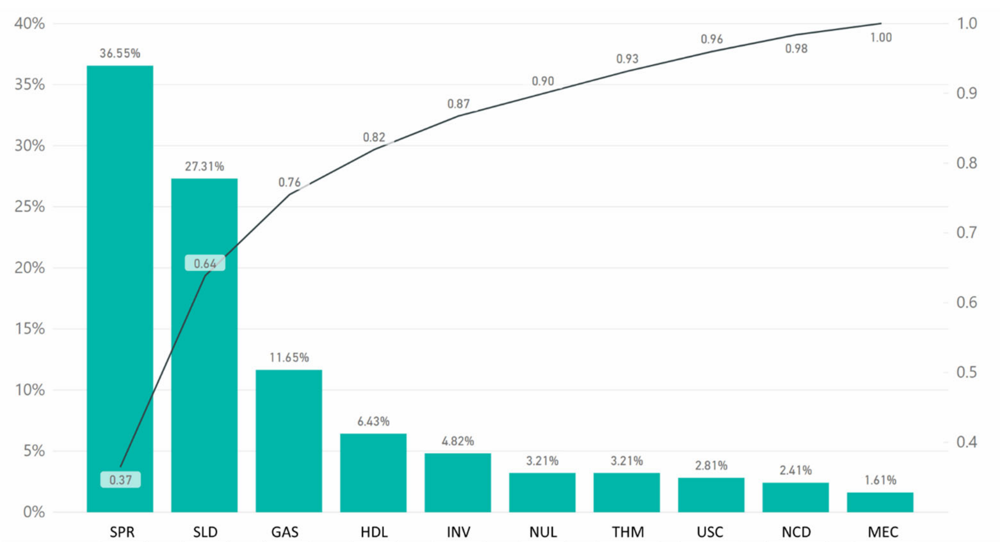

Figure 19 - Pareto's diagram applied to most relevant technical components

In the case study at hand, if a Pareto diagram is re-calculated (see Figure 20) considering only the reports whose status were "in progress "or " in process", it can immediately be observed that the cases relating to the three above-mentioned categories (i.e., SPR, SLD, GAS), are no longer included in the new diagram. This observation confirms that the majority of reports do not represent a current issue, since the related inconveniences had been positively solved.

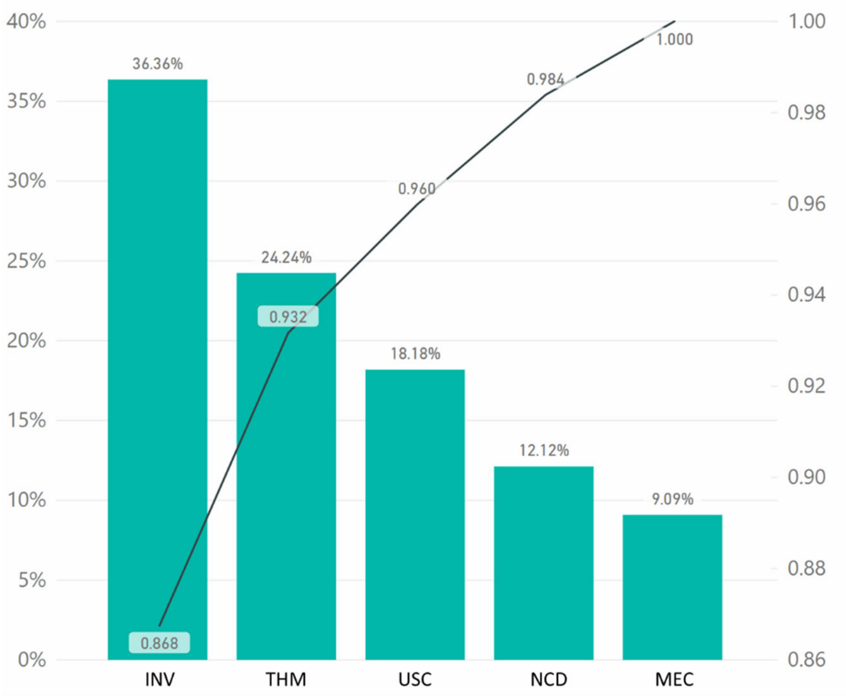

Figure 20 - Pareto's diagram applied to most relevant technical components (only "in progress" or "in process" status)

3.5.5. Dynamic LFI Dashboards

Aiming at creating a dynamic business intelligence tool for the LFI system, further information was integrated into a dynamic dashboard (see Figure 21 and Figure 22). More specifically, Figure 21 shows some summary data regarding the inconveniences divided into categories: (top left) a histogram depicting the distribution of the incidents by category, (bottom left) a sketch of the same incident categories per involved Unit, (right) a geographical map with a bubble pie chart where the size of the bubble represents the total number of reports, broken down per report tag. The dynamicity is developed through the implementation of the database structure into Microsoft PowerBI, which can be interfaced with the majority of data sources, ranging from MS Excel and MS Access to SQL, IBM database, and more.

Note that the dashboard is not static in the sense that the user can click anywhere on any visual to select just one or more items and automatically query the database to get the respective filtered/combined information.

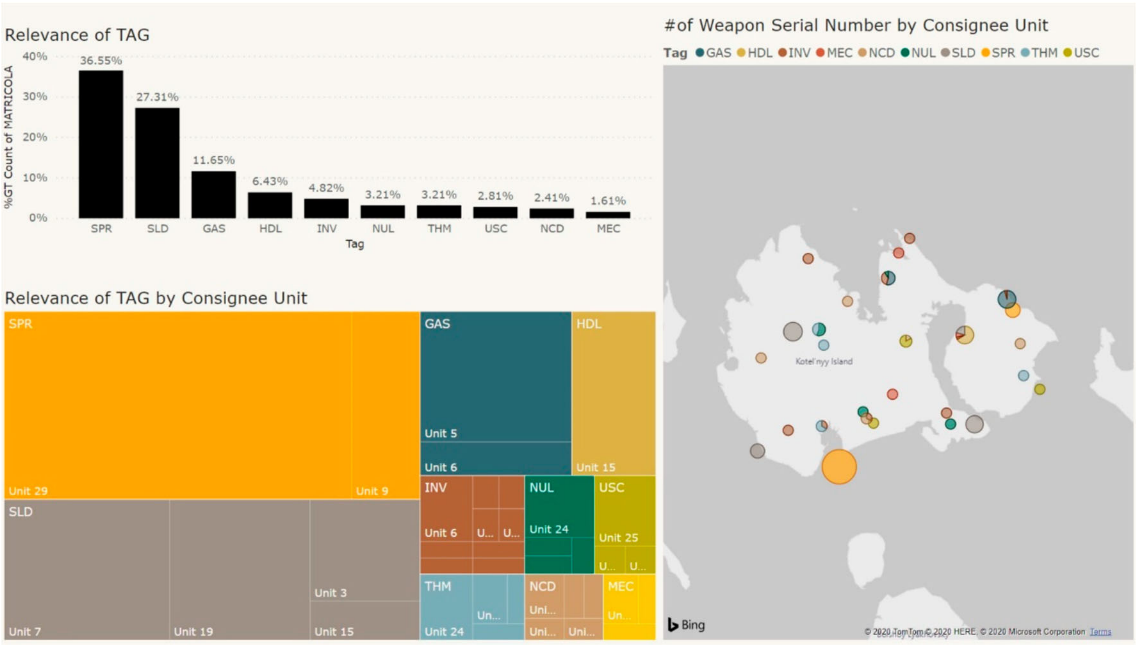

Figure 21 - main dashboard page of the integrated LFI system

As a second example, another dashboard page is proposed to show the framework potential, and its feasibility to accommodate different type of analyses and different visualizations. Therefore, Figure 22 presents a panel where the top right pie chart details the count of Weapon Serial Number by Contract Number, and the respective average rating of technical report. An average target of 90 out of 100 points per report is reported in the gauge (bottom left), while the overall average value is 73. Furthermore, the bottom right graph presents a decomposition tree addressing the count of Weapon

Serial Number that were reported in one or more report, and decomposing this number by the different Armed Forces, Contract Numbers, Consignee Unit, and Tag. In the presented case, the analysis stops at Unit 15, clarifying how the reports issued by this Unit, referred to Contract 5 involved in descending order Handling failure (HDL), Rail slide failures (SLD), Mechanical failures (MEC) and a small portions of aspects to be further investigated (INV). This dynamic dashboard is intended as a support tool for the decision-maker for managing data for the supply chain at hand.

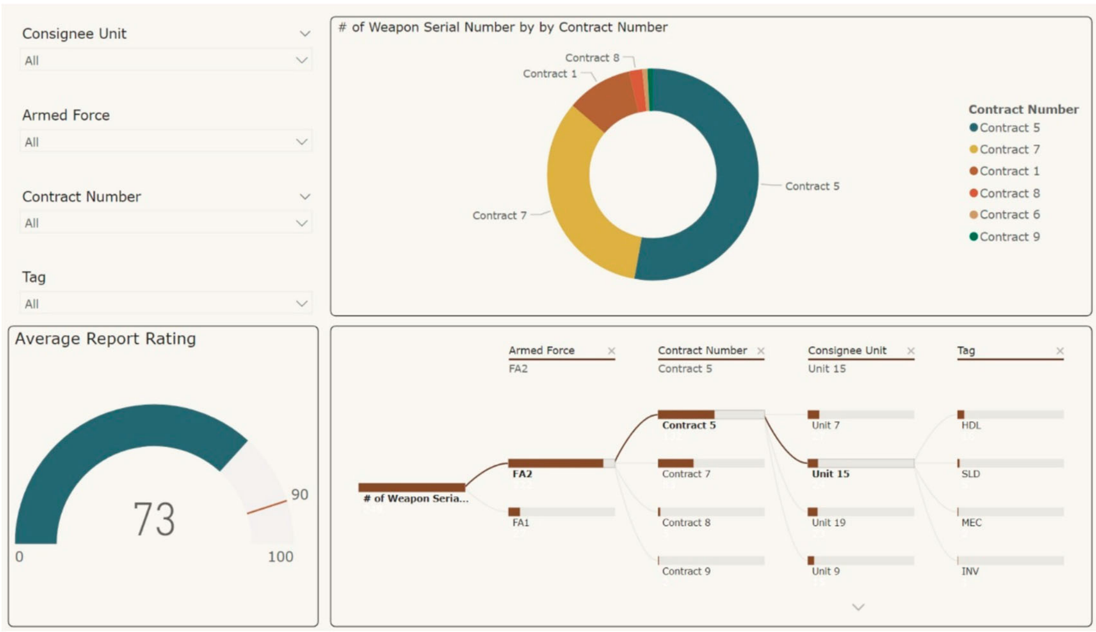

Figure 22 - detailed page on reporting of the integrated LFI system

3.6. Discussion

Following the analysis presented in section 3.5, it is possible to outline improvements aimed at ensuring a sustainable SCM via the proposed LFI system.

3.6.1. Prioritization of reporting

In order to promote and encourage reporting by all the Armed Forces and Armed Corps on the technical incidents related to the weaponry material, it would be desirable to issue an inter-forces technical publication that regulates the process. For example, in Italy still, for the aeronautical sector, the technical publication AER (EP).00-01-6a Ed. 2010 "Instructions for the compilation, forwarding and management of inconvenience reports related to aeronautic material", issued by the Aeronautic Armaments Directorate (AAD), is used as a normative example in this direction. The purpose of the AAD publication is to regulate, through the issue of Inconvenience Reports, the activities related to the flow of information and materials, so that all the necessary actions are taken and implemented to determine the causes of the occurrence of incidents/accidents related to the aeronautic material. This standard is applicable to all aircraft configuration articles registered in the Register of Military Aircraft of the AAD in relation to the production and use phases.

A similar solution could be adopted in the reporting process concerning the armament material, providing for a centralized and unitary management of incidents related to weapons. Furthermore, another cue for reflection, with regard to the aforementioned AAD publication, is the distinction of the Inconvenient Report in two different categories, which activate two different prioritizations of the procedures (based on information, timescale). For the most critical reports (reporting defects or inconveniences of immediate danger that impacts airworthiness and safety for people or things) the AAD publication provides for the immediate involvement of the Design Authority. The latter has to react within three working days, formulating precautionary and/or definitive measures to guarantee that the unacceptable operations are protracted over time. Such an approach should undoubtedly be followed when accidents related to weaponry material have a significant impact on safety.

3.6.2. Improving digitization

The data collection phase for the application of the method was an extremely time-consuming phase, since several documents were still paper-based, or there were scans of paper documents difficult to process by automated IT systems (i.e., OCR systems). For this purpose, it could be beneficial to create an IT data entry form, or more suitably, a dedicated web portal on the intranet of the relevant military authority. This portal should have a section where all the information related to the technical problem can be uploaded, by filling in a digital reporting form. An automatic quality check for the report completeness could be implemented and real-time statistics for the supply chain status could also be obtained. A further recommendation would be linked to the formalization of the incident description field that, being narrative, would benefit from the introduction of a taxonomy.

The taxonomy should allow for the identification of the affected part of the weapon, the failure mode, its effect, and the use condition. On this path, the taxonomy could be developed in a data-driven approach to reduce the efforts for its development. Such an approach would lead to the extraction of relevant information from the reports at hand by machine learning techniques for data extraction and text mining, (e.g., Naïve Bayes Classifiers) [191,192]. Once the taxonomy is built, the "Description of the inconvenience" data field could be potentially structured by providing a self-completing text, or even allowing the choice among a certain set of options, based on the gathered data that have fed the taxonomy. Obviously, for each field, there should also be an option for an "other" choice that provides the possibility to add information not included in the previous list. Such additional data should be revised on a regular basis and, if relevant and significant, added among the permanent selection options, integrating the taxonomy itself. Consequently, the taxonomy could become progressively wider and more representative, with the benefit of having a uniform database, to enable further text-based analytics.

3.6.3. A 4.0 LFI system

A further technology in favour of digitization the reporting process could be related to the introduction of an intelligent weapon management system, in line with recent notions of Industry 4.0, driven by the upsurge and progressive maturity of new information technologies [193]. An intelligent armoury management system would facilitate operations through the entire supply chain. Exemplary areas affected by a smart weapon management system would be: (i) the access control in the armoury based on different privileges and the authorization management to take weapons, providing an undoubted improvement of the process in terms of security; (ii) the logistic and maintenance management of weapons in terms of the potential expressed by the weapon taken from the armoury, and the management of any maintenance needs following anomalies or malfunctions, as well as the management of preventive maintenance; (iii) the management of accidents/incidents related to the armament material in real-time.

Regarding the latter point, the smart system might be interfaced with the portal discussed in subsection 3.6.2, to feed the underlying database favouring and simplifying the reporting process. A series of data could in fact be acquired directly from the weapon, reducing the efforts for the data entry. This would be possible if each weapon had an electronic device, integrated into the weapon, that allows the recording of the number of shots fired, like the odometer used in cars, and RFID (Radio-frequency identification) tags on which to store information such as the model, the serial number, the contract, the number of shots.

It is easy to imagine the great improvement that would follow the introduction of such an intelligent armoury management system in terms of the weapons maintenance process. In fact, it would guarantee the acquisition of a large number of returns from the operational field, which is an essential starting point to proceed in the studies on reliability and maintainability of the various types of weapons.

3.6.4. A healthy reporting environment

Incident reporting starts any LFI system. However, other latent factors ensure the LFI initialization even earlier. It is important to observe how an increase in the safety level should not be connected to a decrease in the number of reported incidents, but rather to their lower severity: in other words, few reports do not imply a higher safety level. This situation could be rather a consequence of under-reporting, due to an unhealthy working environment. As for the wide literature in the safety area, the fear of being punished or accused of negligence in managing the weapon could discourage a reporting action. The participation of personnel involved in the investigation activity could be favoured in a periodic toolbox meeting at the Units responsible for reporting, in order to show the benefits of reporting by means of some significant incidents and recommendations.

On this path, expanding the functionalities of the portal discussed in subsection 3.6.2, the same portal could be further used to gather information on the most significant incidents/accidents, illustrating the investigative activity carried out and the corrective actions (e.g., revision of procedures, emissions of technical notes, and execution of retrofit interventions). Such approach may further advance the spreading of the recommended actions, contributing to the overall LFI system via a healthy reporting culture.

This latter point puts emphasis on understanding work as actually carried out at organizational level, and on empowering sharp-end operator knowledge [45], ensuring sustainable reverse logistics, and in general, systemic supply chain resilience [194].

3.7. Concluding remarks

The literature analysis about LFI has emphasized the importance and the need to implement an effective Incident Learning System in order to achieve higher resilience and safety levels within an organization.

Through the analysis of the supply chain information management process on military technical inconvenience for armaments, [187] has presented an LFI framework valid for military supply chains.

The analysis shows empirical evidence on how technical incident data acquire values that go beyond the technical investigation: a well-structured database can be the basis for an effective decision-making, which can be supported by synthetic user-friendly and easily accessible dashboards.

Using a Business Intelligence perspective, the developed LFI system shows the benefits of a centralized information management system and supports the identification of future developments beyond the company being analysed, i.e., the development of an inter-forces reporting regulation, the enhancement of digitization in the entire process, the adoption of smart systems, and the fostering of a healthy reporting environment. It is important to observe how this work provides just a subset of the possible indexes to be used for monitoring supply chain sustainability in light of the LFI framework.

Furthermore, additional quantitative analyses can be developed to extend the analytical dimension of the proposed framework, e.g., clustering algorithms, trend analyses, multi-dimensional correlations.

Regarding the intelligent data management system, one aspect not considered in this research is related to privacy issues and threats related to cyber-security, which opens the path to future research in the same context [195].

More generally, the proposed LFI system described in this study could be further enhanced, analysing the important connections with the world outside of the organization, i.e., exploring how local learning is shared outside the supply chain agents, i.e., providing an external cycle for shared learnings. This cycle could be closed by the benchmarking process that analyses best practices and adapts them to improve the military system in a sustainable perspective.

Note also that the approach refers to the Italian regulatory framework for military reporting, but since it is grounded in the general NATO learning doctrine, it remains flexible enough to accommodate the needs of other contexts, as long as they rely on the same NATO foundations for systemic learning. Lastly, even though the proposed case study focuses on small arms, it is worth mentioning how the same logic can be applied to technical inconveniences related to other types of weapons and it could be thus reproduced for the analysis of early phases of the item lifecycle.

CHAPTER 4

4. USING FRAM TO QUALITATIVELY ASSESS ORGANIZATIONAL RESILIENCE

The content of this chapter partly relies on a previously published manuscript: R. Cantelmi, R. Steen, G. Di Gravio, R. Patriarca, Resilience in emergency management: Learning from COVID-19 in oil and gas platforms, Int. J. Disaster Risk Reduct. 76 (2022) 103026. https://doi.org/10.1016/j.ijdrr.2022.103026

Acronyms

AC	Authority Coordinator
CIM	Incident & Crisis Management
COS	Chief Of Staff
DSV	Drilling Supervisor
EM	Emergency Management
EMS	Emergency Management System
ER	Emergency Response
ERM	Emergency Response Manager
ERT	Emergency Response Team
FAL	*Faglig Ansvarlig Lege*, in Norwegian language - Professionally Responsible Physician
FRAM	Functional Resonance Analysis Method
HR	Human Resources
HTA	Hierarchical Task Analysis
IC	Information Coordinator
JRCC	Joint Rescue Coordination Centre

LC	Logistics Coordinator
NATO	North Atlantic Treaty Organization
NOFO	Norwegian Clean Seas Association for Operating Companies
O&G	Oil & Gas
OFFB	Operator's Association for Emergency Response
OHS	Offshore Health Services
OSEP	SAR helicopter, Evacuation centre
PC	Personnel Coordinator
PSA	Petroleum Safety Authority
RE	Resilience Engineering
SAR	Search And Rescue
TA	Thematic Analysis
WAD	Work As Done
WAI	Work As Imagined
WM	West Mira
WP	West Phoenix

4.1. Crisis induced learning in Emergency Management

EM is regarded as a complex socio-technical system, since it mainly deals with collective sense making, team decision making, and coordination among different technical and human agents [44].

EM systems have been divided into four interwoven stages [196,197], i.e. preparedness, response, recovery, and mitigation, which can be related to the absorptive, adaptive, and restorative capacities, mentioned in Chapter 2, describing the resilience capacity of a complex system:

- the *preparedness* stage focuses on preparing plans and a range of alternatives about future emergencies and operating conditions. Preparedness shall be systematic to establish appropriate emergency measures and functional requirements based on risk analysis and emergency preparedness analysis [198];

- the *response* stage refers to responding adequately to emergencies and minimizing their negative consequences following emergency plans, instructions and operating policies. Nonetheless, due to the operational complexity, emergency managers often respond adapting plans and improvising solutions [199,200]. Here, individual's cognitive ability to extract cues from the environment, and to adopt certain strategies, at particular time and for particular threats, is a crucial part of improvisation. There should be a balance between system preparedness and individual improvisation [201]. Caution is needed regarding front-line operators' ability to estimate properly inherent risk and vulnerability: improvisation can create a spiral of complexity, where each improvisation may create other unexpected settings, requiring further improvisation up to an escalating lack of control [199];
- when the situation is considered under control, the *recovery* stage begins. While response has well-defined goals (e.g., save lives, environment and properties), recovery is more fuzzy [202]. The primary objective of recovery is bouncing back to normal operations, by means of interaction and effective coordination [203–205], along with reliable communication [206]. Recovery depends on temporal (pace) and spatial (place) settings [207]. Both temporal (e.g., need for a multi organizational coordination) and spatial (e.g., location of a platform to evacuate and high consequence infectious disease) dimensions make the recovery process complex and time consuming;
- *mitigation* further extends the recovery stage. It aims at preventing emergencies occurrence and mitigating their consequences in case they

emerge. It includes those activities undertaken to improve EMS by identifying future risks and reducing vulnerability to identified risks and implement necessary changes and measures. Experiences from response and recovery operations provide updated data that can enhance the EMS capacity building. Lessons learned provide valuable insights to this end. Learning, here, is about how key actors perceive their experience into useful knowledge for dealing with future events. These acquired knowledge could be then used to streamline the ER preparedness (first stage) in terms of reforming contingency plans and training to enhance future resilient responses [208].

The design and application of these stages in modern socio-technical EMS operating in complex environments demands for resilience capacities within the organization [71].

Understanding how planning and resilience were put in place prior to, during and following an emergency is instrumental for crisis-induced learning, i.e. the organizational purposeful efforts, triggered by a crisis event that lead to new understanding and behavior [209]. More formally, crisis induced learning spans between a cognitive perspective, i.e. acquiring new knowledge and understanding, and a behavioral perspective, i.e. transposing the acquired knowledge and understanding into improved organizational actions [210]. About the behavioral perspective, single-loop and double-loop learning cycles can be established [211]. The former refers to the correction of practices within the existing policy paths and organizational plans, without changing core beliefs and fundamental rules of the organization. On the other hand, double loop learning aims at resolving incompatible organizational behavior by setting new priorities and weightings of plans, or by restructuring the norms themselves together with the associated practices or assumptions.

Accordingly, the following research documents learning opportunities following the systematic exploration of adaptive practices as they emerge in a complex socio-technical work domain actioned during ER.

4.2. The Functional Resonance Analysis Method (FRAM)

With the aim of ensuring high EMS resilience, and effective single-loop and double-loop crisis-induced learning at organizational level, a systemic perspective should be set when studying past events and revising existing plans. Frequently interpreted as a core method within RE, the Functional Resonance Analysis Method (FRAM) [56] represents a systems-wide modelling tool particularly helpful to deal with socio technical aspects from a systems-theoretic perspective. The FRAM offers method-sine model features that can be warmly accepted for understanding underlying features of EM operations [212].

On this consciousness, FRAM has been proposed as a method for developing a systematic understanding of adaptive practices, modelling planning and resilient behaviors and ultimately supporting crisis-induced learning.

FRAM's principles and building steps are described in the following subsections 4.2.1 and 4.2.2.

4.2.1. FRAM principles

FRAM relies on four principles aligned to organizational resilience and RE: equivalence of successes and failures; approximate adjustments, emergence, functional resonance. These principles are relevant for modern EMSs, as proved by several use cases descripted in literature [213–216], with specific reference to the O&G sector.

- *Equivalence of successes and failures.* Despite the common opinion, for actions played by individuals and organizations there is an equivalence of successes and failures. RE recognizes that individuals and organizations must adjust to the current conditions in all the activities they perform. Since information, time and resources are limited, these adjustments can only be approximate. Consequently, on one hand success is related to the ability of organizations or individuals to correctly make these adjustments and to anticipate risks before failures occur. On the other hand, failure is due to the permanent or temporary absence of that ability. The aim of RE is to strengthen that ability, rather than just to avoid or eliminate failures.
- *Approximate adjustments.* As previously acknowledged, adjustments can only be approximate. Accordingly, performance variability exists in what individuals or organization do. Performance variability, which is inevitable, ubiquitous, and necessary, constitutes both the reason why everyday work is safe and effective and why things sometimes go wrong and most of the time go well.
- *Emergence.* The variability of a single activity is rarely large enough to be the cause of an accident or even to constitute a systemic visible malfunction. Instead, variability from multiple functions may combine in unexpected ways, leading to consequences that are disproportionally large, hence producing non-linear effects. Both failures and normal performance are emergent rather than resultant phenomena. Socio-technical systems change and develop in response to conditions and demands, therefore it is impossible to know all the couplings in the system, hence impossible to anticipate more than the regular events.
- *Functional resonance.* The performance variability of a single function can be amplified by the combined variability of other functions referred to the

same socio-technical system. This feature goes by the name of functional resonance, i.e. the detectable signal that emerges from the unintended combination of the variability of many signals.

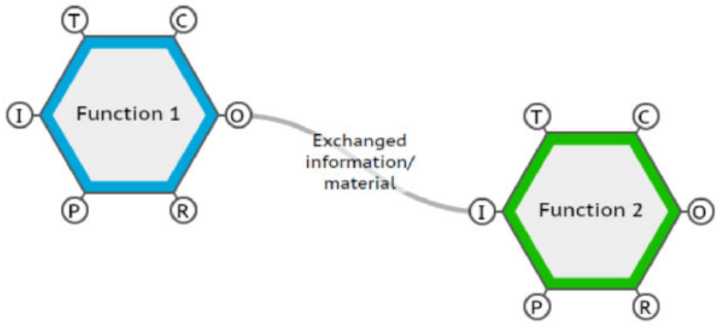

Figure 23 - an example of a trivial FRAM model with two functions and information/material exchange. I: input, O: output, P: precondition, R: resource, C: control, T: time

4.2.2. FRAM steps

Taking into account the above-mentioned principles, the traditional four buildings steps of FRAM have been followed in this research [56].

- *Step 1: identify and describe the essential system functions*. FRAM describes a complex socio-technical system following a functional perspective, where each function refers to tasks or activities required to produce a certain outcome. There are three types of functions: technological, human, and organizational functions. Each function can be described through six fundamental aspects: Input (I), Precondition (P), Resource (R), Output (O), Control (C), Time (T), graphically represented at the corner of a hexagon, the core element of a FRAM model (see Figure 23). In particular, Input is what activates or starts a function and/or that is used or transformed by the function to produce the output. Preconditions refer to those conditions to be satisfied before a function can be actually carried out. Resource is something that is needed or consumed when the function is active. Control is what supervises, regulates, or monitors the function such as guidelines, regulations, or even social expectations. Time refers to the temporal constraints on the function such as duration and starting point. Output is the outcome of a function, the state change or its result. Function identification has been linked to the results of the Hierarchical Task Analysis (HTA) based on triangulation [78] (documents, CIM, focus groups - cf. section 4.3). Each function interacts with others through one or more of their aspects. Interactions connect functions together to form a FRAM net.

- *Step 2: identify the actual or potential variabilities between functions*. The performance variability of a function can be categorized in terms of its origin, endogenous variability, exogenous variability, and/or interaction variability, and characterized by different phenotypes (e.g. timing, precision, speed, distance, sequence, duration). Each function of each FRAM model has been studied in terms of their variability to understand where underlying criticalities may reside.
- *Step 3: analyse the aggregation of variability.* In a FRAM model, the Output of a function interacts or "couples" with other functions. The output of an upstream function may vary and then transfer the variability to its downstream function(s). Since the aggregation of these variabilities may cause functional resonance in the system, leading to an undesired outcome, all upstream/downstream interactions must be studied in terms of timing and precision. This analysis allows to map events that have already happened (favouring crisis-induced learning), but also to explore other varieties of the work domain, such as worst-case scenarios.
- *Step 4: propose ways to manage variability.* This last step aims at mapping what should be the most effective strategies to manage, rather than simply reducing, functional variability. Since the research on organizational learning aims at understanding adaptive practices in an EM company on

handling Covid-19 infection episodes, this fourth step is intended to foster organizational learning, rather than prescribing stricter work tasks.

4.3. Methodology

This study has analysed different actualized organizational resilience aspects in an EM company when handling Covid-19 infection episodes. The research has been contextualized into real operations happened in 2020–2021 and performed by a Norwegian company responsible for second line EM in Oil and Gas (O&G) platforms, i.e. OFFB[2] (Operator's Association for Emergency Response). Specifically, three different operations have been modelled using the FRAM, which allowed to obtain an in-depth picture of actual operations and served as a basis to generate systemic recommendations.

Moreover, the analysis served as a support for a fourth FRAM model, developed to study the evolution of the emergent adaptive capacities into organizational planning, following the OFFB's procedure established in the aftermath of the three Covid-19 episodes.

The FRAM analysis has been built through a triangulation of qualitative approaches, including documents and reports analysis, and focus groups as discussed in the following subsections (cf. subsections 4.3.1, 4.3.2).

4.3.1. Data gathering

Data were gathered from several sources to create a systemic picture of each case:

- Internal documents and procedures related to Emergency Management (EM) were collected from OFFB's archive, including the "Plan for

[2] Operator's Association for Emergency Response (OFFB) is a 2nd line ER organization for O&G operators in Norwegian continental shelf. Details on the company are provided in subsection 4.4.1.

management of Covid-19-related incidents" [217], from which the fourth FRAM model has been elaborated.

– Reports, related to the handling of the three different Covid-19 cases, were acquired from CIM (Incident & Crisis Management) tool. CIM is an electronic crisis handling tool, which gives the 2nd line OFFB's members updated information useful to have a common operating picture of the situation. Through CIM, every member of the Emergency Response Team (ERT) shares the information in their possession, supporting team's situational awareness.
– Finally, five digital focus groups have been organized (through video-conferencing tools) with the OFFB's team members, and especially with the team member who held the OFFB's Emergency Response Manager (ERM) role during the first of the Covid-19 outbreaks. Knowledge exchange during the focus groups was favoured by ethnographic research principles, since one of the authors in [218] had a sabbatical year working in OFFB. This knowledge allows to understand the working environment and to realize the actual organizational orchestration during each crisis event.

The several utilized data sources allowed to reconstruct the incidents in the three different case studies and to focus on the OFFB's involvement, within a broader context that saw a multiplicity of stakeholders.

4.3.2. Data analysis

The internal documents and procedures related to EM were analysed in order to acquire a culture of the company's *modus operandi* and to elaborate an organizational planning, i.e. a Work as Imagined (WAI) model of the OFFB's EM. The CIM tool reports were firstly analysed recurring to Thematic Analysis (TA) [219], following its most commonly used steps: familiarization, codes and themes generation, themes review, themes definition and naming, reporting. Afterwards, a HTA was performed to group the information into tasks based on a hierarchical nature. As a result of these analyses, some questions were devised to draw up a semi-structured guide for interviews and to facilitate interactions during focus groups. ERM's support during these virtual meetings allowed to gain an in-depth understanding of what happened during the three cases, by defining roles and functions for the involved actors and by complementing the HTA results. These actions led to elaborate the three FRAM models related to the management of the three Covid-19 cases that occurred on the offshore platforms. In other words, at this stage the adaptive capacities in action emerged in three different representations, i.e. three Work As Done (WAD) models, one per each case.

4.3.3. Operationalizing the FRAM

The theoretical framework based on the four stages (preparedness, response, recovery and mitigation) usually described in EMSs has been rearranged in its operational terms to meet the terminology used by OFFB experts and procedures for Covid-19 infection management. Consequently, four different phases have been identified: mobilization, alert, combat, normalization. For the sake of clarity, Figure 24 represents graphically the relationship between these four operational phases and the four traditional stages of EM. While preparedness and mobilization almost overlap, the other phases straddle two steps. This operational categorization allows to build a FRAM analysis into a multi-layered framework, one per each phase [213].

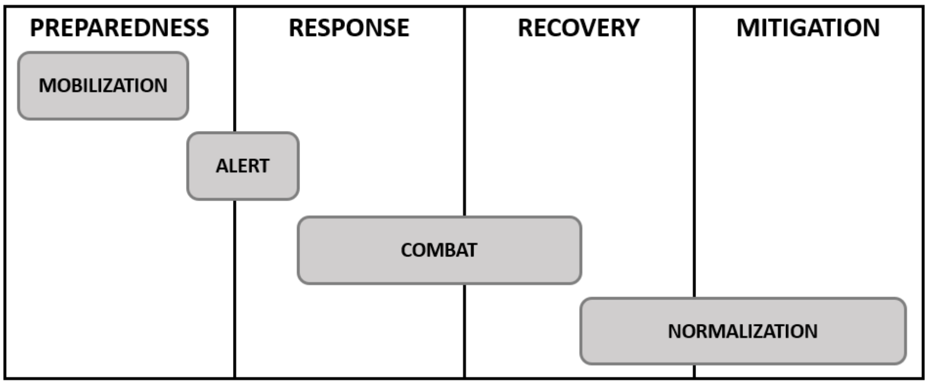

Figure 24 - relation between traditional elements of EM and the operative phases put in place by the company under analysis

From the afore-mentioned analysis, repeated for each case of Covid-19 that occurred, three different FRAM models were developed, referring to the three different episodes, as shown schematically in Figure 25.

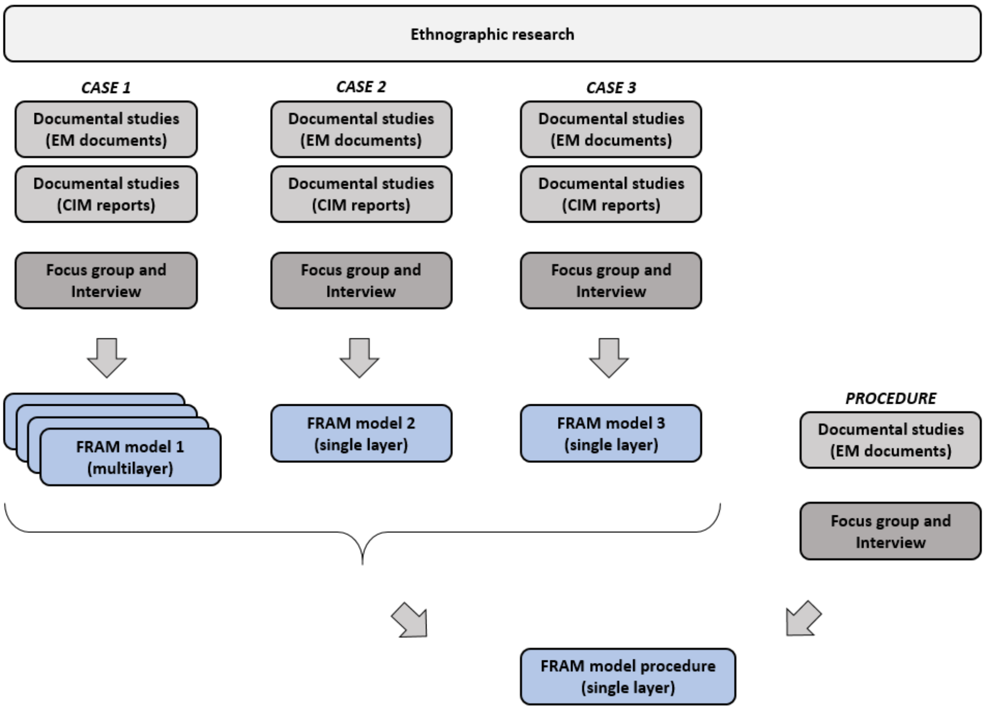

Figure 25 - outline of the research approach

In the first case, due to the situation complexity (first time that OFFB addressed an offshore Covid-19 infection), Time (one of the six aspects of a FRAM function) has also been used as a segmentation variable for the analysis. Accordingly, even though during any emergency time spans over a continuum, four different time moments have been identified in line with OFFB's four operational phases in order to reduce the analytical complexity of a single large-scale FRAM model. This multi-layer modelling choice has been previously successfully applied in the EM context [213]. Thanks to the crisis-induced learning by OFFB during this first case, the management of the other two Covid-19 infection episodes was instead much less burdensome, without activating all the steps of the EMS four phases. Therefore, a single FRAM layer was utilized to model each case. It is worth noting that this modelling process can be generalized to any Covid-19 infection case, or any other emergency episode: starting from a certain number of specific historic cases to the definition of organizational plans (Figure 25). More specifically, in order to study the management of the first Covid-19 outbreak, a FRAM WAD model of what had happened from a procedural point of view has been developed. This model extends the internal plans and procedures (WAI) for the EM. Following crisis-induced learning from the three episodes, a new procedure for Covid-19 infection management was also issued. This latter has been modelled via FRAM (in this case, the model embraces a WAI perspective) to exploit the importance of studying adaptive practices and learning from past events to enhance organizational planning.

4.4. Case studies

In the following subsections (cf. sections 4.4.2, 4.4.3, 4.4.4), three different cases are described as for the respective emergencies managed by OFFB. Nevertheless, to fully understand the cases, OFFB (subsection 4.4.1) is going to be briefly introduced as an EM organization, explaining its mission, responsibilities, functions, and main roles.

4.4.1. Operator's Association for Emergency Response organization (OFFB)

OFFB is a 2nd line ER organization for O&G operators in Norwegian continental shelf. Its core business is to manage, maintain and be responsible for the handling of several 2nd line ER activities, utilized by many O&G operating companies. Its main tasks involve responding to incidents that may have an impact on the people, environment and material assets through operations and providing a proactive support to the 1st line ER organization to minimize the consequences of the emerging situation. The 2nd line ER also includes the communication with media sources and Next-of-Kin. Although OFFB acts as a 2nd line ER manager, the operating companies have the overall responsibility for effective ER in Norway. Looking at the organizational planning, OFFB's roles and responsibilities resemble those of the NATO joint staff functions [220]: besides ERM, which is responsible for the emergency handling as a whole, there are five other experts who assist entire ER operations, on a rotating duty. ERM has to mobilize/notify ERT, perform the initial notification to the Joint Rescue Coordination Centre (JRCC), i.e. the 3rd line ER organization (operators), as well as the OFFB's managing director. The ERM has also financial authority to implement any actions deemed necessary to manage an incident. The Chief of Staff (COS) is responsible for initiating mobilization and notification to ERT and the rig owner. COS's tasks are mainly coordination and sharing of situational awareness with the ERT. The Logistics Coordinator (LC) is responsible for initiating mobilization and notification to the JRCC, the helicopter and the shipping operators, the supply base (e.g., Logbase Florø) and the logistics suppliers. The Authority Coordinator (AC) is responsible for initiating mobilization and notification to the PSA, Police, and the Norwegian Clean Seas Association for Operating Companies (NOFO). The Personnel Coordinator (PC) has main responsibility for initiating mobilization and notification to the On-Call Physician, contingency physician, Next of Kin Call centre, operator HR representative and the rig owner HR representative. Finally, the Information Coordinator (IC) is responsible for initiating mobilization and notification to the media response team leader for the operators, and the liaison representative from the rig owner. IC is also responsible for notification and interactions with contractors.

4.4.2. Case 1

From Saturday August 1st, 2020 to Thursday 13th August, the first Covid-19 event was experienced at West Phoenix (WP) rig, which drilled wells for the oil company Neptune Energy on the Fenja field in the Norwegian Sea.

4.4.2.1. Event summary

On August 2020, 1st an oil worker from the WP rig was tested positive for Covid-19 at Molde hospital in Kristiansund. There was no suspicion of a Covid-19 infection offshore and 126 people were left on the rig. In the following twelve days, three new cases of infection were detected by an extensive testing with a quick test machine on board and through some tests that were sent to the Molde hospital. A total of 46 people were quarantined on the rig as close contacts, while 15 people without safety critical duties on board were sent to the oil company's quarantine hotel on shore. A wide range of stakeholders - both individuals, groups and organizations - were indirectly or directly affected by the incident and needed information, follow-up and coordination. WP's 1st line ER managed the situation at the tactical level, OFFB

2nd line at the operational level and Neptune Energy 3rd line at the strategic one. Kristiansund municipality's ER organization was crucial for the situation handling on land. Public and private health resources, consisting of professionally responsible physician, corporate physician, emergency physician and the municipality's infectious disease control physician, were involved in the infection control and health work. Moreover, Equinor, the Norwegian state-owned company responsible for helicopters used for medical evacuation, and Avinor, responsible for air traffic management, participated in the response operation. On August 5th, Neptune Energy chose to transit from a traditional emergency organization to a nominal one. The rig was declared free of infection on August 13th.

4.4.2.2. 2nd line involvement

The 2nd line involvement has been reconstructed starting from the CIM reports. On August 1st ERM was notified of patient #1 tested positive on Covid-19 in the evening (20.00). ERM made contact with the professionally responsible physician (FAL, Faglig Ansvarlig Lege, in Norwegian language) who mobilized his own team at the rig operator. ERM also notified the 3rd line ER about the incident. At 20.23 ERM decided to handle the case as an emergency situation, mobilizing the ERT. He called the COS to obtain information, plan for further handling in cooperation with FAL and 3rd line and manage media sources. Logistics Coordinator of the ERT alerted Neptune logistics base in Florø and obtained that WP would send a list of everyone who was on board the helicopter to and from WP on 29th of July and on 31st of July. A total of 27 passengers and four pilots were alerted. Table 3 summarized the main events per each day.

Table 3 - synthesis of daily main events for Case 1

DAY	RELEVANT EVENTS
August 1st	At 22.15 the Drilling Manager at WP called ERM, after several attempts made by ERM to establish a contact. The Supervisory Coordinator of the ERT contacted the PSA of Norway and fixed a status meeting for the next day at 12:00.
August 2nd	On August, 2nd there was a meeting between 2nd line and FAL's staff at Seadrill (the rig owner). After the status meeting with the PSA, it was clarified that no notification form was required, as it was disease-related incident. At 19.30 ERM demobilized the 2nd line ERT and handled the incident himself.
August 3rd	On August, 3rd ERM, FAL and the infectious disease doctor in Kristiansund had a coordinating meeting by phone. In the afternoon ERM had several phone calls with the Emergency Manager in Kristiansund municipality about reception of Covid-19-positive patients, exchange of information on follow-up procedures, confirmation of reception of patients, etc.
August 4th	On August, 4th the Drilling Manager informed ERM that he was quarantined in the cabin, further follow-up of Drilling superintendent on land. Patient #2 was sent to isolation facilities in Kristiansund.
August 5th	On August, 5th during a status meeting with Neptune normalization project was established. Fifteen people were received in Kristiansund, OSEP[3] and municipal reception involved up to fifty personnel from quarantine or isolation at WP. A status meeting was organized internally in OFFB to coordinate resources in the event. Patient #3 was sent to isolation facilities in Kristiansund.
August 13th	On August, 13th ERM called the PSA to consider the situation normalised.

4.4.2.3. FRAM model of the 1st case

The first case was handled by OFFB as any other case of emergency: all the ERT was alerted and participated in the management of the situation. In this

[3] SAR helicopter, Evacuation centre (OSEP) is a location for physically uninjured persons who have been involved in an incident, etc.

1st case, 2nd line activities can be divided into the four operational phases described in subsection 4.3.3. As introduced in the methodology section (cf. section 4.3), a four-layer FRAM has been utilized [213]: in such a model each layer is connected to other time layers via functions that belong to multiple layers, or via functions whose *output* in a layer constitutes one of the *inputs* (I, C, R, P) in another layer. For consistency, this model and the others in the following paragraphs are discussed using specific tags for functions and aspects as follows: < *Name of Function* >, 'name of aspect'. For the presentation of our FRAM models, the actors involved in the ER operation were coded through different colours: ERM - Purple; COS - Green; LC - Blue; AC - Yellow; PC - Grey; IC - Red.

The first phase: mobilization (Figure 26).

The mobilization phase starts when ERM < *Receive the first notice* > with the precondition that their duty mobile phone is available. Therefore, ERM < *Assess potential needs and actions* > and < *Notify the COS* > about the situation, by filling-in the Quick Card. ERM < *Establish the event in CIM* > allowing the whole ERT to share information and to have a common operating picture. The COS < *Clarify immediate actions related to potential and resource needs* > and the result (Output) of this function 'Notification to ERT' is used to give notice ERT's four agents and < *Mobilize the ER team* >. The ERT agents perform their usual tasks for an emergency situation: i.e., the Authority Coordinator < *Notify the PSA* > while Logistics Coordinator < *Mobilize SAR helicopter* > and < *Contact the logistic provider* >. This phase ends when the coordination between ERM and 3rd line is complete and the ERT agents mobilize their stakeholders and < *Update info in CIM* >. In this regard, the functions related to CIM constitute the connection with the other time-layers.

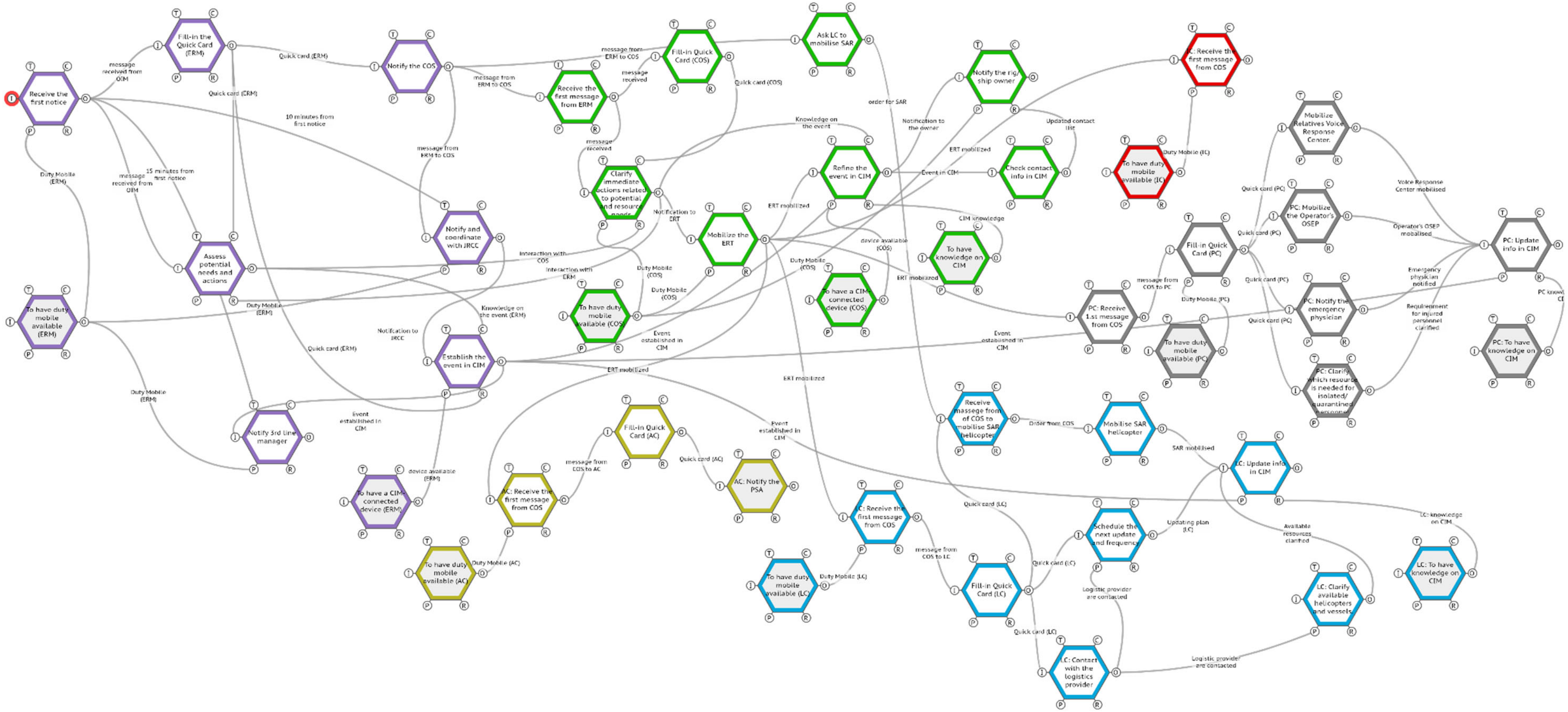

Figure 26 - FRAM model of the first phase: mobilization

The second phase: alert (Figure 27).

In the alert phase, ERT coordinators notify all the relevant stakeholders about the incident. For instance, COS < *Establish contact with the* 1^{st} *line* >, IC < *Contact operators media/communication* >, LC < *Consult with JRCC*[4] *about resource allocation* >, PC < *Notify the oncall physician* >. In this case, unlike the standard ER procedure, ERM decided not to notify the police, NOFO[5], the Norwegian Coastal Administration, as this was a health-related incident. Once these actions are performed and CIM is updated by each coordinator, < *ERM: Conduct* 1^{st} *meeting for Situational Assessment (SA)* >, where the whole ERT identify possible remedial actions and support measures, as well as plan the next operations.

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[4] Joint Rescue Coordination Centre (JRCC) is the 3^{rd} line ER organization (operators).
[5] The Norwegian Clean Seas Association for operating companies.

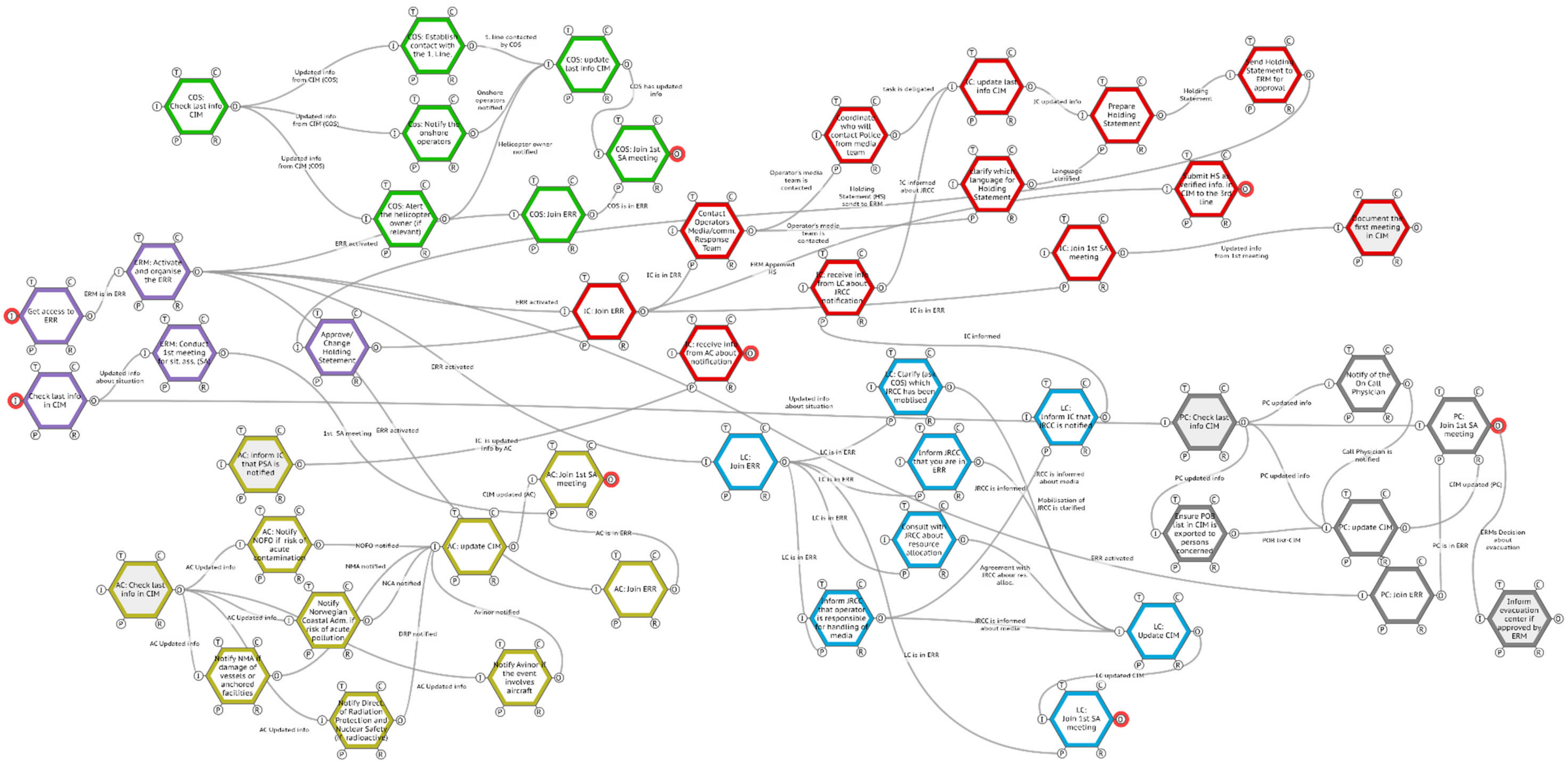

Figure 27 - FRAM model of the second phase: alert

The third phase: combat (Figure 28).

The combat phase is related to the ER handling. In this phase, resources are provided according to the action plan, which is the Output of joining the 1^{st} meeting for situational awareness (second phase). The action plan includes carrying out research of health personnel, procurement of infection control equipment, evacuation, and personnel care to deal with the event. Some of the combat-related actions, typical of 2^{nd} line ER management and conducted by ERT agents are: LC < *Mobilize helicopters following action plan (1^{st} meeting)* > and < *Inform relevant helicopter company about changing scheduled trips >;* PC < *Establish contact & coordinate actions with HR 3^{rd} line (operators & owner)* > and < *Send the POB list to the relevant stakeholders* >; AC < *Update the PSA about the sit. Regularly* >; IC < *Keep the 3^{rd} line up to date with status updates every 30 min >.* During combat phase the role of COS is to ensure that the whole ERT has an updated and common operating picture. In this regard, the technological agent, CIM, has a critical role in ER operation and performs a crucial task: < *CIM: Provide information* > to each coordinator. In the Covid-19 case management, on one hand some actions like updating police or NOFO, submitting oil pollution action plan, or controlling the submission of the warning form for gas emissions have not been performed, because this is a health-related incident.

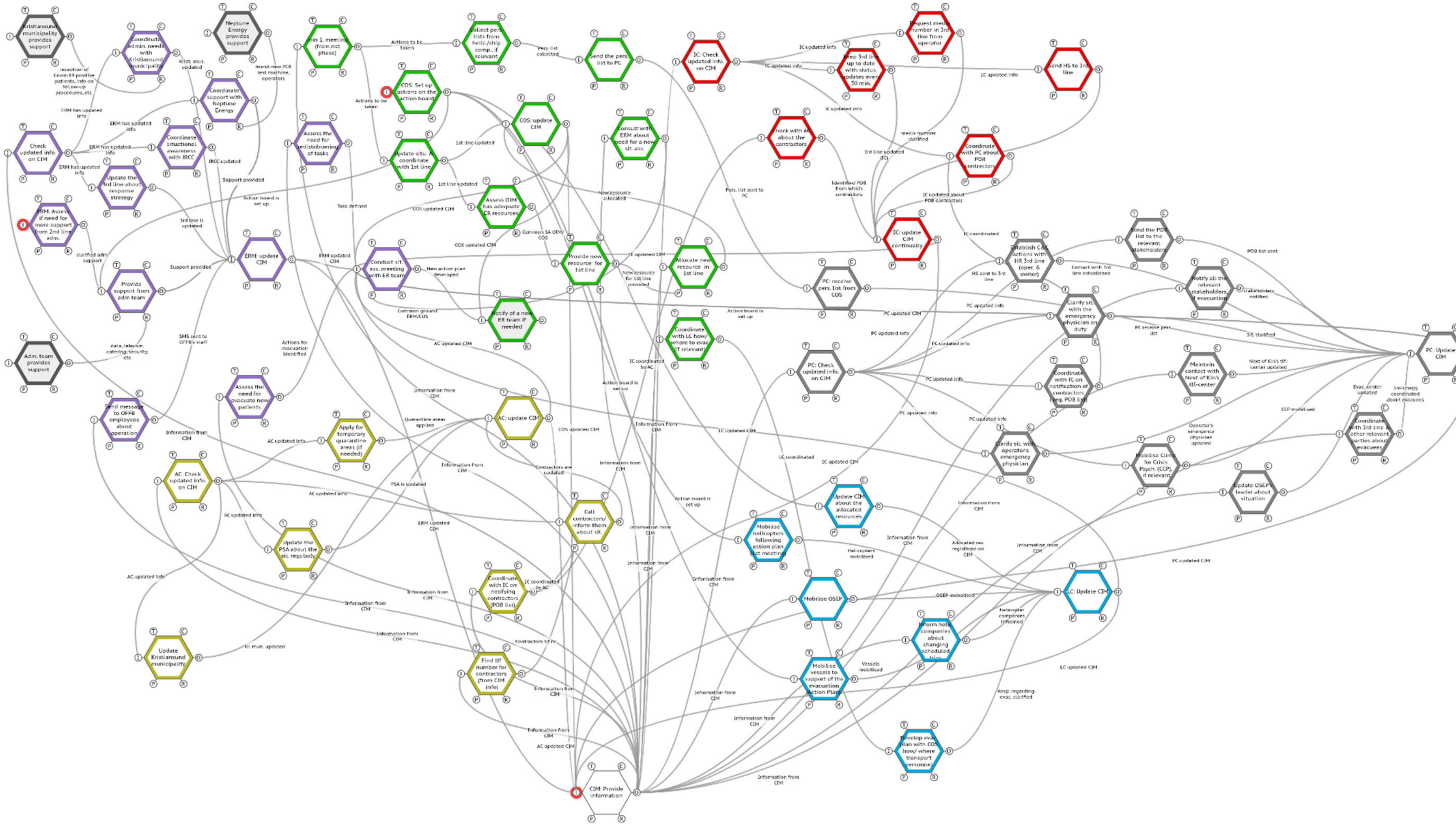

Figure 28 - FRAM model of the third phase: combat

On the other hand, some specific actions have been carried out in addition to those of the standard procedure. For example, ERM < *Assess the need for evacuate new patients* > and shows the 'identified actions for evacuation' during the situation meeting with the ERT and AC < *Update Kristiansund municipality* > regularly and < *Apply for temporary quarantine areas (if needed)* >. Moreover, ERM < *Coordinate support with Neptune Energy* > obtaining 'a brand-new PCR test machine' and 'specialized operators' to test people offshore and < *Coordinate admin. needs with Kristiansund municipality* > in terms of 'reception of Covid-19 positive patients or info on follow-up procedures'. All the performed actions are registered in the CIM by the agents, giving a continuity over each layer. When 1st, 2nd and 3rd line ER authorities agree that the emergency is over, this phase ends for the 2nd line.

The fourth phase: normalization (Figure 29).

The last phase sees a transition from responding to the event to bounce back to a normal situation. Some actions performed by ERM, like < *Verify with 1st line that situation is under control* >, < *Verify with 3rd line any support needed from 2nd line* >, and < *Ensure PSA approval for a transition to normalization* >, are aimed at finding a consent between all the ER authorities about the transition to normalization phase.

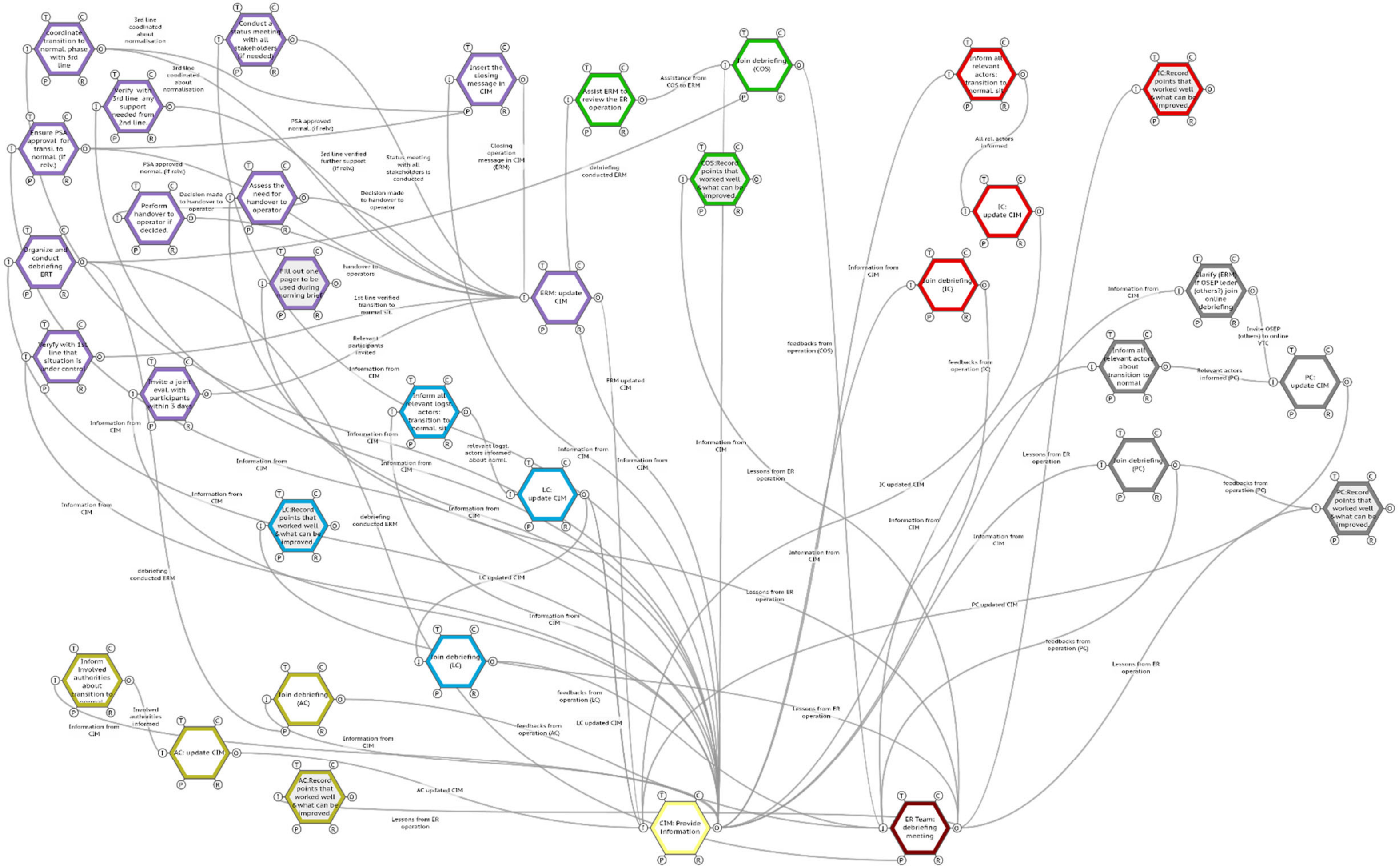

Figure 29 - FRAM model of the fourth phase: normalization

Once there is a mutual agreement, ERM < *Organize and conduct debriefing ERT* >. For the 2nd line ERT, this phase means also debriefing, sharing experience, and assessing the response activities according to best practices. To model this situation, a collective function at organizational level, named < *ER Team: debriefing meeting*>, has been introduced. The Output from this function provides 'Lessons from ER operation'. These lessons will enhance the handling of next emergencies, by identifying and implementing the best practices, through a continuous organizational learning cycle.

Figure 26, Figure 27, Figure 28 and Figure 29, proposing a visual understanding of functions related to the four different phases, confirm the tightly coupled nature of the process at hand. As introduced in section 4.2, in the FRAM model each function can be described through six fundamental aspects: Input (I), Precondition (P), Resource (R), Output (O), Control (C), Time (T), graphically represented at the corner of a hexagon.

4.4.3. Case 2

From Monday 19th to Thursday 22nd of October, another Covid-19 related emergency was reported at WP rig.

4.4.3.1. Event summary

A person with potential Covid-19 symptoms was transported to the city of Kristiansund on Friday 16th and was confirmed infected the following Monday. FAL, Florø logistics and Kristiansund municipality were coordinated by OFFB. Later, fifteen possible close contacts who had left the rig were notified at home to be tested and quarantined; contemporarily several people with symptoms were isolated offshore (8 close contacts). Two days later, on Wednesday, two new cases were confirmed, and new close contacts were isolated on board. A total of three people were confirmed infected by Covid-

19 and isolated; sixteen people were quarantined in a hotel in Kristiansund or at their home, and two more people on the rig. Other personnel were transported to the rig on Thursday and Friday to replace those sent shore side, either isolated or quarantined. The event was considered concluded on Friday 23rd of October (seven days later) when the rig was declared safe once more.

4.4.3.2. 2nd line involvement

ERM was notified by the Neptune Covid-19 project on Monday afternoon (19:10). Neptune emphasized that it was not an emergency situation and communicated that Seadrill (the rig owner) had to be in lead. From the 2nd line, Neptune requested support for the direct notification of the fifteen possible infected people who had returned home. ERM received the list of their names, but telephone numbers were not available on that list. Therefore, ERM asked Florø Air transport office the telephone numbers of the involved people and together with COS started calling the listed personnel. On Tuesday, ERM was asked to draft a PSA form; it was approved by 3rd line and submitted by ERM 2nd line. A total of three updates were sent to the PSA. When it was confirmed that another two people were infected, Neptune strengthened its project group and involved ERM 2nd line as part of the group, whereas traditional 3rd line was not mobilized. ERM had daily contact with Drilling Supervisor[6] (DSV) on the WP, regarding general status on board and progress in the operation. At the same time Neptune expanded its project group, ERM established a new session in CIM, without mobilizing the emergency room. From Wednesday, joint status meetings were set up on Teams between the Neptune project (including ERM/COS 2nd line), Seadrill and other involved actors. 2nd line took

[6] The Drilling Supervisor is the engineer responsible of the drilling operation on board the drilling rig offshore.

the responsibility of updating the situation on board in CIM after joining status meetings. In summary, 2nd line involvement resulted in a hundred of phone calls for ERM or COS. ERM decided to not mobilize further resources in the ERT but coordinators in the 2nd line (i.e. rest of the 2nd line ERT) were continuously updated via SMS by COS.

4.4.3.3. FRAM model of the 2nd case

In this second case, 2nd line involvement was less demanding than the first case (cf. subsection 4.4.2.2), since only ERM and COS were actually managing the situation. The FRAM model reflects this observation (see Figure 30), as visible when compressing the analysis to one single layer (rather than four as for Case 1).

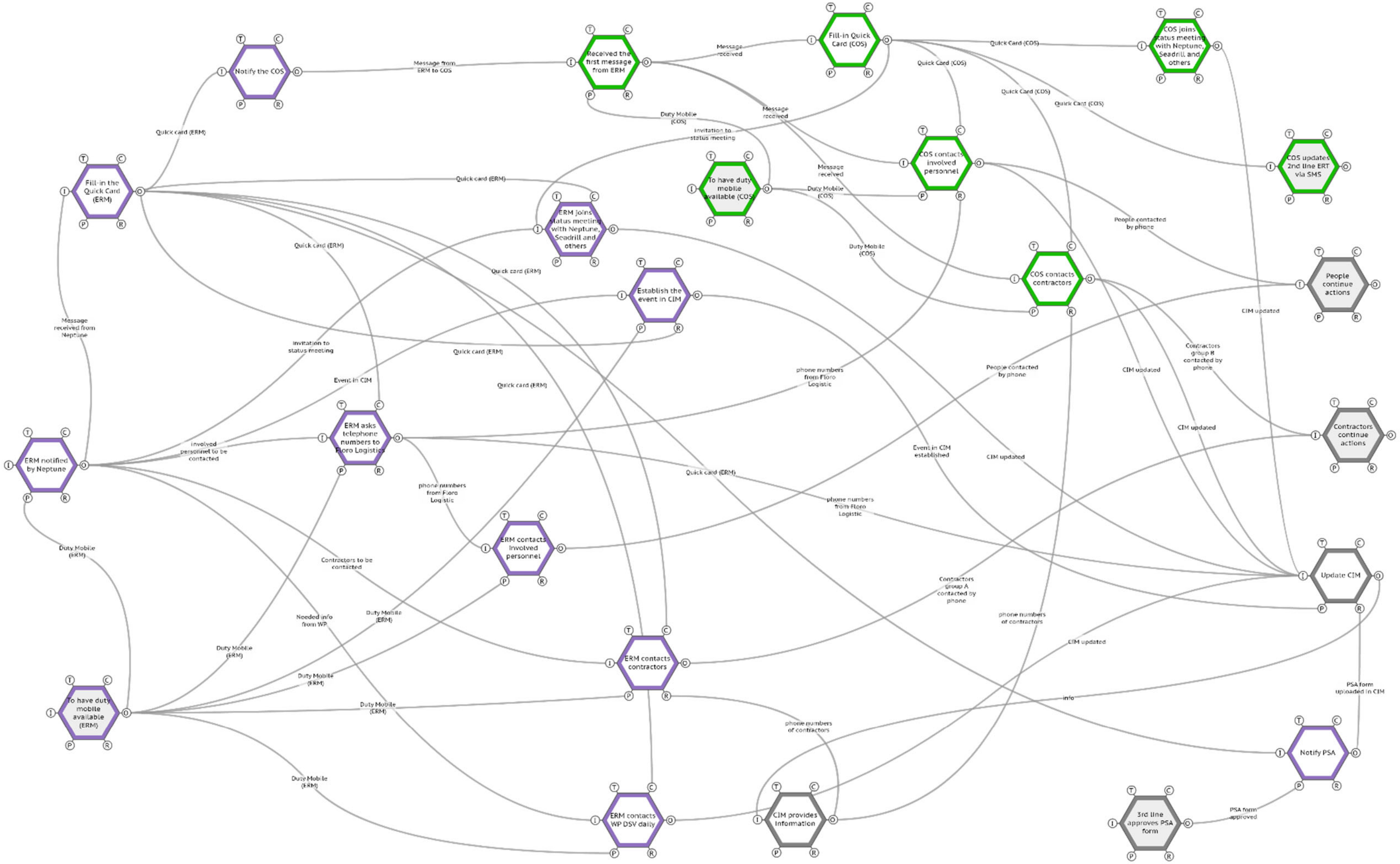

Figure 30 - FRAM model of the 2[nd] case

The process starts when < *ERM is notified by Neptune* > with precondition < *To have duty mobile available* >. Then ERM < *Fill-in the Quick Card* > and < *Notify the COS*>. ERM < *Ask telephone numbers to Floro Logistics* > and after 'phone numbers from Floro Logistics' were available, ERM < *Contact involved personnel* > and < *Contact contractors* > to notify the situation. Same actions are done by COS. Situation awareness is fundamental at this stage. Therefore, ERM < *Contact WP DSV daily* >, to have the situation updated and < *Join status meeting with Neptune, Seadrill and others* > together with COS regularly, in order to monitor the evolution of events. To share information, ERM < *Establish the event in CIM* > and takes care to update the tool every time a new event occurs. ERM < *Notify PSA* > after 'PSA form was approved' by 3rd line, while COS < *Update 2nd line ERT via SMS* >.

4.4.4. Case 3

A third Covid-19 infection case happened at West Mira (WM) rig, operating for Wintershall Dea, from Thursday December 31st, 2020 to Saturday January 2nd, 2021.

4.4.4.1. Event summary

After a flight of the previous day with nineteen people from Flesland to WM, one of the passengers was tested positive on Covid-19 on Thursday December 31st, 2020. The patient was transported to shore by medical evacuation helicopter; twenty close contacts were transported to Bergen - Flesland airport the following day by helicopter from Flesland. These people had to be quarantined at a hotel in Bergen or had to travel home for the quarantine (one infected by Covid-19 and twenty people defined as close contacts). ERM tried to get in touch with the emergency hotel Scandic Kokstad without success, because it was closed for the Christmas period. Afterwards, ERM managed to book some rooms at another hotel, where the people were transferred and tested with the help of a nurse delivered by the Offshore Health Services[7] (OHS) company.

4.4.4.2. 2nd line involvement

On Thursday afternoon (17:23), ERM received a call from the Drilling Superintendent[8] on shore of the Wintershall Dea[9] company and afterwards contacted DSV at WM, regarding the situation offshore, and called 3rd line and COS. ERM learned from the Duty Doctor[10] that the result of triage of the patient was green and gave this information to DSV in order to fill the PSA form. ERM alerted the PSA duty manager about the incident at WM and gave an update on the situation at WM to the Authorities. The following day a Teams meeting was organized with ERM, Wintershall Dea (operator), Seadrill (rig owner) and WM (rig). After some troubles due to the identification of the Covid hotel open during Christmas holidays, ERM obtained the direct number of the Scandic Flesland hotel from the emergency Medical Service Centre in the city of Bergen and booked 15 rooms. ERM called the Managing Director of the OHS company to organize a support scheme for those who were in quarantine. In this case, OHS delivered a nurse to follow up the personnel situated in quarantine at the Scandic Flesland hotel. ERM called the nurse from

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[7] This company delivers the Duty Doctor services and other medical support services to the O&G companies.

[8] The Drilling Superintendent is the person who has the overall responsibility of the drilling operation (drilling engineer). She or he is stationed onshore and is superior of the Drilling Supervisor on board the offshore rig, when it comes to the drilling operation.

[9] Both Wintershall Dea and Neptune Energy are O&G companies, operating on the Norwegian continental shelf.

[10] There are two doctors involved: one is the onshore 24/7 Duty Doctor and the other is the onshore doctor responsible of the health services on board the rig (FAL). Normally, the nurse on the rig will call the 24/7 Duty Doctor for consulting an ill patient. The FAL has the overall responsibility of contagious disease outbreaks on board, and will decide/advise how to handle the situation.

Seadrill who had accompanied the passengers from the heliport to the hotel; 15 people were on the first flight. 3rd line Manager on duty called for an update and agreed to test those in quarantine at the hotel, if possible. Coordination meeting with nurse from Seadrill was organized. All twenty-one people were transported to land and through the hotel; six people were left in the hotel. At the end, ERM called and demobilized resources from the OHS company, that is the psychiatric nurse.

4.4.4.3. FRAM model of the 3rd case

Even for the third case, 2nd line involvement was not as complex as 1st case (cf. subsection 4.4.2.2) and the situation was handled by ERM and COS without activating the whole 2nd line ERT (see Figure 31).

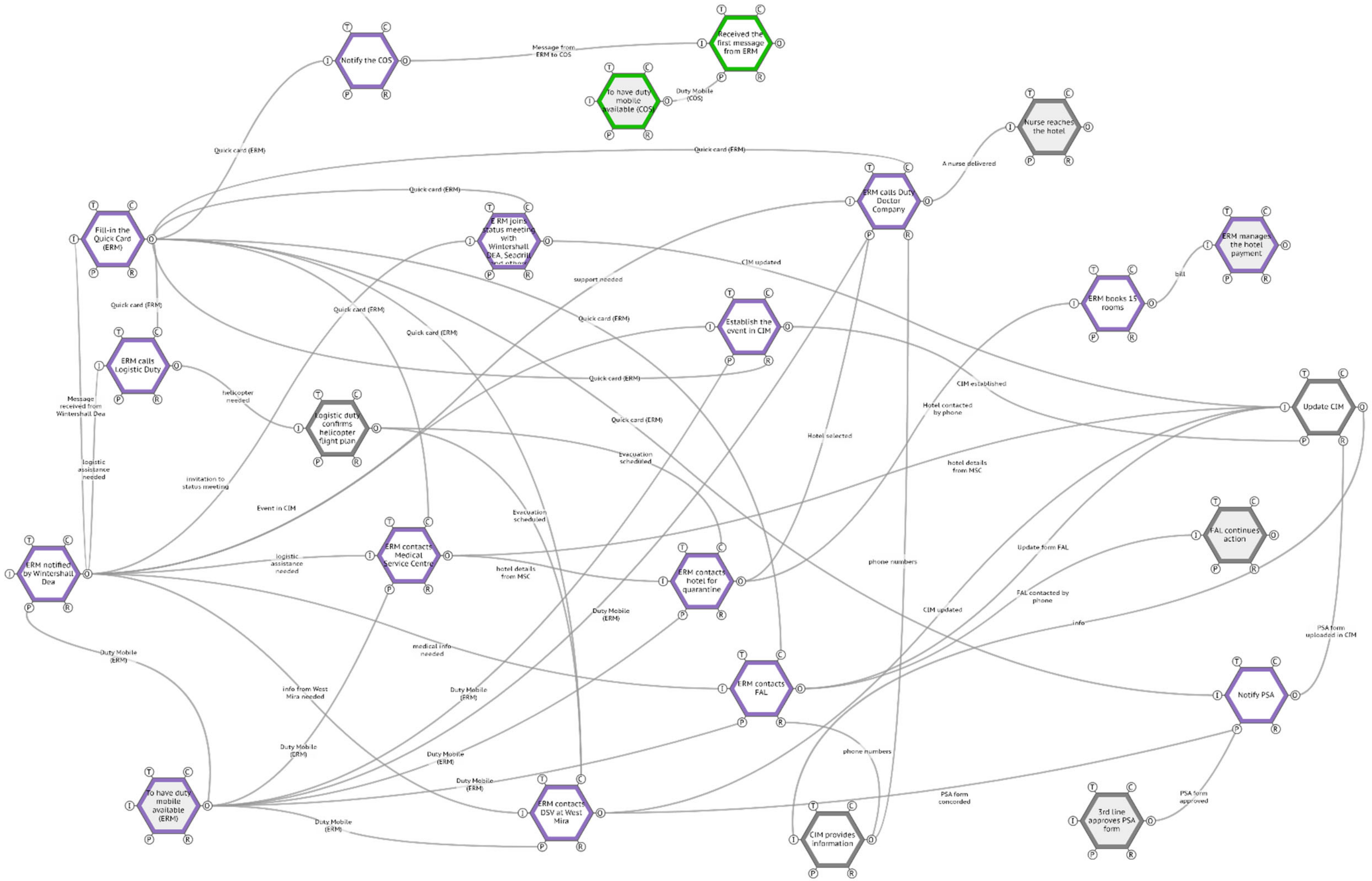

Figure 31 - FRAM model of the 3rd case

At first, with the precondition that ERM's duty mobile was available, < *ERM is notified by Wintershall Dea* > because 'logistic assistance is needed'. As consequence, after notifying COS, ERM < *Call Logistic Duty* > to have a 'helicopter flight planned' and < *Contact Medical Service Centre* >, asking for 'hotel details' where to send people for quarantine. After finding out which hotel was open during Christmas holidays and having a flight scheduled, ERM < *Contact hotel for quarantine* > and < *Book 15 rooms*>. To obtain 'medical info', ERM < *Contact FAL* > and, to have an updated situation awareness, he < *Contact DSV at West Mira* > and < *Join status meeting with Wintershall DEA, Seadrill and others* > together with COS. As in the other cases, ERM < *Establish the event in CIM* >, keeping the tool updated to < *Provide information* > to other members, and < *Notify PSA*> after having the 'PSA form approved' by 3rd line. Finally, ERM < *Call Duty Doctor Company* > to have 'a nurse delivered' at quarantine hotel, who will assist and test the isolated people.

4.5. Discussion

From an empirical point of view, our study on organizational resilience, dynamic adaptive behaviours and learning from past events referred to an EM company was entirely built on FRAM. This method was firstly utilized for elaborating a WAI model based on the available OFFB's documents and afterwards to develop the WAD models of the three episodes, which allowed to understand how to reconcile organizational planning and adaptive capacities. The three Covid-19 events at WP have been handled by ER organizations at different levels and involved a number of actors, who required close cooperation, good coordination and clear communication. The formalization of such interactions between agents through the FRAM offered a methodological solution to consistently investigate each event, maintaining coherence and facilitating a systematic crisis-induced learning. The FRAM models demonstrate a smoother EMS put in place by OFFB following the very first case, both at the level of the actors involved and about the number of activated functions or interconnections between them (see Table 4).

Table 4 - summary table of the three FRAM models

Involved Agents	Case 1 (combat phase)	Case 2	Case 3
ERM	13 functions	11 functions	15 functions
COS	12 functions	7 functions	2 functions
LC	7 functions	-	-
AC	8 functions	-	-
PC	13 functions	-	-
IC	7 functions	-	-
Others:	Kristiansund municipality (1 function); Neptune Energy (1 function); adm. team (1 function); CIM tool (1 function).	3rd line (1 function); contractors (1 function); involved personnel (1 function); CIM tool (2 functions).	3rd line (1 function); Logistic duty (1 function); FAL (1 function); nurse (1 function); CIM tool (2 functions).
Total number of functions	64	23	23
Total number of couplings	112	43	45

The elaborated FRAM models are the result of a structured learning effort, collecting data from different sources into a harmonious representation. The outcomes of the models, and even the process to define them, emphasize the tight relationships among a plethora of agents and respective activities involved in mission command. While each emergency will always be ultimately different, the three cases were considered a reasonable basis to explore examples of crisis induced learning in relation to Covid-19 infections. Considering the qualitative nature of our approach, an inductive thematic saturation was achieved during the focus groups [221]: following the third case, new Covid-19 infection cases were considered standardized incidents, without major unexpected emerging behaviours to be expected. Accordingly, a model of the procedure to manage Covid-19 offshore infections has been developed to describe the migration of take-ways from crises induced learning into organizational planning.

4.5.1. Learning from case 1

In this event, the 2nd line ERM activated all the ERT as in any other emergency case. Since it was all about a novel incident type, the situation suffered from a great uncertainty. According to a 2nd line informant, this uncertainty was related to several aspects: how many people could be infected on board the rig; whether the infection could be limited; whether the infection tracking, carried out from land, was sufficient; how the situation should be managed in terms of privacy; how tests should be done safely; what equipment would be used for testing on the rig; how tests should be transported to shore for analysis; how close contacts should be handled and looked after on the rig and who was responsible for decisions related to new material and personnel sent out to the rig. Moreover, the informants point out that the planning system gave those involved a good overview of formal routines roles, responsibilities and distribution of tasks for actions and interactions. At the same time, plans did not provide clear guidelines about who was responsible for notifying the air traffic management and the helicopter company of Covid-19 cases or suspected ones. There was no clear guideline for mapping close contacts among fellow passengers and crew, testing of personnel offshore and how to proceed to test the entire crew of the rig. This climate of uncertainty and the lack of specific procedures for this new kind of emergency made decision-making an even more difficult and demanding task. As expected from literature, this situation describes an incomplete organizational planning, mainly due to the novelty of the situation. One of the critical decisions was related to the extent of contagion: since the municipality did not have sufficient capacity to carry out the tests, the operator took responsibility for setting up a separate test centre to assess the contagion situation at WP. The operator had created plans and procedures for handling Covid-19 before the situation occurred, but they could not describe all eventualities. Therefore, the crisis management had to improvise and solve larger and smaller challenges as they emerged, without necessarily having prior approval and signature on the decisions made. In this case, examples of improvisation can be identified in the use of a brand new PCR test machine and in the operator that set up a separate test centre. The result of these two specific decisions was satisfactory since they carried out without burdening the public capacity and contributed to the streamlining of the testing process. Despite important progress towards adaptability in contingency planning, this Covid-19 case shows that there was still a need for much more adaptive planning so that ever-changing operational conditions can be met in less predictable circumstances. Nevertheless, adaptation is not about always changing plans, models or past approaches, but ensuring authority, capability and potential to revise and modify them [34].

4.5.2. *Learning from case 2*

As it has appeared evident from the FRAM modelling, this Covid-19 incident significantly differs from the previous one. In this occasion, the handling started as a project in Neptune Energy and there was no mobilization of the "traditional" emergency response organization during the incident. Neptune wanted Seadrill (the rig owner) to coordinate the handling, unlike the previous case where Seadrill held a marginal role. Initially, Neptune Energy decided not to involve the emergency response organization, handling the situation in an established project: therefore, 2nd line was not involved in the very first hours of the incident. Then, the project group asked the 2nd line to notify the contractors, causing some confusion in the 2nd line organization because, despite the project group did not want to define the situation as an emergency, they actually called the 2nd line for support. Neptune expectations for the 2nd line role in the incident were unclear in the first stages. OFFB requested a coordination meeting with the Neptune project group to clarify the composition of the project group and expectations for the 2nd line. The meeting resulted in a better understanding for both parties. In summary, the second case points out an initial uncertainty from the operator about the roles and the task of the various actors and a lack of organization about the handling of notifications to the involved people. Such observations offer recommendations to further improve the process and ensure a smoother organizational planning.

4.5.3. *Learning from case 3*

This third case highlights additional critical aspects. Firstly, ERM did not receive any information/help from FAL about transportation and hotels where send the quarantined people. ERM also called the operational support centre

"Equinor marine[11]", asking for information about quarantine hotel that Equinor normally uses, but there was no result. Finally, ERM was notified by Bergen municipality that Scandic Flesland was the hotel used in this occasion, whereas the regular Covid-19 quarantine hotel at Scandic Kokstad was closed for Christmas holydays. Another issue regarded the failed attempt by ERM to obtain "infection control" taxi, that is to request a taxi allowed to transport personnel going into Covid-19 quarantine. The Bergen Municipality did not give OFFB the right procedure to organize this type of transport and ERM had to find out by himself. Besides these specific issues, the situation was handled very skilfully and resolved within a weekend.

4.5.4. Trading-off organizational resilience and planning

The successful handling of three different Covid-19 cases was translated in double-loop learning [211], and learning opportunities were collected into an organizational procedure by OFFB [217]. This document allows to move from the management of individual specific cases towards a basic management plan, to be interpreted as a guide for handling of Covid-19-related incidents offshore. Acknowledging the inherent variability of such emergency situations, this procedure stays at a relatively abstract level, to ensure the possibility of adapting the plan on a case-by-case basis, giving the right space to improvisation [199]. The document trades-off the need for variability in certain operations with the identification of common hotspots coming from learning, and shared discussions after the three previous cases.

[11] Equinor Marine is a 24/7 operational surveillance and logistics centre. Equinor is the largest operating oil & gas company in Norway. They provide surveillance services to other companies.

4.5.4.1. A newly introduced Covid-19 procedure for EM

In line with the research question and for brevity, only the Operator's 2nd line responsibilities and tasks for the combat phase are described, formalizing them through a dedicated FRAM model. The Operator's 2nd line is expected to be responsible for coordinating operational activities from onshore – to requisition relevant resources and coordinate actions, as per the following tasks:

- to communicate and coordinate activities with: 1st line; 3rd line; the Duty Doctor; the Company Doctor responsible for the rig; the Logistics Department; the helicopter operator (if the Logistics Dept. is not addressing this); relevant personnel employed by the Operator, such as the company doctor or staff responsible for health- or working environment-related matters; the Rig Owner (if the rig is leased); contractors (if the rig is leased, and in consultation with the Rig Owner); the operator providing transport from the helicopter to the hotel; the quarantine hotel; contracted health personnel; area emergency response organization; the Norwegian Joint Rescue Coordination Centre;
- to report and provide status updates to the PSA (carried out in coordination with 1st and 3rd lines);
- to manage the practical reception of personnel at the helicopter base, bus transport, and the reception of personnel at their quarantine/isolation hotel(s). Accordingly, 2nd line operator shall coordinate with the Company Doctor responsible for the rig, 3rd line, the helicopter operator, the transport operator, the hotel(s), on-site representative(s) and the municipality;
- to determine, in consultation with the Company Doctor responsible for the rig, whether people in categories C and D need to be accompanied during helicopter transport. They shall make sure that companion personnel are

obtained, as appropriate. This shall be coordinated with 1st line, the Logistics Dept., and the helicopter operator;

- to ensure that either the Logistics Dept. or 2nd line itself communicates and coordinates with the helicopter operator to make sure that infection control measures are implemented on arrival at the helicopter base;
- to ensure that the Operator/Rig Owner assigns personnel who can meet and take care of persons who are transported onshore;
- to ensure that personnel, who arrive onshore, receive the necessary information and supervision;
- to ensure that the quarantine hotel receives the information it requires;
- to ensure that infection control measures are implemented in cases where personnel require a hired car to drive to the quarantine location;
- to keep 1st line, 3rd line, the Company Doctor responsible for the rig and the municipality updated on the status of personnel who are sent onshore, and shall deal with any questions that may arise;
- to ensure that essential infection control equipment is obtained, as appropriate;
- to check with the Company Doctor responsible for the rig and the municipality to determine if there is any need for support from the Operator to carry out testing onshore. If necessary, he/she shall make sure that the municipality receives the support it requires for testing.

4.5.5. FRAM model of procedure for Covid-19 infection management

Figure 32 depicts the core phase of the procedure, i.e. combat, in FRAM terms. At first, < *offshore nurse visits patients* > and < *Duty Doctor does the triage* >, sharing the 'triage results' with Company Doctor. < *Duty Doctor updates the* *status of personnel offshore* > with 1st line and 2nd line ERM and has 'to notify this information to 3rd line within 15 min'. With the precondition that < *Communication equipment functions regularly* >, ERM < *Communicate and coordinate* > with all the actors mentioned in the previous paragraph. Those communication and coordination functions are essential to guarantee the execution of other relevant actions by ERM. For example, ERM < *Report and update to PSA* > in coordination with 1st line and 3rd line, according to 'Norwegian Law', which constitutes a control for this action. Moreover, ERM < *Manage the reception at helicopter base* >, after communicating and coordinating with 3rd line, Company Doctor, Duty doctor and helicopter operator. Precondition for this action is that ERM < *Implement ASAP infection control measures* > and Resources are 'assigned and trained personnel to handle the situation'. Same couple of Precondition/ Resource can be found for the actions ERM < *Manage the transport by bus/hired car* >, ERM < *Manage the reception at the hotel* >, and ERM < *Manage the transport by helicopter* >.

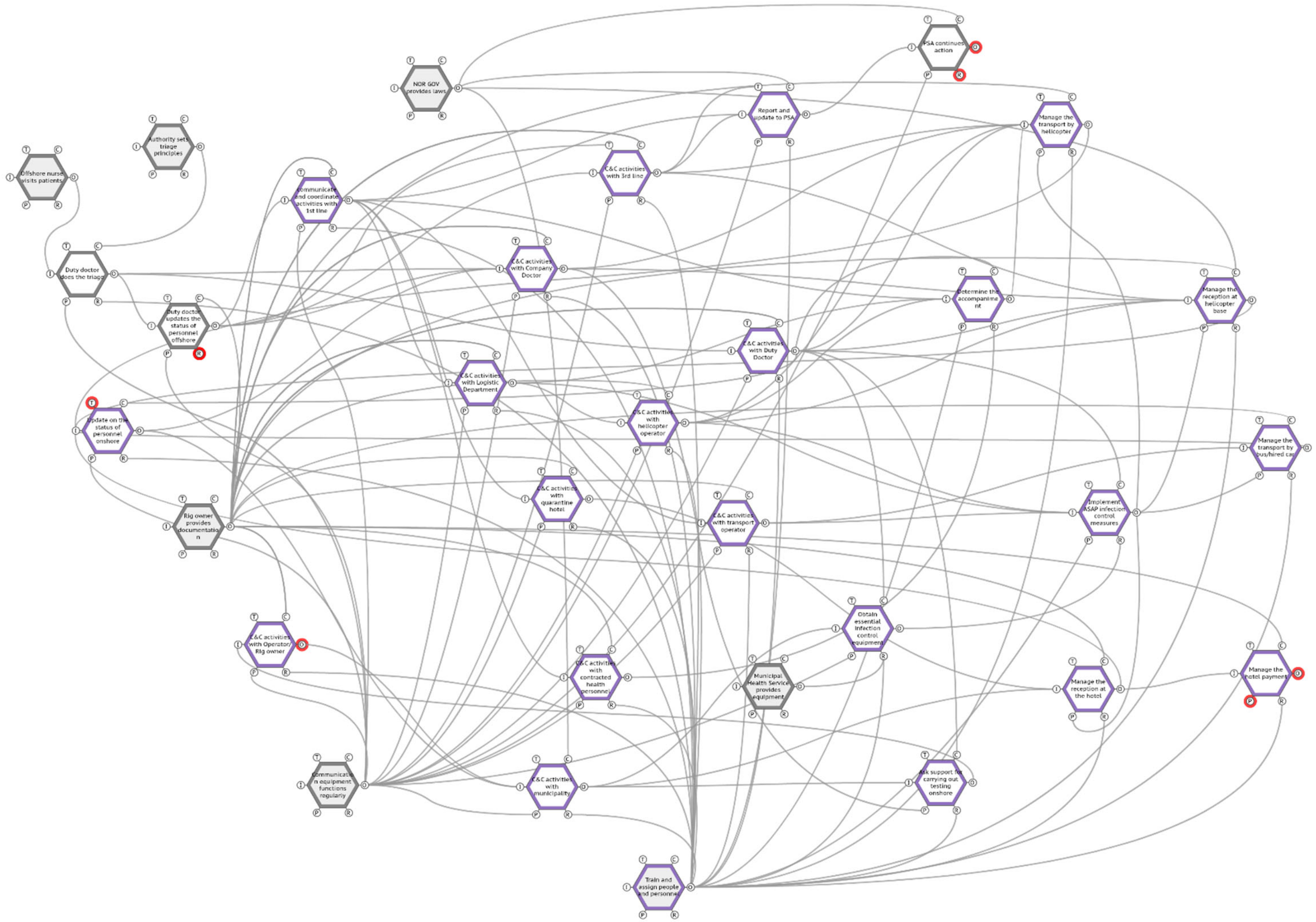

Figure 32 - FRAM model of procedure - combat phase

For this last action, another input is also necessary: ERM < *Determine the accompaniment* >, under control of Duty Doctor, and in coordination with 1st line, Logistics Department, and helicopter operator, having as resource the accompanying people from contracted health personnel. ERM < *Obtain essential infection control equipment* > from Municipal Health Service, under the control of Duty Doctor, and in coordination with the municipality; the output of this action is fundamental for implementing ASAP infection control measure, as seen above. Another action, related to medical needs, is ERM's < *Ask support for carrying out testing onshore* > to rig operator in coordination with municipality and the consultation with Company Doctor as precondition, under the control of Duty Doctor. Most actions of the FRAM model share, as Control, the content of some documents that should be provided by the rig owner: the three plans ('Covid-19 plan', 'infection control plan' and 'communication plan'), the 'Emergency response bridging document' and the several 'contracts' stipulated by the operating company with: the health personnel, the helicopter company, the transport company, and the quarantine hotel. Closing the loop, actions such as ERM < *Manage ….* > have as Output 'updated info': the latter constitutes the input for the action ERM < *Update on the status of the personnel onshore* > towards the Company Doctor and the municipality, in coordination with the Duty doctor. The analysis of this procedure recalls the founding principles of "mission command", i.e. decentralisation and empowerment of subordinates [222]. This reasoning became pervasive also in other operational contexts, such as clinical theatres during Covid-19 emergencies, where great responsibility is pushed down to the level where operators can best employ it [223].

4.6. Concluding remarks

Within the wide literature on organizational resilience, this study allowed to define different learning opportunities from a novel type of emergency, i.e. the management of Covid-19 infection cases offshore. The empirical study of the organizational resilience, based on three Covid-19 related cases in oil platforms offshore, pointed out the evolution of an ER organization, along with its capacity to adapt to new challenges and to learn from previous episodes. The first case was managed through a traditional ER approach revealing uncertainty and lack of specific procedures, with risks to be managed and situations to be faced highly different from the planned ones. Despite this unanticipated complexity, the whole EMS proved to be resilient, being capable of resolving situations that were not included in original emergency plans, via improvisation. The following cases were handled with less involvement of the 2nd line ERT and more participation of the 1st and 3rd line operators, following the crisis induced learning. But difficult case management cannot be delegated only to improvisation: the 2nd line operators enriched its capacity to provide support to both the 1st line and the 3rd line ER organizations through a novel procedure which indicates functional hotspots valid for a wide variety of Covid-19 cases. The case studies confirm that EM organizations benefit from an efficient and transparent reporting system to foster continuous learning from events and consequently enrich decision-making at strategic level. The results adheres to RE traditional expectations [224], highlighting the need for a unity of effort, implemented through centralized planning and decentralized execution to empower mutual understanding and rapid decision-making [225]. It is important to observe how the whole analysis was conducted using the FRAM, a systemic approach currently applied in EMS only to a limited extent. Nonetheless, the study confirms FRAM role to support a structured learning for organizational resilience and planning. The use of FRAM made it possible to identify which actors were involved, to define the various functions and to identify the interconnections between them, for both actual practices and prescribed work. These empirical findings document the benefits arising when studying multiple varieties of socio-technical work. This research is fully aligned with recent RE contextual information and need of integrated investigations on the nuances of adaptation [226] for Work-As-Observed (WAO), Work-As-Prescribed (WAP), Work-As-Normative (WAN), Work-As-Disclosed (WADI) [176]. When looking at an incident, knowledge on each of these varieties, their small disturbances, their inconsistencies, ambiguities, conflicting goals is needed to further extent crisis induced learning [176]. On this path, this research demonstrated the applicability of FRAM to study the responses a socio-technical system puts - or may put - in place to unforeseen emergency situations: FRAM helps gathering knowledge and organizing it systematically. In addition, the study allowed to extract virtuous characteristics of an organization that can be extended to other scenarios, helping to define best practices for a safe and efficient crisis management. This last aspect promotes a positive learning attitude to openness, beliefs and perceptions sharing, and mutual trust to inform decision-making at different organizational levels. All these aspects are recognized to be central for ensuring success in spite of disasters, and should guide decision-makers to ensure organizational resilience [227]. While FRAM exceeds traditional accident analysis and risk management models, which are usually subjected to limitations imposed by linearism and reductionism (e.g. domino models, fault tree analysis, event tree analysis, etc.), it is not yet a complete approach to deal with any situation [212]. For future research, the FRAM could be utilized for analysing procedures and activities of more complex emergency or crisis management organizations, both civilian and military. Next studies could extend the findings of the proposed FRAM models, recurring to quantification approaches, such as Bayesian networks or fuzzy sets, or simulations. FRAM-like methods are expected to support investigations of WAx varieties, increasing the proactive nature of crisis management and crisis induced learning for diverse operational settings [176].

CHAPTER 5

5. QUANTITATIVE EXTENSION OF THE FRAM THROUGH BAYESIAN NETWORKS

Acronyms

BN	Bayesian Network
C&C	Coordination and Communication
CPT	Conditional Probability Table
DT	Definition Table
EM	Emergency Management
ERM	Emergency Response Manager
FRAM	Functional Resonance Analysis Method
ICE	Infection Control Equipment
ICM	Infection Control Measures
MRH	Managing Reception at Hotel
MRHB	Managing Reception at Helicopter Base
MTBRC	Managing Transport by Bus or Rented Car
MTH	Managing Transport by Helicopter
O&G	Oil & Gas
OFFB	Operator's Association for Emergency Response
RE	Resilience Engineering

5.1. From FRAM to Bayesian Networks

In these current challenging times, dominated by uncertainties due to climate change, famine, drought, conflicts or even pandemics, the study of emergency or crisis management resilience acquires a strategical relevance for decision-making, at any modelling tier according to the classification introduced in [4]. Such dynamism requires systemic approaches to study operational practices in terms of effective variability, to deepen adaptive practices and to seek systemic rather than localized solutions [43], according to the concept of Resilience Engineering (RE).

By learning from safety management, organizations which deal with emergency or crisis management can adopt a systemic perspective and take advantage of modern analytical methods, too. A Tier II method according to Linkov's classification [4], particularly helpful to deal with socio-technical aspects from a systems-theoretic perspective including EM operations, is the Functional Resonance Analysis Method (FRAM) [56], already explored in Chapter 4, which has discussed the research conducted in [218].

In that study, the FRAM has been used to investigate how Covid-19 changed some well-established EM procedures, demanding for high levels of organizational resilience. Starting from the findings of that research, the study discussed in the present Chapter aims at providing an explorative method to analyse resilience capacity, calculating the potential cumulative effects of functional resonance in complex socio-technical systems, through a mixed Tier II - Tier III approach, recurring to a combination of FRAM and Bayesian Network (BN). The FRAM is useful to model the actors and the interactions of the system, while a BN, dynamically updated with new available data, can provide a quantitative dimension to the assessment.

Specifically, BNs have been widely used in risk analysis [228–232], risk assessment [233–238], and decision-making [239,240]. The work in [241] implemented a BN model of chemical terrorist attacks to conduct risk analysis, in order to provide theoretical support for the security prevention work of the risk management department. BN analysis allowed also to identify social risk factors and key elements of generation-risk process in the context of High-Speed Rail Projects in China [242]. Furthermore, BNs have been a useful approach to study systems' resilience: [243] conducted a resilience assessment for the Northern Sea Route based on a Fuzzy BN, [244] adopted a BN to assess the resilience of an interdependent electrical infrastructure system. More closely related to the scope of this research, scholars have also introduced BN to study emergency management. [245] applied BN to analyze the role of emergency organization elements in the evolution of flood Na-Tech events. In [239], the authors designed a decision support system for emergency managers based on a BN for the hot and cold phases of coastal risk management in UK. [246,247] presented a risk-based framework of dynamic decision making for dam-break EM based on BN. Finally, [248] suggested a decision support tool to address rare events such as disease outbreaks in confined environments. More specifically, the authors focused on a case study of the Covid-19 outbreak that happened on board the Diamond Princess cruise ship in 2020, by adopting BN as the core of an intelligent decision support tool for emergency management.

Some previous attempts in literature suggest the integration of FRAM, generally to describe system functions and identify potential variabilities and their critical couplings, with a BN model to quantitatively assess a characteristic or a property of the system under exam. [249] introduced a methodological approach, based on FRAM and BN for structuring and organizing expert knowledge and turning it into a probabilistic model to assess the safety and security of Offshore Wind Farms. [250] assessed the resilience involved in maritime liquid cargo emergency response by integrating FRAM and a probabilistic-based BN within the RE framework. [251] adopted FRAM to describe system functions, couplings and variabilities and implementing a dynamic BN to quantify the resilience of chemical process systems, in which technical-human organizational interactions were considered. About the treatment of the human and organizational factors, [252] made a comparison between Fault Tree Analysis (FTA), BN and FRAM to assess the safety of a propane feed control system, demonstrating the value of using different analysis approaches together.

Taking a cue from the previous papers, the purpose of the research discussed in the present Chapter is to formalize previously developed research in this setting, providing a structured methodology to quantitatively assess the resilience potentials of the system by recurring to a combination of FRAM and BN. More specifically, the proposed methodology foresees a first qualitative analysis of the system in accordance with the principles of FRAM, by identifying the functions, their couplings and linked variabilities. Then, a probabilistic BN model is implemented by translating functions and aspects of the FRAM model into BN nodes and edges respectively. BN parameters, i.e. *a priori* and conditional probabilities, are quantified eliciting experts' knowledge. Finally, the BN model is run, in order to quantitatively assess the resilience potentials of the system and conduct forward and backward propagation analyses.

A case study of an EM procedure [217], issued as a learning opportunity after three Covid-19 contagion outbreaks on offshore O&G rigs described in [218], has been selected to demonstrate the validity and verify the performance of the proposed methodology. This case study is intended to provide a proxy measure of the resilience that is called functional resonance, namely the possibility that the variability can become unmanageable, leading to a no longer resilient system. Whenever the assessment of the resilience potentials of the EM procedure is mentioned in the rest of the work, it is to be understood with this meaning.

To the best of our knowledge, there is no research explicitly dealing with assessing the resilience potentials of a newly EM procedure issued as a learning opportunity after the management of three real emergency cases. As above mentioned, some scholars attempted to combine the FRAM with BN, but however, the only use case was of a limited extent, without delving into the analytical aspects in detail and offering operational ways forward for the calculation.

5.2. Theoretical foundation

5.2.1. FRAM building steps

The proposed methodology starts by using FRAM, a systems-theoretic approach grounded in Resilience Engineering (RE), helpful to deal with socio-technical aspects [56]. FRAM principles and steps have been widely discussed in section 4.2.

With respect to the four traditional FRAM building steps, it is worth underlining the following assumptions related to this specific research:

– *Step 1: identify and describe the essential system functions*

  In order to distinguish the different nature of dependences between functions, two types of interrelations have been defined [249]: supportive dependence and compulsory dependence. In the first case, the function provides services that have supportive character, but are not crucial for executing the actual operations. Regarding to the FRAM, these services can be: “Precondition”, “Resource”, “Control”, and “Time”. For compulsory dependencies, the function provides an entity that is essential for other functions: the related FRAM coupling is an “Output-Input”. It is worth mentioning that this classification of dependences, inspired by [249], is a simplification, made in order to give a priority to the “Input” aspect over the others.

- *Step 2: identify the actual or potential variabilities between functions.*

  In the present study, timing and precision have been chosen among other phenotypes because they represent the simplest solution to describe the consequences of performance variability [56]. More on the definitions and use of these two phenotypes can be found in section 5.5 - Discussion.

- *Step 3: analyse the aggregation of variability.*

  To avoid negative consequences from functional resonance in the system caused by the accumulation of these variabilities, the timing and precision of upstream and downstream interactions have been examined, with a particular focus on these specific phenotypes among others.

- *Step 4: propose ways to manage variability.*

  The final step is to identify the most effective strategies for managing, as opposed to just reducing, functional variability.

5.2.2. *Belief Bayesian Network*

A belief Bayesian Network (BN) is a probabilistic model consisting in a directed acyclic graph, usually describing an event or a process that occurs stochastically, according to the presence or not of certain causes. In this work BNs have been used to add a numerical dimension to FRAM. BN founds its theory on the Bayes theorem, which allows calculating the probabilities of the causes that determined an event. Let us consider two different variables A (the cause) and B (the event), whose *a priori* probabilities are indicated as P(A) and P(B), respectively. The posterior probability P(A|B), i.e., the probability that the cause A occurs knowing that the event B has already occurred, following the Bayes theorem, is given by:

$$P(A|B) = \frac{P(B|A) * P(A)}{P(B)} \quad (1)$$

where in Eq. 1 P(B|A) is the conditional probability which expresses the probability of B given A.

BN nodes can be distinguished in child, intermediate or root nodes. The latter ones do not have parents, i.e., they do not have incoming edges, and represent independent variables, which are described by their *a priori* probabilities. Child and intermediate nodes are dependent variables described through conditional probabilities related to their respective parent nodes. Since BN variables are usually discrete, in order to determine the probabilities of these two types of node, Conditional Probability Tables (CPTs) have to be filled for each node, taking into account each combination of parent states. For example, given a system of discrete binary variables, a node with m parents takes 2^m parameters to fully define the CPT of each possible case. This is usually achieved by fitting given data, or by using expert elicitation and data-driven approaches. In the following section 5.3, an approach is presented to reduce the number of parameters, recurring to the Noisy-OR gates proposed and improved by [253] and [254].

BNs allow to perform inference, that is, to take into account incomplete and uncertain evidence on observed variables, and thus dynamically update the marginal distributions of the missing ones. For this reason, BNs are useful for reasoning about the specific causes of the observations, and for estimating their consequences [249].

This kind of inference is called forward analysis to distinguish it from backward analysis; the former is implemented on the basis of *a priori* probabilities and conditional probabilities to predict the occurrence probability of child nodes, while the latter can be used to compute the posterior probabilities of root nodes for the given evidence [243].

Generally speaking, BNs have the following advantages [238]: (i) small samples and incomplete and noisy data sets can be handled; (ii) BNs can be developed consistently using experts' opinions instead of historical data and still make reliable predictions; (iii) BNs can readily calculate the probability of events before and after the introduction of evidence and update, as necessary, their diagnosis or prediction; and (iv) graphs are used to describe the interrelationships among nodes, making those interrelationships intuitive and easy to understand. These properties seem to be aligned with the ones offered by FRAM.

5.3. Methodology

Figure 33 describes the four phases of the proposed methodology. As a walkthrough, a simple example has been proposed, detailing each modelling phase.

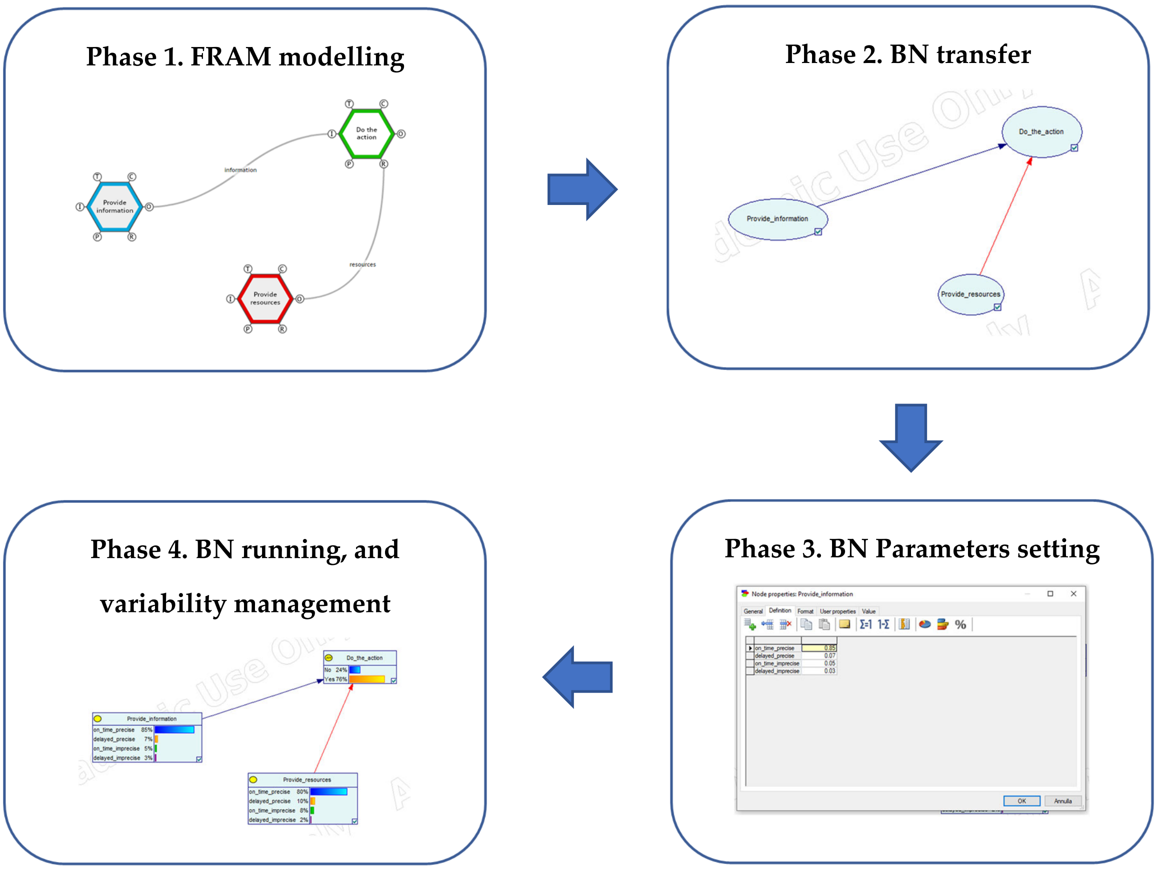

Figure 33 - the proposed methodology to integrate FRAM and BN

Phase 1 - FRAM modelling. According to the basic principles of the FRAM, the functions and the associated couplings should be identified. Figure 34 depicts the FRAM model referred to a conceptual model made up of three agents performing three functions: the green one has to do a certain action but, to perform the action, he needs information from the blue agent and resources from the red one. The aspect "information" has been considered as an Output from the blue agent, while the aspect "resources" has been modelled as a Resource for the green agent. Therefore, "information" results in a compulsory dependence, while "resources" is regarded as a supportive dependence, as previously introduced in subsection 5.2.1.

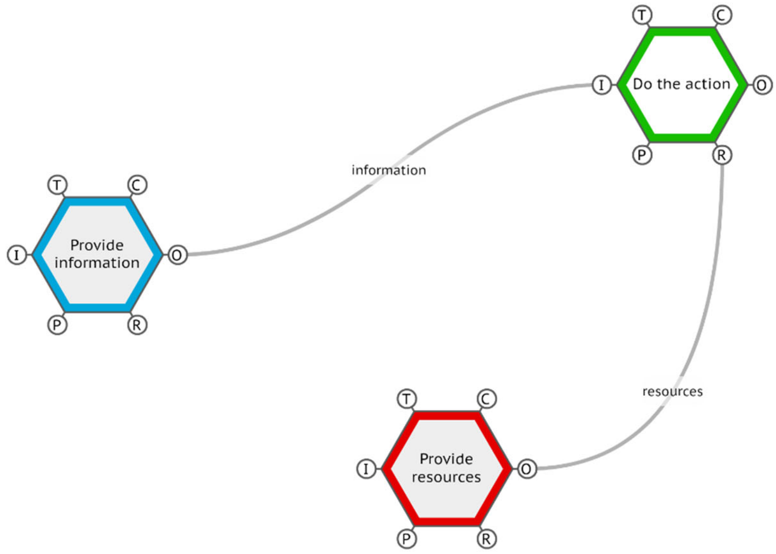

Figure 34 - the FRAM model of the simple example

Moreover, both the functions "Provide information" and "Provide resources" may have different states of variability, referred to the time and the quality of information and resources provided. Studying only timing and precision, four states have been identified: "on time precise", "delayed precise", "on time imprecise", "delayed imprecise".

Phase 2 - BN transfer. The second phase of the methodology deals with the translation of the FRAM model into a belief BN. Each function is associated to a BN node and corresponds to a variable in the process under examination while each aspect becomes a BN oriented edge (arrows in Figure 35), which represents a conditional dependence.

Moreover, each type of variability has to be associated to one of the states of the referred nodes and a probability value has to be assigned. In this step, a choice of the most relevant functions, to be translated in BN nodes, can be done in order to reduce the size and complexity of the network.

Figure 35 depicts the BN model of the walkthrough example. The edges are presented in two different colours according to their type of dependence: blue ones are compulsory, red ones are supportive.

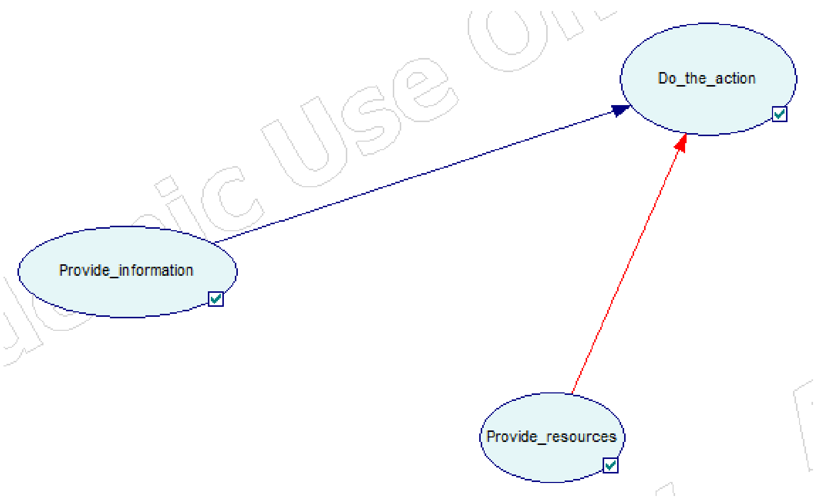

Figure 35 - BN model of the simple example

Phase 3 - BN Parameters setting. By interviewing experts, or using historical data, the probability distribution of root nodes (*a priori* probabilities), intermediate nodes and child node (conditional probabilities) are quantitatively determined. In the walkthrough example, *a priori* probabilities of the nodes "Provide information" and "Provide resources", for each of the above mentioned four levels of variability, have to be defined. This means three parameters for each parent node, since the sum of *a priori* probabilities for each node must equal to 1. Consequently, a total number of six values need to be determined for the root nodes.

The definition of the CPT related to the child node "Do the action" is slightly more complicated, since it contains a total of 32 parameters (32 = 2*4*4: two possible states for the child node and four possible states for each root nodes).

Actually, since the sum of the conditional probabilities referred to the two states of the child node, for a given status of variability of each root node, must equal to 1, the number of independent parameters for the CPT related to the child node is 16.

In summary, for this simple BN a total of 22 probability values (six related to the root nodes and 16 referred to the child node) need to be determined. For much more complex BNs than the one of the trivial case under investigation, CPT parameter definition could be a demanding issue, raising the problems of consistency and resourcefulness. The multi-valued Noisy-OR gates proposed and improved by [253] and [254] can help model interactions among variables with multiple states and allow to specify these interactions with a reduced number of parameters [255]. By undertaking this step, the number of required conditional probabilities can be reduced to the number of a given node's parents [256]. In the walkthrough example, this number reduced to six by applying the theory of multi-valued Noisy-OR gates. Table 5 and Table 6 show respectively the CPT for the child node "Do the action" set as general type node and the Definition Table (DT) for the same node set as Noisy-Max node [255].

Table 5 - CPT for the child node "Do the action" set as general type node

Provide information	on time_precise				delayed_precise				ontime_imprecise				delayed_imprecise			
Provide resources	on time_pre	delayed_pre	ontime_impre	delayed_impre	on time_pre	delayed_pre	ontime_impre	delayed_impre	on time_pre	delayed_pre	ontime_impre	delayed_impre	on time_pre	delayed_pre	ontime_impre	delayed_impre
NO	0	0,6	0,62	0,68	0,86	0,944	0,9468	0,9552	0,9	0,96	0,962	0,968	0,94	0,976	0,9772	0,9808
YES	1	0,4	0,38	0,32	0,14	0,056	0,0532	0,0448	0,1	0,04	0,038	0,032	0,06	0,024	0,0228	0,0192

Table 6 - DT for the child node "Do the action" set as Noisy-Max node [255]

Parent node	Provide information				Provide resources			
State	delayed_impre	ontime_impre	delayed_pre	on time_pre	delayed_impre	ontime_impre	delayed_pre	on time_pre
NO	0,94	0,9	0,86	0	0,68	0,62	0,6	0
YES	0,06	0,1	0,14	1	0,32	0,38	0,4	1

The parameters in the DT of the Noisy-Max node for a parent X_i express the probability of the effect happening, when the cause X_i is present and none of the other causes of the effect, whether modelled or not modelled, is present.

Referring to Table 6, "on time precise" is the distinguished state, i.e. the neutral state which represents the absence of anomaly [257], for both the node "Provide information" and "Provide resources". The value 0,06 (in blue) in the DT's first column represents the probability that the green agent will "Do the action" in case of the information will be provided delayed and imprecisely, taking into account that resources will be provided on time and precisely. Another example: the value 0,32 (in yellow) in the DT's fifth column represents the probability that the green agent will "Do the action" in case of the resources will be provided delayed and imprecisely, taking into account that information will be provided on time and precisely. The exact same values can be read in the classical CPT of Table 5, calculated starting from the values inserted in the DT [255].

In the walkthrough example, it has been assumed that the *a priori* probabilities of the root nodes have been given by experts, while the DT of "Noisy-Max" node "Do the action" has been calculated starting from those probabilities and considering the type of root node dependence. More specifically, following [249], two influence factors have been introduced: factor F_c for compulsory dependences (cf. subsection 5.2.1 - step 1) to be multiplied for the minimum of *a priori* probabilities of each variability state of the parent nodes with compulsory dependence; factor F_s for supportive dependences (cf. subsection 5.2.1 - step 1) to be added to the minimum of *a priori* probabilities of each variability state of the parent nodes with supportive dependence.

In terms of measurement scales, the Likert type has been adopted, with three divisions ranging from Low, Medium and High. Using a 1-5 scale, Table 7 represents the levels of impact for both compulsory (F_c) and supportive (F_s) dependences. For the sake of simplicity, a medium level impact for the dependences has been considered in the walkthrough example.

Table 7 - influence factors for different levels of impact. Numbers are used for exemplary purposes. Actual values are context dependent and should be adapted based on the context and the system at hand

Parameter	Low (L)	Medium (M)	High (H)
Influence factor F_c (compulsory: I)	1,5	2	5
Influence factor F_s (supportive: R, C, P, T)	0,1	0,3	0,5

The choice to use only two influence factors and to attribute to them the values of Table 7 represents a limitation for the study which will be discussed in section 5.5.

Phase 4 - BN running, and variability management. Once all the essential parameters were determined, the developed BN model has been simulated to evaluate the characteristic under examination (i.e., a process resilience or, in the simple example, the probability of "doing the action") through BN inference and to perform belief propagation, causal chain and sensitivity analysis.

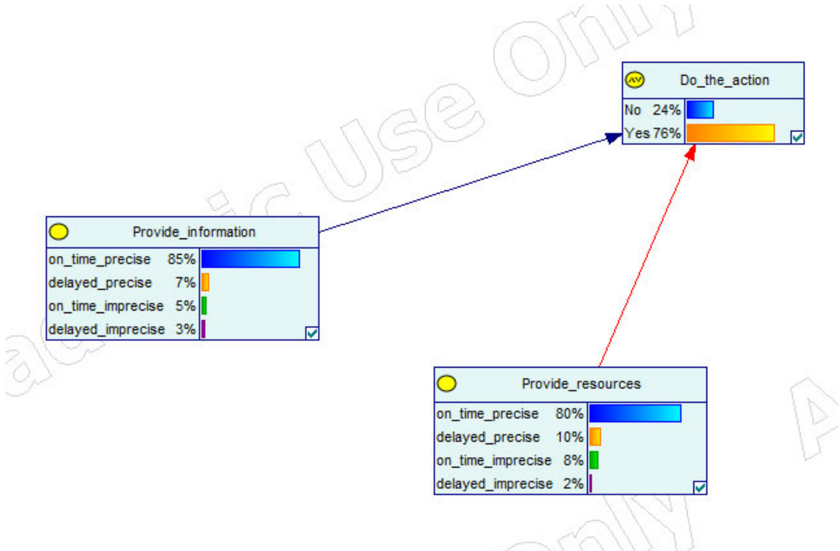

Figure 36 - exemplary results for the BN simulation

In the case study, the software GeNIe Modeler[12] has been utilised (see Figure 36).

5.4. Results

This section describes the full application of the proposed methodology to a real case study, the same explored in Chapter 4, and presents some results.

5.4.1. *Case study*

From August 2020 to January 2021, three different episodes of contagion from Covid-19 occurred at some oil rigs off the Norwegian coast. These facts represented a demanding issue for OFFB (Operator's Association for Emergency Response), a 2nd line Emergency Response organization for O&G operators in Norwegian continental shelf, since the company had to face a new kind of emergence never managed before, without any specific prepared plans or procedures.

In [218], as previously described in Chapter 4, the authors explored the adaptive capacity put in place by this leading Norwegian organization in providing EM support, addressing the unexpected challenges (at the time of the event) represented by the handling of Covid-19 infection outbreaks on offshore oil rigs. The study, conducted through the FRAM, highlighted the relevance of organizational learning, which has allowed to handle emergencies by adapting plans to the specific context and by renewing EM procedures derived from lessons learned. More specifically, after the three episodes, a new procedure was developed by OFFB, taking into account what

[12] GeNIe Modeler by BayesFusion, LLC is a graphical user interface (GUI) to SMILE Engine and allows for interactive model building and learning. It is written for the Windows environment but can be also used on macOS and Linux under Wine. It has been thoroughly tested in the field since 1998, has received a wide acceptance within both academia and industry, and has thousands of users world-wide [255].

happened during the Covid-19 emergency. This document represents a guide for handling Covid-19-related incidents offshore. It is structured according to the four traditional operative phases put in place by OFFB's EM: mobilization, alert, combat and normalization. In the previous research paper ([218]) a focus on the 2nd line Operator's responsibilities and tasks for the combat phase has been proposed, formalizing the system in a dedicated FRAM model.
Subsection 4.5.4.1 has deeply dealt with this specific topic.

5.4.2. Applying Phase 1 - FRAM modelling

The functions and coupling associated with the OFFB's Covid-19 infection management procedure have been identified and qualitatively analysed within the framework of RE in [218], who focused on the combat phase of the newly introduced OFFB's procedure and formalized 2nd line responsibilities and tasks through a dedicated FRAM model (see Figure 32 in subsection 4.5.5). Thirty-two functions were identified, highlighting the relevant role of the coordination with several actors and the need of specific resources to guarantee the resilience of the Covid-19 infection management. The work introduced in the present Chapter starts from the same list of functions and couplings.

5.4.3. Applying Phase 2 - Belief BN implementation

Taking into account the findings from [218], a BN has been realized listing the foreground functions of the FRAM model. BN implementation starts from the single child node of the whole network, called "resilience potentials", which is intended to give a measure of the OFFB procedure's resilience potentials. The success of the procedure implementation depends on how four consecutive actions are carried out to conduct the evacuation of the people infected by Covid-19 from the offshore platforms to the mainland.

These four different actions, corresponding to the functions "managing transport by helicopter" (MTH), "managing reception at helicopter base" (MRHB), "managing transport by bus or rented car" (MTBRC), and "managing reception at hotel" (MRH), significantly contribute to the value of the procedure's resilience potentials and have been translated into the four parent nodes of the "resilience potentials" node.

While transferring the FRAM model into a BN, a simplification has been made in order to reduce the size and complexity of the network. Since the resilience potentials are highly influenced by the four "managing" functions, it has been chosen to consider only the functions of the FRAM model that interact directly with those four "managing" functions and to translate them into homonymous nodes of the BN. Most of these nodes describes the coordination with other actors that interact with 2nd line operator (i.e. 1st line, 3rd line, doctors, rig owner, municipality, etc.), other nodes are referred to the resources needed for the proper management of the infection contagion (i.e. trained people, infection control equipment, test onshore, etc.). Moreover, some functions, which are common to all nodes, like "Communication equipment functions regularly" or "Rig owner provides documentation", have not been translated into BN nodes because it is assumed that their output always occurs.

Figure 37 depicts the final BN model where the edges are represented in different colours, according to their dependence: they are blue and red, in order to distinguish the corresponding "input" aspect from the other "resource", "time", "control" and "precondition" aspects, explicating the dependence type (compulsory or supportive), as already introduced in subsection 5.2.1.

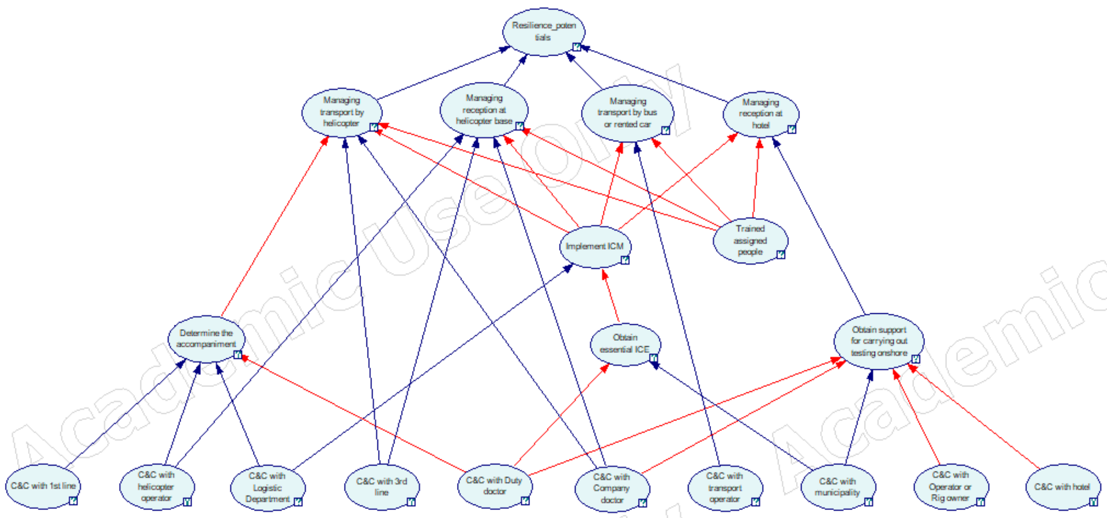

Figure 37 - final BN model of OFFB's Covid-19 EM procedure

5.4.4. *Applying Phase 3 - Determination of BN essential parameters*

By interviewing an operation manager from OFFB, the probability distribution of root nodes, intermediate nodes and child node have been quantitatively determined. More specifically, a team member, who participated in all the three Covid-19 cases and held the OFFB's Emergency Response Manager (ERM) role during the first case, was asked to assess the probability distribution of root nodes and the level impact for the intermediate nodes. These data were validated by one researcher, who had a sabbatical year working in OFFB. An additional validation step was performed by two researchers with experience in safety and resilience.

The choice to interview only the 1st Covid-19 case ERM is due to the following reasons: i) the context of this study is related to the three Covid-19 incidents where the interviewee was directly involved; ii) the emergency response operations are in general highly context related; iii) no other OFFB member participated in all the three cases. Obviously, this is a limitation and in the future a larger sample of experts will be needed for more in-depth studies.

With the above premises, on one hand each root node has been modelled taking into account the variability on timing and precision: therefore, four different values have been assigned by the expert to the four combinations ("on time precise", "delayed precise", "on time imprecise", "delayed imprecise") to determine the *a priori* probabilities of root nodes.

On the other hand, to model intermediate nodes, which had many parent nodes, GeNIe's Noisy-Max type has been adopted instead of general one. This choice simplified CPT's filling (e.g., for the node "Obtain support for carrying out testing on-shore" the number of parameters shifted from 4^5 = 1.024, with 4 levels of variability of each parent node and 5 parent nodes, to just 15).

In general, according to the expert's evaluations, a medium level impact has been fixed with reference to section 5.3 - phase 3. Specifically, for the node "Obtain support for carrying out testing on-shore", the corresponding influence factors $F_c = 2$ and $F_s = 0{,}3$ have been utilized to determine the 15 above mentioned parameters, starting from the *a priori* probabilities of each parent nodes.

5.4.5. Applying Phase 4 - Bayesian network running

The *a priori* probabilities of root nodes and the conditional probabilities of the intermediate nodes and child node have been imported into the developed BN, which has then been simulated with GeNIe Modeler software to assess the resilience through inference (see Figure 38) and to perform belief propagation, causal chain and sensitivity analysis about the OFFB procedure.

After running the model, resilience potentials have scored High 34% - Medium 28% - Low 38%, while the four managing functions, mentioned in section 5.4.3, can be ranked sequentially by effectiveness as follow:

– “managing transport by bus or rented car” (MTBRC): 62%;
– “managing reception at hotel” (MRH): 57%;
– “managing reception at helicopter base” (MRHB): 40%;
– “managing transport by helicopter” (MTH): 32%.

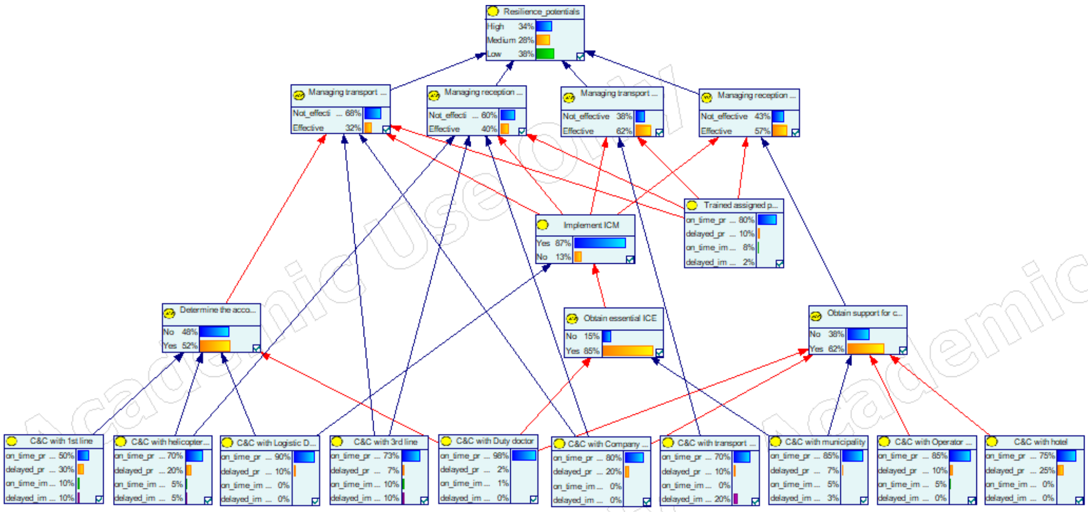

Figure 38 - results of the BN model of OFFB’s Covid-19 EM procedure

5.4.5.1. *Forward-propagation analysis*

The Forward-propagation analysis has been implemented to explore the influence mechanism of root nodes on the EM procedure resilience potentials. The joint probability of conditional nodes is calculated at the child node “resilience potentials” dynamically. It is noticeable that the absolute values of resilience potentials obtained from BN simulation have little numerical significance in absolute terms, and in the present study the quantified resilience potentials are used to indicate the EM procedure effectiveness: the higher value of resilience, the better the EM process.

The values found after BN running are strictly connected to the *a priori* probabilities given to the root nodes by the OFFB expert. More specifically, two root nodes have affected the effectiveness of the two lower values managing functions (i.e. MRHB and MTH): for the "Coordination and Communication (C&C) with 1st line", the event "on time precise" was scored just 50% and the same event for the root node "C&C with helicopter operator" received a score of 70%. The OFFB expert commented all their estimates: for example, for "C&C with 1st line" he argued that 1st line mainly communicated with 3rd line instead of 2nd line in the first hours after the incidents, while for "C&C with helicopter operator" he reported that the uncertainty, associated with the Covid-19 situation, created an arena for discussion and teamwork. OFFB and helicopter operator needed to find the best possible course of action to deal with Covid-19 in a collaborative way.

Consequently, a gross improvement in the procedure resilience potentials would certainly be obtained by enhancing the communication and coordination with 1st line and helicopter operator. This statement is easily demonstrated through BN running: by setting effectiveness to 100% for both the root nodes at hand, the resilience potentials increase from High 34% - Medium 28% - Low 38%, to High 44% - Medium 24% - Low 33% while MTH and MRHB raise respectively to 50% and 53%.

5.4.5.1.1. Different scenarios

In order to complement the previous analysis, it would be desirable to determine (e.g.) which are the root nodes with the highest impact on the child node and the consequences of improved or deteriorated timing and precision variability. Therefore, a set of diverse scenarios has been investigated (see Table 8). These scenarios have been constructed, assigning a single node at time a value equal to 100% for the "delayed precise" event, while in all the other root nodes the "on time precise" event was set at 100%. It is worth recalling that setting the node status to “delayed precise” to 100% means that the event certainly occurs with a delay, while precision is not affected. The developed BN has been simulated for each scenario, and the variations in the EM procedure resilience potentials and the effectiveness of the four managing functions involved in resilience (MTH, MRHB, MTBRC, and MRH) are summarized in Table 8. The results in Table 8 can be used to evaluate the impact of the delay of each root node on the EM procedure resilience potentials and over the four managing functions.

Table 8 - results of different scenarios

		Resilience potentials			**MTH**	**MRHB**	**MTBRC**	**MRH**
ID	**Root node “set to delayed precise = 100%”**	*High*	*Medium*	*Low*	*Effective*	*Effective*	*Effective*	*Effective*
1	C&C with Municipality	22%	18%	60%	38%	38%	38%	10%
2	Trained people assigned	23%	35%	42%	40%	40%	40%	40%
3	C&C with Duty Doctor	24%	22%	54%	20%	49%	49%	20%
4	C&C with 3rd line	34%	45%	21%	14%	14%	100%	100%
5	C&C with Helicopter operator	42%	40%	16%	49%	10%	100%	100%
6	C&C with Company Doctor	47%	38%	22%	40%	40%	100%	58%
7	C&C with Logistic Department	63%	23%	14%	29%	91%	91%	91%
8	C&C with Transport operator	64%	28%	8%	100%	100%	20%	100%
9	C&C with Operator/Rig Owner	77%	18%	5%	100%	100%	100%	49%
10	C&C with the hotel	83%	13%	4%	100%	100%	100%	62%
11	C&C with 1st line	85%	12%	3%	66%	100%	100%	100%
	Managing functions effectiveness mean values				54%	62%	76%	66%

The node, whose delay impacts negatively on the resilience potentials more than others, is “C&C with municipality” followed by “Trained people assigned". The model confirms the importance of effective and punctual coordination and communication with the municipality and the need to have readily available well-trained people.

From the calculation of the mean values for the managing functions, it is shown that MTH and MRHB are the two functions majorly affected than the others by the delays that can occur in the root nodes. These findings are due to the fact that these two functions are the first to be carried out following the occurrence of the emergency and the most difficult to coordinate.

5.4.5.2. Backward-propagation analysis

The Backward-propagation analysis also known as reverse inference, target-driven or hypothesis-driven reasoning, is useful for diagnosing and explaining the cause of an accident in a manner that runs counter to a directed graph.

5.4.5.2.1. Key root nodes

Based on reverse inference algorithm in BNs, "resilience potentials - Low level" is set to 100%, which means that the EM procedure is set in a condition where it is exposed to unmanageable variability. Root nodes with a value of "on time precise" state less than 80% are called key root nodes and are marked yellow in Figure 39.

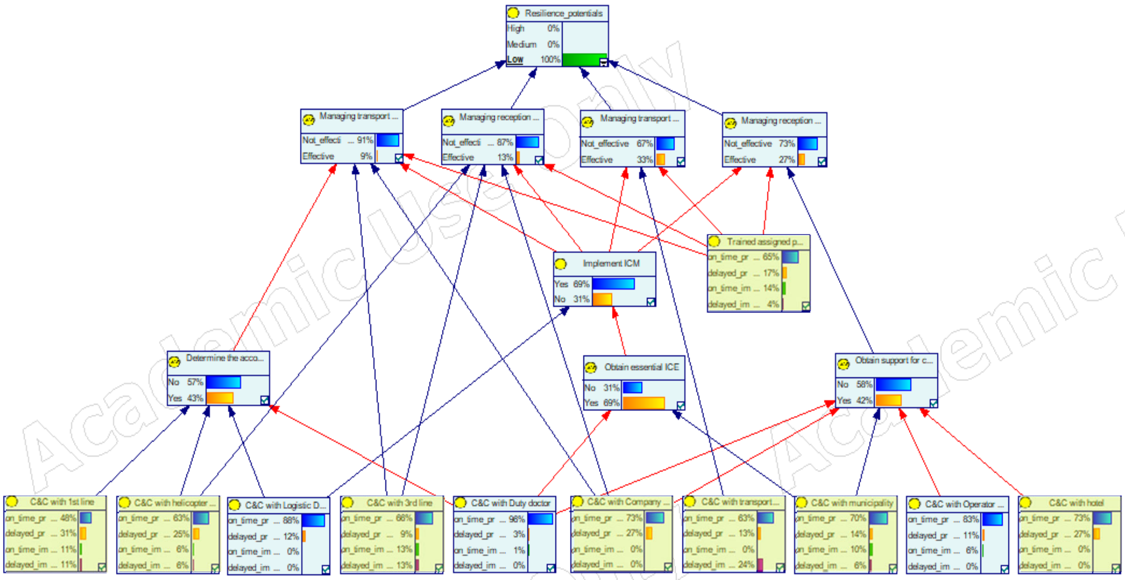

Figure 39 - Key root nodes (in yellow)

The percentages, reported in Table 9, are influenced by the expert's estimates: key root nodes are the same nodes which should be enhanced, in order to have a gross improvement in the EM procedure resilience potentials, among them the communication and coordination with 1^{st} line (cf. subsection 5.4.5.1).

Table 9 - key root nodes for "resilience potentials - Low level" set to 100%.

Root node	**"precise on time" state value**
C&C with 1^{st} line	48%
C&C with Helicopter operator	63%
C&C with Transport operator	63%
Trained people assigned	65%
C&C with 3^{rd} line	66%
C&C with Municipality	70%
C&C with Company Doctor	73%
C&C with the hotel	73%

5.4.5.2.2. Maximum Causal Chain

In the present study, a maximum causal chain refers to the most likely path that causes the decreasing of resilience potentials. By using the "strength of influence” tool in GeNIe Modeler, the maximum causal chain, shown in bold in Figure 40, can be generated. The coordination and communication with municipality, in order to obtain essential ICE (infection control equipment) and implement the ICM (infection control measures), when people are being received at the hotel, is the maximum causal chain of the resilience potentials. The results of this analysis are basically consistent with the previous findings.

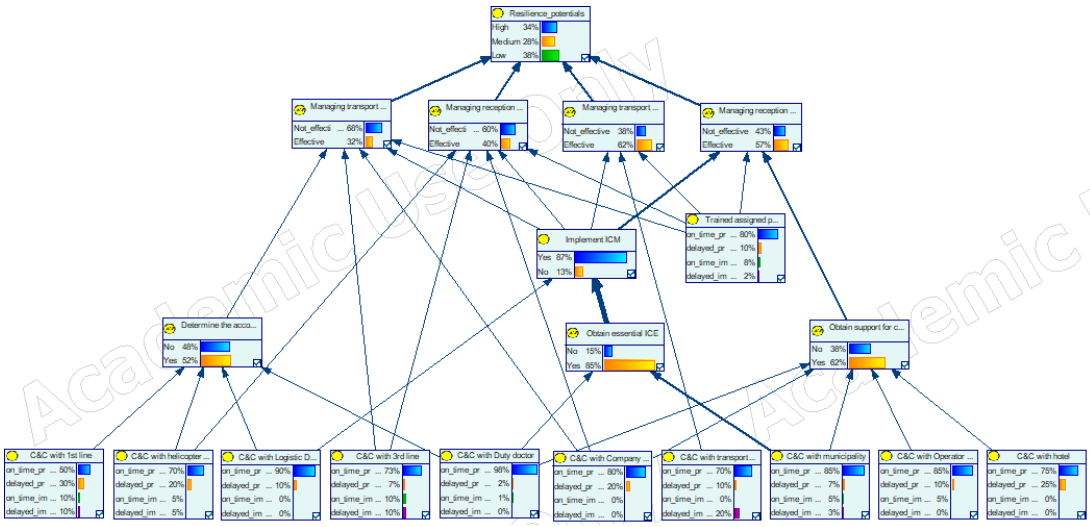

Figure 40 - Maximum Causal Chain (in bold)

5.4.5.2.3. Sensitivity Analysis

Sensitivity analysis facilitates identifying the nodes that have a high impact on the resilience potentials. This assessment is meant to guide the prioritization of specific improvements, when applying to the EM procedure. In the present study sensitivity analysis is employed to distinguish the influence of root nodes on the EM procedure resilience potentials and can be implemented with the backward propagation of the developed BN. The influence mechanism of root nodes on the target node, usually referring to the child node, is presented under a given set of conditions. Setting “resilience potentials” as the target node, the root nodes have been ranked according to their sensitivity values (Table 10 and Figure 41).

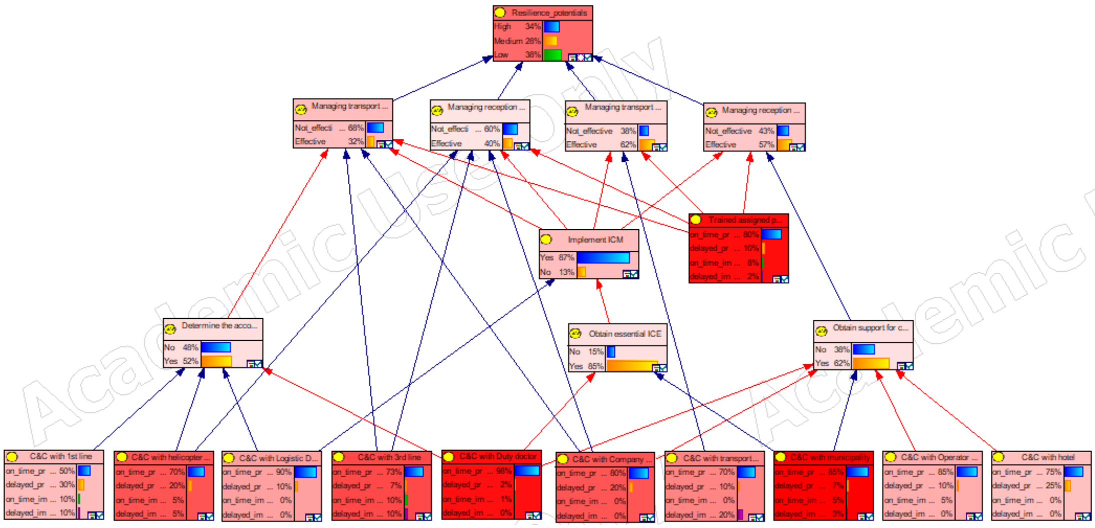

Figure 41 - Sensitivity analysis: Darker red background indicates root nodes with higher impact on the "Resilience potentials" target node

Table 10 - sensitivity values of root nodes for "resilience potentials" set as target.

	Sensitivity	
Root node	**Max**	**Avg**
C&C with Municipality	0,461	0,143
Trained people assigned	0,357	0,110
C&C with Duty Doctor	0,347	0,086
C&C with 3rd line	0,214	0,061
C&C with Helicopter operator	0,195	0,055
C&C with Company Doctor	0,194	0,032
C&C with Transport operator	0,128	0,029
C&C with Logistic Department	0,095	0,016
C&C with Operator/Rig Owner	0,080	0,019
C&C with 1st line	0,064	0,018
C&C with the hotel	0,060	0,010

The most sensitive nodes are "C&C with municipality" and "Trained people assigned", in accordance with the results from scenario analysis and maximum causal chain. Moreover, note that "C&C with Duty doctor" is the third root node in terms of sensitivity analysis, but the last among the key root nodes. This fact is explained by the probabilities given by the expert (i.e. 98% for the event "on time precise"): according to OFFB's ERM the communication and coordination with the duty doctor during the EM process was excellent, but, according to our BN, this node has a high impact for the child node "resilience potentials" and, as such, represents a crucial node. This observation may force considering current status of duty doctor, checking on working hours, and ensuring a well-trained practitioner able to act promptly and precisely.

As regard the intermediate nodes, the same analysis could be performed to identify the sensitivity level of the root nodes with respect to the four managing functions, selected one at time as target node, in order to understand which root nodes are the most influencing for each managing functions.

Table 11 - sensitivity values of root nodes for the four managing functions, after having selected one at time as target node

		Sensitivity	
Managing function	**Root node**	**Max**	**Avg**
MTH	C&C with 3rd line	0,332	0,142
	C&C with Duty Doctor	0,243	0,091
	C&C with Municipality	0,225	0,105
MRHB	C&C with Helicopter operator	0,454	0,180
	C&C with 3rd line	0,416	0,178
	C&C with Municipality	0,282	0,131
MTBRC	C&C with Transport operator	0,518	0,178
	C&C with Municipality	0,442	0,205
	Trained people assigned	0,437	0,200
MRH	C&C with Municipality	0,588	0,272
	C&C with Duty Doctor	0,448	0,167
	Trained people assigned	0,399	0,182

In Table 11 the most three sensitive nodes for each managing function have been reported. "C&C with Municipality" is the only root node which is present in all the sensitivity analyses conducted for the four managing functions: this is a further confirmation of the importance of reliable and punctual coordination and communication with the municipality involved in the EM process.

5.5. Discussion

According to the findings related to the case study, besides the two root nodes that received the lowest probability values in terms of timing and precision by the expert (i.e. "C&C with 1st line" and "C&C with helicopter operator"), the BN forward and backward propagation analyses reveal that "C&C with municipality" and "Trained people assigned" are the nodes whose delay and lack of precision negatively impact on the resilience potentials more than others. The model highlights the importance of effective and punctual coordination and communication with the municipality and the need to have on time and well-trained people, in order to cope with all the contingencies and difficulties that may arise during an emergency response operation such as Covid-19 outbreaks management on offshore O&G rigs. These results are confirmed by the maximum causal chain of the resilience potentials which is sequentially constituted by the coordination and communication with municipality, the obtaining of essential ICE, and the implementation of the ICM, when people are being received at the quarantine hotel. Furthermore, the mean values of the managing functions effectiveness, calculated from eleven scenarios, show that MTH and MRHB are the two functions that are more affected than the others by the delays that can occur in root nodes. These functions are the first to be carried out following the occurrence of the emergency and the most difficult to coordinate.

The following lessons can be derived from the case study, with the application of the proposed methodology:

- the need for clear and on time coordination and communication with the municipality involved in the Covid-19 outbreak management;
- the need for assigning people properly and on time, prioritizing the most critical actions for training;
- the attention to the sequencing of actions, which have to be performed close to the occurrence of cases of contagion (i.e., the actions related to MTH and MRHB functions);
- the need of obtaining essential ICE and implementing the ICM to manage all the phases of the EM process.

More generally, this study has provided an explorative method to analyse resilience capacity, calculating the potential cumulative effects of functional resonance in complex socio-technical systems, through a combination of FRAM and BN where the former has been used to model the actors and the interactions of the system and the latter has provided a quantitative dimension to the assessment. This methodology has allowed to understand how to evaluate the resilience potentials of a system, like EM, that evolves during time with continuous data updates.

Some simplifications have been adopted, which in fact represent some limitations for the study. For instance, this research has focused on timing and precision phenotypes among the others because they represent the simplest solution to describe the consequences of performance variability [40]. Nonetheless this is a study limitation, it is fair to point out that, in the majority of socio-technical applications, timing and precision are the main items to investigate [212].

More specifically, in terms of timing an Output can occur too early, on time, too late, or not at all [258]. An Output that is not available on time can affect the variability of downstream functions in several different ways. This research has used two different status to describe timing: "on time" and "delayed". The latter means that the event in question certainly occurs but with a delay.

In terms of precision, an Output can be precise, acceptable, or imprecise [258]. Since the Output provides the coupling between upstream and downstream functions, the meaning of precision is relative rather than absolute. In the present study, two different status have been used to describe precision: "precise" and "imprecise". A precise Output meets the needs of a downstream function: therefore, it will not increase the variability of downstream functions, and may potentially even reduce it. On the other hand, an imprecise Output is incomplete, incorrect, ambiguous or otherwise misleading: consequently, it cannot be used as it is, but requires interpretation, verification, comparison with other data or with the situation as such. These are all things that can increase the variability in the receiving function, typically by consuming resources and time that could and should have been used for other purposes.

Another limitation regards the classification of FRAM dependences, distinguishing between supportive and compulsory. It is worth mentioning that this classification, inspired by [249], is a simplification made in order to give a priority to the "Input" aspect over the others.

Related to the latter question, another simplification has been adopted by choosing only two different influence factors in order to calculate the CPTs of the intermediate nodes. In future, a specific influence factor could be associated to each type of FRAM aspects. For example, these factors could be obtained through a data driven approach, based on real data.

Finally, the choice to interview only the 1st Covid-19 case ERM represents a further limitation and in the future a larger sample of experts will be needed for more in-depth studies.

5.6. Concluding remarks

The study introduced in the present Chapter has proposed a novel comprehensive methodology to assess the resilience potentials of a socio-technical systems, instancing the analysis in an EM procedure for Covid-19 outbreaks management on O&G rigs offshore. The case study has been intended to provide a proxy measure of the resilience namely the functional resonance, i.e. the possibility that the variability can become unmanageable, leading to a no longer resilient system. Starting from a FRAM model of the EM system, the four main functions (i.e. the "managing" functions) that contribute most to the EM procedure resilience potentials and their coupling functions have been transferred into a BN. The *a priori* probabilities of root nodes have been assigned by expert judgments and the conditional probability tables have been computed quantitatively based on the probability distribution of the root nodes. Finally, the developed BN for the EM procedure resilience potentials evaluation has been simulated in GeNIe Modeler, by which the different scenarios analysis, the key root nodes, the maximum causal chain, and the sensitivity analysis have been performed. The results demonstrate that this methodology can comprehensively identify the active functions involved in the EM procedure and effectively evaluate the EM procedure resilience potentials for the Covid-19 outbreaks management on O&G rigs offshore.

The proposed probabilistic-based methodology introduced in the present Chapter still has some limitations. For instance, the BN parameters, i.e. the *a priori* probabilities for root nodes and the level of impact for functions dependences have been determined by a single expert who was involved in all the three Covid-19 cases: larger samples should be needed for in-depth studies. Only timing and precision have been considered among other phenotypes and only two influence factors have been utilized distinguishing between supportive and compulsory dependences. Moreover, the acyclic nature of a BN requires also further revisions in case of loops in the FRAM model. This point could be easily solved recurring to dynamic BN, where staged functions are presented at different time steps.

This work is precisely contextualized in an emergency management procedure, paving the way to a systematic modelling of interdependencies in a safety-critical domain. The following aspects are the main contributions of the research: i) proposing a systematic assessment of the potential for functional resonance, as a proxy for resilience that relies on the integration of FRAM and BN; ii) offering an instantiation of this approach in the domain of emergency management, taking advantage of expert-based judgements; iii) fostering the capacity to optimize resilience performance of an EM procedure, by updating BN parameters based on newly available information. This aspect is particularly relevant for scenarios like Covid-19 management, where information is fragmented and updated dynamically.

The nature of the proposed methodology complements the weakness of a typical FRAM model, adding a dimension to allow numeric assessment and inference management. From the systematic nature of the investigation that can be obtained from the BN, the proposed methodology results suitable to be transferred to other civilian or military contexts, especially where command-and-control mechanisms are in place to enable decision makers exploring the impacts of timing and precision on normal and abnormal operations.

CHAPTER 6

6. SUMMARY AND CONCLUSIONS

6.1. Summary of the dissertation

This dissertation is grounded on the management of resilience in Critical Infrastructures, emphasizing the strategic role these managerial aspects play in response to internal and external stressing factors.

The initial literature review, deeply discussed in Chapter 2, explored the qualitative and semi-quantitative approaches to the CIs' resilience analysis and identified four principal dimensions of resilience referred to CIs (i.e., techno-centric, organizational, community, and urban).

The following research focused on the resilience organizational dimension and aimed at answering the dissertation research question: *how can learning improve resilience in an organization*?

Chapter 3 discussed the Learning From Incident theory and introduced a theoretical LFI model, which was tested addressing a real case study, the reverse logistics supply chain of small arms. This case study takes its cue from the reports of technical inconveniences concerning a specific weapon. The considered reporting activity covered a period of six years, while the type of weapon at hand was acquired through various contracts with different stipulation dates and supplied quantities. The first step of the work was the data collection from the received reporting forms. Then, a centralized digital archive was created, structuring the data in a relational database, used to aggregate the information from which to extract useful indications for process improvement. More specifically, a Business Intelligence (BI) study was conducted on this database, in order to facilitate data extraction and analysis in a dynamic way, allowing an immediate consultation and supporting a holistic analysis according to a multiple perspective.

Speaking of BI, the latter has been adopted in several domains as it provides a greater understanding of the fundamental factors underlying a certain process. Thanks to the interpretation of structured data, combined and aggregated information, it was possible to make some considerations from which proposals for changes or solutions arose, in order to improve the resilience of the supply chain of small arms.

Since there was the intention not to damage intellectual property and not to disclose further information that went beyond the scope of the work, i.e. the discussion of the importance of ILS and the potential of the method applied to the case study, the data were deliberately not detailed, not reporting in any case values in absolute terms but always in percentages. Moreover, the description of the inconveniences was not deepened, avoiding revealing the content of the reports in detail. This decision did not compromise the use of the Learning From Incidents framework, applicable to diverse CIs.

In summary, this first study has empirically demonstrated how data on technical inconveniences acquire a value that goes beyond technical investigation: using a BI approach, a centralized information management system, based on Learning From Incidents theory and developed for the small arms SCM, can be the basis for an effective decision-making process, capable of increasing the systemic resilience of the supply chain itself.

After exploring the benefits of a LFI system for the resilience of a supply chain, the research question was extended to another extremely topical context, i.e. Emergency Management operations. In this case, in order to understand how learning could improve organizational resilience, the study has examined learning opportunities that emerge through the exploration of adaptive practices put in place by an EM company named OFFB to face the complexity of a socio-technical work domain as the management of three Covid-19 outbreaks on Oil & Gas platforms. Chapter 4 and 5 discussed qualitative and quantitative approaches that have been adopted to analyze the resilience potentials of this specific socio-technical system.

More specifically, this part of the research started with the analysis of data collected through various sources to broaden the information framework. In order to acquire a culture on the company's *modus operandi*, internal documents and procedures related to EM were examined, and reports of an application called CIM (Incident & Crisis Management) tool, used by OFFB's members for the real-time dissemination of information and the creation of a clear and constantly updated situation picture of the emergency in progress, were analyzed. Finally, several digital focus groups were organized with expert staff from the OFFB who held the role of Emergency Response Manager for the management of the first case of Covid-19.

Over CIM tool reports, a Thematic Analysis was first carried out and then a Hierarchical Task Analysis, for grouping the information into tasks of a hierarchical nature, was performed. Following these analyzes, some questions were devised, aimed at constituting a semi-structured guide to facilitate the telematics focus groups. The whole study was conducted following an ethnographic research approach that allowed to understand the working environment and to fully understand what had happened during the real case studies, taking advantage of the presence of expert staff from OFFB and scholars from the University of Stavanger, who had spent a period of time in OFFB for other research activities.

Thanks to the various sources used, a reconstruction of what happened in the three different case studies was possible and the OFFB's involvement in EM was deeply analyzed within a broader context that saw a multiplicity of stakeholders.

To study the management of the first case of infection from Covid-19, through the FRAM a Work As Done (WAD) model of what had happened from a procedural point of view was developed. This model highlighted the differences with respect to the provisions of the internal procedures (Work As Imagined - WAI) for EM. Given the complexity of management referred to the first case, four different FRAM layers were elaborated, one for each operational phase of OFFB's procedure. Thanks to the experience gained by OFFB during the first episode, the management of the other two Covid-19 cases was instead much less burdensome and for this reason a single FRAM layer for each case was utilized.

The use of FRAM made possible to identify which actors were involved, to define the various functions and to underline the interconnections between them in the three occurred episodes. More specifically, the FRAM models, through an increasingly lean representation of the procedures, showed an ever less complex and articulated EM by OFFB both at the level of the involved actors and the number of activated functions or interconnections between them. Therefore, the developed models objectively highlighted the adaptive capacity and the organizational resilience of OFFB company in the EM of a case not envisaged by internal procedures.

In summary, the models were able to highlight the organization's ability to adapt and learn after the occurrence of each Covid-19 case and constitute a method of qualitative analysis of the organizational resilience of a socio-technical system, such as that constituted by the organization of OFFB company.

Starting from the learning following the occurred episodes, a new procedure for the Covid-19 cases management was issued and modeled once again using FRAM (in this case it was a WAI model). Chapter 5 detailed a novel methodology to conduct a quantitative assessment of the resilience potentials of this specific procedure. This evaluation recurred to a Bayesian Network that allowed forward and backward analyses on the EM procedure, adding a numeric dimension to the study previously conducted through the FRAM.

6.2. Concluding remarks

The research activity carried out during the PhD period has offered some significant contributions to the current scientific panorama of the Critical Infrastructures management, by improving their resilience through learning from past events.

The systematic review on qualitative and semi-quantitative approaches provides a hitherto unexplored view of the reference literature, but the repeated failures and disasters in Critical Infrastructures highlight the importance of improving scientific understanding and policy-making related to CIs' resilience. To effectively manage resilience in modern CIs, it is necessary to understand the functioning of CIs, as well as the needs and key characteristics of all stakeholders involved. This requires the use of methodologies that can capture the diversity, heterogeneity, and interconnectedness of CIs, particularly in the context of cyber-physical systems ([176]). Qualitative research has been shown to be particularly useful in this regard, as demonstrated by the results of the systematic review presented in Chapter 2. Through qualitative research, the analysis of CIs can more accurately reflect the intricate and closely-linked factors that influence individual, group and societal behaviours as they interact with technological systems.

The LFI system proposed in the study on reverse logistics (see Chapter 3) fills a gap present so far in the available literature: thanks to the implementation of a BI architecture, the learning system from the incidents in question, supporting a large number of analyses and a dynamic investigation of variables, offers the decision maker a valid tool for a resilient reverse supply chain in the military sector. In Chapter 3, the literature analysis about LFI has emphasized the importance of implementing an effective incident learning system in order to improve resilience and safety within an organization.
The findings of the analysis provide empirical evidence of how technical incident data can have value beyond the technical investigation itself, and how a well-structured database can serve as a foundation for effective decision-making, which can be facilitated by synthetic user-friendly and easily accessible dashboards.

From a Business Intelligence perspective, the LFI system developed in this dissertation demonstrates the benefits of a centralized information management system and suggests potential areas for future development beyond the scope of the specific organization analysed, such as the creation of inter-forces reporting regulations, increased digitization throughout the process, the adoption of smart systems, and the promotion of a culture of effective incident reporting.

The ability to learn and adapt was also analysed in the OFFB organizational resilience study, conducted using a qualitative approach. The research presented in Chapter 4, extending the applicability of the FRAM to other contexts, such as that of Emergency Management, demonstrates the potential of this method in objectively detecting the adaptive capacity and resilience of an organization dealing with the EM of an event not foreseen by internal procedures.

That study has contributed to the literature on organizational resilience by identifying different learning opportunities from a unique type of emergency, specifically the Covid-19 pandemic. The analysis, which focused on three cases of Covid-19 related incidents on offshore oil platforms, revealed the evolution of an emergency response (ER) organization and its ability to adapt to new challenges and learn from previous incidents. The first case was managed using a traditional ER approach, which resulted in uncertainty and a lack of specific procedures, and highlighted the risks and challenges that were different from those anticipated in the emergency plans. Despite this unanticipated complexity, the ER organization as a whole was able to improvise and resolve situations not included in the original emergency plans. The following cases were handled with less involvement of the 2nd line ERT and more participation from the 1st and 3rd line operators, following the crisis induced learning. However, it was recognized that difficult case management cannot be delegated solely to improvisation.

The 2nd line operators enriched their capacity to provide support to the 1st and 3rd line ER organizations through the development of a new procedure that identified functional hotspots that were applicable to a wide variety of Covid-19 cases. The case studies confirm that EM organizations benefit from an efficient and transparent reporting system to foster continuous learning from events and, as a result, improve decision-making at the strategic level. The results align with traditional expectations of Resilience Engineering [224] highlighting the need for a unity of effort, implemented through centralized planning and decentralized execution to empower mutual understanding and rapid decision-making [225].

This part of the research also demonstrated the applicability of the FRAM, a systemic approach that is currently applied in emergency management systems to a limited extent, to support a structured learning for organizational resilience and planning. The use of FRAM helped to identify the actors involved, define the various functions, and identify the interconnections between them, for both actual practices and prescribed work. The research also confirmed the benefits of studying multiple varieties of socio-technical work and highlighted the need for knowledge of these varieties, their small disturbances, inconsistencies, ambiguities, and conflicting goals to further extend crisis induced learning [176], when looking at an incident. The research is fully aligned with recent RE contextual information and need of integrated investigations on the nuances of adaptation [226] for Work-As-Observed (WAO), Work-As-Prescribed (WAP), Work-As-Normative (WAN), Work-As-Disclosed (WADI) [176].

The study demonstrates the usefulness of the FRAM approach in understanding the responses of a socio-technical system to unexpected emergency situations: FRAM, helps gathering and organizing knowledge systematically. Additionally, the work identifies positive characteristics of organizations that can be applied to other scenarios, and suggests best practices for effective crisis management. The study also emphasizes the importance of a positive learning attitude, openness, trust, and the sharing of beliefs and perceptions in decision-making at various organizational levels. These factors are crucial for success in the face of disasters, and should guide decision-makers to ensure organizational resilience [227].

Finally, to complete the analysis of Critical Infrastructures management in terms of security, a quantitative approach has been adopted, by utilizing Bayesian networks for expert-driven probabilistic analysis, in order to propose a method for a possible proactive assessment of the resilience potentials of the internal procedures of complex socio-technical systems.
More specifically, the research presented in Chapter 5 introduced a novel method for evaluating the resilience potentials of socio-technical systems, specifically focusing on an emergency management procedure for controlling Covid-19 outbreaks on offshore O&G rigs. The case study used in the research aims at providing a proxy measure of the resilience, specifically through the concept of functional resonance, which refers to the potential for variability to become overwhelming and compromise the system's ability to remain resilient. Starting from the FRAM model of the EM procedure introduced in Chapter 4, a BN has been implemented transferring the four main functions (i.e., the "managing" functions) that contribute most to the EM procedure resilience potentials and their coupling functions into nodes and edges of the network. The *a priori* probabilities of parent nodes have been derived from experts evaluations and the CPTs have been computed quantitatively based on the probability distribution of the parent nodes. Finally, the implemented BN for the EM procedure resilience potentials assessment has been set in GeNIe Modeler. Specifically, different scenarios, key root nodes, maximum causal chain, and sensitivity analyses have been assessed. The findings show that this methodology can comprehensively identify the active functions involved in the EM procedure and effectively assess the EM procedure resilience potentials for the Covid-19 outbreaks management on O&G rigs offshore.

The following aspects are the main contributions of the research discussed in Chapter 5: i) introducing a systematic approach for assessing the potential of functional resonance as a proxy for resilience by combining FRAM and BN; ii) providing an example of this approach in the field of emergency management using expert-based judgments; iii) enhancing the ability to optimize the resilience of an emergency management procedure by updating the BN parameters with new information, which is particularly important in scenarios such as managing Covid-19 where information is constantly changing.
The proposed method addresses the limitations of a traditional FRAM model by incorporating a numeric component for assessment and decision-making. The systematic approach gained by using the BN makes it suitable for use in other civilian or military contexts where command-and-control mechanisms are in place, specifically for assessing the effects of timing and precision on normal and abnormal operations.

6.3. Future research

The research presented in Chapter 2 discusses how qualitative research can be used to improve the resilience management of Critical Infrastructures, but there are still areas that need further study. These include combining qualitative and quantitative methods, integrating information from different scales and stakeholders, and ensuring that knowledge is shared and used to continuously improve resilience. Therefore, future research on Critical Infrastructures resilience should focus on integrating information in order to support the survival and development of organizations, communities, cities, and societies in our rapidly changing world.

As regard the research introduced in Chapter 3, it provides just a subset of possible indexes for monitoring supply chain sustainability and increasing its resilience using the LFI framework. Additional quantitative analysis techniques, such as clustering algorithms, multi-dimensional correlations, and trend analyses could be employed to further expand the framework capabilities. The intelligent data management system described in the research does not take into account privacy and cyber-security issues [195], which represents a potential area for future research. The LFI system could also be enhanced by examining the connections between the supply chain and the outside world, i.e., exploring how local learning is shared outside the supply chain agents, providing an external cycle for shared learnings. This cycle could be closed by the benchmarking process that analyses best practices and adapts them to improve the military system. The described approach is based on the Italian regulatory framework for military reporting but is flexible enough to be adapted to other contexts that rely on the NATO foundations for systemic learning. It is important to note that although the case study discussed in Chapter 3 focuses on small arms, the same logic can be applied to other types of tools and other phases of the item life cycle.

The FRAM approach introduced in Chapter 4 is an improvement over traditional accident analysis and risk management models, which often have limitations imposed by linearism and reductionism (e.g. domino models, fault tree analysis, event tree analysis, etc.), but it is not necessarily a comprehensive solution for any operating case [212]. Future research could use the FRAM to study the procedures and activities of more complex emergency or crisis management organizations, both civilian and military. Using FRAM-like methods is expected to aid in the investigation of WAx varieties, and increase the proactive nature of crisis management and crisis induced learning in diverse operational settings [176].

Finally, even the proposed probabilistic-based methodology in Chapter 5 has some limitations. For instance, the BN parameters, such as the initial probabilities for root nodes and the level of impact for functional dependencies, have been determined in this early attempt by a single expert who, however had large expertise in handling the scenario, being him involved in all three Covid-19 cases. To conduct more thorough research, a larger sample size should be used, taking advantage of the recursive probability updated typical of a BN. Additionally, the study only took timing and precision into consideration as phenotypes and only used two influence factors to differentiate between supportive and compulsory dependencies. In the future, a data-driven approach could be used to associate specific influence factors with each type of FRAM aspect, even using near real-time data. Furthermore, the acyclic nature of a BN may need to be revised in cases where there are loops in the FRAM model. This can be naturally addressed by using a dynamic BN, which may allow to present functions at different time steps and their updated functional values over time as per a functional loop.

While the study of Critical Infrastructures is still an open and challenging topic, this dissertation has provided methodologies and running examples on how systemic approaches may support data-driven learning to ultimately improve organizational resilience. These results, possibly extended with future research drivers, are expected to support decision-makers in their tactical and operational settings.

APPENDIX

Table 12 - summary of reviewed papers in Chapter 2

Authors	Title	Year	Main dimension	Domain	Approach
Banks L.H., Davenport L.A., Hayes M.H., McArthur M.A., Toro S.N., King C.E., Vazirani H.M.	Disaster Impact on Impoverished Area of US: An Inter-Professional Mixed Method Study	2016	Community	community	interview; questionnaire; ethnographic research
Glavovic B.C.	Sustainable coastal communities in the age of coastal storms: Reconceptualising coastal planning as 'new' naval architecture	2008	Community	not specified	interview
Mavhura E.	Applying a systems-thinking approach to community resilience analysis using rural livelihoods: The case of Muzarabani district, Zimbabwe	2017	Community	community	interview; questionnaire; focus group; observation
Ong J.M., Jamero M.L., Esteban M., Honda R., Onuki M.	Challenges in Build-Back-Better Housing Reconstruction Programs for Coastal Disaster Management: Case of Tacloban City, Philippines	2016	Community	community	questionnaire; focus group; interview
Herrmann Lunecke M.G.	Urban planning and tsunami impact mitigation in Chile after February 27, 2010	2015	Community	urban infrastructures	interview; questionnaire

Authors	Title	Year	Main dimension	Domain	Approach
Simpson D.M., Lasley C.B., Rockaway T.D., Weigel T.A.	Understanding critical infrastructure failure: Examining the experience of Biloxi and Gulfport, Mississippi after Hurricane Katrina	2010	Community	community	interview
Rogers L., Borges D., Murray J., Molthan A., Bell J., Allen T., Bekaert D., Loftis J.D., Wang H., Cohen S., Sun D., Moore W.	NASA's Mid-Atlantic Communities and Areas at Intensive Risk Demonstration: Translating Compounding Hazards to Societal Risk	2019	Community	community	workshop
Johnsen S.O., Øren A.	10 years from risk assessment to regulatory action—is complacency creating a reactive and brittle regulatory regime in Norway?	2015	Community	not specified	interview
Grosse C.	Airports as Critical Infrastructure: The Role of the transportation-by-air System for Regional Development and Crisis Management	2019	Community	transportation systems; aviation	interview; questionnaire; workshop
Verma R., Karimi S., Lee D., Gnawali O., Shakery A.	Newswire versus Social Media for Disaster Response and Recovery	2019	Community	community	social network
Murphy S.A., Brown J., Shankar A., Lichtveld M.	A quantitative assessment of institutions of higher education disaster preparedness and resilience	2019	Community	community	questionnaire

Authors	Title	Year	Main dimension	Domain	Approach
Petersen L., Sjöström J., Horvath E.	Evaluating critical infrastructure resilience via tolerance triangles: Hungarian Highway pilot case study	2019	Community	transportation systems	questionnaire
Bunney S.L., Ward S., Butler D.	Can UK water service providers manage risk and resilience as part of a multi-agency approach?	2016	Community	water facilities	interview
Cradock-Henry N.A., Fountain J., Buelow F.	Transformations for resilient rural futures: The case of Kaikōura, Aotearoa-New Zealand	2018	Community	community	interview; focus group
Akhtar R., Santos J.R.	Risk-based input-output analysis of hurricane impacts on interdependent regional workforce systems	2013	Community	not specified	questionnaire
Pagán-Trinidad I., Lopez R.R., Diaz E.L.	Education and building capacity for improving resilience of coastal infrastructure	2019	Community	community	workshop
Bouchon S., Urquhart J., Gibson R., BaMaung D., Dimauro C., Trucco P.	The role of public-private stakeholder collaboration to achieve critical infrastructures resilience: Main findings from the EU-CIPS MIRACLE project	2014	Community	not specified	questionnaire; focus group; interview
Petersen L., Lange D., Theocharidou M.	Who cares what it means? Practical reasons for using the word resilience with critical infrastructure operators	2020	Community	not specified	workshop; interview;

Authors	Title	Year	Main dimension	Domain	Approach
Rosenqvist H., Reitan N.K., Petersen L., Lange D.	ISRA: IMPROVER societal resilience analysis for critical infrastructure	2018	Community	logistics	focus group; questionnaire
Adini B., et al.	Striving to be resilient: What concepts, approaches and practices should be incorporated in resilience management guidelines	2017	Organizational	aviation; healthcare	Delphi method; questionnaire
Van Laere J., Berggren P., Gustavsson P., Ibrahim O., Johansson B., Larsson A., Lindqwister T., Olsson L., Wiberg C.	Challenges for critical infrastructure resilience: Cascading effects of payment system disruptions	2017	Organizational	payment system	interview; workshop
Labaka L., Comes T., Hernantes J., Sarriegi J.M., Gonzalez J.J.	Implementation methodology of the resilience framework	2014	Organizational	not specified	interview; workshop; Delphi method; questionnaire
Pathirage C., Al-Khaili K.	Disaster vulnerability of Emirati energy sector and barriers to enhance resilience	2016	Organizational	energy systems; supply chain management; oil and gas infrastructures	questionnaire; interview
Johansson B.J.E., Jaber A., Van Laere J., Berggren P.	The lack of preparedness for payment disruptions in local community core businesses	2018	Organizational	payment system	interview
Mendonça D., Wallace W.A.	Factors underlying organizational resilience: The case of electric power	2015	Organizational	energy systems	interview; questionnaire

Authors	Title	Year	Main dimension	Domain	Approach
	restoration in New York City after 11 September 2001				
Brown C., Seville E., Vargo J.	Measuring the organizational resilience of critical infrastructure providers: A New Zealand case study	2017	Organizational	energy systems; water facilities; transportation systems; telecommunication networks; oil and gas infrastructures	questionnaire
Field C., Look R.	A value-based approach to infrastructure resilience	2018	Organizational	not specified	interview
Kachali H., Stevenson J.R., Whitman Z., Seville E., Vargo J., Wilson T.	Organisational Resilience and Recovery for Canterbury Organisations after the 4 September 2010 Earthquake	2012	Organizational	logistics; construction; IT networks	questionnaire
Burbidge R.	Adapting European airports to a Changing Climate	2016	Organizational	transportation systems; aviation	questionnaire; workshop
Hiete M., Merz M., Schultmann F.	Scenario-based impact analysis of a power outage on healthcare facilities in Germany	2011	Organizational	healthcare	questionnaire
Comes T., Bertsch V., French S.	Designing dynamic stress tests for improved critical infrastructure resilience	2013	Organizational	energy systems	questionnaire

Authors	Title	Year	Main dimension	Domain	Approach
Bandecchi A.E., Pazzi V., Morelli S., Valori L., Casagli N.	Geo-hydrological and seismic risk awareness at school: Emergency preparedness and risk perception evaluation	2019	Organizational	community	questionnaire
Große C.	Sources of uncertainty in Swedish emergency response planning	2019	Organizational	energy systems	interview; questionnaire
Petersen L., Fallou L., Carreira E., Utkin A.	Public tolerance levels of transportation resilience: A focus on the Oresund region within the IMPROVER project	2018	Organizational	transportation systems	questionnaire
Sapeciay Z., Wilkinson S., Costello S.B., Adnan H.	Building Organisational Resilience for the Construction Industy: Strategic Resilience Indicators	2019	Organizational	construction	questionnaire; interview
Förster P., Schachtebeck P.M., Feuerle T., Hecker P., Branlat M., Herera I., Woltjer R.	An Approach for Attribute- and Performance-Based Evaluation of Interdependent Critical Infrastructures	2019	Organizational	aviation; healthcare	simulation game; focus group
Carpenter A.M.	Critical infrastructure resilience: A baseline study for Georgia	2014	Organizational	supply chain management; transportation systems; emergency response; water facilities; healthcare; energy systems; defense	interview

Authors	Title	Year	Main dimension	Domain	Approach
Line M.B.	A study of resilience within information security in the power industry	2013	Organizational	energy systems	interview
Kachali H., Seville E., Vargo J.	Recovery and resilience of industry and geographic sectors after the 2010 and 2011 canterbury earthquakes	2012	Organizational	community	interview
Olausson P.M.	Planning for resilience in the case of power shortage: The Swedish STYREL policy	2019	Organizational	energy systems	questionnaire; interview
Räikkönen M., Molarius R., Mäki K., Forssén K., Petiet P., Nieuwenhuijs A.	Creating stakeholder value through risk mitigation measures in the context of disaster management	2017	Organizational	energy systems	AHP
Berggren P., Van Laere J., Johansson B.J.	Using a mixed-methods assessment approach in a gaming-simulation environment to increase resilience	2018	Organizational	payment system	simulation game; questionnaire
Linkov I., Palma-Oliveira J.M.	An Introduction to resilience for critical infrastructures	2017	Organizational	not specified	workshop
Cedrini V., Mancini M., Rosi L., Mandarino G., Giorgi S., Herrera I., Branlat M., Pettersson J., Jonson C.-O., Save L., Ruscio D.	Improving resilience management for critical infrastructures—strategies and practices across air traffic management and healthcare	2018	Organizational	aviation; healthcare	Delphi method

Authors	Title	Year	Main dimension	Domain	Approach
Pathirage C.	The role of knowledge management in effective disaster mitigation strategies: Critical infrastructure	2010	Organizational	not specified	qualitative analysis
Save L., Branlat M., Hynes W., Bellini E., Ferreira P., Lauteritz J.P., Gonzalez J.J.	The Development of Resilience Management Guidelines to Protect Critical Infrastructures in Europe	2019	Organizational	aviation; healthcare	workshop; interview; questionnaire; simulation game
Woltjer R., Hermelin J., Nilsson S., Oskarsson P.-A., Hallberg N.	Using requirements engineering in the development of resilience guidelines for critical infrastructure	2018	Organizational	aviation; healthcare	Delphi method; interview; workshop; focus group
Herrera I., Grøtan T.O., Woltjer R., Nevhage B., Nilsson S., Trnka J., Adini B., Cohen O., Forsberg R., Jonson C.O.	Applying resilience concepts in crisis management and critical infrastructures—The DARWIN project	2017	Organizational	aviation; healthcare	interview
Petersen L., Lundin E., Fallou L., Sjöström J., Lange D., Teixeira R., Bonavita A.	Resilience for whom? The general public's tolerance levels as CI resilience criteria	2020	Organizational	water facilities	questionnaire; interview
Storesund K., Reitan N.K., Sjöström J., Rød B., Guay F., Almeida R., Theocharidou M.	Novel methodologies for analysing critical infrastructure resilience	2018	Organizational	water facilities	focus group; interview; questionnaire

Authors	Title	Year	Main dimension	Domain	Approach
Lange D., Honfi D.	Novel techniques and approaches for risk based application of resilience concepts to critical infrastructure: An introduction to the IMPROVER project	2017	Organizational	community	questionnaire
Hsieh C.-H., Tai H.-H., Lee Y.-N.	Port vulnerability assessment from the perspective of critical infrastructure interdependency	2014	Techno-centric	transportation systems	interview; questionnaire; workshop; AHP; Delphi method
Cutts M., Wang Y., Yu Q.	New Perspectives on Building Resilience into Infrastructure Systems	2017	Techno-centric	transportation systems; energy systems; supply chain management; water facilities; telecommunication networks	workshop; focus group
Münzberg T., Wiens M., Schultmann F.	A spatial-temporal vulnerability assessment to support the building of community resilience against power outage impacts	2017	Techno-centric	energy systems	Delphi method; workshop; questionnaire
Petit F.D., Eaton L.K., Fisher R.E., McAraw S.F., Collins III M.J.	Developing an index to assess the resilience of critical infrastructure	2012	Techno-centric	not specified	questionnaire

Authors	Title	Year	Main dimension	Domain	Approach
Feldpausch-Parker A.M., Peterson T.R., Stephens J.C., Wilson E.J.	Smart grid electricity system planning and climate disruptions: A review of climate and energy discourse post-Superstorm Sandy	2018	Techno-centric	energy systems	focus group
Münzberg T., Wiens M., Schultmann F.	The effect of coping capacity depletion on critical infrastructure resilience	2015	Techno-centric	energy systems	questionnaire
Bloomfield R.E., Popov P., Salako K., Stankovic V., Wright D.	Preliminary interdependency analysis: An approach to support critical-infrastructure risk-assessment	2017	Techno-centric	energy systems; telecommunication networks	questionnaire
Sircar I., Sage D., Goodier C., Fussey P., Dainty A.	Constructing Resilient Futures: Integrating UK multi-stakeholder transport and energy resilience for 2050	2013	Techno-centric	transportation systems; energy systems; supply chain management	interview; focus group
Johnsen S., Skramstad T., Hagen J.	Enhancing the safety, security and resilience of ICT and SCADA systems using action research	2009	Techno-centric	supply chain management	questionnaire
Valiquette L'Heureux A., Therrien M.-C.	Interorganizational dynamics and characteristics of critical infrastructure networks: The study of three critical infrastructures in the greater Montreal area	2013	Techno-centric	transportation systems; energy systems; telecommunication networks	questionnaire

Authors	Title	Year	Main dimension	Domain	Approach
McBurnett L.R., Hinrichs M.M., Seager T.P., Clark S.S.	Simulation Gaming Can Strengthen Experiential Education in Complex Infrastructure Systems	2018	Techno-centric	water facilities	workshop; simulation game; interview
Petersen L., Lundin E., Sjöström J., Lange D., Teixeira R.	Creating comparable public tolerance and technical performance measures for critical infrastructure resilience evaluation	2018	Techno-centric	water facilities	interview; questionnaire
Bernroider E.W.N., Margiol S., Taudes A.	Towards a general information security management assessment framework to compare cyber-security of critical infrastructure organizations	2016	Techno-centric	cybersecurity	workshop; interview; questionnaire
Leu P.O., Peter D.	Case study: Information flow resilience of a retail company with regard to the electricity scenarios of the sicherheitsverbundsübung schweiz (swiss security network exercise) SVU 2014	2016	Techno-centric	supply chain management	interview
Trucco P., Ward D.	A clustering approach to the operational resilience analysis of Key Resource Supply Chains (KRSC): The case of Fast Moving Consumer Goods	2011	Techno-centric	supply chain management	interview; questionnaire

Authors	Title	Year	Main dimension	Domain	Approach
Lykou G., Anagnostopoulou A., Stergiopoulos G., Gritzalis D.	Cybersecurity self-assessment tools: Evaluating the importance for securing industrial control systems in critical infrastructures	2019	Techno-centric	cybersecurity; IT networks	questionnaire
Landegren F., Höst M., Möller P.	Simulation based assessment of resilience of two large-scale socio-technical IT networks	2018	Techno-centric	IT networks	focus group; interview
Hedel R., Boustras G., Gkotsis I., Vasiliadou I., Rathke P.	Assessment of the european programme for critical infrastructure protection in the surface transport sector	2018	Techno-centric	transportation systems	workshop; interview; questionnaire
Adelmeyer M., Teuteberg F.	Cloud computing adoption in critical infrastructures - Status Quo and elements of a research agenda	2018	Techno-centric	IT networks	interview
Reilly P., Serafinelli E., Stevenson R., Petersen L., Fallou L.	Enhancing critical infrastructure resilience through information-sharing: Recommendations for European critical infrastructure operators	2018	Techno-centric	not specified	interview; focus group
Rajamaki J., Nevmerzhitskaya J., Virag C.	Cybersecurity education and training in hospitals: Proactive resilience educational framework (Prosilience EF)	2018	Techno-centric	healthcare; cybersecurity	workshop

Authors	Title	Year	Main dimension	Domain	Approach
Seppänen H., Luokkala P., Zhang Z., Torkki P., Virrantaus K.	Critical infrastructure vulnerability—A method for identifying the infrastructure service failure interdependencies	2018	Techno-centric	energy systems; telecommunication networks	workshop; questionnaire
Badea D., Bârsan G., Virca I., Iancu D.	Quantitative and qualitative differences worth considering in approaching critical infrastructures resilience	2017	Techno-centric	not specified	AHP
Student L.R., Goubran R., Kwamena F.	Computer vision-assisted human-in-the-loop measurements: Augmenting qualitative by increasing quantitative analytics for CI situational awareness	2018	Techno-centric	energy systems; telecommunication networks	social network
Vugrin E.D., Warren D.E., Ehlen M.A., Camphouse R.C.	A framework for assessing the resilience of infrastructure and economic systems	2010	Techno-centric	community	qualitative analysis
Vugrin E.D., Warren D.E., Ehlen M.A.	A resilience assessment framework for infrastructure and economic systems: Quantitative and qualitative resilience analysis of petrochemical supply chains to a hurricane	2011	Techno-centric	supply chain management	qualitative analysis

Authors	Title	Year	Main dimension	Domain	Approach
Comes T., Van De Walle B.	Measuring disaster resilience: The impact of hurricane sandy on critical infrastructure systems	2014	Techno-centric	transportation systems; energy systems; supply chain management	qualitative analysis
Hughes L., de Jong M., Wang X.Q.	A generic method for analyzing the risks to energy systems	2016	Techno-centric	energy systems	interview
Beheshtian A., Donaghy K.P., Geddes R.R., Rouhani O.M.	Planning resilient motor-fuel supply chain	2017	Techno-centric	supply chain management	social network; interview
Matsika E., O'Neill C., Battista U., Khosravi M., Laporte A.D.S., Munoz E.	Development of Risk Assessment Specifications for Analysing Terrorist Attacks Vulnerability on Metro and Light Rail Systems	2016	Techno-centric	transportation systems	workshop
Haass M.J., Warrender C.E., Burnham L., Jeffers R.F., Stevens-Adams S.M., Cole K.S., Forsythe C.	Toward an Objective Measure of Automation for the Electric Grid	2015	Techno-centric	energy systems	interview
Riegel C.	Infrastructure resilience through regional spatial planning - prospects of a new legal principle in Germany	2014	Techno-centric	urban infrastructures	qualitative analysis;
Gheorghe A.V., Georgescu A., Bucovețchi O., Lazăr M., Scarlat C.	New Dimensions for a Challenging Security Environment: Growing Exposure to Critical Space Infrastructure Disruption Risk	2018	Techno-centric	space systems	qualitative analysis

Authors	Title	Year	Main dimension	Domain	Approach
Pfeiffer K.B., Burdi C., Schlueter S.	Local supply chains: The disaster management perspective	2017	Techno-centric	energy systems; water facilities; supply chain management	questionnaire
Bellini E., Gaitanidou E., Bekiaris E., Ferreira P.	The RESOLUTE project's European Resilience Management Guidelines for Critical Infrastructure: development, operationalisation and testing for the urban transport system	2020	Techno-centric	transportation systems	focus group
Ferreira P., Bellini E.	Managing interdependencies in critical infrastructures—a cornerstone for system resilience	2018	Techno-centric	transportation systems	interview
Pescaroli G.	Perceptions of cascading risk and interconnected failures in emergency planning: Implications for operational resilience and policy making	2018	Urban	not specified	workshop; questionnaire;
Monstadt J., Schmidt M.	urban resilience in the making? The governance of critical infrastructures in German cities	2019	Urban	urban infrastructures	interview; workshop
Heino O., Takala A., Jukarainen P., Kalalahti J., Kekki T., Verho P.	Critical infrastructures: The operational environment in cases of severe disruption	2019	Urban	energy systems; water facilities	workshop

Authors	Title	Year	Main dimension	Domain	Approach
Dierich A., Tzavella K., Setiadi N.J., Fekete A., Neisser F.	Enhanced crisis-preparation of critical infrastructures through a participatory qualitative-quantitative interdependency analysis approach	2019	Urban	energy systems; water facilities; emergency response	interview; focus group
Gonzalez J.J., Bång M., Eden C., Gimenez R., Hernantes J., Howick S., Maraña P., Pyrko I., Radianti J., Rankin A., Sarriegi J.M.	Stalking resilience: Cities as vertebrae in society's resilience backbone	2017	Urban	urban infrastructures	workshop; Delphi method; questionnaire
Lomba-Fernández C., Hernantes J., Labaka L.	Guide for climate-resilient cities: An urban critical infrastructures approach	2019	Urban	urban infrastructures	focus group; workshop; interview
Fekete A., Fiedrich F.	Synthesis	2018	Urban	urban infrastructures	workshop; focus group; interview
Räikkönen M., Mäki K., Murtonen M., Forssén K., Tagg A., Petiet P.J., Nieuwenhuijs A.H., McCord M.	A holistic approach for assessing impact of extreme weather on critical infrastructure	2016	Urban	not specified	qualitative analysis
Fekete A., Bogardi J.J.	Considerations about urban disaster resilience and security—Two concepts in tandem?	2018	Urban	urban infrastructures	qualitative analysis

Authors	Title	Year	Main dimension	Domain	Approach
Marana P., Eden C., Eriksson H., Grimes C., Hernantes J., Howick S., Labaka L., Latinos V., Lindner R., Majchrzak T.A., Pyrko I., Radianti J., Rankin A., Sakurai M., Sarriegi J.M., Serrano N.	Towards a resilience management guideline — Cities as a starting point for societal resilience	2019	Urban	urban infrastructures	questionnaire
Bellini E., Nesi P., Pantaleo G., Venturi A.	Functional resonance analysis method based-decision support tool for urban transport system resilience management	2016	Urban	transportation systems	AHP; interview

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