Coordination Dynamics in Disaster Response Operations: A Network Based Discrete Event Analysis

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Coordination Dynamics in Disaster Response Operations:

A Network Based Discrete Event Analysis[1]

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Abstract

Coordination is an important factor that affects directly the outcome of response operations in disaster management networks. Disaster management frameworks and protocols establish a foundation for organizational coordination in the event of a crisis (natural or man-made). Existing disaster management frameworks are based on concepts borrowed from military practices (i.e. command and control) and conventional organizational operations. Due to the complex nature of a disaster or emergency, the existing approach is failing to cope with such high levels of uncertainty and intense occurrence of changes during the course of a disaster. Instead of being locked-in rigid response plans, organizations and individuals managed to cope with disasters' complexities by forming network-governed structures. Those networks are formed in response to the unfolding needs of coping with a disaster incident.

Understanding the characteristics of those emerging networks in disaster response operations is critical to the whole process of developing proper disaster response frameworks that would help in preventing losses in human lives and assets.

In this research, we examine examples of response operations related to disasters casued by natural events such as floods or fires for the puspose of studying the patterns of networked-coordination between the organizations engaged in those operations. To achieve the research goals, we develop a new methodology for examining the coordination dynamic in disaster response networks. The analysis outcome provides a dynamic perspective that describes the evolution of coordination-clusters in network-governed structures. Understanding characteristics of coordination-clusters helps to identify critical tasks and units beyond the resources required during disaster response operations. The research work contributes to the continuous changes in concepts of disaster and crisis management and the shift towards a network and function-based response systems.

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I still wish for any readers to share their views on my research with me at saadnouri@gmail.com

Nadia Noori
Barcelona
July 18, 2016

List of Publications

Several publications were produced as a result of this research work in the fields of crisis management and of complex systems. Below is a list of those publications:

Noori, N. S., Weber, C. (Expected October 2016). Dynamics of Coordination-Clusters in Long-Term Rehabilitation Operations. *Journal of Humanitarian Logistics and Supply Chain Management*. (Accepted for publications)

Noori, N. S., Wolbers, J., Boersma, K. Vilasis-Cardona, X. (2016). A dynamic perspective of emerging coordination clusters in crisis response networks. In *Proceedings of the 13th International ISCRAM Conference – Rio de Janeiro, Brazil, May 2016*. Tapia, Antunes, Bañuls, Moore and Porto (eds).

Noori, N. S., Paetzold, K., & Vilasis-Cardona, X. (2016). Network based discrete event analysis for coordination processes in crisis response operations. I*n 2016 Annual IEEE Systems Conference (SysCon)* (pp. 1-5). IEEE.

Chahin, A., Hoffmeister, J., Paetzold, K., Noori, N., & Vilasis Cardona, X. (2016). A Practical Approach To Structure The Product Development Process Using Network Theory. In DS 84: Proceedings of the DESIGN 2016 14th International Design Conference.

Sabou, J., Noori, N., & Husch, J. (2015). Recognizing Competitive Cultures: A case for describing the complexity of coordination between dynamic crisis response actors. In *Proceedings of the 12th International ISCRAM Conference - Kristiansand, Norway, May 2015*. Palen, Büscher, Comes & Hughes (eds).

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1 Introduction

Over the course of response operations to disasters events, organizations (public and private), non-profits, community-based associations and volunteers tend to form a network of hierarchies to work together towards achieving common goals of saving lives and limiting damages. The diversity of the involved groups of organizations and individuals create a complex environment for collaboration during disaster response. In order to facilitate those groups working together, there is a need for coordination of actions and resource consumption during disaster events. The formal disaster management frameworks for facilitating coordination during response operations are highly structured and hierarchical systems, otherwise known as Incident Command Systems (ICS). Such frameworks are adopted from the military command and control operational style. Yet, they are modified to fit the requirements of responding to a wide spectrum of incidents (Kapucu, 2005). Command and Control Centers (C2C) are a key operational element to such ICS because they function as information hubs and decision making focal points. However, in reality, the coordination dynamics in response operations take another shape where networked-coordination structures. Otherwise called coordination-clusters, those structures emerge throughout the response operations (Kapucu, 2009; Boersma, Ferguson, Groenewegen & Wolbers, 2014). The formation of coordination-clusters is influenced by factors such as trust, authority, and information flow. The emergence of those network-based coordination-clusters raised few challenges to the existing disaster and crisis response frameworks (Kapucu, 2009; Moynihan, 2009; Comfort, Oh, Ertan, Scheinert, 2010)

In this research, we focus on studying the characteristics of those emerging networked-coordination structures (i.e. coordination-clusters) during response operations in relation to the existing ICS systems. To achieve the research goal, we developed a new methodology to analyze the coordination dynamics in network-governed settings in response operations. As a first step, we focus on examining the phenomenon of networked-coordination during onset sudden disaster events. The proposed methodology provides an integrated perspective of the evolution of coordination-clusters and the coordination dynamics inside disaster response networks.

In this chapter we provide a quick glance of the research work presented in this thesis. The upcoming sections represent the research background, motivations, and goals. Research gap, questions, and method used are introduced in this chapter as well. Finally the structure of the dissertation will be presented in the last section of this chapter.

1.1 Related Work

The beginnings of the 21st century witnessed several incidents that reshaped research in the field of crisis management and how organizations and individual act in event of a crisis. Most notable examples are September 11 terrorist attacks in 2001 and Hurricane Katrina 2005 in the United States of America, and the Great Japan Earthquake in 2011. The response operations to the Great Japan Earthquake in 2011 involved many parties from inside Japan and outside to handle the disaster impact that reached as far as the shores of the Pacific Ocean shores in Canada and the United States of America. According to Japan's foreign ministry, 116 countries and 28 international organizations had offered assistance and had sent aid to the devastated areas. Japan, on the other hand, had specifically requested assistance from teams from Australia, New Zealand, South Korea, and the United States of America (Cafarno, 2011). The 2011 Japan incident exemplifies the case of a large-scale incident where national, international and cross-organizational coordination was required to respond to the chain of disasters that stemmed from the earthquake.

The continuous change in our planetary environment contributed to an increase in occurrence and severity of natural disasters in recent years. Besides natural disasters, politically unstable regions and under-developed economies contributed to an increase in humanitarian disasters and man-made disaster (i.e. acts of terrorism). Those changes implicated how we, as societies, are handling disaster events whether natural, humanitarian, or man-made.

Disaster management research goes back to a few decades ago when a Canadian, Samuel Henry Prince, initiated a formal study of *Sociology of Disaster* with his dissertation on Canada's worst catastrophe, the 1917 Halifax explosion (Quarantelli, 2005). The focus for those studies was the behaviors of the communities under stressful disaster conditions (Dynes & Aguirre, 1979; Dynes & Quarantelli, 1968; Dynes & Quarantelli, 1970; Forrest, 1974; Parr, 1969; Parr, 1970; Teuber, 1973). Based on the nature of tasks carried out during response operations and structure of organizations involved, Dynes and Quarantelli (1968) were able to distinguish four types of behaviors in crisis response (See Figure 1).

Structure \ Task	Regular	Non-regular
Old	Type I (Established)	Type III (Extending)
New	Type II (Expanding)	Type IV (Emergent)

Figure 1. Types of organizational groups' behavior in disasters. (Dynes & Quarantelli, 1968)

An *established* behavior is linked to routine tasks that are carried out in normal routine, such as police regulating traffic during or after a severe storm. An *expanding* behavior is linked to non-routine tasks carried out, such as army units pumping water out of basements in a flood event. An *extending* behavior is related to unusual tasks carried out by an organization such as a construction company involved in search and rescue operations. The last type is the *emergent* behavior that is related to performance of certain tasks by a group consisting of actors from different organizations such as Red Cross volunteers helping the Army soldier with enforcing dikes in case of a flood.

The planned interorganizational coordination (i.e. ICS) falls within Type I and II organizational behavior where tasks performed can be routine or non-routine but they are executed within the existing organization hierarchy. However, disasters create unstable environments with high levels of uncertainty and complexity. Such conditions can lead organizations to stretch out beyond their routine tasks causing new structures to emerge outside the existing hierarchies (Dynes & Aguirre, 1979, Bram and Vestergran, 2012; Public Safety Canada, 2011). Many scholars had recognized coordination between organizations involved in disaster response leaning towards Type III or Type IV behavior when organizations find themselves in a *networked-coordination* environment.

In such environment, the involved parties work together towards common goals, responsibilities and unified action to produce a shared outcome (Kapucu, 2005; Moynihan, 2009; Abbasi & Kapucu, 2012; Kapucu & Garayev, 2013, Sabou et al, 2015, Noori, 2016, Noori, 2016b).

On one hand, the highly hierarchical arrangements of organizational collaboration frameworks represented by ICS's have proven to fail in several occasions (Dynes, 1994, Quarantelli, 1997; Comfort, 2007; Kapucu, 2009). On the other hand, evolution of the interorganizational coordination during response operations did not only fail to follow the command system, but it came to a form of networked-coordination that evolved into coordination-clusters based on required functionalities throughout the response operations. In Figure 2, shows a transition from a network structure based on the hierarchical ICS to a task-oriented network structure where the circulated groups represent the emerging task-based coordination-cluster.

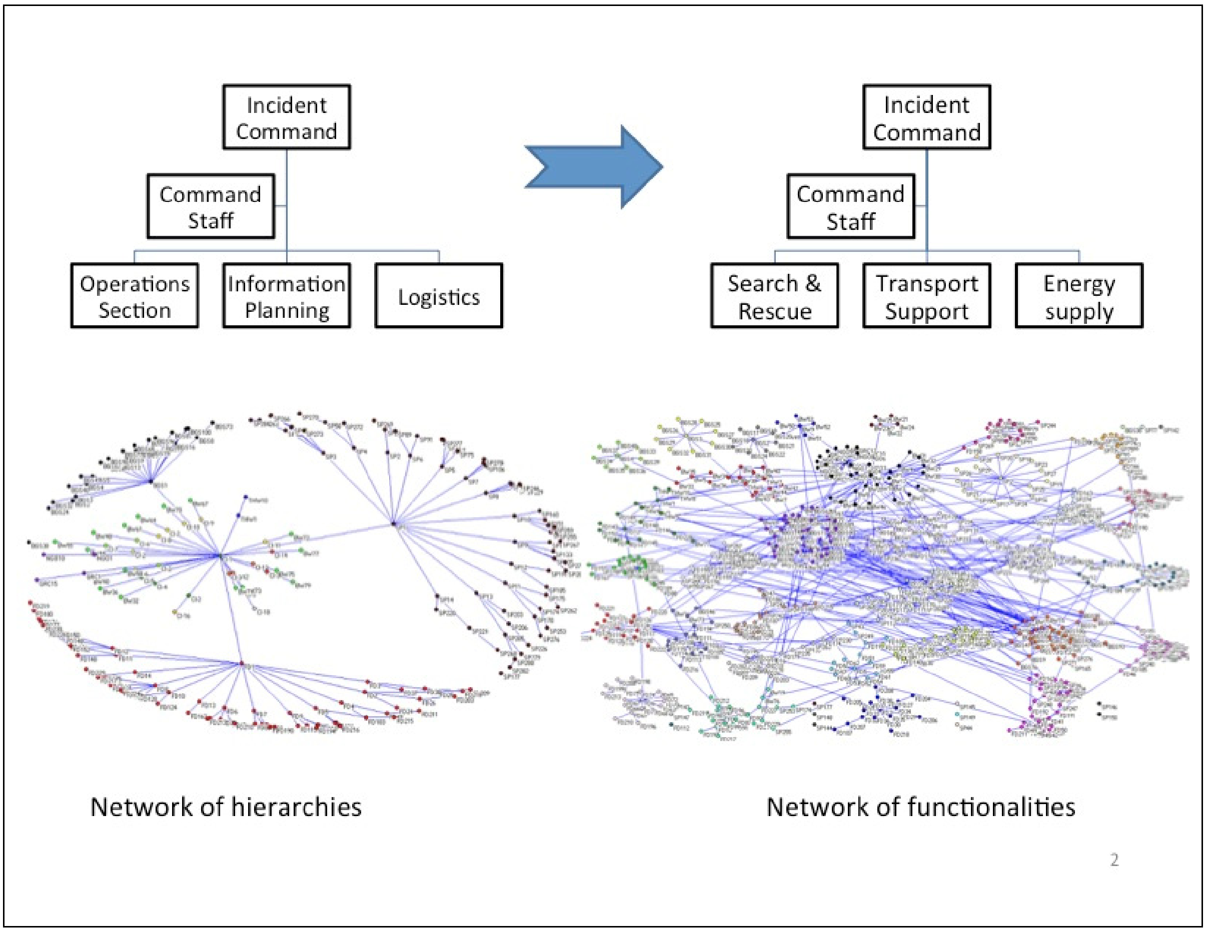


Figure 2. Evolution of interorganizational coordination in response operations.

Although, Dynes and Quarantelli pointed out Type III (extending) and Type IV (emerging) organizational behaviors in 1960's, in this research work we focus on patterns of networked-coordination and evolution of response networks in disaster management. Our work extends and contributes to the efforts of several scholars who studied the interorganizational coordination in response networks to understand the dynamics of coordination in unstable and intense environments (Topper & Carley, 1999; Comfort & Haase, 2006; Butts, Acton & Marcum, 2012; Boersma, Passenier, Mollee & van der Wal, 2012; Boersma, Comfort, Groenendaal & Wolbers, 2014; Boersma, Fergusson, Groenewegen & Wolbers, 2014).

1.2 Research Motivation and Goals

Today's world is witnessing an increase in the multitude and the severity of natural and man-made disasters (e.g. floods, fires, terrorist attacks etc.) due to several contributing factors such as climate change, growing population, scares resources and unstable economies. Such disturbances affect the routine of society causing damages, loss of lives and properties. The existing crisis management systems are constantly challenged with rising numbers of crisis incidents and increasing severity of the incidents. Despite of a rising trend in the public engagement in disaster response, it is the duty of governmental institutions to plan and execute crisis response operations within different levels of authority in any political system.

There are increasing demands for developing more agile disaster response plans to avoid losses in lives and assets. In order to achieve such goals, there is a need to bridge the gap between the existing systems and the reality of the evolution of response operations. By examining past experiences with the proper tools in hand we can develop effective and agile response systems to face the challenges of disasters of the world today and ultimately save human lives efficiently.

The research goal is to address the gap between existing ICS systems and the reality of emerging coordination networks. This gap can be described as a multidimensional puzzle of organizational coordination, dynamic representation of coordination and net-centric response operations (Kapucu, Arslan, Collins, 2010a; Richter, Heumüller, & Lechner, 2010; Bharosa, 2011).

With the right set of motivations in mind, we recognized other goals for the research work. The research aims to develop a methodology that would provide a holistic and dynamic perspective of response operations based on historic data extracted from well-documented official reports. The method would serve as a tool for academics and practitioners to help in the development and planning of crisis management systems and ultimately provide guidelines to understand how operations are conducted and how to improve existing systems and integrate new technologies, new strategies in the future disaster response systems.

1.3 Research Gap and Research Questions

To summarize, the phenomenon of emerging networked-coordination and coordination-clusters in disaster response operations was recognized by several researchers. However, there is a gap between existing disaster management systems and the reality of response operations. Despite that fact, a methodology that provides an integrated perspective in studying interorganizational coordination dynamics within uncertain and intensive environments like disasters and emergencies still does not exist. Furthermore, there remains a lack of proper tools to study networked-coordination in response operations and characteristics of emerging coordination-clusters.

In order to fill the gap, our research aims to develop a novel approach to study the dynamic nature of coordination evolution in disaster response networks. The anticipated results would help to answer key two questions.

RQ1: What are the patterns of interorganizational coordination in disaster response operations?

In order to answer the question above, the following needs to be investigated:

a. Coordination characteristics in disaster response operations.

b. Relationships, authority decentralization, actions, information flow and resources involved in response operations to construct a network-based representation of ongoing dynamics inside response operations.

c. Characteristics of emerging structures inside the emerging coordinative networks during disaster response operations.

d. Position of influential nodes in the disaster response operations.

RQ2: How does networked-coordination evolve in disaster response operations?

This question will lead to the following inquiries:

a. Structure of existing disaster management systems (i.e. Incident Command Systems).

b. Existing coordination functions and resources included in the ICS and dependencies between them.

c. Hierarchical structure of organizations engaged in disaster response operations.

d. Time-based analysis of coordination networks and event-based analysis of emerging coordination-clusters

Despite the importance of interorganizational coordination in response operations of humanitarian disasters or terrorist attacks, we limit the scope of this work to disasters caused by natural events such as floods, fires or earthquakes.

1.4 Expected Research Contribution

The dominant phenomenon in disaster management has generally been a state of *chaos*, *command* and *control*; assuming that disaster events can be controlled by employing a strict centralized command structure (Quarantelli & Dynes, 1977). However, the ICS hierarchical approach had proven insufficient to handle intensive disaster events (Dynes, 1994, Quarantelli, 1997; Comfort, 2007; Kapucu, 2009). This research work provides insights of a clear transformation from ICS hierarchical-based systems to network-based structures of coordination dynamics in response operations. The results showed a great deal of resilience in the networks behavior compared to the classical strict command and control based systems. The results provide answers to the questions of how we can analyze and model networked-coordination and its consequent dynamics. However, steps to create flexible response plans stay open to future research.

In addition, the research work offers a framework to study coordination dynamics in disaster response operations. The proposed approach helps examining the evolution of crisis response operations as a network structure in combination with dynamic modeling of coordination flow. The implication of having an integrated view of coordination dynamics in response networks would broaden the empirical basis for planning and management of complex disaster response operations.

1.5 Research Methodology

The research problem we are addressing inherits the complexity of the phenomenon subject of this research, coordination dynamics in disaster management. Examining coordination dynamics in any settings involves several elements such as human factor, resources availability, trust, and authority. In addition, the unexpected natural development of disaster events themselves adds an extra layer of complexity to the problem we are addressing here. Therefore, to handle the complexity of the phenomenon and its context at hand, we followed a mixed methods research approach (Johnson & Onwuegbuzie, 2004; Johnson, Onwuegbuzie & Turner, 2007; Creswell, 2013). Using the mixed methods research enabled us to combine qualitative and quantitative techniques for data collection and data analysis to study the phenomenon of coordination dynamics in disaster response operations. The framework that guided the research process from the beginning of data collection to determining results consists of three stages as illustrated in Figure 3.

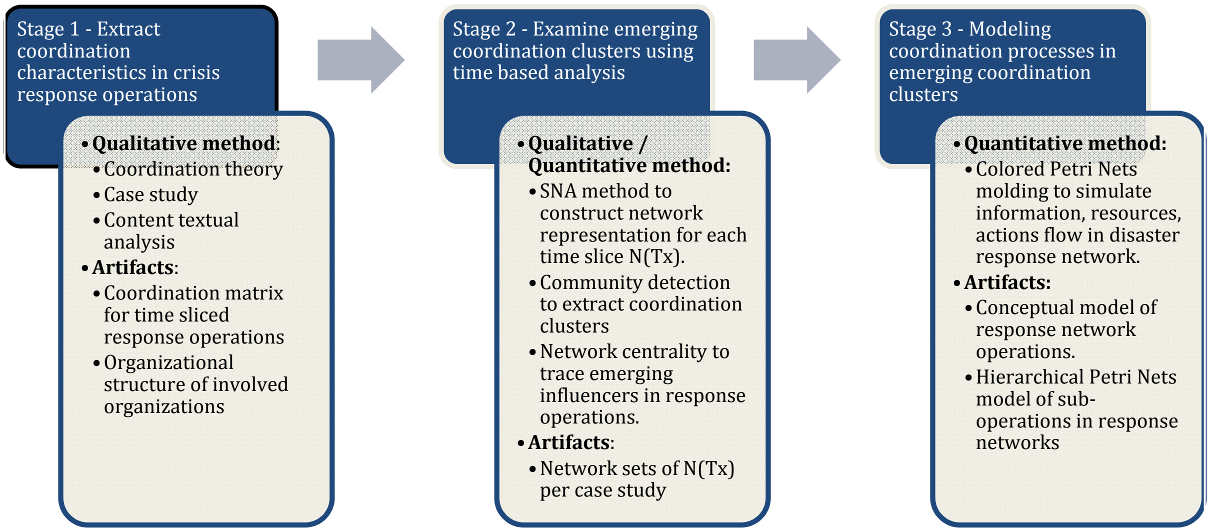


Figure 3. The three stages of the research method showing mixed techniques used in data collection, representation, and analysis.

As we mentioned, the framework comprises of a set qualitative and quantitative methods for *data collection* and *data analysis*. *Stage 1,* is the qualitative stage in our framework where we employ *Case Study* method (Eisenhardt, 1989; Yin, 2003; Baxte & Jack, 2008) as a guideline for case selection, data sources and data triangulation. Still within Stage 1, we perform *contents textual analysis* on the data gathered earlier to extract coordination specifics using *Coordination Theory* (Crowston & Malone, 1994). We organize the results of the textual analysis into time slots where each slot has a time stamp and the size of the time slot depend on the details provided in the contents. Afterward, contents of each slot are used to construct a *Coordination Matrix* that contains the following information: Time stamp, organizations involved in operations, actions taken by organizations, resources used throughout the response operations. Table 1, is an example of the coordination matrix at Tx (e.g. day 1, hour 10 or week 3) of T, where T is the entire duration of the response operations.

Date	Organization	# of units	Resources	Actions
Day 1	Federal Forces	79 units	Cars (10) Personnel (2300) Boats (30) Floating bridges (20)	-Search & rescue -Medical assistant -Evacuation -Roads clearance
	Federal police	230 units	Cars (40) Personnel (3400)	-Traffic control -Evacuation -Search & Rescue

Table 1. Example of coordination matrix constructed from response operations reports

In the same stage we extract the details of organizations engaged in the response operations such as organization's structure, operating procedures, tasks performed routinely, planned duties in case of disaster response. We can see examples of that in Appendix A, as we provide details about every organization involved in the response operations of our case studies.

In *Stage 2*, we use *Social Network Analysis* (SNA) to transform the qualitative outcomes (i.e. coordination matrix) from Stage 1 to a quantifiable data as well as provide a visual presentation of the emerging relationships in the response operations. For each time slice we construct the snapshot of network representation to obtain numerical readings of nodes centrality and strength of ties between the nodes of the response network. Such readings enable us to trace the changes in the roles played by different units in the response operations. Figure 4 and 5 illustrate examples of initial networks of organizations involved in response operation case study.

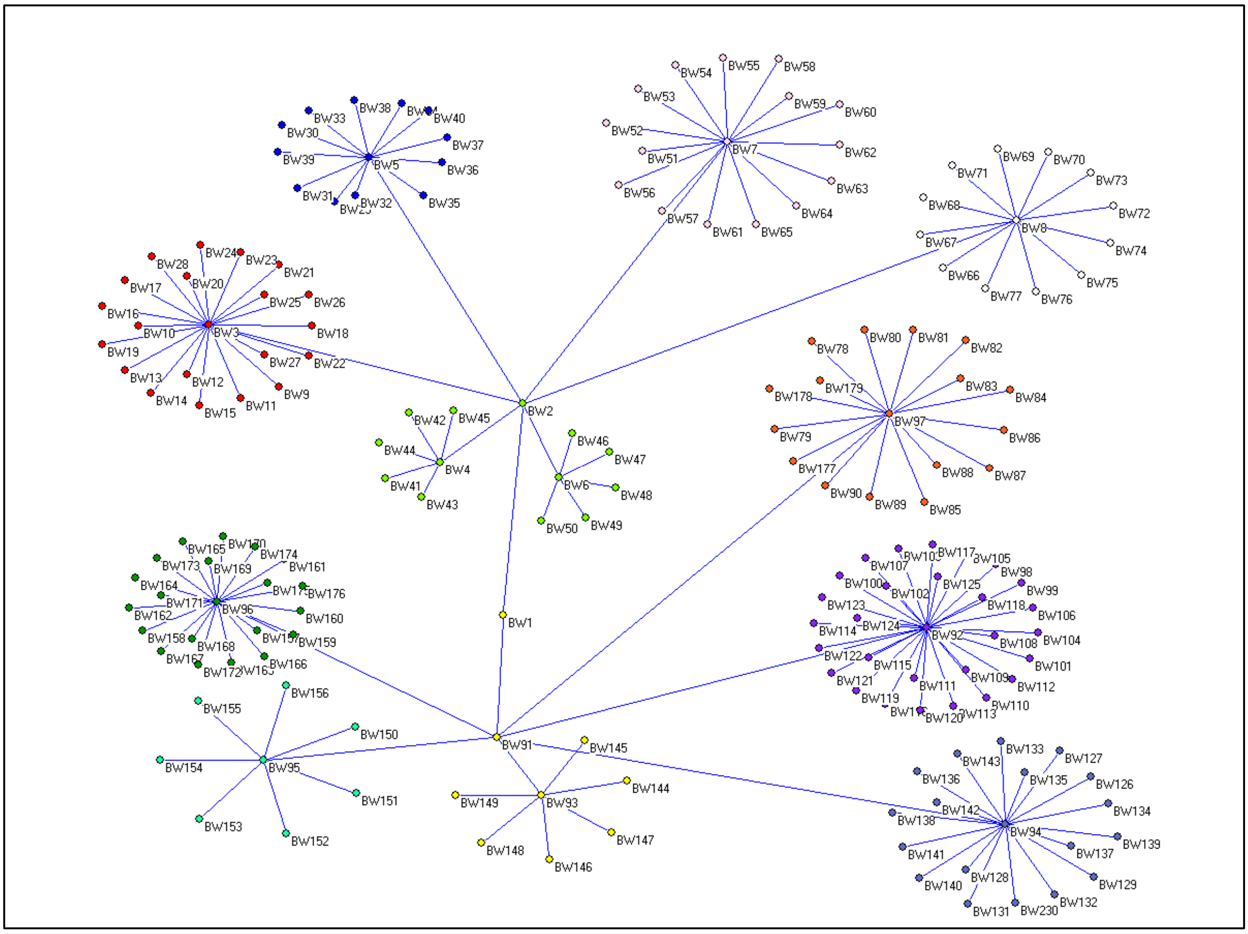


Figure 4. Network representation of the German Armed Forces hierarchy in Saxony.

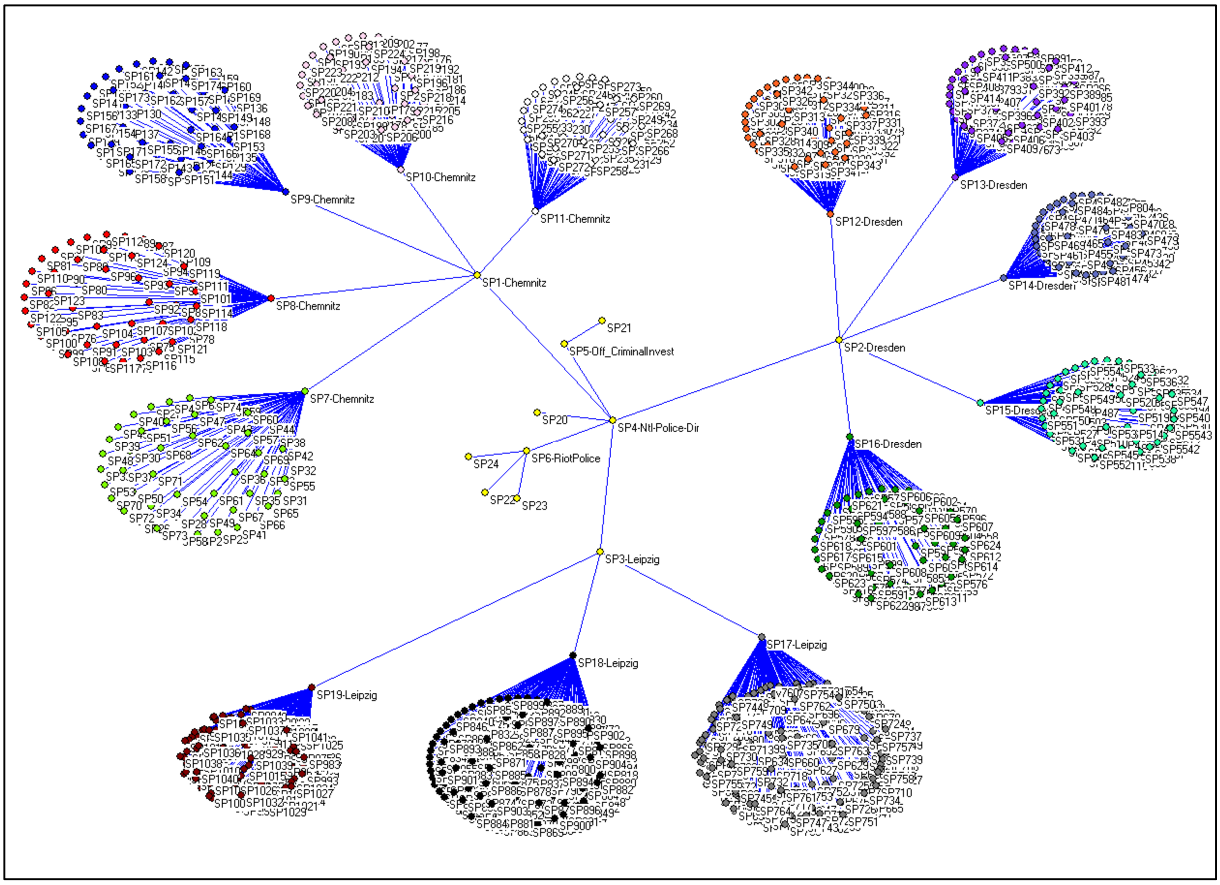


Figure 5. Network representation of Saxon Police hierarchy in Saxony.

Still within Stage 2, we used *community detection techniques* to examine the emerging coordination structures in the network representation of the snapshots of the response operations. There are several algorithms that are based on different principles to divide a network and detect clusters such as number of nodes or number of links or average number of nodes/links per cluster (Fortunato, 2010; Leskovec, Lang, & Mahoney, 2010). Those methods require initial values of the cluster's size, which was not suitable for our purposes, as we require detecting emerging structure without having biased initial values. Therefore, we employed methods that detect clusters based on the cluster or the partition modularity values. The modularity is a measurable value between -1 and 1 that compares the number of links inside communities with respect to the ones in a random network preserving the degrees of the nodes (Fortunato & Barthelemy, 2007; Blondel, Guillaume, Lambiotte & Lefebvre, 2008; Fortunato, 2010). Community detection methods are used to detect or partition static networks or single snapshots, therefore, some algorithms can produce inconsistent data if they were used for evolving networks. Yet, Aynaud and Guillaume (2010) pointed out the suitability of the Louvain Method for detecting communities in evolving networks (Aynaud & Guillaume, 2010). In addition, the Louvain Method is well known for the high quality of its partitions and its speed (Leskovec, Lang, & Mahoney, 2010; Waltman, L., & van Eck, N. J. 2013). In Figure 6, shows an example of the detected coordination-cluster in a network snapshot of Tx of a response operation.

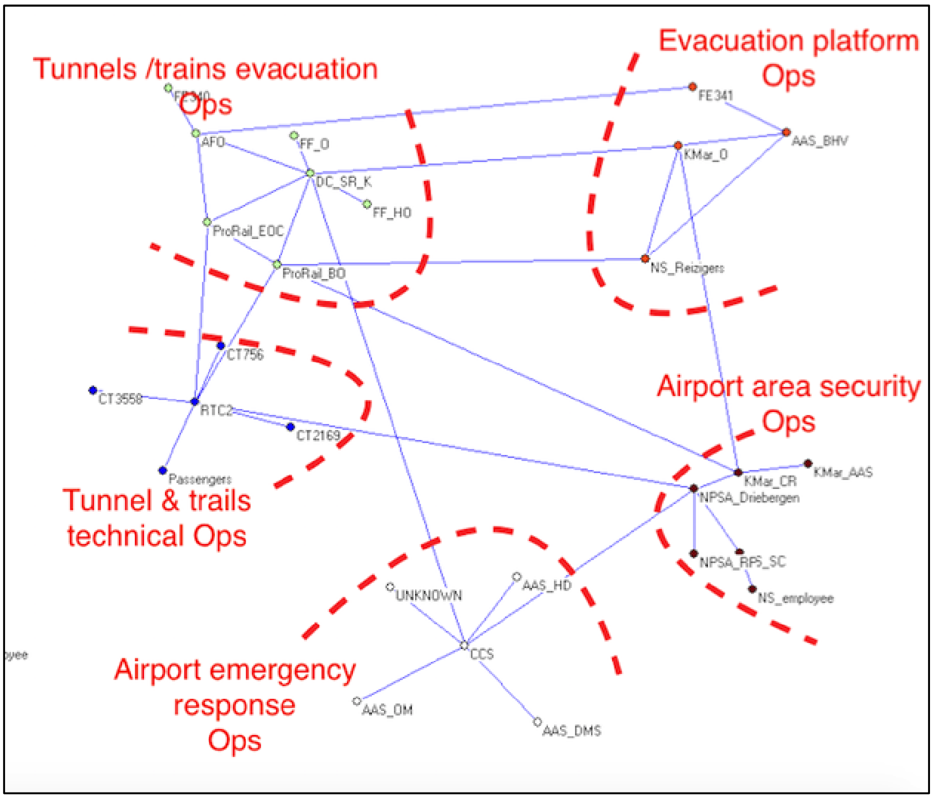


Figure 6. Coordination-clusters in response network for the 2009 Schiphol Tunnel Fire.

The Coordination matrices contain information about organizations involved, resources used and actions taken at a specific moment of time, Tx (e.g. day 1, hour 10 or week 3) of Tn period of time over the duration of response operations. The size of Tx depends on details provided by data used for each case. In Stage 3, we use the combination of Stage 1 and Stage 2 outcomes (i.e. Coordination matrix and coordination-clusters) to use discrete-event methods to describe the coordination flow in the response operations. Petri Nets are widely used to describe event systems and coordination in control systems. In our work, we used colored and hierarchical Petri Nets to describe the resources used in the response operations and simulate the different tasks carried out inside the response operations. With Petri Nets capability to represent hierarchical operations, we were able to capture and simulate operations' flow on different levels of crisis management authorities (i.e. local level, regional level and national level). The models were used to simulate ongoing coordination processes as a first step to analyze stages of response operations. By having a dynamic view of coordination processes flows, we still lack a view of "who" is performing tasks, "how" the teams consume the resources. Therefore, we combine outputs from PNs with complex network analysis to create an integrated perspective of the relationships formed and tasks executed by teams from the different organizations engaged in response operations.

1.6 Dissertation structure

The rest of the document is organized as follows:

Chapter TWO: In this chapter we discuss details of the literature review process in order to lay the theoretical and conceptual foundation for the research. The literature review provided a global understanding of existing problems in the field of disaster and crisis management, helped in shaping research questions and is bridging different topics related to the identification of proper elements of the research design.

Chapter THREE: In this chapter we address details of the research method adopted to examine the phenomenon of interorganizational coordination in disaster response networks. The research method is not a mere group of theories and tools used to study a phenomenon. The research method represents a framework and a guideline crafted carefully to investigate phenomena to help in advancing human knowledge. While, the literature review provides the solid groundwork of conducting scientific research, the research method is the vehicle, which facilitates the conduct of sound and credible research.

Chapter FOUR: In this chapter we provide details regarding case studies selected in this research. Information such as timelines, engaged parties and response operations' details are discussed in this chapter. Also the coordination matrices and SNA were used to construct and visualize the response networks for every case.

Chapter FIVE: In this chapter we present the results generated from applying the proposed methodology to the selected case studies (i.e. Elbe River Flood in 2002 and Schiphol Tunnel Fire in 2009). The results are divided into two main parts related to the qualitative and the quantitative stages presented in the research method.

Chapter SIX: In this chapter we shed the light on the main outcome of the research work and the introduction of a novel methodology to study the dynamic nature of coordination evolution in disaster response networks. In addition, we highlight some of the limitations of the work presented in this thesis.

Chapter SEVEN: In this chapter we conclude this thesis work and outline some potential venues to expand the research work in the future.

In addition, Appendix A includes detailed profiles of organizations involved in the disaster response operations of the 2002 Elbe River Flood, the first case study in this dissertation. While Appendix B includes the timeline of the Elbe Flood River and sample of the coordination matrices extracted from the reports.

Appendix C covers the timeline of the second case study of the 2009 Schiphol Tunnel Fire in the Netherlands.

Appendix D includes a feedback report form a subject matter expert evaluating the methodology proposed in this thesis work.

Finally, Appendix E contains a listing of abbreviations used in this thesis.

2 Literature Review

In this chapter we discuss the details of the literature review process in order to lay the theoretical and conceptual grounds for the research. Conducting the literature review provided a global understanding of existing problems in the field of disaster and crisis management, helped in shaping research questions and in bridging different topics related to identification of proper elements of the research design.

The aim of the literature review is to provide adequate information regarding the context and the history on which the current research is routed. Literature reviews are a critical element to any research process and serve as guide to identify key theories and theorists, identify research gaps, trends and explain the selection of the research questions and research methodology (Steward, 2004; Creswell, 2013a).

Since we adopted a mixed methods research strategy, as described briefly in section 1.5 “Research methodology”, this approach required adapting the literature review process to suite the research method (Steward, 2004; Dellinger, 2007; Creswell, 2013a; Creswell, 2013b). The literature review was divided into two main parts in order cover the different aspects of the research requirements; being the qualitative and quantitative stages. In the upcoming sections we will describe two parts of the literature review in detail.

Finally, we would like to list some of the sources used to conduct the literature review: ACM Digital Library, Business Source Complete, IEEE Explore Digital Library, JSTORE, ProQuest Databases, SAGE Journals Online, SpringerLinks Journals, Wiley Online Journals, Scholars Portal Journal, eBook Collection (EBSCOhost), Google books, Google Scholar, Oxford University Press eBooks, Safari Books Online, Routledge Online, Scholars Portal Books, Springer eBooks, Wiley Online Books, Congress.gov, CERN Document Server, Canadian Disaster Database, and Eurostat.

2.1 Stage-1 Literature Review (Qualitative Stage)

The literature review at that stage was conducted to complement the qualitative phase of the research method and help achieve the goals of the research work. The process of the review was guided by an earlier work by Lettieri, Masella, & Radaelli (2009); where they conducted a systematic literature review in the field of disaster management to understand the trends and key issues in the field. Hence, the main purpose of the first stage of the review was to explore the intricacy of disasters, disaster management and response operations in order to construct a sound framework in analyzing the qualities of coordination in disaster response operations. Therefore, Stage-1 literature review focused on the following aspects:

- Theoretical framework used to research disaster management;
- Phases of the general process of disaster management;
- Actors involved and protocols followed within disaster management;
- Information and technology and other resources utilized for disaster management.

Stage-1 review itself was implemented on two iterations, where the first iteration aimed to build a comprehensive understanding of the disaster management field. The second iteration dedicated itself to examining work related directly to coordination specifics in the field of disaster management and operations research. Furthermore, the second iteration lead to the identification of issues related to interorganizational coordination in response operations and to the role of networks in disaster response.

The outcomes of Stage-1 literature review provided a substantial amount of knowledge regarding key principles, trends, critical problems and research gaps in disaster management research. This knowledge contributed to valuable insights that generated the formation and selection of research questions and research methodology. The outcomes also considered an essential reference upon which to formulate the discussion of results.

For the purposes of Stage-1 literature review, publications (peer-reviewed papers, books, conference proceedings, journal papers, and official government reports) from disaster management, organizational science, operational research, sociology, and public policy and administration were carefully selected. Keywords that were used in the search related to *disaster management, command and control, incident command centers, interorganizational coordination, coordination networks, organizational coordination, disaster response operations, and net-centric crisis response*. In Table 2 we provide selective examples of literature used in this review.

Domain	Publication
Disaster management	• International Journal of Emergency Management • Natural hazards (Journal) • Disasters (Journal) • Journal of Homeland Security and Emergency Management • Proceedings of the International ISCRAM Conference • Journal of Contingencies and Crisis Management
Public policy and administration	• Public Works management & policy (Journal) • The American Review of Public Administration (Journal) • Administration & Society (Journal) • Public Performance & Management Review (Journal)
Management and organizational science	• Academy of Management Review (Journal) • Research in organizational behavior (Journal) • Organization Science (Journal) • Journal of Management
Sociology	• Sociology and Social Research (Journal) • Journal of Mathematical Sociology • Social Science & Medicine (Journal)

Table 2. Stage-1 literature review - selective literature sources and their domain

The review process results were organized in the following topics:

- Disaster management definitions and concepts
- Disaster response systems
- Interorganizational coordination in disaster response operations
- Disaster response networks

In the upcoming sections 2.1.1 – 2.1.4 we will discuss details of each topic and how it contributed to the construction of the different parts of the research work.

2.1.1 Disaster Management, Definitions and Concepts

Societies are under constant threats of geophysical, climatological, and technological factor that result disasters and generate social and physical disturbances. In response, societies engage in activities to develop techniques and technologies aim to provide protection from such threats. From practitioners' point of view, we cite an example from the Canadian Emergency Management Framework (2011), to define a "disaster",

"Essentially a social phenomenon that results when a hazard intersects with a vulnerable community in a way that exceeds or overwhelms the community's ability to cope and may cause serious harm to the safety, health, welfare, property or environment of people; may be triggered by a naturally occurring phenomenon which has its origins within the geophysical or biological environment or by human action or error, whether malicious or unintentional, including technological failures, accidents and terrorist acts."

Similarly, and from the same source above, an "emergency" is defined,

"A present or imminent event that requires prompt coordination of actions concerning persons or property to protect the health, safety or welfare of people, or to limit damage to property or the environment."

Despite of the different definitions for the terms "disaster" and "emergency" among practitioners and academics but the common concept most agree upon is that disasters and emergencies are events, which cause social disturbance and involves high levels of uncertainty (Dynes & Quarantelli, 1968; Dynes & Aguirre, 1979; Lindell, Tierney, & Perry, 2001; Quarantelli, 2005). Dynes & Aguirre (1979) went further to describe it as "extreme environmental uncertainty".

The occurrence of disasters and emergencies can produce *direct* and *indirect* effects that can impact the society in different ways. *Direct* effects are a direct result of the disaster events such as fatalities, injuries, and physical damage of assets. The *indirect* effects are related to consequent impact (some might call it "ripple effect") of the disaster such as fires triggered by an earthquake and environmental pollution resulting from flooding or a Tsunami. Those kinds of occurrences generate additional risk factors that can implicate the losses over and above those caused by the primary disaster events and produce complications to the response operations (Lindell, et al, 2001, Quarantelli, 2005; Carafano, 2011). In order to circumvent direct and indirect effects of disasters, preventative actions must be taken and adequate response plans must be developed to orchestrate collaboration among different organizations (public and/or private) and/or individuals.

In disaster management, there are several sets of protocols and frameworks called disaster (emergency) management plans. By definition, *coordination* is "the process of organizing people or groups so they work well together" while *collaboration* is "the actions of working together in order to achieve something". Those sets of protocols are activated in event of a disaster to facilitate interorganizational and intraorganizational collaboration, to coordinate actions and facilitate communications through out the different stages of the disaster management cycle (Bigley & Roberts, 2001; Lindell, et al, 2001; Comfort & Haase, 2006a; Moynihan, 2009; Richter, Heumüller, Lechner, 2010; Bram & Vestergran, 2012). Figure 7, is an illustration of the phases of disaster management cycle.

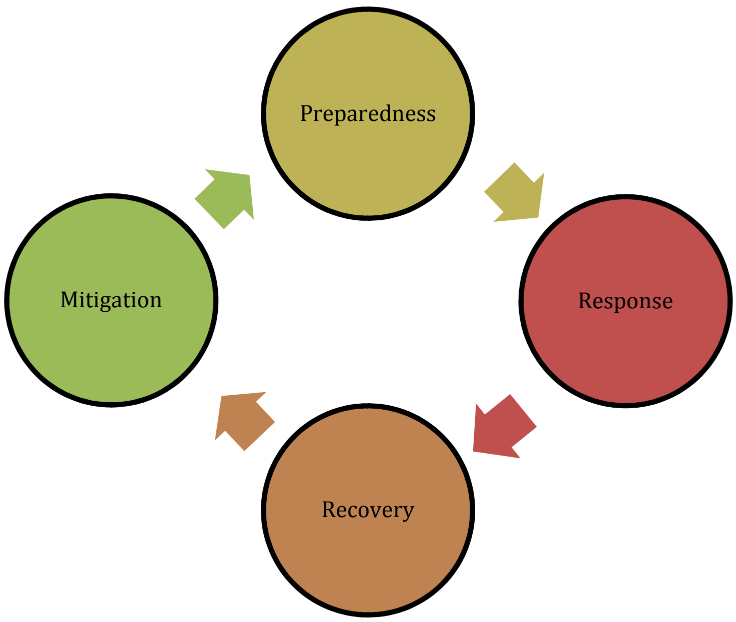


Figure 7. The four stages of disaster management cycle.

As shown in Figure 7, there are four distinctive stages for disaster management cycle: *mitigation*, *preparedness*, *response*, and *recovery* (Public Safety- Government of Canada, 2011; Department of Homeland Security, 2013). *Mitigation* stage includes any activities that prevent an emergency, reduce the likelihood of occurrence, or reduce the damaging effects of unavoidable hazards.

Mitigation activities should be considered long before an emergency. Mitigation measures include land use regulations that reduce hazard exposure and building codes and construction practices designed to ensure that structures resist the physical impacts created by elements, such as wind, water, or seismic forces.

Preparedness stage includes developing plans for what to do, where to go, or who to call for help before an event occurs. Organizational preparedness activities might include activates such as developing emergency response plans, training employees and response personnel on what to do in an emergency situation, identify required resources (i.e. equipment, supplies, and materials) and finally conducting drills and exercises.

Response stage encompasses all actions taken during a short period prior to, during, and after disaster impact to reduce casualties, damage, and disruption and to respond to the immediate needs of disaster victims. These actions can include detecting threats, disseminating warnings, evacuating, searching and rescuing victims, providing emergency medical care, taking action to contain ongoing threats, and providing emergency food and shelter.

Recovery stage is final stage and it comprises actions taken to repair, rebuild and construct-damaged properties and to restore disrupted community social routines and economic activities. Recovery activities typically center on the provision of aid for temporary housing and residential reconstruction, the restoration and reconstruction of public infrastructure and facilities, and the provision of assistance to households and businesses that experienced physical damage and other losses (Public Safety- Government of Canada, 2011; Bram and Vestergran, 2012; Department of Homeland Security, 2013).

In this research we focus on the *response* stage (or the active phase) in disaster response operations of onset sudden disasters such as earthquakes, floods or fires. We examine existing response systems in comparison with real world disaster response examples during the active stage. The process of analyzing the actions taken by the organizations and resources consumed in response operations will contribute to a better understanding of the coordination patterns and dynamics of coordination in response operations. Therefore, it is essential to examine existing disaster management systems to obtain insights that would contribute to improving the reality of disaster management.

2.1.2 Incident Command Systems (ICS) in Disaster Management

In disaster and crisis management if we talk about coordination in response operations then Incident Command Systems (ICS) must be included in the discussion. The ICS is the term used to describe an approach followed by police, firefighters and other public safety entities to create temporary systems. The ICS organization is built using the top-down approach with responsibilities initially placed with the Incident Commander. The incident is appointed and attains the highest authority to serve as the primary coordinator to orchestrate efforts in the events of a disaster event (Bigley &Roberts, 2001; Lindell, 2001; Crichton, Lauche, Flin, 2005; Moynihan, 2009). Figure 8, illustrates an example for a partial ICS, a basic command system. As need arises, four functional sections can be established and each has its own branches, with a set of primary and supporting organizations. Note that Figure 7 below shows just a partial organizational chart of the ICS, focusing on the high level structure of ICS only. The ICS provide a temporary framework to primarily facilitate communication, coordination, and collaboration between the responders and the commanders. The ICS is a top-down command and control structure at principle although the exact implementation is adaptive to the situation requirement in event of a disaster. All units with commanding positions are arranged hierarchically and related to one another on the basis of formal authority.

Since the ICS is considered a framework to facilitate coordination and collaboration of multiple organizational, the basic system objectives and plans are established at or near the top of the hierarchy and used as a basis for decisions and behaviors at lower levels. However, each function area can have its own sub-goals from its functional focus. This decomposition continues along the organizational levels. Another characteristic of ICS is having multiple protocols of different communications and actions are made based on well-defined protocols.

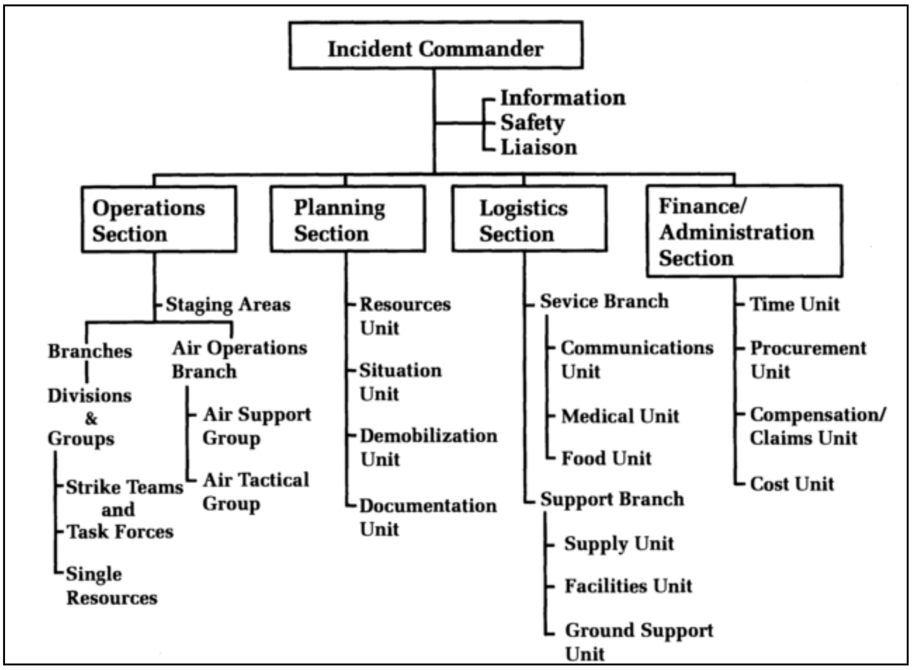


Figure 8. Partial ICS with main functional divisions.
(*Adapted from two 1999 publications: California's Fire Service Field Operations Guide (ICS 420-01) and IS 195-Basic Command System (Federal Emergency Management Agency: http://wwwfema.gov/EMI/isl951st.htm.)

In case of an incident, a fire for example, the following activities might take place:

1. Initiate emergency on local level upon a 112 or 911 call.
2. Dispatch first responders' team(s) (Firefighters, Police, and Paramedics).
3. Rescue and evacuate of victims to medical facilities.
4. Assess the situation in case further forces are required to contain the fire or announce end of emergency.
5. In case of additional force needed then request regional aid.
6. Provide shelter and food for evacuees.
7. Prepare media report and issue a statement.

In general, the response operations process is divided into three levels:

- *First response (Municipal level)*, which is activated by local firefighters and policemen immediately after the 122 or 911 call;

- *Regional response (State or province level)*; in case the firefighting operations requires extra forces or require transferring victims to medical facilities outside the municipality jurisdictional area

- *National response (Federal level)* in case the severity oft he incident becomes beyond the capabilities of local or regional responders, and national resources are requested.

In Figure 9, illustrates the distribution of response activities on the different levels of the operation process in case of the fire incident scenario.

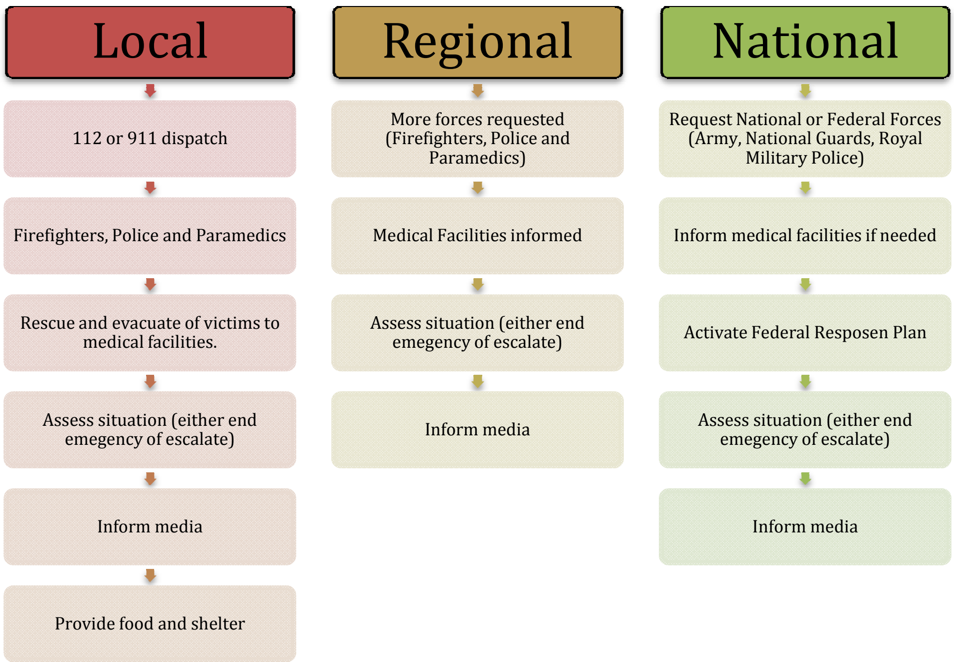


Figure 9. The different levels of response operation for a fire incident and activities required.

Despite the reality of the net-centric behavior of organizations in responding to an emergency situation (Kapucu, Arslan, Collins, 2010a; Richter, Heumüller, & Lechner, 2010; Bharosa, 2011); the existing response plans and protocols are strictly hierarchical and the structure of levels of authority, communication channels and actor roles based on the traditional organizational operations concepts (Bigley & Roberts, 2001; Crichton, Lauche, Flin, 2005; Moynihan, 2009;

Kapucu, 2009). Thus far, designing "a one size fits all" emergency response framework to coordinate multi-organizational efforts and adaptive to uncertainty levels in crisis situation has been the goal of many public administration officials, policy makers, and emergency management experts.

Examples of such efforts can be seen in the publically available in the Emergency Management Framework of Canada or the US National Response Framework documents, where the proposed framework and protocols are designed to be used in responding to all types of hazards and to facilitate a *harmonized coordination* among organizations involved in crisis response.

> *"The FERP is designed to harmonize federal emergency response efforts with those of the provinces/territorial governments, non-governmental organizations, and the private sector."*
>
> *Canadian Federal Emergency response Plan (FERP)*
>
> *"The NRF is a guide to how the Nation responds to all types of disasters and emergencies. It is built on scalable, flexible, and adaptable concepts identified in the National Incident Management System (NIMS)2 to align key roles and responsibilities across the Nation. The NRF describes specific authorities and best practices for managing incidents that range from the serious but purely local to large-scale terrorist attacks or catastrophic natural disasters. "*
>
> *US National Response Framework (NRF)*

From this we conclude that it is essential for disaster management systems to enable rapid mobilization of a dynamic interorganizational coordination that moves from individual to organizational to system levels of action, analysis, and aggregation of information. These different operational scales of action require different types of information and different means of communication to create a "common operational picture" to support collective action against threats at any jurisdictional level. Unfortunately, the escalation transition points during response operations are the bottlenecks where human cognitive, communicative, and coordinating skills frequently fail despite the rigid ICS (Lindell, et al., 2001; Comfort, et al., 2006a; Comfort, et al., 2006b; Comfort, et al., 2010).

The response to the complicated impact (direct and indirect) of a disaster had been proven beyond the capabilities of a single organization, therefore, the organizations form coordinative networks among themselves to work collaboratively in responding to complex disaster events (Comfort, et al., 2006a; Comfort, et al., 2006b; Comfort, 2010).

The phenomenon of emerging coordinative networks in response operations during the response (active) stage is one of the main subjects under investigation in this research. Moreover, it is critical to examine the organizational behavior in the context of network-governed structures to attain proper knowledge when analyzing coordination in such context. The next section represents a detailed of networked organizational behavior and some existing work within the scope of disaster management.

2.1.3 Organizational Networks in Disaster Response Operations

Disasters are described as disruptions to daily routine of society, they create an environment with high levels of uncertainty and complexity, especially in medium and large-scale disasters, which apply pressure on the organizations' capacity to provide adequate response (Parr, 1969; Dynes & Quarantelli, 1970; Parr, 1970; Dynes & Aguirre, 1979). In the context of harmonized response, Dynes & Aguirre (1979) had highlighted this issue and introduced the notion of "coordination by feedback" where organizations attempt to restructure to adapt to the uncertainty conditions in the surrounding environment of an emergency event. In more recent years, several scholars came to recognize the phenomenon of networked response operations; in which organizations engaged in disaster response operations operate in a networked-governed structure. In a networked response operation, involved organizations work collectively towards shared goals, responsibilities and unified action to produce a common outcome (Kapucu, 2005; Comfort & Kapucu, 2006b; Moynihan, 2008; Moynihan, 2009; Abbasi & Kapucu, 2012; Butts, Acton, Marcum, 2012; Kapucu & Garayev, 2013; Boersma, Ferguson, Groenewengen, Wolbers, 2014a).

The concept of organizational networks is becoming more understood in the organizational context, although there is still some ambiguity regarding the use of the term by different organizational scholars. The term network sometimes differ in what it describes; sometimes it's used to describe partnerships, strategic alliances, interorganizational relationships, coalitions, or collaborative agreements or other transactions taking place within and between organizations (Brass, Galaskiewicz, Greve, Tsai, 2004; Provan, Fish, Sydow, 2007; Easley & Kleinberg, 2010.; Borgatti & Halgin, 2011). However, the common theme among the different representations is the social interaction element (among individuals, departments or organizations), connectedness, collaboration, and collective action. A general definition of a network can be defined as "a set of nodes and the set of ties representing some relationship, or lack of relationship, between the nodes." (Brass, Galaskiewicz, Greve, Tsai, 2004, Jackson, 2008a & 2008b). Furthermore, an organizational network can be a representation of a variety of intraorganizational or interorganizational relationships that emerge as constellations of organizations that come together by establishing a form of social contracts or agreements (e.g., working together toward a common goal under stress) rather than established legally binding contracts. An organizational hierarchy or an established business process care examples of a legally binding contracts and they exist within a network, but relationships and connections established through social contracts have an emerging nature (Provan, & Sebastian, 1998; Moliterno & Mahony, 2011).

SNA is used as a methodology to study the composition (and a tool to visualize the relationships) of organizational networks. Relationships among network members are primarily nonhierarchical, and participants often have substantial operating autonomy (Borgatti & Everett, 2000; Bonacich, 2007; Jackson, 2008a & 2008b). Using SNA, network members are represented with nodes (or vertices). The links between these nodes can represent different types of relationships such as information, materials, financial resources, services, and social support. Connections may be informal and totally trust based or more formalized, as through a protocol or a hierarchy. Examination and analysis of a whole organizational network facilitates the understanding of the structure and the formation of interorganizational relationships between the nodes (organizations) and formations of their links (Zaheer, Gözübüyük, Milanov, 2010). Using network analysis can help examine the impact of network ties on organizational performance, examine links that are most or least beneficial to the network members, locate that nodes are most influential in the network, and finally the changes in the organization or unit position can influence the network (Jackson, 2008c & 2008d; Rodriguez, Leskovec, Krause, 2010). These are some network analysis metrics used to measure an organizational network characteristics such *degree of centrality, closeness, and cliques.*

The *Degree of Centrality* provides information about the organization's (or a unit) position within the network whether it occupies a central or a more peripheral position in the network based on the number of network ties it maintains with other members. Degree of centrality is based on the number of links maintained by an organization with other members in the network. The *Closeness* provide information about the position of an organization whether it is central to the network and have short "paths" (connections) to all other organizations in the network. Closeness is calculated by considering the shortest path connecting a focal organization to any other organization in the network. The final measure is the *Cliques*, which they are clusters of three or more nodes (organizations) connected to one another. The level of an organization's connectedness to a clique may affect organizational performance in ways that are different than when the organization is connected only to a single organization (Freeman, 1977; Freeman, Borgatti, White, 1991; Provan, & Sebastian, 1998; Provan, Veazie, Staten, Teufel-Shone, 2005; Provan & Kenis, 2008).

In our work we focus on coordinative organizational networks or what we call coordination-clusters. Coordination-clusters consist of organizations from multiple sectors, and their effectiveness depends on high levels of trust and dense relationships between actors. In order to assess the effectiveness of a coordination network, interorganizational relations need to be examined. As a function of service integration among subgroups, or cliques, of core organizations, the strength of the ties within the cliques determines the effectiveness of the overall network. The closeness of relations between members of a network is another indicator of a network's effectiveness (Provan, & Sebastian, 1998; Topper & Carley, 1999; Provan & Kenis, 2008; Kapucu & Demiroz, 2011). Therefore, members' ability to build relations among other members can facilitate effective coordination dynamics in the network. In later sections we are going to discuss the details of the tools used to examine the different characteristics of the coordination networks in disaster response operations.

In disaster management, there are few examples for applying SNA to analyze the performance of the disaster response systems. One of them is the disaster response system in the US, where since the creation of FEMA in 1978 (Kapucu, 2009). Kapucu (2005); Kapucu (2009); Moynihan (2009); Hossain & Kuti (2010); Kapucu, Bryer, Garayev & Arslan, (2010), Vasavada (2013) had examined the coordination and the effectiveness of response systems in the US and other countries in order to address the existing gap of having a unified framework for a response (or an incident management) system that can accommodate response to wide spectrum of disasters and including concepts of organizational networked coordination in response operations.

Throughout the course of the different stages of a disaster, different patterns of network formation emerges and different levels of interaction take place among the actors in the disaster response network. In addition, high levels of uncertainty, which a disaster involves, require a dynamic response and an adaptive structural behavior for organizations to cope with the disruptive environment that is caused by the disaster (Dynes and Aguirre, 1976; Kapucu, 2009; Topper, and Lagadec, 2013). In such environment, response operations take the form of complex networks, which are the type of networks that emerge under such diversified and complex condition. Furthermore, the emerging clusters can involve heterogonous actors; both conditions would lead to the notion of the emergence of complex network in emergency response management. Levels of coordination and collaboration are different among the different coalition inside such network and it is yet to be discovered (Hossain and Kuti, 2010; Kapucu, 2012; O'Sullivan, Kuziemsky, Toal-Sullivan, and Corneil, 2013).

Incidents such as a car collision will probably require the local police, fire department and paramedics at the max to respond such incidents. Unlike the day-to-day incidents, a catastrophic event (such as East Japan Earthquake, 2011 or the Super Storm Sandy, 2012) requires a multinational and multi-jurisdictions response and high degrees of cross-organizational collaboration. As the response networks become more complex, a need emerged of providing facilities where authorized personnel and decision makers can have rapid access to information, real-time visibility and management to the situation. Such facilities are manifested by the command and control centers, such centers operate as dispatch center, surveillance center, coordination office and alarm monitoring center (Bigley, and Roberts, 2001). The command and control centers represent a focal point in information dissemination and decision-making process in the emergency response network. In Figure 10, shows response networks with different levels of complexity that depends on the scale of the incident and the required response forces. Also we can see the change in the position of the command and control nodes in case of escalation.

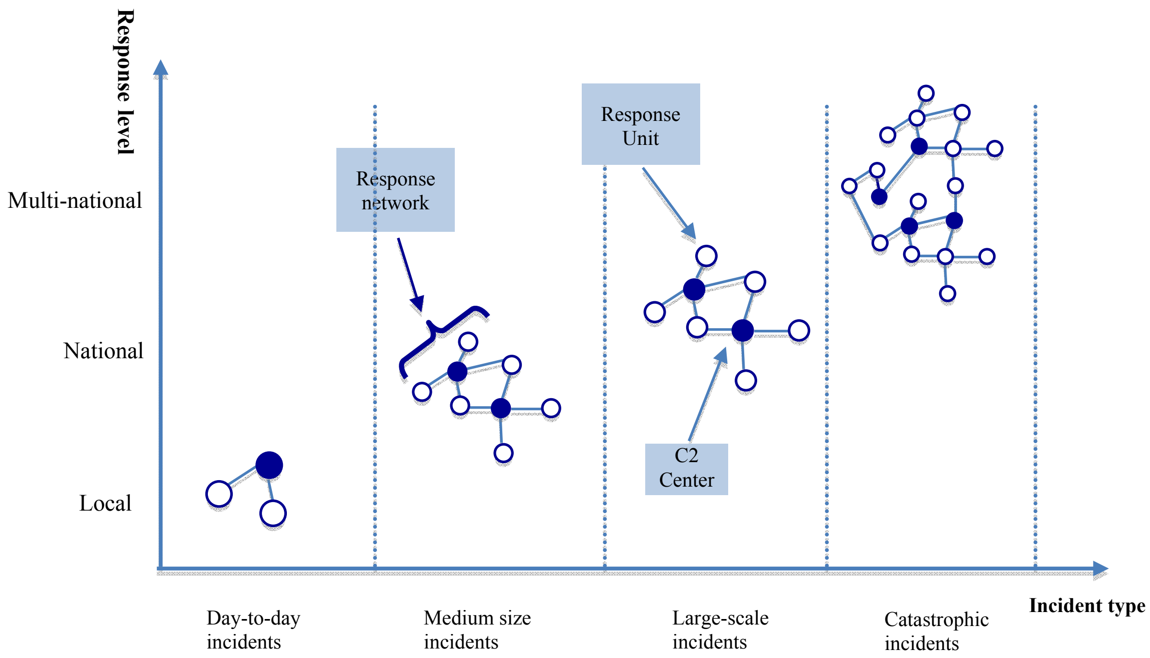


Figure 10. Response network evolution as incident intensity increases.

In Figure 11 we show in an incident there are different types of information (i.e. alert update, status reports, commands, etc.) flowing in a bidirectional mode among the members of the coordination network. Information such as incident location, number of victims and incident severity would be traveling inwards from other nodes to feed into the C2C nodes. Other information such as actions or commands would be traveling from C2C nodes outwards to other nodes. In any response operation network, the path and time of information travel in the network impact the decision making process and it depends on the position of the response unit and the C2C in the network.

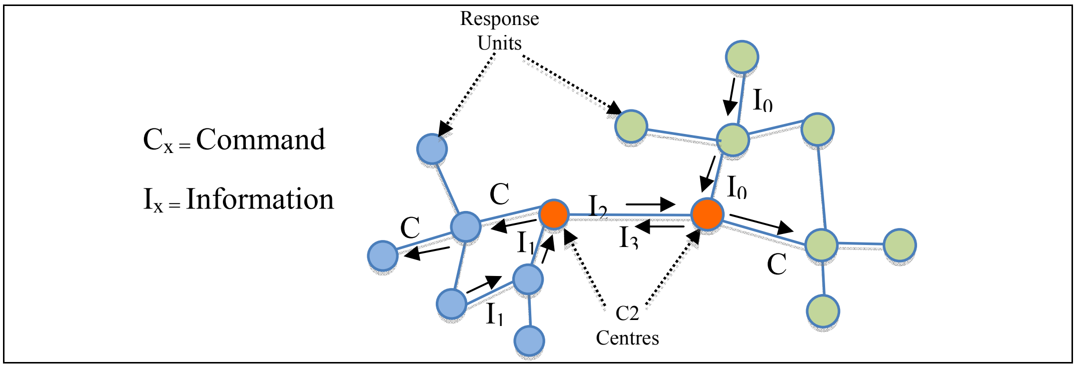


Figure 11. Information flow between coordination-clusters in a hypothetical response network.

Thus far, the research work aim to introduce an approach that would complement the studies mentioned earlier. The approach represents a combination between SNA, complex networks and other dynamic methods (i.e. discrete event analysis) to examine the evolution of response networks and the evolution of the coordination-clusters in those networks. The anticipated results of the analysis will contribute to the process of creating a framework to analyze coordination dynamics for a network governed disaster response system.

2.1.4 Interorganizational Coordination in Disaster Response Operations

Circumstances associated with disasters and disasters' response had highlighted the importance of the interorganizational coordination in disaster response networks (Hossain and Kuti, 2010; Kapucu, Bryer, Garayev and Arslan, 2010). In such networks, several organizations are required to collectively coordinate in responding to the occurring crisis events. In order to study the coordination in disaster response networks, we used coordination theory (Crowston & Malone, 1994) as a framework to extract coordination specifics "between" and "within" actors (organizations and/or individuals), actions and resources by outlining the types of dependencies involved with achieving a certain goal within certain context.

In general, when two or more parties (individuals, teams or organizations) work together to achieve same goals, they have to organize themselves where one party does not replicates others work unless necessary and manage shared resources and dependencies. Such organization is called *Coordination* (Malone & Crowston, 1990); they define *coordination* as;

"… the additional information processing performed when multiple, connected actors pursue goals that a single actor pursuing the same goals would not perform."

From here we conclude that coordination implies that following components: a set of two or more actors, tasks to perform, goals to achieve. In addition to coordination components, in order to analyze coordination, the observer must have some idea of what goal the activities help achieve. The actors themselves, however, may not all have the same goals or even have any explicit goals at all.

The *coordination theory* defined by Malone and Crowston (1994) as;

" *… the body of principles about how the activities of separate actors can be coordinated. A test of the generality of a concept or principle is whether it can apply to more than one kind of actor.* "

The coordination theory was applied in various fields of science such computer science, engineering, supply chain management, organizational science and economics (Malone, 1987; Bailetti & Callahan, 1993; Crowston et al., 2006; Arshinder, Kanda, Deshmukh, 2011). For the purposes of our research work, coordination theory was a normal fit to examine interorganizational coordination in disaster response networks. Applying coordination theory lens to investigate tasks and dependencies in a disaster response event provide the main constructs for coordination structure in disaster response networks. Worth to mention that few scholars used coordination theory for studying coordination mechanism in disaster and crisis management research (Shen & Shaw, 2004; Bharosa, 2011; Abbasi & Kapucu, 2012) but not in the context of coordination evolution within a network governed environment.

In this research, coordination theory was adopted to examine coordination dynamics in emerging networks throughout disaster response operations. Consequently, there was a need to modify the existing framework to satisfy the research requirements for understanding how relationships formed, information exchanged, actions propagated and decisions made in disaster response networks. We explore new areas of applying coordination theory within the context of networked organizations and disaster response operations. As a result, we extend the theory to help examine emerging coordination structures in dynamic environments and complex networks. In Figure 12, illustrates how to position the contribution of this research work to coordination theory in contrast to the existing fields.

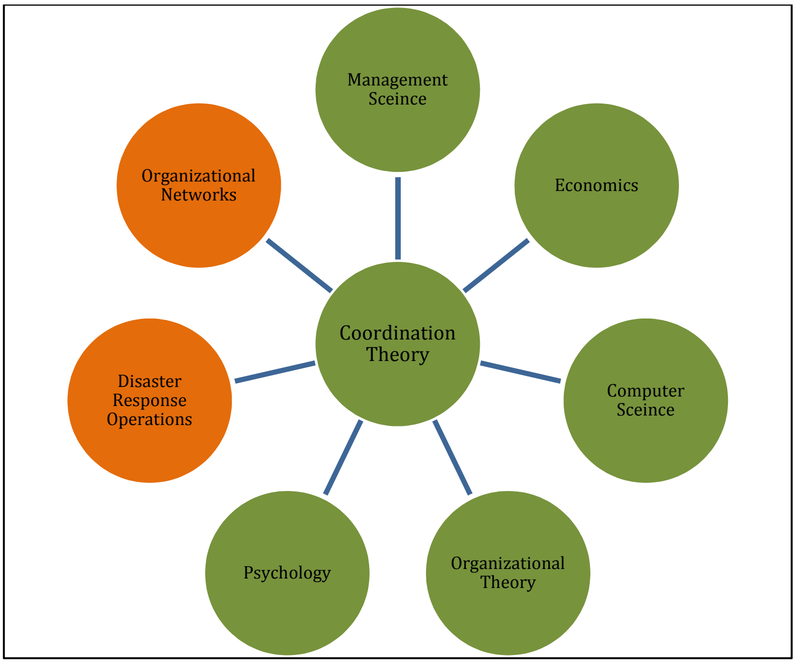


Figure 12. Areas of focus and contribution to Coordination Theory

Coordination theory provides a framework to identify the problem space and variables such as context boundaries; dependencies and actors then design a process in order to achieve the goals (Crowston, 1997; Crowston, Rubleske, Howison, 2006). Unfortunately in disaster conditions, the problem space and variables are not fixed due to the high levels of uncertainty. Thus far, coordination theory framework is lacking the capability of designing and representing processes based on dynamic input and complex network variables like node position, connectivity, information proliferation, and clustering. However, Bailetti and Callahan (1993) proposed a combination of coordination theory and Object-Oriented modeling to introduce the notion of "*coordination ensemble*" to manage coordination in multi-organizational and international IT projects where uncertainty and tasks intensity are high. The approach is based on object-based representation of coordination actions to capture and make visible the interorganizational coordination specifics on the system level in complex projects (Bailetti, Callahan, DiPietro, 1994). Such approach help reshape coordination theory to be used in complex situation yet it was lacking the networked organizations perspective settings. However, phasing out and decomposing coordination processes was one of the strategies to help extract actors, actions and resources and flow the coordination process. Such approach assimilates to disaster response operations complexity and provides insights to phase out the coordination processes.

In that sense, the coordination theory with coordination ensemble concepts can offer a modeling framework to identify the various actors engaged, activities coordinated, and distinguish of the dependencies between actions and tasks required to achieve common goals (Malone, 1987; Malone 1988; Malone & Crowston, 1990). Examples of such dependencies are, sharing resources like rescue crews, vehicles, equipment, used shared facilities to evacuate affected individuals and many others. In coordination theory there are three types of dependencies: flow, sharing, and fit. In Figure 13 we can see the three types of coordination dependencies in a process flow (Malone, Crowston, Lee, Pentland, Dellaroca, Wyner, Klein, 1999).

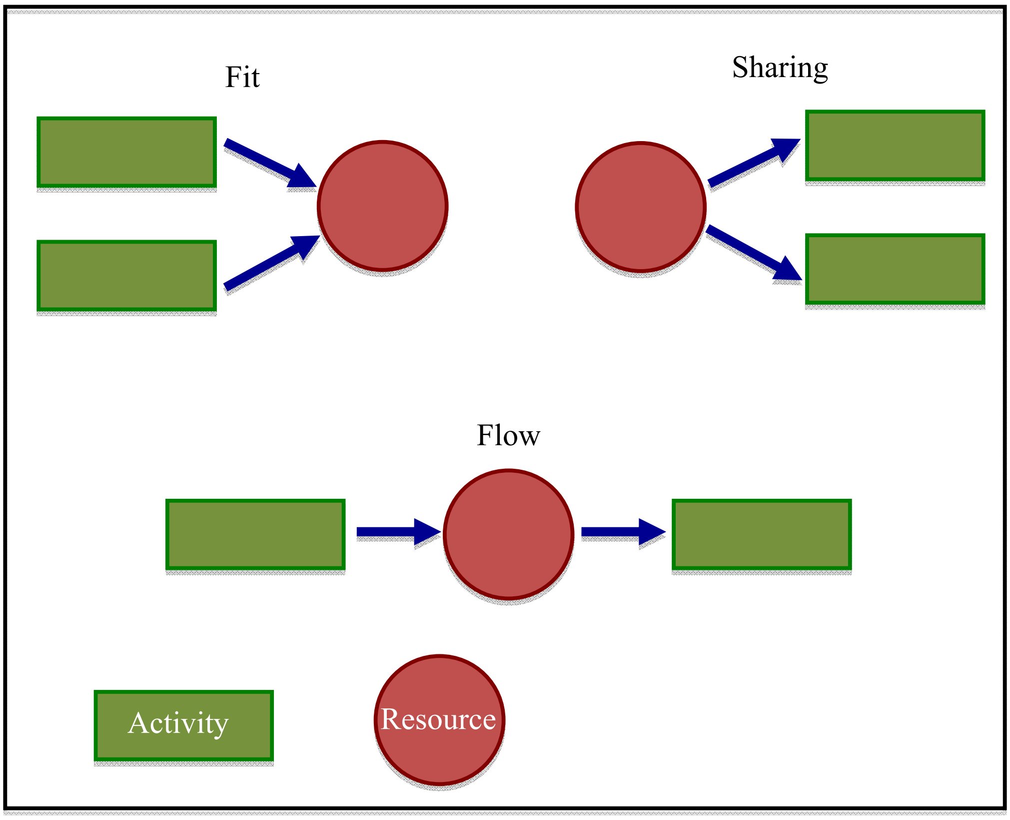


Figure 13. Three types of dependency based on resources and activity distribution.

Those three types of dependencies are classified based on the distribution of resources and activities. The *Flow* dependencies happen whenever an activity produces a resource that is used by another activity. The *Sharing* dependencies occur when multiple activities tend to use same resource. The *Fit* dependencies happen when multiple activities produce a single resource.

Back to disaster management, Shen and Shaw (2004) applied coordination theory to identify some of the dependencies apply to case of disaster response, however in the context of designing IT-based platforms for response teams. We adapted their framework (shown in Table 3) help us categorize the dependencies and the links between the different parties involved in response operations and resources required in such operations.

Generic Dependency	Specific Dependency		
	Activity-Actor	Activity-Activity	Actor-Actor
Sharing	Task assignment	Activities must happen simultaneously	Response personnel share a common source
Flow	Delegation of agent to tasks	Prerequisite tasks	Sequence activities → local, regional, federal activities
Fit	Agents must be capable to perform a task	Activities interact or have counter effects	Agents must have compatible goals
An adaptation of the coordination mechanisms by Shen and Shaw (2004)			

Table 3. The dependencies categorization in disaster response systems.

As shown in Table 3, we can see the three generic types of dependencies that can involve different combinations of an activity and an actor. *Sharing* implies the ability to share resources, activities happening at the same time. In delegating tasks we can see a *flow* type of dependency where some inputs are expected from previous stages in the coordination process. Lastly, a tailored task that must *fit* the owner task owner describes the last type of dependency.

Coordination problems generates from situations where actors and processes are dependent upon each other's. In many cases, dependencies constrain how tasks can be performed and resources being distributed. In order to solve coordination problems, there are coordination mechanisms that are sued. Those mechanisms can be quite specific per case and depending on the application, therefore, there is no generic framework for coordination mechanisms. However, Malone and Crowston (1994) had identified some of those mechanisms that are related to common dependencies to manage different activities such as operations decomposition, resource allocation and synchronization.

The main focus of this research is on definitions of coordination core elements such as; actors, activity and resource to locate different dependencies in the coordination processes in disaster response operations. *Resources* are everything consumed by the activities taking place in response operations. Things that are not somehow used or affected by an activity are not considered; if they are not involved in the activities of some actor, then they are irrelevant to the analysis of the behavior of that actor. Resources include material goods and the effort of actors. For example, in the case of disaster response, resources include heavy equipment, medical supplies, food, vehicles, personnel and funds. We identified the *actors* as organizations involved in the response efforts; however, the units participating are considered as resources. Finally, *Tasks* were defined as activities performed by the actors to achieve certain goals.

Due to the complexity of the response operations, operations were broken-down into sub-operations. The breakdown of the processes generated phase-based operational levels that represent an abstract of the overall response operations following the coordination ensemble strategy (i.e. three levels of response) (See Figure 9). In addition, decomposing the response operations to sub-tasks such as *search and rescue* or *evacuating victims* and other tasks. With the information extracted about tasks and dependencies in the response operations, a *Coordination Matrix* (as shown in Table 4) is constructed. The coordination matrix contains information about each organization was engaged in the response at certain time, details about resources contributed and tasks carried out either separately or in collaboration with other organizations.

Time	Actor	# Of Units	Resources	Tasks
Tx	Organization A	X units	Soldiers, helicopters	*Establish C2 for regional level * Evacuation operation w/ local police
	Organization B	Y Units	Policemen, specialized units	*Search and rescue w/ Fire Fighters, NGO
	Organization C	Z Units	Experts from different backgrounds	*Evacuate people *Cleaning roads

Table 4. Example of Coordination Matrix for time slice Tx.

The outcome of the coordination matrix represents the first step of constructing a dynamic view of the coordination evolution in disaster response networks. Moreover, we extended the coordination theory framework to include the time factor where we organize the information based on time slices. Depending on each case study, we define a fixed time slice to analyze the response operations and construct the associated coordination matrix. This process allowed us to have a outlook of the coordination evolution in response operations.

With this section we end Stage-1 literature review where we discussed the main theories and concepts we used in qualitative part of this research. The next sections represents Stage-2 of the literature review that complement Stage-1 contents and offer in depth information regarding the tools sued to represent the data and model the coordination processes in response operations.

2.2 Stage-2 Literature Review (Quantitative Stage)

The Stage-2 literature review was conducted to support the quantitative phases of the research method. In order to accommodate the qualitative requirements of the research stages, the purpose of the literature review was to identify proper theoretical instruments to quantify the outcomes of *Stage 1* (i.e. the coordination matrix, time-based response operations representation and coordination evolution in response operations).

The results of Stage-2 review provided us with key concepts and methodologies to build the data analysis framework used for examining the phenomenon of emerging networks and coordination-clusters in disaster response operations. It provided insights for the selection of research questions and research methodology.

Similar to Stage-1 literature review, a collection of publications was included in the process (i.e. peer-reviewed papers, books, conference proceeding, and official reports) from disaster management and operational research in addition to social networks analysis, dynamic networks analysis, and dynamic systems modeling with relation to disaster management. Keywords combinations were used for the search related to *network analysis & disaster managements, SNA, community detection, coordination modeling, Petri Nets & coordination, Petri Nets & disaster management, discrete-event systems & coordination*. In Table 5 we provide selective examples of literature used in this stage of the review.

Domain	Publication
Social network analysis and complex networks	• Connections: Journal of International Network for Social Network Analysis • IEEE Transactions on Systems, Man, and Cybernetics: Systems (Journal) • Circuits and Systems Magazine • Social Networks (Journal) • Proceedings of the 16th ACM SIGKDD international conference on Knowledge discovery and data mining
Community detection in complex networks	• Proceedings of 11th International Conference on Intelligent Systems Design and Applications • Proceedings of the National Academy of Sciences • The European Physical Journal • Physics reports (Journal) • Journal of Statistical Mechanics: Theory and Experiment • Dynamics On and Of Complex Networks
Discrete event systems and modeling	• Proceedings of International Conference on Information and Communication Technologies for Disaster Management (ICT-DM) • Journal of mechanical science and technology • Theoretical computer science (Journal) • International Journal of Hybrid Information Technology • Information Technology and Management (Journal) • Theoretical computer science (Journal)

Table 5. Stage-2 literature review, selective literature sources and their domain

The literature review process results were organized in the following topics:

- Complex networks for disaster response operation analysis
- Community detection in complex networks and emerging coordination-clusters
- Discrete event systems and Petri Nets approach to analyze coordination dynamics disaster response networks

In the upcoming sections 2.2.1 – 2.2.3 we will discuss details of each topic and how it contributed to the construction of the different parts of the research work.

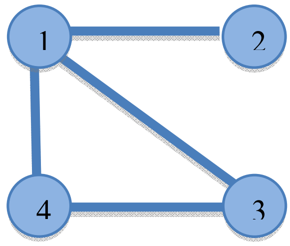
2.2.1 Complex Networks and Disaster Response Operations Analysis

In Section 2.1.3 we discussed inter-organizational networks in details and in relation to disaster response operations. The discussion was more focused on main concept used to analyze organizations and metrics used to provide the different measure about the characteristics of organizations networks such as centrality, clustering and most important visualization of the organizational network evolution. Relationships among network members are primarily nonhierarchical, and participants often have substantial operating autonomy. Using SNA to represent an organizational network, the members are represented with nodes (or vertices). The relationships between those nodes (or organizations) are translated to links (or ties). Those relationships can be information, material, financial resources and social support and it can be unidirectional or bidirectional. The links or ties representation in a network can be a directed or undirected. In *undirected* graphs (networks) the relationships (links) are a two-way relationship without a direction; where in directed graphs (networks) the relationships (links) are a one-way relationship.

The sets of relationships between the nodes of a network (or a graph), whether it was directed or undirected, are translated to an *n x n* (a square matrix), it is also called *adjacency matrix*. The set of relationships G(n) is used to represent the network mathematically where and n is the number of nodes and g_{ij} represents relationships (ties) between j and i nodes. Network graphs are used to visualize the mathematical representation of the network, i.e. the “g” matrix (Jackson, 2008a).

In Figure 14a, we illustrate an example of a graph G(n) representing an *undirected graph* with number of nodes = 4. Thereafter, the adjacency matrix size is n=4, where n is the number of nodes of the network. An undirected graph, is represented with a symmetric matrix where each tie or link is represented by 1 and 0 means there is no connections. The graphical representation of the G(n) is shown in Figure 14b.

$$g=\begin{bmatrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}$$

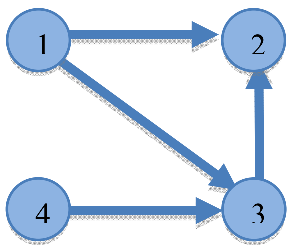


(a) (b)

Figure 14. A 4 nodes undirected graph representation (a) 4x4 adjacency matrix and (b) network graph

The mathematical and graphical representation of directed graphs are a bit different from the undirected graphs. In a directed graph the links have an orientation (from x, to y) and the connection are represented by a set of ordered pairs. The adjacency matrix is a asymmetric matrix where each tie or link is represented by 1 and 0 means there is no connections in the adjacency matrix. The adjacency matrix and graphical representation of a directed g(n) is shown in Figure 15 a and b.

$$g=\begin{bmatrix} 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$



(a) (b)

Figure 15. A 4 nodes directed graph representation (a) 4x4 adjacency matrix and (b) network graph

The links between the nodes can be informal and totally trust based or more formalized, as through a protocol or a hierarchy and the examination of those relationships understanding of the structure and the formation of interorganizational relationships. In our work we construct the response operations' networks based on the information from the *coordination matrix* for each time slot. Figure 16 illustrates disaster response network of Day 1 for the Elbe river flood in 2002 based on the coordination matrix data for Day 1 (See Table 6).

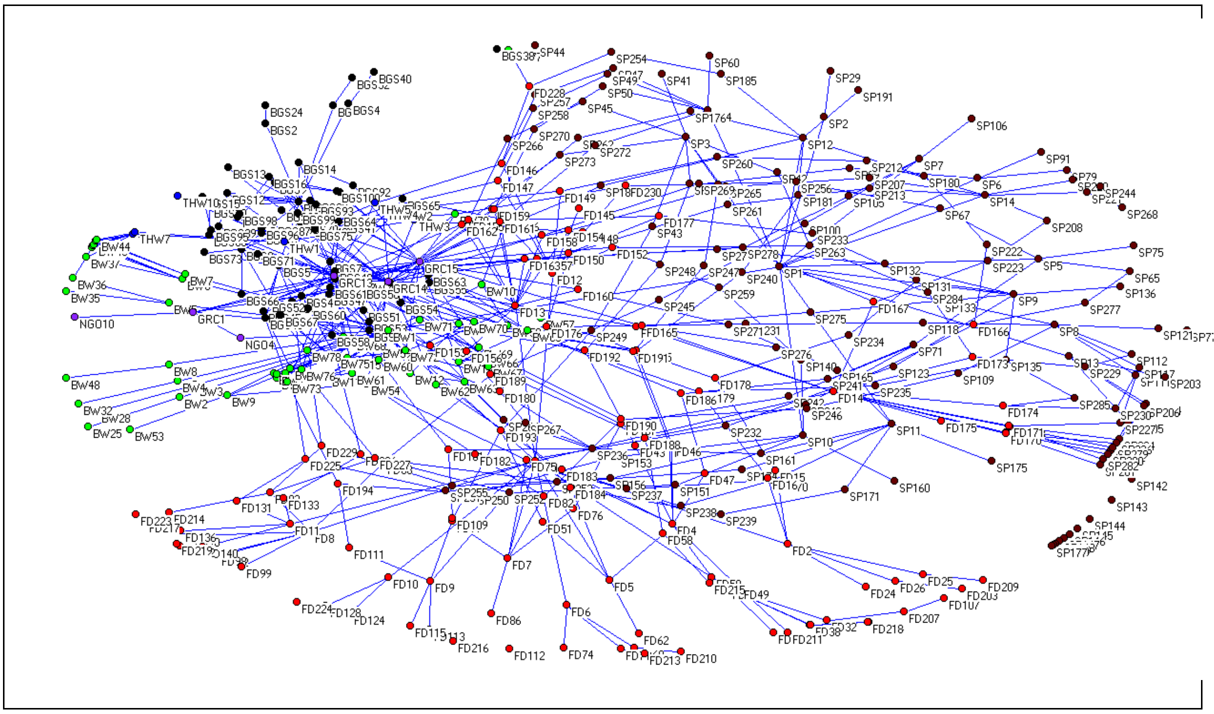


Figure 16. Disaster response network for the 2002 Elbe River flood– at T1 (Day 1).

Date	Organization engaged	# of divisions	Resources	Actions
Day 1	BW	79 Units	Soldiers, heavy machinery equipment, helicopters, boats	Establish C2, protection Protect bridges, transport roads, evacuation operation, work with NGO's to erect evacuees camp
	BGS	100 squads	Policemen, search and rescue specialized units, helicopters	Support affected areas with energy + water Search and rescue
	THW	10 units	Personnel from different backgrounds, equipment	Establish C2, clear roads, evacuate people, cleaning oil leakage
	SP	285 squads	Policemen	Traffic control, avoidance of plundering
	FD	230 units	Fire fighters, boats, fire engines, vehicles, equipment, boats	Establish Incident Command, search and rescue
	GRC	15 platoons	Personnel, administrative, medical supply, doctors	Search and rescue administration, missing people registration, medical care, first aid stations
	Other NGO's	10 platoons	Tents, vehicles, equipment	Evacuation operation, building tents,

Table 6. Coordination matrix for T1 (Day 1) – Elbe River flood 2002.

The total number of nodes is extracted from the reports as we can see in Table 7 the list of organizations and the number of units or personnel involved in the operations.

Organization name	
German Armed Forces (Bundeswehr) - BW	15,500 soldiers (179 units)
Federal Boarder Police (Bundesgrenzschutz) BGS	2,200 police office
Federal Agency for Technical Relief (Technisches Hilfswerk) - THW	2,835 person
Saxon Police - SP	1,600-4000 police office
Fire Departments - FD	20,000-23,000 firefighters
Non Governmental Organizations (e.g. German Red Cross - GRC) -NGO	6,352 volunteer

Table 7. Organizations involved in Elbe River flood 2002 (Richter, Huber, Lechner, 2002)

With SNA, we are able to examine network members that are most or least beneficial to the network members, locate that nodes are most influential in the network, and finally the changes in the organization or unit position can influence the network. In order to be able extract such information, we used network analysis metrics to measure the organizational network characteristics such degree of centrality, betweenness, and cliques.

The centrality is measure of how many connections one node has to other nodes, then the *degree of centrality* refers to the number of ties a node has to other nodes. The *standardized degree of centrality* measures the ties in relation to the network, therefore it is calculated as follows:

$\mathbf{C_{standardized} = C / n\text{-}1}$, (Eq. 1)
Where C is *degree of centrality* and n is *total number of nodes*

In Table 8, we show the values of degree of centrality and standardized degree of centrality for the graph in Figure 14.

Node	Degree of centrality	Standardized degree of centrality
1	3	3/3
2	1	1/3
3	2	2/3
4	2	2/3

Table 8. Degree of centrality and standardized degree of centrality for graph in Figure 14

Furthermore, in a directed graph, degree of centrality represents the number of links going in or coming out of a node. The calculation is affected by the direction of the link itself; therefore, there are two types of centrality, *In-degree* and *out-degree*. *In-degree* of centrality calculates the number of incoming links into a node and the *out-degree* calculates the number of links outgoing from a node.

There are other measures of centrality that are based on the travel paths of the information between nodes such as *closeness centrality* and *betweenness* centrality. Those depend on calculating the shortest path for the information travel between nodes and calculate the number of those short paths a single node lies on. With this measures shows how well connected the node and the role it can play in a network as a communication hub (Freeman, 1977; Freeman, Borgatti, White, 1991). Nodes with high number of links translate to retaining multiple alternative ways and resources to reach goals and thus be relatively advantaged. Therefore, the measures of centrality offer a mechanism to trace the changes in position and the role of different units in the disaster response network. In addition to the SNA metrics, the other powerful characteristic is network visualization to study details of the social structure of the network; it helps to identify points of interest such as clusters (Newman & Girvan, 2004), boundary spanners (Levina & Vaast, 2005; Kapucu, 2006), central and peripheral layers (Borgatti & Everett, 2000), and other structural properties that otherwise would not be captured via the numeric representation of the adjacency matrix. Figure 17 shows an example of a visual representation of a disaster response network where we can distinguish functional clusters. The functional clusters are not recognizable if we only examine numeric representation of the network (i.e. adjacency matrix).

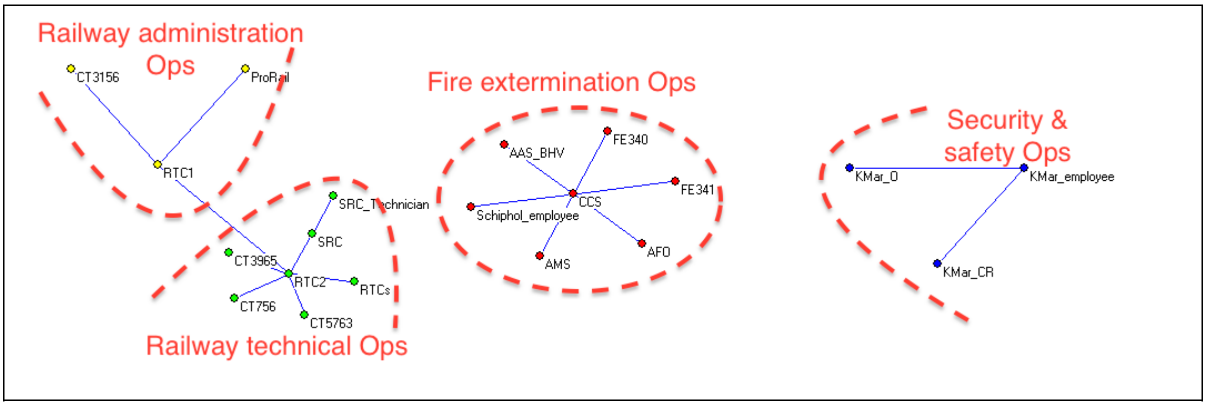


Figure 17. Coordination-clusters in response network from the Schiphol Tunnel Fire 2009 incident.

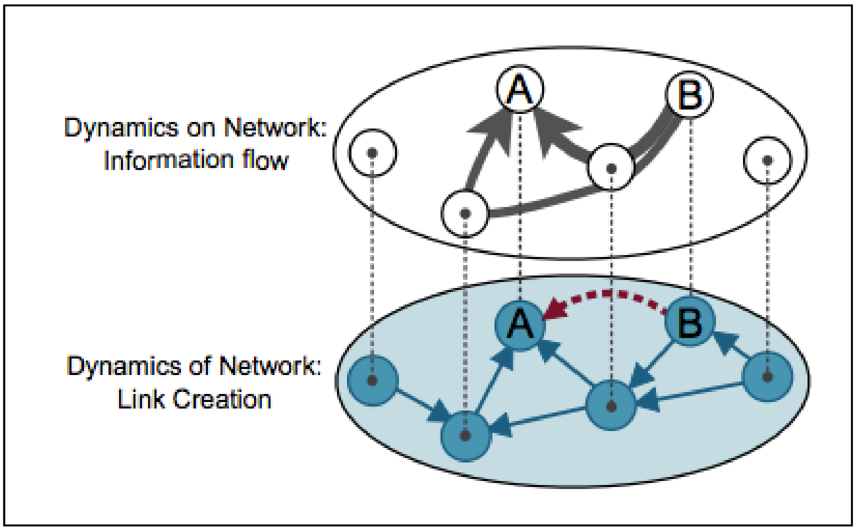
The SNA provided the ability to learn more about the similarities and differences in positions occupied by the actors, searching for groups and positions, and understanding the patterns that link the sets of actors. However, finding patterns of social behaviors within a population has several applications such as disease modeling, cultural and information transmission, and action proliferations. Hence, such property fits with the goal of this research in examining the patterns of coordination actions in the population of a disaster response network. A main characteristic of disaster response networks is that disasters produce continuous changes affecting the network structure over the time.

The SNA techniques provide a static view that may cause many details to be discarded. Based on that, Dynamic Network Analysis (DNA) is another approach to study network and the evolution of relationships in network (Carley, 2003; Berger-Wolf & Saina, 2006; Chu, Wipfli, Valente, 2013). DNA can provide an aid to longitudinal SNA research that targets the evolution of communities or evolution of performance in an organizational network.

However, DNA is a relatively young field, many aspects have not been explored and there are few standards that have been established. The core concept of DNA is that the nodes in a network representing "rational" actors that make choices to form relationships and maintain them. Jackson (2008c & 2008d) looks at networks' formation based on the process of information diffusion and expected actors' payoffs in forming relationships with other nodes in the network.

Weng, Ratkiewicz, Perra, Gonçalves, Castillo, Bonchi, Schifnella, Menczer & Flammini (2013) examined the role of information in the evolution of social networks from a dynamic perspective based on network structure and information travel. A static network represented relationships or links established based on formal or legal contract; where a dynamic network emerged based on information travel or action proliferation that is a result of decisions made by network members. It was observed that ongoing dynamics took place on two levels in the shape of two networks, a static level that represents the static network structure of established relationships and a dynamic level that is formed a meta-network based on information diffusion processes. The process of diffusion can describe different contexts in networks such as ideas dissemination, diseases out breaks or information and/or actions transmission. The diffusion is the process of which information is communicated via certain channels overtime throughout the network (Rogers, 1983; Jiu-chang, Ding-tao, and Sha-sha, 2006; Jackson, 2008c; Easley & Kleinberg, 2010).

Weng et al. found two types of dynamics in a network are: "*dynamics on the network*" that is a result of the information flow in the network and "*dynamics of the network*" that is a result of the link creation process in the network. Figure 18 illustrates the two types of dynamics observed in a dynamic network. In such system, we can notice it is a directed network where the network g(n) represent relationships such as friendships, marriage relationship, trading. The meta-network g`(n) had the same number of nodes n but it is formed based on the information flow between the members of the original network. Information transfer between nodes influence the creation of new relationships in network g`(n) as we can see that in the dashed red arrow in Figure 18.



*Adopted from Weng et al. (2013)

Figure 18. Dynamics of-network and on-network based on information diffusion in social networks.

In disaster response networks we have a network of established links and protocols that is created based on the ICS, yet the developments of disaster events resulted a meta-network to emerge based on actions and information diffusion in the response network.

In Figure 19, we illustrate an example of informal links formation in the meta-network based on information diffusion. The example is based on the Schiphol Tunnel fire in 2009 (Inspectorate of Security and Justice, 2009) where the solid lines represent established links based on the ICS and dotted lines are the new links created based on communications between the network members.

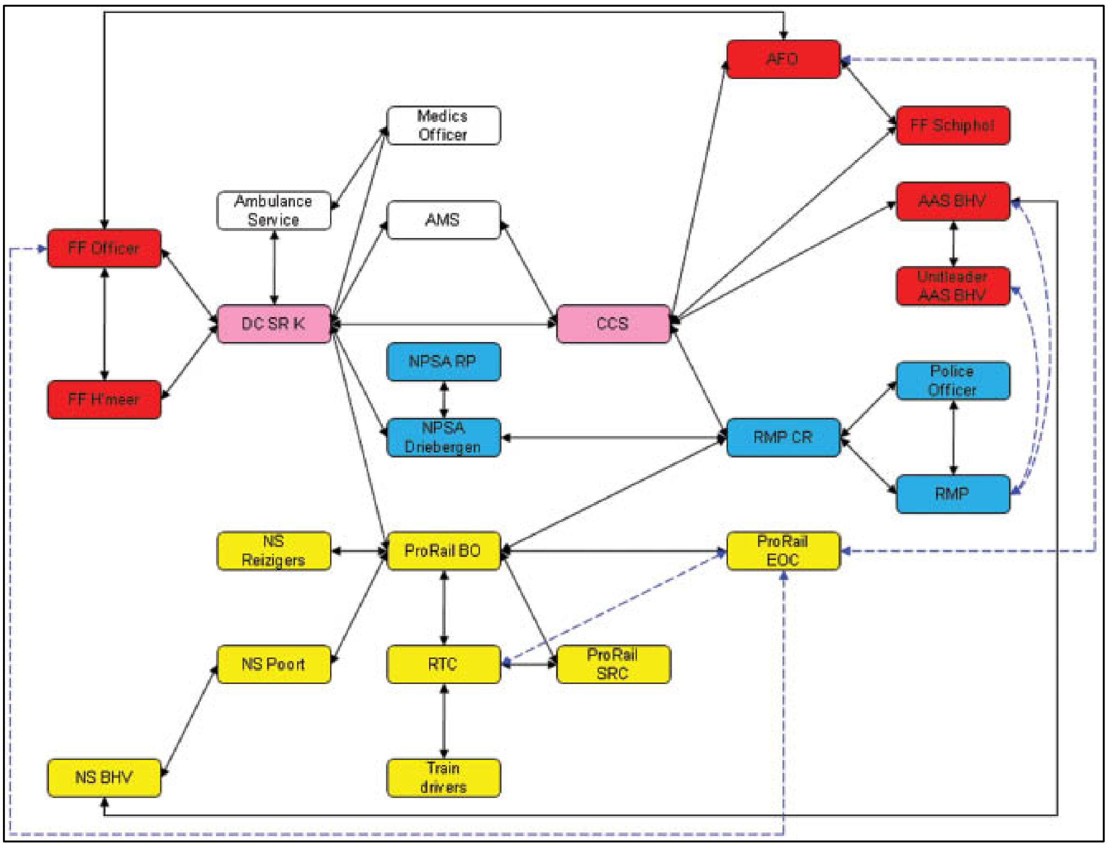


Figure 19. Communication network for the Schiphol Tunnel Fire Incident. (Inspectorate of Security and Justice, 2009, p. 62)

Furthermore, the DNA approach that is based on process diffusion and examine the interaction of network members and evolution of process based on network members' behavior. Another path taken to study the evolution of networks is to include the time factor and order of social interactions to examine patterns of evolution of social behaviors in a network (Berger-Wolf & Saia, 2006; Chu, Wipfli, Valente, 2013; Wolbers, Groenewegen, Mollee, Bím, 2013).

By having the capability of locating influential nodes and tracking path of information, we are able to create a mechanism to measure the effectiveness of the disaster response networks (Provan & Kenis, 2008). Incorporating the time factor is also considered a critical element that enables a close observation of the patterns of coordination and the evolution response networks (Wolbers, Groenewegen, Mollee, Bím, 2013; Noori, Wolbers, Boersma, Vilasis-Cardona, 2016b).

In this research, SNA and DNA were used to examine disaster response to draw a comparison between the existing disaster management systems (i.e. ICS and C2C) and reality of emerging disaster response networks. Studying the structure of initial ICS and designated C2C's in a response network will allow us to understand the factors implicating the evolution of response networks and how coordination is taking place among the different actors.

With SNA and DNA methodologies we are able to examine the evolution of the entire disaster response networks. However, to examine the patterns of coordination we need to study the nature of the sub-networks (or clusters) forming inside the disaster response operations (Provan & Sebastian, 1998; Provan, Veazie, Staten, Teufel-Shone, 2005). The characteristics of those clusters depend on the nature of the relationships represented by the network and it can change over the time. Figure 20 shows the degree of centrality for actors engaged in the response network associated with the Schiphol Tunnel fire (shown in Figure 17). We can see few nodes with high degree of degree of centrality beside the Command and Control (CCS node).

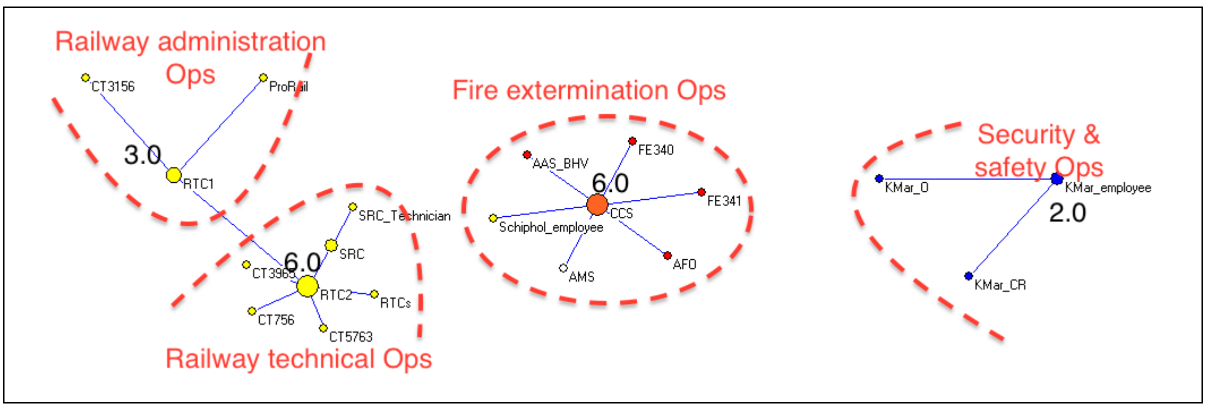


Figure 20. Coordination-clusters in response network from Schiphol Tunnel Fire 2009 incident.

Fortunato (2010) explains that real networks are not random and there exist some order and organization within such structures. Disaster response networks are not much different; therefore, analyzing the clusters within the response network is the first step towards understanding the coordination processes associated with response operations. In the next section we are going to discuss the details of clustering and community detection in networks in relation to disaster response networks.

2.2.2 Coordination-Clusters in Evolving Disaster Response Networks

In disasters response operations different organizations collectively coordinate efforts to handle the unfolding disaster events. Interorganizational coordination becomes a critical factor to the success or the failure of response operations (Hossain & Kuti, 2010; Kapucu, Bryer, Garayev & Arslan, 2010). The wide spectrum of parties involved in response operations, from macro institutions to micro individual, creates a set of complex relationships that needs to be identified and different contributions need to be mapped and measured (Kapucu, 2005; O'Sullivan, Kuziemsky, Toal-Sullivan & Corneil, 2013). The disruptive nature of disasters creates high levels of uncertainty; such conditions require a dynamic response and an adaptive organizational structure to cope with the intense changes resulted from those disruptions (Dynes & Aguirre, 1979; Kapucu, 2009; Topper & Lagadec, 2013). Therefore, throughout the course of disaster response operations, different network structures emerge at different levels of interactions inside the overall response network. In Figure 10 (p. 33) we showed changes in the complexity of response networks. While, Figure 21, is a modification of Figure 10 (p.33) where we encircled the emerging sub-networks or clusters in the response operations, it is what we called, *coordination-clusters.*

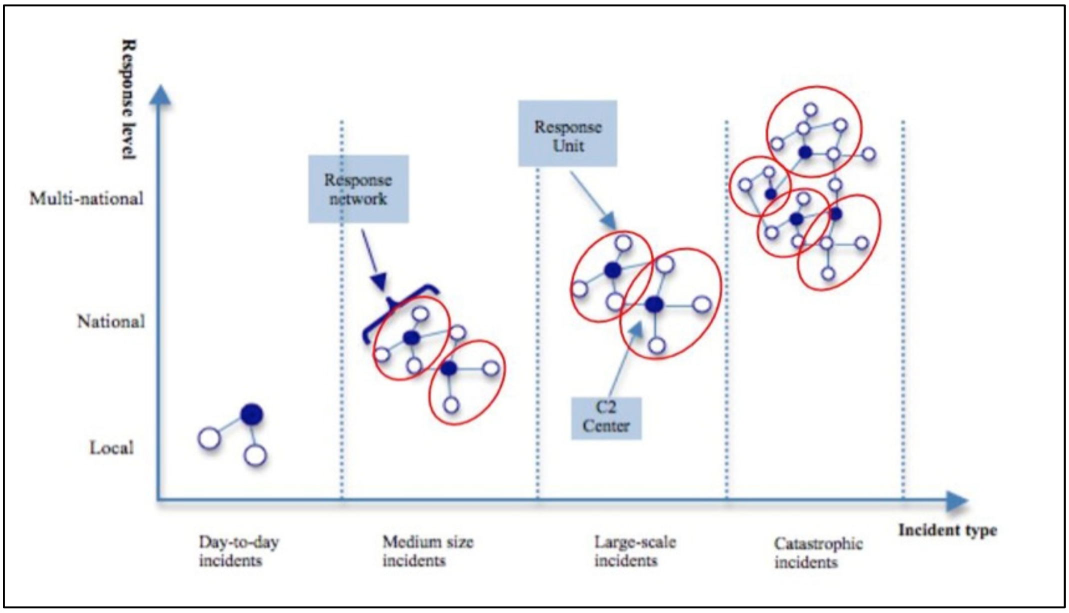


Figure 21. Illustration of coordination-clusters formation within disaster response networks.

The importance of emerging coordination-clusters in response operations has been recognized by several scholars (Topper & Carley, 1999; Comfort & Haase, 2006; Butts, Acton & Marcum, 2012). An important factor to depict the structure in a network is based on assessing its level and form of clustering. Clusters form as a response to the escalating series of disaster events and the availability of resources, such as personnel, equipment, supplies, and funds. These structures are dynamic in nature and change rapidly throughout the disaster evolution. Over the course of time, different sub-networks will emerge based on tasks needed and this leads to a different information exchange in the network such as incident location, number of victims or incident severity.

2.2.2.1 Community Detection in Complex Networks

SNA and DNA methodologies enabled us to visualize and examine the evolution of disaster response networks as a whole, but we needed further tools to understand the emerging coordination patterns in disaster response networks. *Community Detection in complex* networks is a method used to identify community like structures (also called partitions) in networks based on individual node characteristics (e.g. connectivity) in relation to its locale and the rest of the networks. In this section we are going to provide details of community detection definitions and methods used (Clauset, Moore, Newman, 2007; Fortunato, 2010).

The detection of communities in complex networks has attracted a lot of interest and many definitions of a community have been proposed. In general, algorithms are looking for a good partition of the nodes. This implies that no node belongs to more than one community and the main issue is to define what good means. However, from intuition we get the notion that there must be more links "inside" a community than links connecting nodes of the community with the rest of the "outside" network. This is the guideline for the basis of most community (or partition) definitions (Newman & Girvan, 2004; Newman, 2006; Fortunato, 2010)

Lets assume we have network of *G(N)* with *n* number of nodes and a sub-network g*(Nc)* with *nc* number of nodes. In Figure 22 we show an example of a network *G(N)* with three sub-networks (also called *communities, clusters or* partitions) *g(Nc)*.

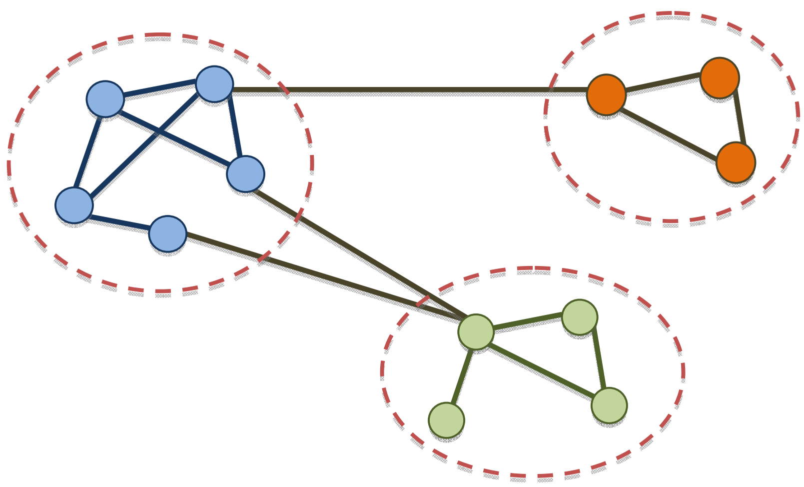


Figure 22. Example of Network G(N) with three partitions (clusters or communities) g(Nc) .

In Figure 22, we define the *internal* and *external degree* of a node *nc* in sub-network g(Nc) as D_{nc}^{int} and D_{nc}^{ext}, as the number of links connecting node (nc) to other nodes of sub-network *g* or to the rest of the network, respectively. If D_{nc}^{ext} = 0, the node has neighbors only within g(Nc), which is likely to be a good partition; if D_{nc}^{int}= 0, instead, the n node is disjoint from g(Nc) and it should better be assigned to a different partition. The *internal degree* D_{int}^{g} of g(Nc) is the sum of the internal degrees of its nodes. Likewise, the *external degree* D_{ext}^{g} of g(Nc) is the sum of the external degrees of its nodes. The *total degree* D^g is the sum of the degrees of the nodes of g(Nc). By definition, $D^g = D^g_{ext} + D^g_{\text{int}}$.

In addition to node degree characteristic, number of connections (links) between partition nodes or *partition density* is another characteristic to calculate a partition. *Intra-cluster density* $\delta_{\text{int}}(g)$ of sub-network g(Nc) can be defined as the ratio between the number of internal links of g(Nc) and the number of all possible internal links, where

$$\delta_{\text{int}}(g) = \frac{\sum l^g_{\text{int}}}{nc(nc-1)/2} \quad , \qquad \textbf{(Eq. 2)}$$

Where $\sum l^g_{\text{int}}$ s total number of internal links between g(Nc) nodes

Similarly, the *inter-cluster density* $\delta_{ext}(g)$ is the ratio between the number of links running from the nodes of g(Nc) to the rest of the network graph and the maximum number of inter-cluster links possible, where

$$\delta_{ext}(g) = \frac{\sum l^g_{ext}}{nc(n-nc)} \quad , \textbf{(Eq. 3)}$$

Where $\sum l^g_{ext}$ s total number of links between g(Nc) nodes and the rest of the network

For g(Nc) to be a community, the $\delta_{\text{int}}(g)$ should be larger than the average link density δ(G) of the whole network G(N), which is given by the ratio between the number of links of G(N) and the maximum number of possible links n(n−1)/2. On the other hand, $\delta_{ext}(g)$ has to be much smaller than δ(G). Looking for the best tradeoff between a large $\delta_{\text{int}}(g)$ and a small $\delta_{ext}(g)$ is implicitly or explicitly the goal of most portioning algorithms. Another required property of a community is connectedness. A sub-network g(Nc) is expected to be a community if there is a path between each pair of its nodes, running only through nodes of g(Nc).

With those basic requirements for graph-partition characteristics in mind, now we can introduce some main definitions of community. When studying community structure, we often analyze structural properties of communities in the networks. The notion of communities can be formalized based on statistical properties. There are basic defections that are used to detect a community structure in a network; we can distinguish three types of community definition: *local definition*, *global definition*, and the definition based on *node similarity*.

With *local definitions*, we define the community based on the local characteristics of the sub-network or sub-graph. Therefore, a *community* is a group of nodes within a network in which the connections are dense and connections between other groups are sparse. In some specific systems or applications, they can be considered as separate entities with their own autonomy, which do not depend on the whole network. Sometimes, communities are defined in a very strict sense and require that all pairs of nodes to be connected, that is, a subset of nodes where every two nodes in the subset are connected by a link. Another extended definition is *k-clique* community, where a k-clique community is a sequence of adjacent cliques and the two k-cliques are adjacent if they share k-1 nodes. Another criterion for community cohesion is the difference between the *internal* and *external* degrees of the community. This principle was used define strong communities and weak communities. A set of nodes is a community in a strong sense if the internal degree of each node D_{nc}^{int} is greater than its external degree D_{nc}^{ext}. In a weak community, the internal degree of the community D_{int}^{g} (sum of all its node internal degree) should exceed its external degree D_{int}^{g}. Note that a community in a strong sense is also a weak community, while the converse is not generally true.

With *global definitions,* Communities are defined with respect to the network as a whole where many global criteria are used to identify communities. The criterion is based on a principle of a graph can form a community structure if its structure is far from a random graph. Random networks such as *Erdös–Renyi's* graphs do not display community structure because in a random graph, any pair of nodes is independently linked with the same probability. In random graphs there is no preferential linking between special groups of nodes. Therefore, one may define a null model as a random graph that shares some structural properties of the original graph such as degree distribution. The null model is the basic element in the conception of the notion of quality function named *modularity*. The *modularity* evaluates the quality of a partition into separate communities. Based on Newman and Girvan, (2004) definition of modularity, it is a result of comparing the number of links inside a community to the expected number of internal links in the null model.

Lets assume network G(N) with N number of nodes with a particular division of two groups where $s_i = 1$ if node i belongs to group 1 and $s_i = -1$ if it belongs to group 2. And let the number of links between nodes *i* and j be A_{ij}, which will normally be 0 or 1, although larger values are possible in networks where multiple links are allowed. The values A_{ij} are organized in an adjacency matrix A. At the same time, the expected number of links between nodes i and j if links are placed at random is $k_i k_j/2m$, where k_i and k_j are the degrees of the nodes and

$m = \frac{1}{2}\sum_i k_i$,(Eq. 4), (Fortunato, 2010)

Where *m* is the total number of links in the network. The modularity can be written

$$Q = \frac{1}{2m}\sum_{ij}\left(A_{ij} - \frac{k_i k_j}{2m}\right)\delta(C_i C_j) \text{ , (Eq. 5)}$$

In Eq. 5 the δ-function yields 1 if vertices i and j are in the same community (Ci = Cj), zero otherwise.

The common problem with community detection algorithms is often the definition of a good partition where partition parts are drawn separately. A classical approach is to define a *quality function*, which gives a score to a partition: the good partition is the one that maximizes this quality function. One of the most used quality function is the *modularity*. Modularity values range between -1 and 1. Higher modularity scores means better partitions (or communities).

Another way to define communities is based on *nodes similarity* where nodes characteristics are taken into account to group similar nodes. An important class of node similarity measures is based on properties of random walks on graphs, such as travel time. The travel time between a pair of nodes is the average number of steps needed for a random walker, starting at either node, to reach the other node for the first time and to come back to the starting node. In a community, the random walks will be shorter than walks between nodes located among different communities.

2.2.2.2 Community Detection Algorithms

In this research we examine the phenomenon of the emerging coordinative clusters within the context of the overall response operation without excluding any members or parts. Those intentions generated a need to seek a method capable of detecting coordination-clusters in a whole disaster response network. Therefore, the methods that are based on the global definition of a community represented a good fit because it compares the internal composition of a partition in respect to the network as a whole. As a result, the algorithms that are using modularity as quality function were of a great interest for this research. There exist several community detection algorithms based on modularity (Fortunato, 20110), however, due to the complex nature of disaster response that can involve large numbers, algorithms that can handle large networks were considered in this research. Lancichinetti (2013) had examined several of algorithms that detects communities in large networks and used modularity as a quality function. The following is a list of the surveyed algorithms:

- Betweenness centrality algorithm (Girvan & Newman, 2002; Newman & Girvan, 2006).
- Fast greedy modularity optimization (Clauset, Newman, Moore, 2004).
- Exhaustive modularity optimization via simulated annealing (Guimera, Sales-Pardo, Amaral, 2004; Guimera & Amaral, (2005).
- Fast modularity optimization (Blondel et al., 2008).
- Structural algorithm (Rosvall & Bergstrom, 2007) □
- Dynamic algorithm (Rosvall & Bergstrom, 2008) □
- Spectral algorithm (Donetti & Muñoz, 2004) □
- Expectation-maximization algorithm (Newman & Leicht, 2007)□

- Potts model approach (Ronhovde & Nussinov, 2009).

The fast Modularity Optimization method by Blondel et el. (2008) (or known as Louvain Method) was among the best algorithms in producing high quality partitions based on modularity optimization. In addition to partition quality, the computation time for Louvain method is highly competitive in comparison to the algorithms mentioned earlier in large networks (Blondel, et al., 2008; Lancichinetti, Fortunato, Radicchi, 2008; Lancichinetti; 2013).

2.2.2.3 Fast Modularity Optimization (Louvain Method)

With the Louvain method we were able to detect coordination-clusters in the different disaster response networks that we constructed for the case studies. The Louvain method is described as a hierarchical greedy algorithm. It is composed of two phases, executed iteratively. Initially, lets take our example G(N), we consider each node in the network as its own community, therefore, and we have N number of communities in the network. For each node *i* we consider the neighbors *j* of *i* and we evaluate the gain of modularity that would take place by removing *i* from its community and by placing it in the community of *j*. The node *i* is then placed in the community for which this gain is maximum (in case of a tie we use a breaking rule), but only if this gain is positive. If no positive gain is possible, node *i* stays in its original community. This process is applied repeatedly and sequentially for all nodes until no further improvement can be achieved and the first phase is then complete. So the first phase stops when a local maxima of the modularity is reached. The gain in modularity ΔQ is calculated by moving an isolated node *i* into a community *C* can easily be computed by:

$$\Delta Q = \left[\frac{\sum_{in} + k_{i,in}}{2m} - \left(\frac{\sum_{tot} + k_i}{2m} \right)^2 \right] - \left[\frac{\sum_{in}}{2m} - \left(\frac{\sum_{tot}}{2m} \right)^2 - \left(\frac{k_i}{2m} \right)^2 \right]$$

, (Eq. 6)(Blondel, et al, 2008)

Where $\sum_{in}$ is the sum of the weights of the links inside *C*, $\sum_{tot}$ is the sum of the weights of the links incident to nodes in *C*, k_i is the sum of the weights of the links incident to node *i*, $k_{i,in}$ is the sum of the weights of the links from *i* to nodes in *C* and *m* is the sum of the weights of all the links in the network.

The second phase of the algorithm consists of building a new network where each node represent a community found during the first phase. The new nodes are given by the sum of the weight of the links between nodes in the corresponding two communities. Links between nodes of the same community lead to self-loops for this community in the new network. Once this second phase is completed, it is then possible to reapply the first phase of the algorithm to the resulting weighted network and to iterate. Let's denote by "pass" a combination of these two phases. By construction, the number of meta-communities decreases at each pass, and as a consequence most of the computing time is used in the first pass. The passes are iterated (see Figure 23) until there are no more changes and a maximum of modularity is attained.

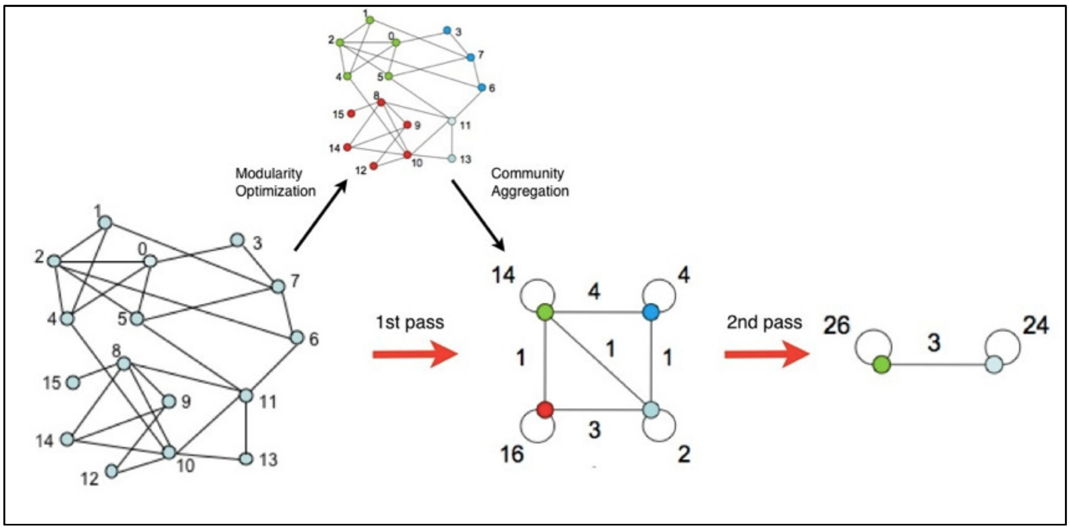


Figure 23. Louvain method phases

Detecting communities in complex networks was one requirement to achieve the research goals in examining coordination cluster. The other part was the ability to trace the evolution of the coordination cluster that translated to being able to evolution of communities. In order to study the evolution of communities can be achieved by tracking communities using different snapshots in combination with algorithms suited for static graphs. Aynaud & Guillaume (2010) found that Louvain method was among the static community detection algorithms that provided a stable analysis and most accurate results to examine evolution of communities in networks. Therefore, we came to choose Louvain method to trace the evolution of the coordination-clusters in the disaster response networks for our case studies.

2.2.3 Modeling Coordination Dynamic in Disaster Response Operations

In the previous sections we studied the utilization of static network analysis methods to analyze networks' evolution in disaster response operations. In addition to response networks evolution, we studies methods to examine emerging coordination cluster with using community detection methods in complex networks (Blondel, et al., 2008; Lancichinetti, Fortunato, Radicchi, 2008; Aynaud & Guillaume, 2010; Lancichinetti; 2013). As we indicated earlier that time factor is essential to be considered in order to provide a full understanding of response operation's evolution Topper & Carley, 1999; Comfort & Haase, 2006; Butts, Acton & Marcum, 2012; Boersma, Passenier, Mollee & van der Wal, 2012; Boersma, Comfort, Groenendaal & Wolbers, 2014; Boersma, Fergusson, Groenewegen & Wolbers, 2014). Yet, despite having a time-based view of coordination evolution in disaster response networks, we still lack a view of "who" is performing tasks, "how" resources are consumed by participating teams. As a result, we sought to adopt an approach based on dynamic systems and complex network analysis to study evolution of collaboration and coordination in disaster response operations.

Disasters by nature are the occurrence of certain disruptive events that can happen at anytime; consequently the response to disasters is dependent on the events types and severity (Lindell, Tierney, Perry, 2001; Quarantelli, 2005). Such characteristics make disasters analogous to *Discrete Event Systems* (DES) where the evolution of the system is driven by the occurrence of certain events at unknown time intervals, therefore, the DES methods was a good fit to be utilized to analyze coordination processes in disaster response operations (Tavana, 2008; Karmakar, & Dasgupta, 2011; Shan, Wang, Li, 2012). While, *coordination theory* was used to extract the qualitative elements of coordination among multiple organizations such as actions, actors and resources. In order to represent processes involving multiple actors, we may want to focus on the interactions between the actors and resources exchange in the response operations. With the results presented in the *coordination matrix* was utilized those to construct a model to simulate coordination processes in disaster response operations. One approach for modeling interacting processes is the *Petri nets* and various representations derived from them (Peterson, 1977; Bruno & Marchetto, 1986; Crowston, 1997; Holloway, Krogh, Giua, 1997; Dilmaghani, & Rao, 2009). Petri nets were used in disaster and emergency management to model of processes of emergency response plans and use as a tool to evaluate different procedures and process flows in order to improve the disaster and emergency management systems. For example, Bammidi & Moore (1994) used the method to develop models for industrial fire response process in Department of Energy (DoE) in the United States. Dilmaghani and Rao (2009) used Petri nets to improve communications in emergency response systems and develop a model to improve the overall emergency response system. Moreover, in Karmakar and Dasgupta (2011), Petri nets were used in modeling emergency management systems for Railway stations and the approach proved to be on of the most useful graphical-tools to represent the various complex elements in an emergency management system. Another application of Petri nets and one of its extensions, the *colored* Petri nets, was used to model emergency plan business processes by Wei-dong and Zhe (2011), the analysis and evaluation of the emergency plan processes were important to improve the efficiency of the emergency management systems in general. Guided by the insights from the various examples mentioned above, we followed a similar methodology to model the coordination processes in response operations using *classical* Petri nets and the *colored* Petri nets. In the upcoming sections we are going to provide an overview of the *classical* Petri nets and *colored* Petri nets within the context of our research work.

2.2.3.1 Classical Petri Nets

Petri nets (PNs) is a DES modeling method that were developed in the 1960's by Carl Adam Petri during his PhD thesis on communication with automata (Petri, 1966). Petri nets were introduced to help describing the causal relationships between conditions and events in a computer system. However, since then many extensions related to PNs have been developed that gave a wider spectrum to their applicability. PNs can be used to describe logical models Place/Transition (P/T) nets, Colored PNs, hierarchical PNs, performance models such as Timed PNs, Stochastic PNs and others (Bruno, & Marchetto, 1986; Holloway, et al., 1997; Jensen, 1981; Murata, 1989; Chen, Ke, Wu, 2001; Zhovtobryukh, 2007; Huang, Chen, Huang, Jeng, Kuo, 2008; Cassandras, & Lafortune, 2009; Chen, & Hofestädt, 2010; Liu & Yang, 2013). In this section we shall review Petri nets in general with a focus on Colored Petri nets as an modeling method for the coordination flow in response operations.

In general, Petri nets have been specifically designed to model systems with interacting components and as such are able to capture many characteristics of an event driven system, such as concurrency, asynchronous operations, deadlocks, conflicts, etc. They allow a modular representation of systems and decompose the system to several subsystems that interact among them and each subsystem can be presented with a simple subnet and then, via appropriate operators, combine the subnets to obtain a model of the whole system (Jensen, 1981; Murata, 1989; Holloway, et al., 1997; Cassandras, & Lafortune, 2009; Cabasino, Giua, Seatzu, 2013; van der Aalst, Stahl, Westergaard, 2013).

A Petri net is a graphical representation of an underlying mathematical structure used to model DES. It may be identified as a particular kind of bipartite directed graph, which contains two parts (Peterson, 1977; Jensen, 1981; Bruno, & Marchetto, 1986; Murata, 1989; Holloway, et al., 1997):

- *Static part* which include three objects:
  - *Place*, depicted as circles or ovals in the graphical representation, are states of system components.
  - *Transition*, drawn as bars or boxes, corresponding to potential events that change the state of a Petri Net. Delays may be assigned to transitions (e.g. required time to carry out a given task).
  - *Oriented arcs*, those connect places to transitions (upstream or input arcs) and transitions to places (downstream or output arcs). Arcs are weighted with a positive number. For example, the weight of an upstream arc may indicate the required resources to achieve a given action whereas that of a downstream arc may indicate the amount of the output resulted from this action. This weight equals to one if it is not explicitly mentioned on the graph.

The *place/transition* PN net has two types of vertices; *places* (represented by circles) and *transitions* (represented by bars or rectangles). Lets assume a PN net shown in Figure 24 that represents a structure $N = (P, T, \boldsymbol{Pre\_net}, \boldsymbol{Post\_net})$ where:

- $P_m = \{p_1, p_2, \cdots p_m\}$ is the set of m *places*. □
- $T_n = \{\{t_1, t_2, \cdots t_n\}$ is the set of n *transitions*. □
- *Pre_net*: $P \times T \rightarrow N$ is the pre-event function that specifies the number of arcs □directed from places to transitions (called “pre” arcs) and is represented as $m \times n$ □matrix. □

- *Post_net*: $P \times T \rightarrow N$ is the post-event function that specifies the number of arcs directed from transitions to places (called "post" arcs) and is represented *as m* × *n* matrix.

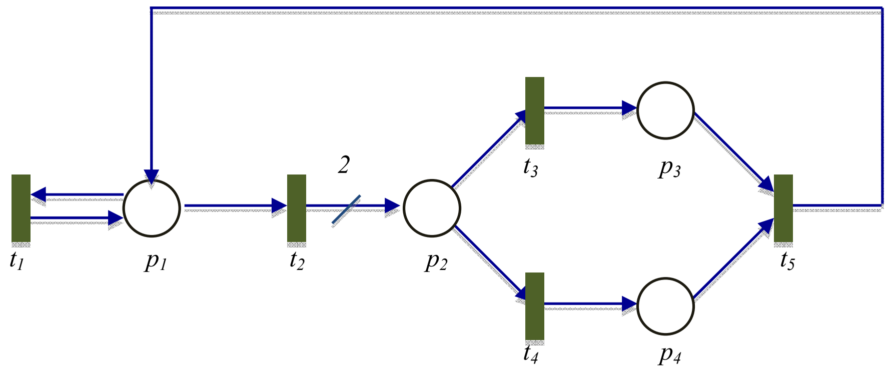


Figure 24. Example Petri net of P_m x T_n. m=4, n=5

The Petri net in Figure 24 represents the net $N = (P, T, \textbf{Pre\_net}, \textbf{Post\_net})$ with set of places $P = \{ p_1, p_2, p_3, p_4\}$ and set of transitions $T = \{ t_1, t_2, t_3, t_4, t_5\}$. Here:

$$pre\_net = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{matrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{matrix} \qquad post\_net = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 \\ 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{matrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{matrix}$$

$$t_1 \quad t_2 \quad t_3 \quad t_4 \quad t_5 \qquad\qquad t_1 \quad t_2 \quad t_3 \quad t_4 \quad t_5$$

In our Petri net example, we have $Post\_net[p_2, t_2] = 2$ and this denotes that there are two arcs from transition t_2 to place p_2. The notation is shown by a barred arc between t_2 and p_2 with weight of 2 be seen in Figure 24. We denote by $Pre\_net[\cdot, t]$ the column of *Pre_net* relative to *t*, and by $Pre\_net[p, \cdot]$ the row of *Pre*_net relative to *p*. The same notation is used for matrix *Post*_net.

The *event matrix* of a Petri net defined as **C = Post_net – Pre_net** is represented by an m × n matrix of integers where a *negative* value is associated with a "*pre*" arc (from place to transition), while a *positive* value is associated with a "*post*" arc (from transition to place). The *event matrix* for Figure 24 is as follows:

$$C = \begin{bmatrix} 0 & -1 & 0 & 0 & 1 \\ 0 & 2 & -1 & -1 & 0 \\ 0 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{matrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{matrix}$$

$$t_1 \quad t_2 \quad t_3 \quad t_4 \quad t_5$$

- *Dynamic part* which includes the following:
  - *Tokens* that are presented by small solid dots. Each place can hold either none or a positive number of tokens, which illustrate that the corresponding place is currently allocated. The distribution of tokens in places is referred as the *marking*. A *marking* is a function ***m***: P → N that assigns to each place a positive integer number of tokens. For example the PN in Figure 24 can have the following *marking:* ***m*** is $m[p_1] = 1$, $m[p_2] = m[p_3] = m[p_4] = 0$. A PN with an initial marking $\boldsymbol{m}_0$ is called *marked net* or *net system*, and is denoted (N, $\boldsymbol{m}_0$). This *marked net* is representing a discrete event system with a dynamical behavior (Cassandras, & Lafortune, 2009; Cabasino, et al., 2013)). A marking is usually represented with a column vector with the same number of places in the PN itself. Similar in this case the *marking* vector for our example can be presented as follows, $\boldsymbol{m}=[1000]^T$. Figure 25 shows the marking distribution in the PN example of Figure 24.

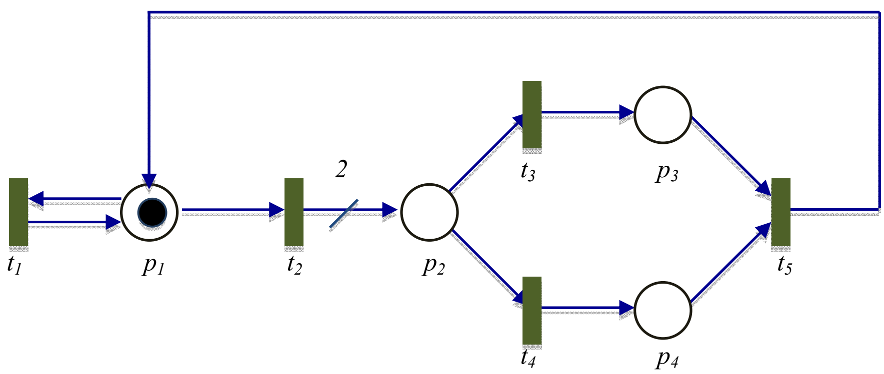


Figure 25. Example Petri net in Figure 24 with tokens present.

When an event occurs, a token (or tokens) will transition from on *place* to another based on a certain condition. A token can represent the presence or absence of a resource inside a process. □

- *Predicates or guards*, any formula, which may be true or false, enabling, transitions. □
- *Assertions*, any equation, updating some variables when a transition is *fired.* □

The other important PN principles are *enabling* and *firing* of a transition. It is important to make a distinction between the two actions of transitions:

- A transition is *enabled* when all input places contain at least the number of tokens required by each input arc (indicated by the weight on the arc) and all predicates must be 'true'. □
- A transition is *fired* when all preconditions are satisfied (i.e. *enabled*) and a required delay is elapsed (duration from the enabling until the firing).

On the firing of a transition: □

- *Input* places lose as many tokens as specified by the weights of input arcs. □
- *Output* places gain as many tokens as specified by the weights of output arcs. □
- *Assertions* are updated. □

Thus far, classical PNs provided a graphical and mathematical formularization for information flow and processes flow in different fields, which is a property that fit with our work research requirement to model coordination processes in different fields (Huang & Zhou, 2005; Gil-Costa, Lobos, Inostrosa-Psijas, Marin, 2012; Fares, Rachida, Choayb, 2014). However, the classical PNs were insufficient to help modeling such complex environment of disaster response operations but we found in *colored* PNs a tool to model coordination processed in disaster response operations.

2.2.3.2 Colored Petri Nets

Classical PNs proved to be a useful visual tool both in the design and analysis phases, however, in the complex environment of a disaster, there are many types of resources and multiple actors involved in the response operations. While, *colored* Petri nets (CPNs), a flavor of PNs that extended the classical PNs formalism with data, time, and hierarchy (Huber, Jensen, Shapiro, 1989) offered a better choice. These extensions of CPNs and its programming language make it possible to model complex processes using CPNs without being forced to abstract from relevant aspects (van der Aalst, Stahl, Westergaard, 2013). In addition to CPNs, the CPN-Tool (http://cpntools.org/) is a powerful toolset that supports the design and analysis of processes in complex environments (Jensen, 1986; Jensen, 1990; Jensen, 1992; Jensen, 1997; Kristensen, Jørgensen, Jensen, 2004; Jensen, Kristensen, Wells, 2007; Girault & Valk, 2013).

In classical PNs, the tokens are a representation of resource availability and they are a set of identical entities. Tokens are usually represented with solid black dots (see Figure 25). While in CPNs the tokens are a representation of different types of resources and tokens can be identified with different colors (or *data* types) to distinguish them. With colored tokens, we can assign data types and attributes to tokens, which define tokens it represents. As we mentioned earlier, CPNs are an extension of PN that enables model processes using PNs in combination with a programming language to produce compact and precise models. With systems having multiple types of resources, actors and nested processes, CPNs provide a modeling technique that enable us to model such complex systems without losing their details.

In principle, CPNs basic components are similar to classical PNs; they have *places*, *transitions*, and *transition arcs*. Figure 26 represents an example of a CPN that is created using the CPN-Tool.

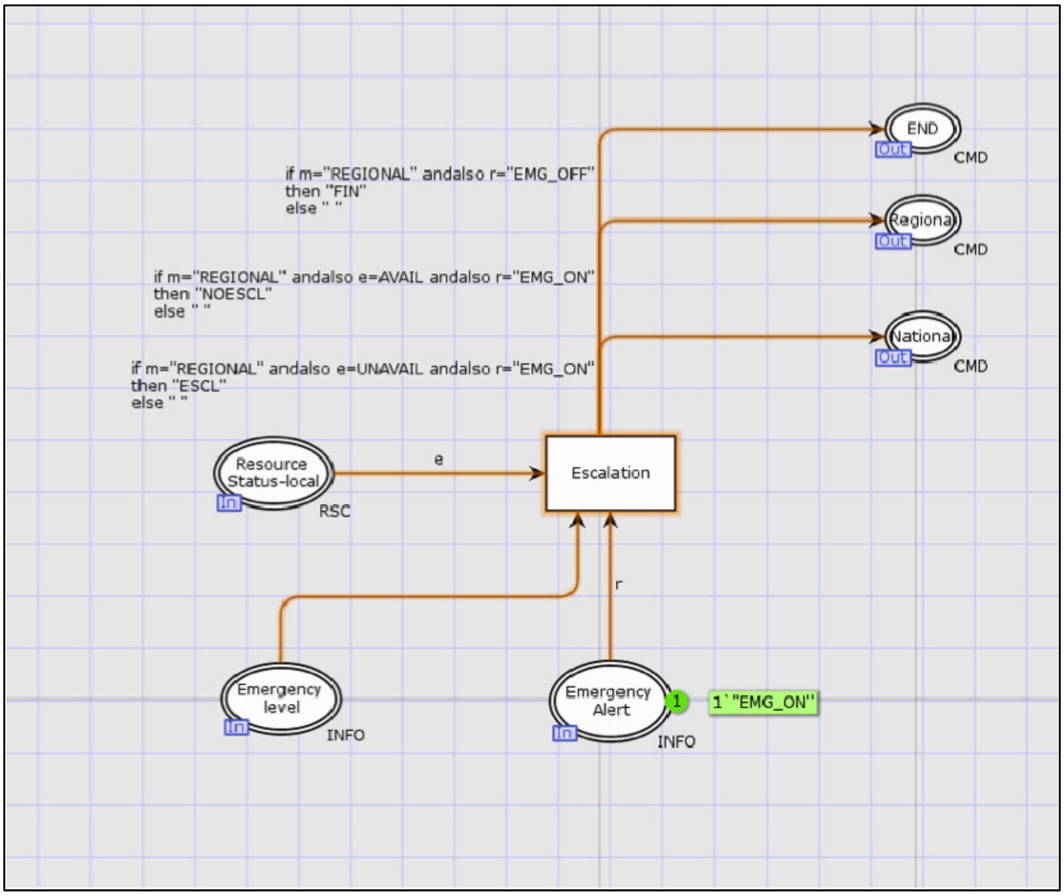


Figure 26. An example of a CPN for a decision-making process.
*Model created using CPN-Tools 4.0.

We can notice a difference between CPN and classical PNs in the representation of the basic elements. In the example CPN of Figure 26, each *place* is represented with an *eclipse* with an identifier representing it (similar to function declaration in programming languages), the *transitions* are represented with a *rectangle* with an identifier representing it and finally *transition arcs* from places to transitions and vice versa. Beside the basic elements, we notice differences in the *marking* and token representation. Example of that, in Figure 26, we notice at each *place* has a color (or a data type) attached to it (e.g. places “Emergency level” and “Emergency Alert” have INFO data type (or color) and other places had other colors attached to them). The *tokens* in each place have same color (or data type) as the place and they are represented with a positive integer (e.g. place “Emergency Alert” has 1 token of type INFO with value of EMG_ON). In addition to the *marking*, we notice that some *arcs* have conditional statements (or called *arc expressions*) attached to them. Those *arc expressions* are the conditional statements that govern enabling and firing processes of the CPNs.

The CPNs are a combination of graphical and mathematical representations of complex systems that incorporate a flavoring of a programming language. That combination made it possible to represent the complex dynamics of systems. Similar to PNs, CPNs have two parts to its representation and modeling, *static* and dynamic. The following sections we are providing a brief description of those parts.

- *Static part* which includes the following:
  - *Places* are states of a CPN that are graphically represented by an eclipse. Unlike PNs, a CPN place has names assigned and written inside the ellipses. The names have no formal meaning but they have a practical importance for the readability of a CPN. Similar to PNs, a place can hold a positive number of tokens. In CPNs, the tokens are attached to a color set (or a data type). We can see that in Figure 27, where p_1, highlighted in red, is a place with color set (*COLSET*) of STR (or a data type:: String). In addition, p_1 holds two tokens as shown inside the circle to the top right with values set = {“yes”, “No”}.

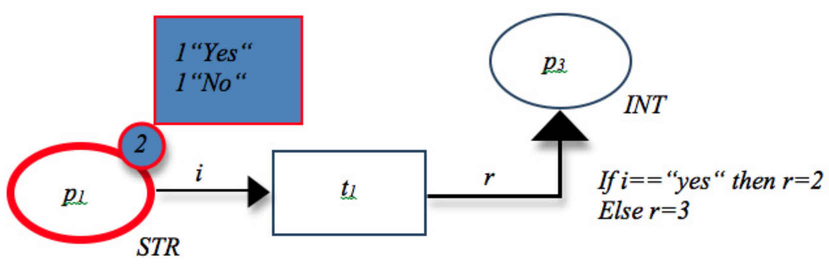


Figure 27. Simple CPN with p_1 of color_set of STR::String.
(p_1) place holds two tokens with values “Yes” and “No”

- *Transitions* represent the actions of CPNs and they are graphically represented by a rectangle, as shown in Figure 28 and highlighted in red. Similar to *places*, a *transition* is assigned a name written inside the rectangle that describes the action it represents. For example, in Figure 27, the transition represents an escalation action in response operations.

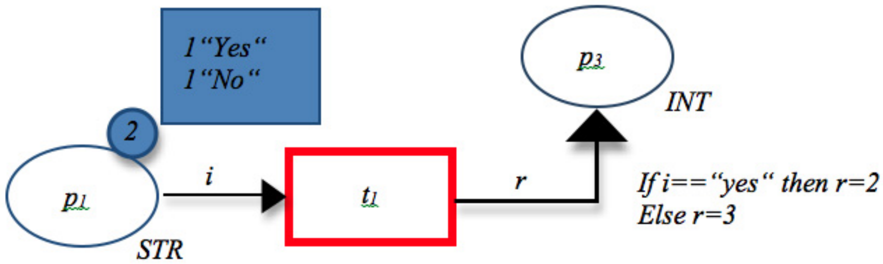


Figure 28. Simple CPN with transition t_1.
The transition represents an action such as escalation decision.

- *Arcs and arc expressions* represent the connections between *transitions* and *places* in a CPN. The occurrence of an action in a CPN results a transition. The occurrence of a transition results removing tokens from places connected to incoming arcs (input places), and adds tokens to places connected to outgoing arcs (output places), thereby changing the marking (state) of the CPN. For example, in Figure 29, when t_1 is enabled, then a token i will be removed from p_1 and transmitted to t_1. After updating the marking of p_1; the marking of p_2 will be changed based on the results of the *arc expression* attached to the arc between t_1 and p_2. Variable r represents the results of the arc expression.

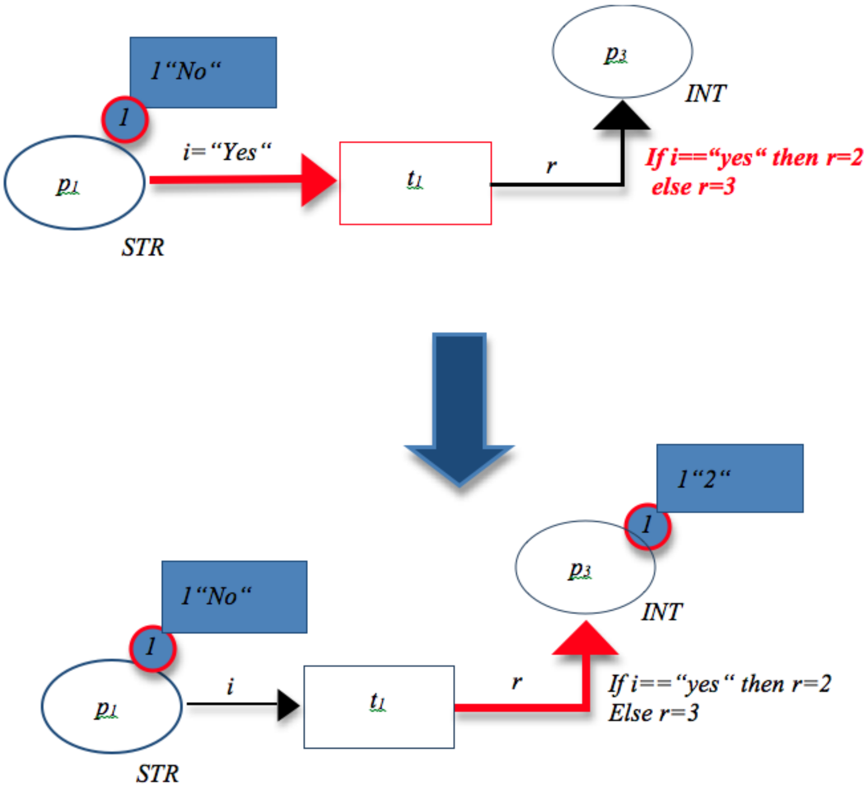


Figure 29. Example of transferring tokens between places when a transition is fired.

- *Types* are representing the color set (or a data type) associated with each place in the CPN. The *type* of a place is written in *italics*, to the lower left or right of the place. The types are similar to data types in a programming language. The color sets (or data types) of a CPN can be range from standard data types such as integers, floating numbers or strings to user defined data types. In Figure 30 we can see that p_1 has a color set or type of a *STR* (a string) and p_2 has a color set or type of an *INT* (an integer).

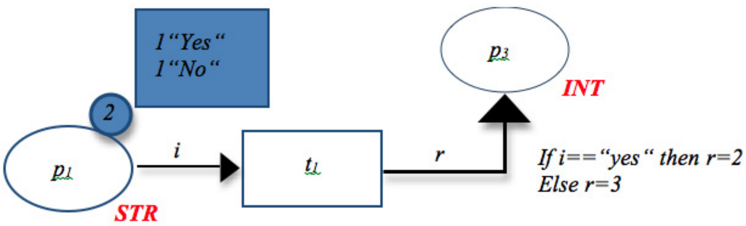


Figure 30. Example of Petri Net with different data types (i.e. INT and STR).

- *Dynamic part* which includes the following:
    - *Variables and bindings* in CPNs are associated with the *firing* of a transition. During the *firing* events, variables become a vehicle for information to travel in the CPN. The exact number of tokens added and removed by the firing of a transition, and their data values are determined by the arc expressions, which are positioned next to the arcs. We've shown in Figure 29 that values (i.e. variables *i* and *r*) are assigned (bound) to the arcs connecting places and transitions in our example CPN. Furthermore, arc expressions are validated based in the values of those variables.
    - *Markings* represent the state of a CPN same as the classical PNs. A CPN state is described as the number of tokens placed in the individual places. Each token carries a value that belongs to the color set (or data type) of the place where the token placed. The tokens that are present on a particular place are called the marking of that place. Furthermore, *Initial marking* of a CPN has a distinguished marking representation that is used to describe the initial state of the system. The initial marking of a place is written on the upper left or right of the place (see p_1 in Figure 27)
    - *Enabling* is the event of having assigned data values of binding variables to a place appearing on the attached arc expressions. An enabled transition means that each arc expressions valuation of tokens is present on the corresponding input place and the conditional statement (if any) is satisfied.
    - *Firing* event is the occurrence of a transition in an enabled binding that removes tokens from an input place and adds tokens to corresponding output place(s) of the transition. The values of the tokens removed from an input place are determined by evaluating the arc expression on the corresponding input arc. Similarly, the values of tokens added to an output place are determined by evaluating the arc expression on the corresponding output arc (see Figure 29).

The CPNs' features offered a valuable toolset to visually and mathematically represent complex systems in detail. The unique combination of graphical and mathematical representations and a programming language enabled us to create sophisticated models without having to abstract its relevant aspects. Despite that magnificent features, as systems get larger and more complex, the CPNs representing them become less readable and more complicated to trace.

As we mentioned before, disaster response operations involve a set of complicated processes that takes place over different authoritarian and jurisdictional levels. So there are multiple layers of coordination actions happening simultaneously that created a very large and complex system to model using either classical PNs or CPNs alone.

Fortunately, there exist another extension to CPNs, *hierarchical* CPNs, offered mechanisms that enabled us to represent large complex systems aspects (Kristensen, Christensen, Jensen, 1998; Jensen, Kristensen, Wells, 2007; van der Aalst, Stahl, Westergaard, 2013). The hierarchical CPN modeling is also supported by CPN-Tool software (Ratzer, Wells, Lassen, Laursen, Qvortrup, Stissing, Westergaard, Christensen, Jensen, 2003; Kristensen & Wells, 2007), which is a great asset to have to model complex systems such as disaster response operations.

2.2.3.3 Hierarchical Colored Petri Nets

So far classical PNs and CPNs proved to be a useful asset in the world of modeling complex systems for both design and analysis phases, however, in the complex environment of a disaster, there are multiple actions, resources, and actors involved in the response operations simultaneously with different levels of authority. Having the colored tokens and programming languages mechanisms offered by CPNs, it was possible to model the diversified elements involved in disaster response operation ((Huber, Jensen, Shapiro, 1989, Jensen, K., Kristensen & Wells, 2007; Dilmaghani & Rao, 2009; Wei-dong & Zhe, 2011). However, response operations are far more complex due to the involvement of actors from different levels of authority that may or may not belong to the same jurisdictional region (Bammidi & Moore, 1994; Dilmaghani & Rao, 2009; Wei-dong & Zhe, 2011). The *hierarchical* CPNs offered the proper mechanisms to model such complex environment of multi-layer response operations (Dilmaghani & Rao, 2009; Karmakar & Dasgupta, 2011; van der Aalst, Stahl, Westergaard, 2013).

Hierarchical CPNs are another extension of the PNs that allow a modular approach to construct a complex model by decomposing the system to a number of small CPN (Beaudouin-Lafon, Mackay, Jensen, Andersen, Janecek, Lassen, Lund, Mortensen, Munck, Ratzer, Christensen, Ravn, 2001; Ratzer, et al., 2003; Jensen, K., Kristensen & Wells, 2007). In Figure 31 illustrates an example of a hierarchical CPN of a high level representation of a disaster response system.

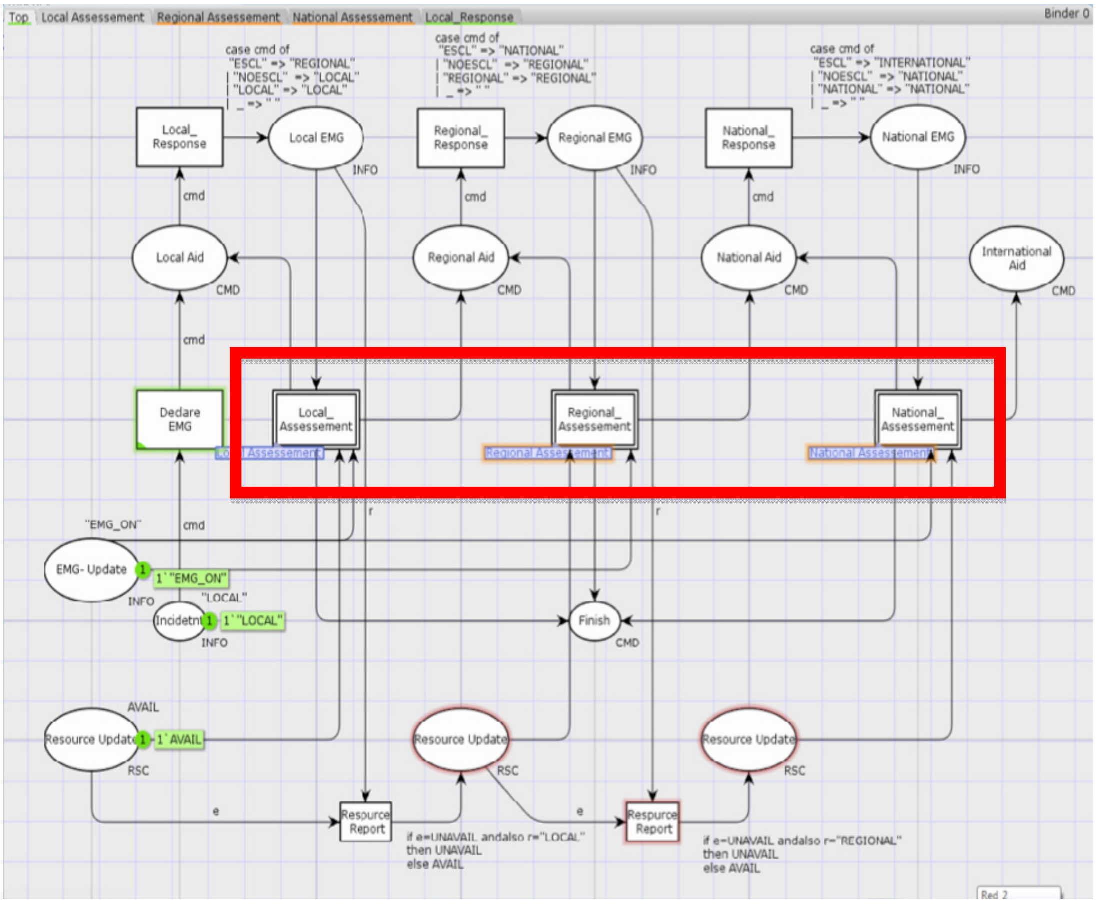


Figure 31. Example of a hierarchical CPN. Model was created using CPN-Tools 4.0.

The transitions inside the red rectangle represent top-level transitions (or called *substitution transitions*). Those substitution transitions encapsulate smaller CPNs that represent sub-processes modeled using CPN and connected through communication sockets to the rest of the system. Hierarchical CPNs are similar to CPNs except few additional features and mechanisms such as the *substitution transitions* feature we see in Figure 31. The main features of hierarchical CPNs are:

- *Substitution transitions and sub-pages* are mechanisms used by hierarchical CPNs similar to Object Oriented Programming (OOP). In OOP we have a top-level abstraction of the system and modules (or classes) used to represent the various aspects of the system such as functionalities, variables and user-defined elements. The system shown in Figure 31 represents the high level abstraction of a disaster response operation. The *Substitution transitions* are the means of communication with sub-systems. The sub-systems are modeled using CPNs and they are called *pages.* Those pages represent a module or a subsystem in the model. The pages (or modules) are connected to each other through *ports*. The concept of ports is similar to defining a class interface in OOP where the socket is used as a communication channel between the module and the rest of the program. Each hierarchy inscription (represented by a substation transition) specifies the sub-page that contains the detailed description of the activity represented by the corresponding substitution transition.

- *Port and socket places* are the communication mechanisms used by hierarchical CPNs sub-systems. Each sub-page has a number of places which are marked with an *In-tag*, *Out-tag*, or *I/O-tag*. These places are called *port* places and they constitute the interface through which sub-pages communicate with the rest of the system. Figure 32 illustrates a sub-page belongs the "*local assessment"* substitution transition in Figure 31. We highlighted the *In-ports* and *Out-ports* that exist in the sub-page.

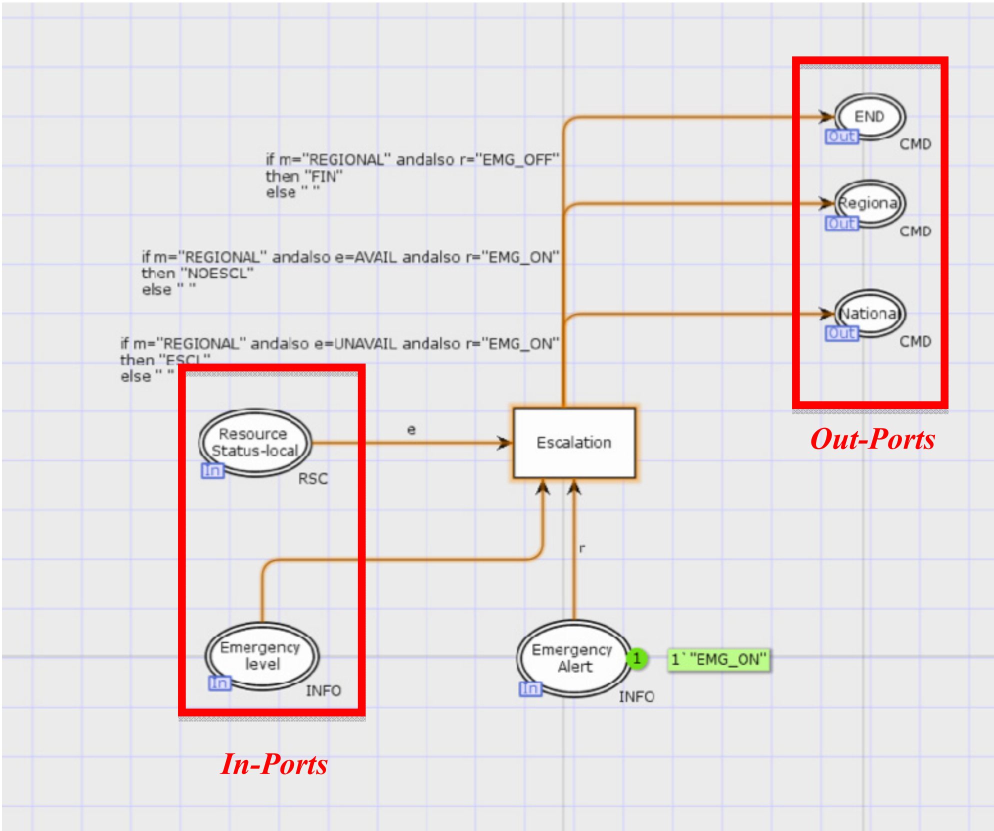


Figure 32. Sub-page associated with *substitution transition* "local assessment" in Figure 31. Model was created using CPN-Tools 4.0.

Through the *In-ports*, sub-pages receive tokens from the system and tokens are delivered to the system through the *Out-ports*. A place with an *I/O-tag* is both an input port and an output port at the same time. When a port place is assigned to a socket place, the two places become identical. The port place and the socket place are just two different representations of a single conceptual place. More specifically, this means that the port and the socket places always have identical markings. When an input socket receives a token from the substitution transition, the token becomes available at the input port of the sub-page, and hence the token can be used by the transitions on the sub- page. In a similar manner, when a token becomes available sub-page on an output port, it becomes available at the corresponding output socket and hence they can be used by the substitution transition.

It is important to mention that relationships in hierarchical CPNs do not translate to a formal relationship in terms of behavioral equivalence between the elements of the system, that is, a substitution transition and its corresponding sub-page. Therefore, the hierarchical concepts of CPNs offer an abstraction of systems at the syntactic rather than at the semantic level. As a result, hierarchical CPNs represent a decomposition of a large complex system from a functional perspective rather than based on the structural hierarchy of its elements.

With hierarchical CPNs we conclude the second part of the literature review that was aiming to discuss main theories and tools applied in the quantitative part of this research and to complement the qualitative part as well.

2.3 Summary

In this literature review, a wide selection of literature was covered, ranging from management and organizational research contents to pure mathematics and modeling literature. We learned that disaster management research goes back to a few decades ago when a Canadian, Samuel Henry Prince, initiated a formal study of *Sociology of Disaster* with his dissertation on Canada's worst catastrophe, the 1917 Halifax explosion (Quarantelli, 2005). Despite the fact, the rapid changes in societies and technologies have generated several gaps between the theory of disaster response systems and the reality on the ground. As a result more research is required to address the various issues related to coordination dynamics, network behavior, interorganizational relations and integration of emerging technologies.

The two stages in literature review were conducted to support a mixed research method approach that consists of a qualitative part and quantitative part. Therefore, the process was adapted to accommodate the needs of such research methodology. In general, this literature review served the following goals:

- Creating a solid foundation that would support this research by understanding the intricate details of disaster management systems and entangled realities of response operations.

- Seeking in depth knowledge of different research approaches, techniques and technologies that exist in the field of disaster management as learn from such past experiences.

- Investigating methods and technologies beyond disaster management to understand ways of analyzing organizational relationships, coordination dynamics and networks analysis.

The literature review process provided a solid foundation to understand the principles and core concepts of disaster management in different countries and political systems (e.g. United States, Germany, Canada etc.). Both Stage-1 and Stage-2 provided a deep knowledge of aspects associated to coordination (i.e. coordination theory and applications), interorganizational coordination and organizational network behavior. Such knowledge leads to the creation of a framework based on coordination theory and network analysis to help investigate the realities of disaster response operations. Although, Stage-2 review aimed to investigate techniques outside the disaster management field to seek tools and techniques to analyze the dynamics in disaster response operations. Methodologies like complex network analysis, community detection and discrete event analysis- petri nets were an outcome of a long process of reviewing various tools used to understand coordination dynamics and operation evolution in organizational relationships.

With this section we conclude the “Literature Review” chapter. Equipped with the outcomes, we move forward to the next chapter, the “Research Design”. In the next chapter we shall discuss relevant issues to research method, data collections, and units of analysis and others.