Applying Complex Network Theory to the Assessment of Organizational Resilience

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Abstract: Recent disasters reveal that crisis can no longer be considered rare events. In these circumstances, the study of those situations demonstrates that there is a need to test and improve organizational resilience. Complex network theory is a methodology that allows us to model organizations and test their resilience. In this work, we analyze the resilience of an organization applying complex network theory to a real case study: an external Nuclear Emergency Plan.

Keywords: Organizational resilience, Complex network theory, Nuclear emergency plans, Nuclear emergency, Communication management.

1. INTRODUCTION

In contemporary societies, crisis can no longer be considered improbable events (Rosenthal et al., 1996). Examples of recent disasters are the accident at TEPCO's Fukushima Nuclear Power Plant (NPP) in 2011, Darfield earthquake in New Zealand in 2010, Hurricane Katrina in 2005 and 11th September terrorist attacks in the United States.

After the accident at TEPCO's Fukushima NPP, it was found out that the offsite emergency management centre lost functionality. This was caused by the unavailability of communication systems, a lack of good implementation of the emergency plan in the public sector, an insufficient assignment of responsibilities, and poor communication, which resulted in misunderstandings. This suggested a review of the communication and management systems (Omoto, 2013). Similarly, the International Atomic Energy Agency (IAEA) stated the need for improvements to strengthen management systems, response arrangements and transparency and effectiveness of communications mechanisms (Langlois, 2013). Zhou et al. (2011) proposed five critical success factors for emergency management, including the structure of the organization, a clear definition of the responsibilities and the effectiveness of the information systems to ensure the transference of information.

These works remark the importance for organizations to test their resilience and robustness, especially regarding to their communication and organizational structure and information management systems. Complex network theory is a useful methodology to model and study the structural and communicative relations in organizations. The idea is to represent an organization as a network composed of the organization's staff (represented as nodes in a graph) and the relations between them (represented as links). This representation allows us to answer the following question: "*Which nodes or links in the network are the most crucial to the network's connectivity if it were removed?*" (Newman, 2003). The answer to this question is a measure of the resilience of the network and therefore of the resilience of the organization.

Here, we focus on how to assess the resilience of an organization by applying complex network theory. The idea is to study the external Nuclear Emergency Plan (NEP) (Spanish Government Gazette, 1985 and 2009). More specifically, we study the NEP resilience against a downfall in different communication channels based on complex network theory.

In the following sections, we will discuss the results obtained by this research. In section 2, we describe briefly the case study and the methodology. In section 3, we study the effect of a collapse in different communication channels in the nuclear emergency management. Section 4 discusses the results obtained and the conclusions of our work.

2. RELATED WORK

Nuclear emergencies usually involve a large number of organizations in separate domains (population, environment, transportation, communications, food, etc.). Therefore, NEPs need to define a number of resources to be committed, a set of actions to be taken, and a communication structure that has to be managed. In this sense, NEPs are one of the most complex emergency plans we may need to manage.

In our previous research (Ruiz-Martin et al., 2014) we built a theoretical model using the information provided by the organizations responsible for NEP in Spain (Spanish Government Gazette, 1985 and 2009). The study identified the people involved in the plan (agents), its organisational structure, their communication (distinguishing the different technologies), and the messages and actions to take before (preventive), during (control and mitigation) and after (recovery) the emergency. We formalized the model and we studied the characteristics and properties of the communication and the command chain network based on complex networks theory to provide some key indicators to improve the NEP resilience, adaptability and responsiveness.

Network theory is a powerful methodology that has been widely applied in other fields with strong interdependence within entities, including Biology (food chains, relations among organisms), Medicine (disease diffusion), Technology (power grids, transport networks), and Communications (World-Wide Web, social networks) (Newman, 2003). It has also been applied to model, compare and study different problems that influence social-ecological resilience (Janssen, 2006). In (Lee et. al, 2013) the authors presented a survey tool to measure the resilience of organizations, and in (Turoff et al.2003) the authors built Information systems for emergency response. In (Lv *et al.* 2013) the authors introduced methods for evacuation management support and in (Hammond et al 2015) the authors studied different alternatives for nuclear emergency evacuation. In (Park *et al.* 2007) the authors proposed a measure to quantify the complexity of tasks in emergencies in NPP. They also found that this measure is correlated with the time to develop the tasks. Bañuls *et al.* (2013) developed collaborative scenarios to assist in emergency planning and to be used as a training tool. Karagiannis et al (2010) proposed a functional-generic model for industrial emergency plans. The authors used the model to perform an iterative risk analysis for the assessment of the robustness of the emergency plans. Mendonça et al (2006) applied gaming simulation to assess decision support system for emergency response. They employ staff from Port of Rotterdam as case study. None of these works tackles the resilience of the emergency communication systems.

3. CASE STUDY

As discussed in Section 1, we want to study the NEP resilience against a collapse in different communication channels based on complex network theory. For this purpose, we study how a downfall in the communication channels changes the structure of the communication network. We also study what are the influences in the command chain network, in particular to see if the failures cause the isolation of some groups or individuals, and to study the consequences.

The communication channels designated in the NEP include wired and mobile phone, fax, special mixed radio-phone networks, satellite, Internet, two different radio channels (Remer & Reman), and direct in-situ communication. Further, military channels can also be used upon request (and they are not available until the infrastructure is deployed). Because of its characteristics, we assume that military channels are used when the communication system fails, and not a communication channel used in the NEP organization.

2.1 Organizational Structure

The structure of the NEP is presented in Figure 1. The chair is delegated on the NEP Director, although higher National Government ranks such Government Presidency can relieve her and assume control. The Nuclear Safety Commission (NSC) President and PENCRA Director are at the same level as the NEP Director. The NSC Inspector at the NPP is in direct communication to the NEP Director. The Advisory Committee has to advise the NEP Director in decision-making. The Information and Communication Cabinet is in charge of communications. The Executive Body has to execute the actions commanded by the NEP Director, and it is constituted by several groups (Radiological, Health, Logistical Support, Public Security and Order, and Technical Assistance and Coordination), each one has a predefined structure and they use different communication systems. Additional Team Leaders from other institutions can be asked to join the Executive Body. (Ruiz-Martin et al., 2014)

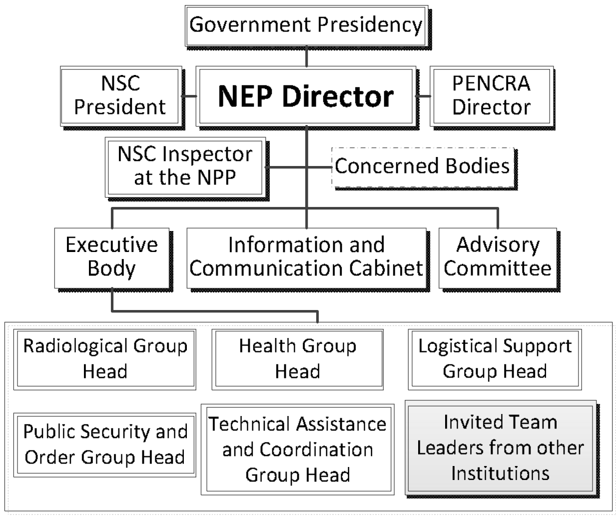

Figure 1. NEP structure

2.2 Communication Channels

The communication channels described in the NEP and involved while managing an emergency are used for both transmitting information and commands. They include:

a) Wired and Mobile Phone Communications

These are the most extended in the NEP. They are used by all groups, based on the structure shown in Figure 1, and the particular structure of each member of the executive body.

b) Fax and Internet Communications

The NEP defines Fax and Internet communications at different levels. They can be used between:

- Technical Assistance and Coordination group following the internal structure.
- NEP Director and the head of the Public Security and Order Group
- Heads of the Public Security and Order Group.

c) Special Mixed Radio-Phone Communications

There are three different mixed radio-phone communication systems, one in the Radiological Group and two in the Public and Security Order Group.

The *Radiological Group* has its own special mixed radio-phone communication system. It only allows communications within the group members. Communications between the head of this group and other members of the executive body have to be by regular phone (wire or mobile), or in person if they are located in the same area.

The *Public Security and Order group* is composed by three different police bodies: Civil Guard, Autonomous Police and Local Police. The two first have their own specific mixed radio-phone communication system (which also supports satellite communications): one for the Civil Guard and another for the Autonomous Police. These systems only allow communications within the members of these bodies. Communications between them have to be made by regular phone, and/or fax if they only involve the heads.

d) Satellite Communications

Satellite communication system only allows communication within the following individuals:

- Nuclear Emergency Plan Director
- PENCRA Director
- NSC President
- Government Presidency
- The city council of a single town located in zone I.

e) Radio Communications

There are two radio channels (Reman & Remer) to be used while managing an emergency. The *Reman* radio channel is used for communications between the following groups or individuals:

- The head of the Technical Assistance and Coordination group
- The town emergency plan heads of zone I. (Zone I is composed by towns at most 10km away from the NPP)
- One of the communication centres of the Public Security and Order group
- The three communication centres of the Technical Assistance and Coordination group.

The communications handled by this radio channel are heard by all the members connected to the network.

The *Remer* radio channel supports the same communications as Reman, but it is extended to the following individuals:

- The town emergency plan heads of the zone II (Zone II is composed by towns between 10 and 30km away from the NPP)
- The town emergency plan teams.

Communications along the Remer channel are heard by all the members connected to the network, but they can also be heard by the population. This issue makes the Remer radio channel not reliable to transmit confidential information. Therefore, some commands and/or information cannot be transmitted by this specific channel.

Despite all the members connected to these two networks can hear the messages, the communications must follow the NEP structure. For example, a town plan head of zone II cannot command or tell information directly to any other town plan head; it must be done by the head of the Technical Assistance and Coordination group.

3. ANALYSIS OF THE RESILIENCE OF THE COMMUNICATION SYSTEM

The communication network in the NEP case study is modelled as a multiplex network composed by 832 nodes (representing the agents or people involved in the nuclear emergency). There are 10 layers representing specific communication channels: fax, Internet, wire and mobile phone lines, satellite, Reman and Remer radio channels, Civil Guard mixed radio-phone network, Radiological Group mixed radio-phone network, Autonomous Police radio-phone network and in-situ communications.

Although multiplex networks are capable of including specific properties in each layer, characterising the interconnections between layers and the appropriate global network description measures is still challenging (Gomez et al., 2013). There have been advances in this area, for example, centrality measures for multiplex networks were proposed (Solé-Ribalta et al., 2014) and visualization software for multiplex networks was developed (De Domenico et al., 2014)

However, in this study we can assume that communication links are equivalent in the sense that all of them allow communications between agents. Therefore, the network will be analyzed as a simplex one. We used the tool Gephi[1] to elaborate network figures and support the analysis process.

We analyze how a downfall in the telephone, satellite and radio communications will change the structure of the communication network, and what will be the influences in the command chain network. We made the following assumptions:

- We group fax, Internet, wire, and mobile phone line under *telephone communication*, as they are supported by the same communication network.
- We do the same with Reman and Remer radio channels, as they are different frequencies of the same communication network. In fact, if we only have one radio device, we can only be connected to a single channel at time.
- We assume that in-situ communications will not fail.
- We assume that Civil Guard mixed radio-phone network, Radiological Group mixed radio-phone network and Autonomous Police mixed radio-phone network are resilient communication systems and would not fail as they are supported by, at least, two different communication networks. The failure of these communication systems implies the inter-

[1] https://gephi.github.io/

ruption of both phone and radio network at the same time. In the Autonomous Police, it implies that the satellite communication system fails too.

For our analysis, the NEP's communication network was considered static. Two scenarios for the analysis were proposed: Scenario 1 represents the communication network once the nuclear emergency has been declared, the Executive Body is assembled but no further action has been taken; Scenario 2 represents a situation in which all teams have already been positioned.

In each scenario, we analyze two cases: Case 1 includes the whole network, composed by 832 agents containing the replacement teams; Case 2 represents the network composed only by the people working at a certain time during the emergency, excluding the replacement teams. This network is constituted by 522 agents.

We will study the effect of a collapse in the different communication channels by evaluating if these downfalls bring isolation to some groups or individuals during the emergency. The metric used for analysis is the number of connected components in the network. The existence of more than one component in the resultant network means that the collapse in that particular communication channel has caused the isolation of some groups.

4.1 A downfall in the telephone communication channel

We have simulated a collapse in the telephone communication channel deleting all the links in the network that only support fax, internet and phone communications.

This downfall carries out the isolation of some individual while managing the emergency in both scenarios and both cases, but the consequences are not the same.

Scenario 1

In Case 1 (including the full network, with replacement teams), there are 214 components in the network. Figure 2 shows the major component in the middle, which is composed by 64.9% of the nodes (540 nodes). In the centre of the major component is the NEP Director. The nodes around the major component represent the isolated teams or individuals. If we do not include the replacement teams (Case 2), this number is reduced significantly to 88 components. In this new case, the major component is composed by the 74.71% of the nodes (390 nodes).

The difference in the number of nodes in the major component between Case 1 and 2 points out that some of the replacement teams are connected to the major component despite the downfall: all these teams belong to the Public Security and Order group.

The isolated individuals or teams, a part of those replacement teams mentioned above, are:

- The Autonomous Police group
- The Local Police group (which is only located in Zone II)
- The Education system (which is composed by the Principals and teachers from the different schools in Zones I and II and the Government Education Supervisor)
- The different ministries involved in the emergency
- The NSC Inspector at the NPP
- The whole Health group.

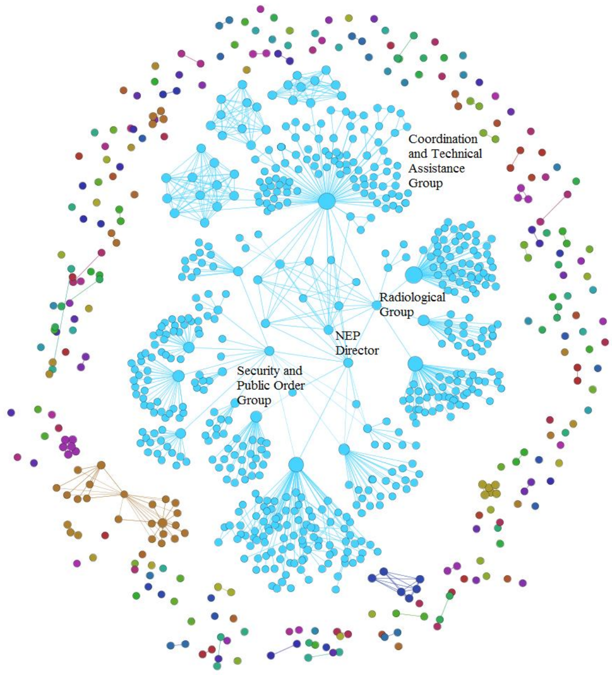

Figure 2. Collapse in the thelephone communication channel. Scenario 1. Case 1

The Health group head is connected to the major component, but the heads of each service, such as the Welfare Service, the First Response Health Service and the Emergency Medical Service are isolated. Each team of these services is also isolated.

Scenario 2

The network in Case 1 has 139 components. The major component is composed by the 83.41% of the nodes (694 nodes). If we do not include the replacement teams (Case 2), the number of components is significantly reduced to 19 components. Figure 3 shows in the middle the major component that is composed by the 96.55% of the nodes (504 nodes). Around the major component, we find the 18 isolated agents

As in scenario 1, we conclude that some of the relay teams are connected to the major component despite the collapse: all these teams belong to the Public Security and Order group.

Once the network is deployed, the number of isolated individual decree considerably, but the isolation problem do not disappear. A part from the relay teams there are other 18 isolated individuals or agents. These agents are:

- The 5 ministries
- The NSC Inspector at the NPP
- The 5 heads of the different services in the health group
- The emergency medical team and the first response health team in the capital of the province where the NPP placed
- One welfare team
- The Government Education Supervisor
- The Local Police heads

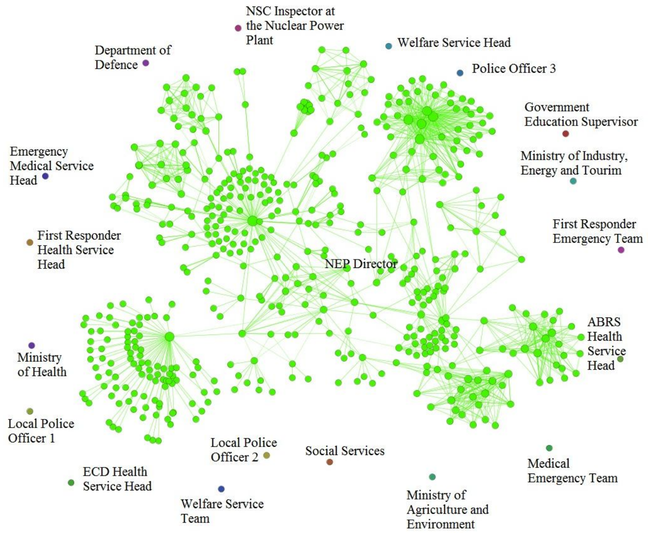

Figure 3. Collapse in the thelephone communication channel. Scenario 2. Case 2

4.2 A downfall in the radio communication channel

A collapse in the radio channel does not affect the structure of the network, as the number of components remains one in all scenarios. That means that the radio channel is redundant.

This communication channel has some drawbacks:

- In the area where the NPP is located, there are areas without radio Remar coverage due to relief.
- The radio device which connects to the Raman radio channel is only located in the city council of the municipalities in Zone I.

4.3 A downfall in the satellite communication channel

The number of components in the communication network remains one in all scenarios when a downfall in the satellite communication channel occurs. This demonstrates that it is also a redundant communication system.

The drawback of this redundancy than it is not an extended communication network. It only supports the communications between five nodes: *Nuclear Emergency Plan Director, PENCRA Director, NSC President, Government Presidency and the city council of a single town* and the Autonomous Police. Moreover, four of the five nodes connected by this network are high ranks and three of them only have to be informed (they do not take any action).

This network does not support important communications between land agents, who are responsible for taking the actions to solve the emergency, and their supervisors, except those from the Autonomous Police.

5. CONCLUSIONS

In this study, we demonstrate that the NEP communication network is resilient against a collapse in the satellite and radio communication channels, but it is not resilient against a downfall in the telephone communication channel, which includes communications via wire and mobile phone, Internet and Fax. A collapse in the telephone communication system will trigger important consequences.

First, the replacement of teams will only be possible within the Public Security and Order group, because the other replacements teams will not be able to connect to the communication network and they will not be able to receive the orders to take action.

Since the NSC Inspector at the NPP is isolated, there would not be in-situ information about the evolution of the incident at the NPP. This causes that the contra measures taken outside will be defined with obsolete information. We have to remark that the telephone, which connects the NPP to the NEP director, is a special cable line, which only connects these two individuals. A lesson learned is that we should define redundant communication mechanisms between the inside of the organization and the out-side management systems.

When the Local Police is isolated, the only way to receive orders is through the Civil Guard. It means that the Civil Guard must move to meet the Local Police. It causes an increase in the time and the complexity of the communications.

In Scenario 1, the isolation of each member of the health group provokes that the teams would receive neither the instructions about the actions to be taken nor the information about the evolution of the situation. This can cause several problems such as the paralysation of the teams. The lack of information and a command chain may carry that each team take their own decisions, which could be accurate or erroneous.

This problem is partially mitigated when the network is deployed and the in-situ communications are added. In this new situation (Scenario 2), the heath group teams cannot communicate with their supervisors. They receive information and orders from the Public Security and Order group teams. The consequence is that both the time and the complexity in transmitting information/orders increase: the communication instead of taken 3 steps would take at least 5.

Not receiving feedback is also a key issue. Feedback about the execution of the actions taken by the Local Police or the Heath Group teams would not often be communicated as it can only be done through the Civil Guard.

The isolation of the Government Education Supervisor in both scenarios and the isolation of the school Principals and teachers in Scenario 1 have special importance only if the scholar centres have to be evacuated. In Scenario 2, the evacuation will probably be handled without any problem since the Civil Guard and/or Local Emergency Teams will communicate the order. However, in Scenario 1, the Civil Guard has to be positioned, so the action will be delayed. In both cases, the Education Supervisor would not have information about the evolution of the emergency.

The isolation of the five ministries implies that the NEP Director cannot ask them if she needs information or their support in different issues.

The isolation of the Autonomous Police in Scenario 1 implies that the NEP Director could not have the assistance of this group until the Civil Guard is deployed, they activate their satellite communications and/or the in-situ communications appear.

We have demonstrated that efforts to improve the resilience of the telephone communication network are needed. It is not necessary to duplicate the whole network. However, the addiction of alternative means of communication to the individuals isolated in the network will facilitate the emergency management. In future works, we will consider the dynamics on the network and we will develop simulation tools to provide cost-effective and agile ways to stress and evaluate emergency plans.

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